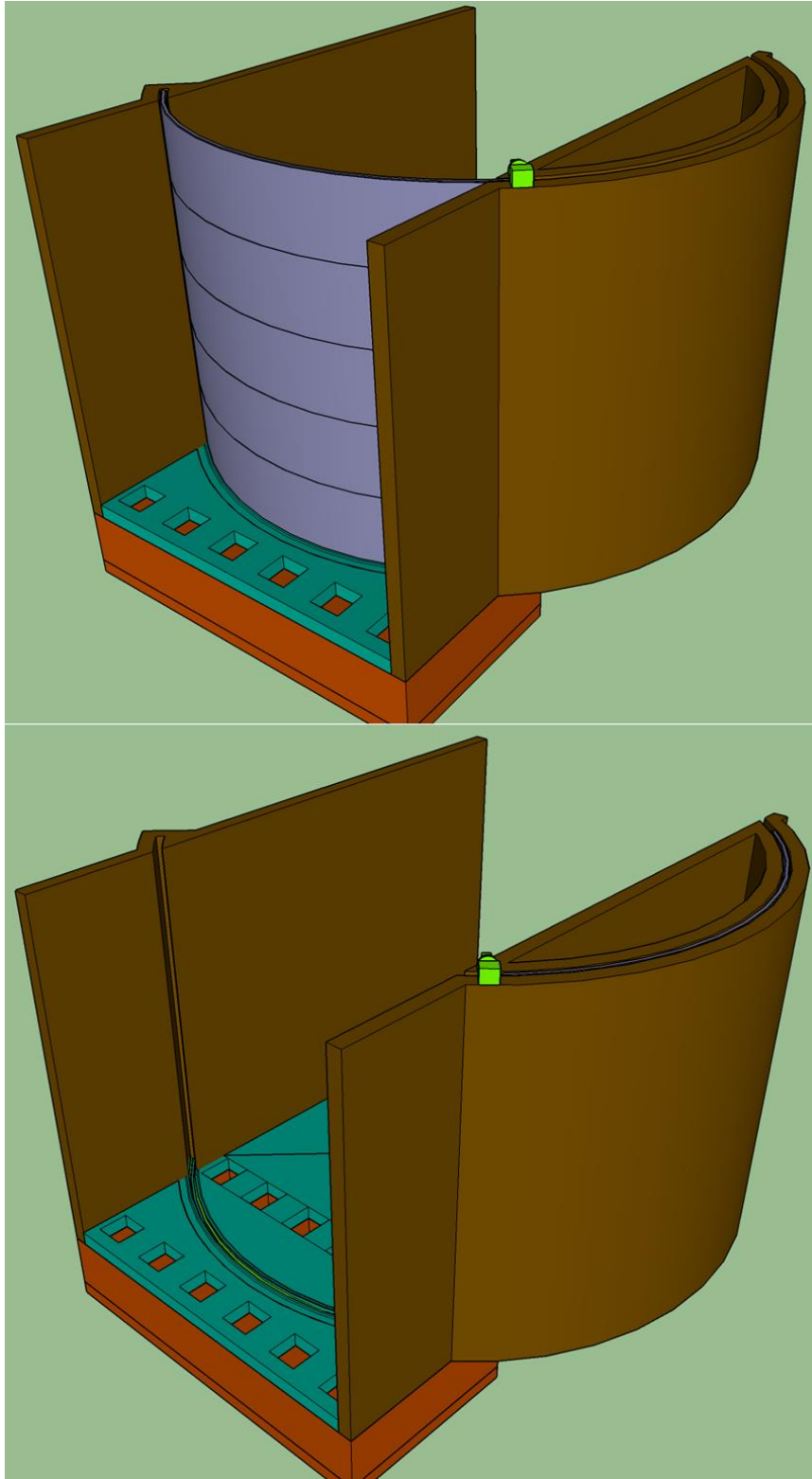


ROAD TOWARD A STANDARDIZED LOCK GATE

DESIGN OF A CONCRETE MODULAR ROLLING ARC GATE



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ABSTRACT

Goal and motivation

Between now and 2040, 52 locks will need to be replaced. Rijkswaterstaat has noticed that the current contracting method results in many differences between locks. These differences cause high maintenance costs and a low predictability of the (availability of) locks. The solution could be standardisation of locks. Counterarguments for the standardisation are the presumable over-dimensioning and lack of incentive for innovation.

Two studies that have done predictions on how much value (a reduction on the total Life Cycle Costs of the lock arsenal) could be gained from standardisation have shown different results. One of them showed a great amount of gained value while the other study concluded no increase in value by standardisation, mainly due to over-dimensioning. However, the increase in predictability was noted in the latter study as a reason to decide to still standardize locks. Hence, the decision is made to find a standard for a lock.

Lock gates are the part of a lock for which the alternatives are abundant and the potential value (reduction of costs) of standardisation could be surprising. This makes that they are an interesting choice to design a standard for. To also negate the counterargument about innovation, the goal is set to designing an innovative standard for a lock gate.

Zooming out on the Dutch waterways – standardisation by adapting the boundary conditions

From the perspective of the whole waterway system, some standardisation solutions can be found. One of the solutions is to restructure the waterway network in such a way that it is categorised in less CEMT-classes. This solution will require many locks (and the waterways going to and from those locks) to be upgraded to higher CEMT-classes. Cost efficiency can then only be reached if these upgraded waterways will also be actively used by bigger ships.

The waterways can also be adapted by rerouting waterways that have many locks in them, the new waterway could then be created in such a way that only at the start and the end of that waterway a lock is required. Besides, these new waterways can then be placed in an optimized way for the current and future Dutch situation. Though there are examples of this rerouting, it is presumably too expensive for most situations to be feasible. Hence, standardisation on bigger scales is not possible through this solution.

The last solution is on a corridor scale. One could opt for changing the water levels on several corridors so that they will all have the same head differences at the point where a lock could be installed. Also this solution is thought too expensive to use solely for the purpose of standardizing locks. Mainly because water level changes also have effects on ground water levels surrounding the waterway. A lot of effort is required to make sure the negative effects are negated.

Standardisation of the lock

On lock level, one of the options to standardize is by applying a grid. The lock can then only be designed larger (or smaller) by steps of the grid size. All elements within the lock can then be designed accordingly and are applicable in every other lock of the same grid measurements. Applying bigger

grid sizes will result in a more significant economy of scale. However, the over-dimensioning disadvantage of standardizing will also become more significant. Hence, a good balance should be found.

Another option is to build a lock from smaller building blocks. Each bigger component, like the lock gate, lock head or lock chamber, would then be built from smaller parts that can be easily connected. These smaller parts should be big enough to make fast assembly possible but small enough so that no specialised machinery is required. These blocks should also be small enough to allow for flexibility in combining more of those blocks to create bigger components; or combining less of those blocks to create smaller components. This should result in an optimum where mass production of the building blocks including installation, transportation and possibly maintenance could result in a cheaper alternative than having a specialised component for each lock.

The last option is to standardize certain components of the lock. Some components are more standardisable than others. Cable housings, lightning, signalling and boarding components are examples of parts that are already standardised or else should be standardised. Other (mostly bigger) parts, like the lock heads, the chamber and the lock gates are more dependent on the boundary conditions. If those are standardised, they will still require different dimensions for different boundary conditions.

Because the goal is to find a standard for a lock gate, a part of the lock that requires different dimensions depending on the boundary conditions. The decision is made to build the lock gate from building blocks, hence combining the latter two options (standardising a component and building it from blocks). The lock gate could then be made smaller or bigger depending on the situation by assembling the right amount of building blocks.

Gate choices

Currently, most lock gates are mitre gates. In some situations however the gate choice will deviate from this because of a much wider than usual lock or because the lock gate is also loaded with a negative head. To find a possible standard for the future, many different concepts are looked into.

The gate is chosen on the basis of its innovativeness (being relatively unexplored and having some points on which a cost reduction or increase in reliability might be found). This criterion is set to look outside of the basic gate types in the hope to find a gate that may be useable and ideally more feasible (when applied as a standard) than other gates in a wide range of situations.

Another point on which the gate concepts are assessed is the possibility to build the gate from modules without reducing its structural integrity; or increasing the costs beyond the point where gains from the resulting standardisation are nullified. This criterion is required because of the decision to make a modular gate.

Innovativeness

The mite gate types, as the most widely used gate type does not fit the innovative criterion; neither do the flat gate types and the tainter gates as they are also widely applied gate types. Their uses are already proven and depending on the situation one of these gate types is applied. Through the innovative criterion the idea is however to find something better than what already exists.

This is where the arc gate type may find its use. It is a gate type that bears the hydraulic pressure by normal stresses that flow through the curved gate to the lock head. This elegant flow of stresses in

contrast to the stresses resulting from moment- or shear forces, results in much lighter designs for structures, as should also be the case with lock gates.

Though, as with mitre gates and depending on the curvature, there will, besides transversal forces, be lateral forces going into the lock heads. Lock heads that need to bear both lateral and transversal forces are more expensive than lock heads that only need to bear transversal forces. This, as well as curvatures being harder to build precisely, could give the arc gate type a slight disadvantage over the flat gate types, even though the gate itself is lighter.

Modules

The mitre gate does not lend itself to be modularized because of the hinged connection with the lock head, mostly only at the top and bottom of the gate. All modules in between the connected modules will then need very stiff and well applied connections, which could make the construction and installation relatively expensive. The same reasoning is applicable for tainter gates, which also have more complicated structures behind the gate plating, making modularising these gates even harder.

For the flat gate types and the arc gate types, the possibilities for modularisation are better, though it is dependent on how they move. A single leaf pivot gate has the same disadvantage as mitre gates for example. In contrast the lift gates, rolling gates and drop gates can be modularised quite easily. Modules can, in these cases, be placed relatively easily on top of each other with little notches that bring over any shear stresses that may be present between the modules. The bottom module(s) will then bring the resulting vertical forces to the lock bottom. For lift gates it may be somewhat more laborious to connect the modules as this gate will be pulled up when opened.

Decision

Combining the potential innovativeness of the arc gate and the possibility of building the gate from modules from the rolling gate, the decision is made to design a modular rolling arc gate.

On top of that, the material to design the gate with will be Ultra High Performance Fibre Reinforced Concrete. This choice was made in the context of innovations and a personal preference to design the gate in a, for gate design, aberrant material.

Gate design

Only the bottom module, on which the hydrostatic water pressure is at its highest, will be calculated, because this is most likely the governing situation for a module. The modules above will have the same properties as the bottom module.

Loads

The loads on the gate are given by the hydrostatic water pressure, the self-weight, the buoyancy force, the wave load, the wind load, the forces from gate movement and possibly the collision of a ship.

On the bottom module, the governing load situation (in a closed situation) is given by the hydraulic water pressure, plus any wave pressure that is still present at the bottom of the gate. In the top module, ship collision will become the most important part of the governing load situation. An initial estimate of the ship collision force resulted in a much lower load than the hydrostatic water pressure on the bottom module. Hence, the top module(s) will be able to bear this force, given that they are loaded by a smaller water pressure, while having the same properties as the bottom module.

Interaction between the gate and the lock head

The most important part of the modular rolling arc gate is the support in the lock head when closed. This has to be designed in such a way that the gate clamps into the lock head and forms an arch-like structure wherein normal forces are governing.

The support reactions of the lock head on the lock gate were modelled with three different methods that would cover the real situation as good as possible given the available software. One of these methods turned out to simulate the gate as an arch-like structure with governing normal forces while the other two methods resulted in governing moment forces that were as high as they would have been if the gate was flat.

Without scale model or something similar, there turned out to be no way of knowing if the gate would really act like simulated in the one method that simulated the gate as an arch-like structure. Also, displacement analysis of the gate near its supports, did not give results that would indicate that the gate would really be supported by the lock head through clamping between the gate recess walls.

However, the forces obtained from the model do match expected forces if the gate were modelled exactly like an arch. Hence, this model is used in further designing the gate. But it must be noted that it could not be proven whether the supports are correctly modelled. Because both, the displacement analysis resulted in much smaller displacements of the gate in the recess as expected, and the direction of the support reactions is input in the model, where this is actually unknown (the reason why first 3 methods were tried to model the gate).

Gate module design

The modules are dimensioned based on their global buckling resistance and the hydrostatic water pressure. A high redundancy is taken into account for other loads and load factors that need to be taken into account when the modules are optimized. This resulted in a very thin hollow cross section with a width of 0.15 m and a wall thickness of 0.03 m. Spacers are added every 2.5 m between the walls of the cross section to enhance the wall buckling resistance.

To make the simulated support reactions more likely, some notches are added to the modules, and the lock head. These notches need to be big enough to bear the forces in a closed gate situation, but small enough for the gate to freely move between them when the gate is not loaded.

When doing strength checks for the moment resistance, the applied cross section turned out to need a reinforcement ratio of 7.0 %. Also, the normal stresses in the walls resulting from the moment present in the gate, exceeded the wall buckling strength. The relatively high reinforcement ratio and the exceedance of the wall buckling strength, led to the conclusion that the current design is not sufficient.

Solutions like increasing the thickness of the modules or filling the cross section will increase the stiffness of the gate. This would result in a reduction of the clamping at the supports because the gate will not bend enough to reach all of the support points. Hence, the concept of a concrete arch gate that clamps in the gate recess is technically unfeasible.

Getting a standard on the market

Having gotten the idea of a modular curved lock gate (or anything else) as a standard for future lock gates, it will need to be implemented and used on a large scale to reach benefits of economies of scale. Three methods of implementing such an idea have been compared.

The first method is by imposing (parts of) a design. As a big client that deals with many structures of the same type, one could decide that every one of these structures will be built exactly the same. This is on the scale of one client, the easiest way to come to a standard. Though, it may result in a reduction in innovations and will likely not result in a wider application range besides the client himself.

The second method is by letting several alliances of companies in cooperation with governmental bodies develop the new standard in competition with each other. This would give more room for innovations than imposing a standard would due to the sharing of knowledge. But this method most likely comes with complicated contracts and a low design efficiency, because several groups of people/companies work on the same project simultaneously while not cooperating.

The third method is designing in the open. This can be done in several ways ranging from only openly sharing conceptual sketches to having a full working model of the project and all its details online, even when it is still in development. The standard will, in this way, be developed with the community, of which everybody can give input and share knowledge, giving the most widely accepted standard possible (in theory), which is its biggest advantage. The disadvantage lies in the difficulty of filtering input from different persons that may not be compatible or even contradict one another.

When comparing the methods, it can be reasoned that imposing a design will be the easiest way of beginning to implement a new standard, though the scale at which the standard is applied will not likely grow larger than the client himself. In contrast the scale at which a standard can potentially be applied is much greater in open design, though the process of implementing the standard takes much more effort/time.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Surface area of a cross section	[m ²]
A _s	Cross sectional area of reinforcement	[m ²]
A _{turb}	Surface area of the turbine	[m ²]
a ⁺	Gate acceleration	[m/s ²]
a ⁻	Gate deceleration	[m/s ²]
b	Module height	[m]
C _C	Configuration coefficient	
C _E	Coefficient of eccentricity	
C _s	Softness coefficient	
D	Ship draught	[m]
d	Water depth	[m]
E	Young's modulus	[kN/m ²]
E _{kin}	Kinetic energy	[kNm]
F _c	Maximum compressive load = $f_{cd} * A$	[kN]
F _{c1} ¹	Support reaction parallel to lock axis and with a positive hydraulic head	[kN]
F _{c2}	Support reaction perpendicular to lock axis and with a positive hydraulic head	[kN]
F _{collision}	Collision force	[kN]
F _{f1,2,3}	Gate rolling resistance during movement at supports 1, 2 and 3	[kN]
F _e	Euler buckling load = $\frac{\pi^2 EI}{l_k^2}$	[kN]
F _{max}	Buckling capacity	[kN]
F _R	Axial compressive or tensile force in the lock gate	[kN]
F _{R1}	Support reaction parallel to the gate longitudinal axis	[kN]
F _{R2}	Support reaction perpendicular to the gate longitudinal axis	[kN]
F _{t1}	Support reaction parallel to lock axis and with a negative hydraulic head	[kN]
F _{t2}	Support reaction perpendicular to lock axis and with a negative hydraulic head	[kN]
F _{v1,2}	Vertical support reactions at the sides of the gate from its carts	[kN]
F _{v3}	Vertical support reaction at the middle of the gate from its carts	[kN]
F _w	Gate mechanism pull force	[kN]
f _{cd}	Design compressive stress of material	[kN/m ²]
F _e	Euler maximum load = $\frac{\pi^2 EI}{l_0^2}$	[kN]
FRP	Fiber Reinforced Polymers	
F _{max}	Buckling strength	[kN]
g	Gravitational acceleration: 9.81	[m/s ²]
H	Arch height	[m]
H _t	Head (as a function of time)	[m]
HPC	High Performance Concrete	
I	Second moment of Area	[m ⁴]
k _{fender}	Fender stiffness	[kN/m]
L	Ship length	[m]
LCC	Life Cycle Costs	
l	Span	[m]
l ₀	Effective buckling length	[m]
M	Moment	[kNm]
M _{max,span}	The maximum bending moment that occurs along the span of the gate	[kN]
M _{gate}	Mass of the gate	[kg]

¹ See Figure 22

MWW	Multiwaterwerk	
m_s	Mass of the ship	[kg]
m_w	Mass of the water moving with the ship = $\rho L \frac{1}{4} \pi D$	[kg]
N_c	Force in compressive zone	[kN]
N_{buckII}	The buckling stress capacity of the module walls	[kN/m ²]
$N_{RdbuckII}$	The total buckling strength of the module walls	[kN]
P_1	Hydrostatic water pressure from convex side of the gate	[kN/m ²]
P_2	Hydrostatic water pressure from concave side of the gate	[kN/m ²]
P_s	Resultant hydrostatic water pressure	[kN/m ²]
Q	Discharge (as a function of time)	[m ³ /s]
q	Line load (resulting from the hydraulic head)	[kN/m]
q_{sw}	Self weight as seen from the side/front	[kN/m]
r	Gate radius	[m]
RINK	Risico Inventarisatie Natte Kunstwerken	
RWS	Rijkswaterstaat	
s	Length of gate curvature and distance it has to translate	[m]
T	Time per locking cycle	[s]
T_w	Wave period	[s]
t	Thickness module	[m]
t_w	Thickness module web	[m]
UHPC	Ultra High Performance Concrete	
VONK	Vervangingsopgave Natte Kunstwerken	
v_s	Velocity of the ship	[m/s]
v_{max}	Gate top speed	[m/s]
w_0	Deflection in the middle of the gate	[m]
x_u	Height of compressive zone	[m]
α	Surface factor of the compression zone	
ΔH	Head difference between the two sides of the gate	[m]
ρ	Density of water: 1000	[kg/m ³]
ρ_s	Reinforcement ratio	[%]

TERMINOLOGY

Gate	The watertight door which seals off the chamber from the upper and lower pounds
Arc-	A gate that transfers loads to its supports mainly through compression or tension
Guillotine-	A gate translating from above the lock to in the lock when closing and vice versa when opening
Mitre-	A set of gates that close in a V-shaped form, often pointing towards the upper pound in order to let the water pressure seal the gate
Hydraulic head	A measurement of liquid pressure expressed as a surface elevation in meters
Negative-	The high water is on the concave side of the gate
Positive-	The high water is on the convex side of the gate
Innovation	The process of translating an idea or invention into a good or service that creates value or for which customers will pay
Evolutionary-	Innovations brought about by many incremental advances in technology or processes
Revolutionary-	Also called discontinuous innovation, an innovation that is disruptive and/or new
Parallel axis	The axis parallel to the ship movement direction in the lock chamber
Perpendicular axis	The axis perpendicular to the ship movement direction in the lock chamber
Pound	The level stretch of water between two locks
Rise	The difference in water level over the lock, also called lift or head difference. The rise causes a hydraulic head over the lock/lock gate

1 INTRODUCTION

1.1 BACKGROUND

From now until 2040, Rijkswaterstaat (RWS) foresees the need to replace 52 locks [1]. Part of these locks lack capacity [2] and another part is reaching the end of their technical design life [3]. Several initiatives have already analysed (part of) the problem, namely RINK (Risico Inventarisatie Natte Kunstwerken) and VONK (Vervangings Opgave Natte Kunstwerken). The focus of these studies lies on all Dutch hydraulic structures, not just the locks. These studies listed which hydraulic structures needed to be renovated/replaced based on their structural integrity and capacity.

In 2011 the first initiative for the project Multiwaterwerk (MWW) is formed by Rijkswaterstaat during a LEF session, which is a sort of brainstorm session. This project does focus solely on locks and attempts to find cheaper ways of building and maintaining locks through standardization. The project published its results in the report *Multiwaterwerk, verkenning vervangingsopgave van de natte kunstwerken* on which the Werkgroep Innovatieversnelling later published a second opinion [4].

Multiwaterwerk estimates that standardization of (parts of) the locks has a net value ranging from €13 million to €197 million [5],[6]. The maximum net value is, according to the source, reached when replacing all locks that are in need of replacement (52, see above) through the Multiwaterwerk project; when this project is deployed optimally; and when savings on upgrade costs are taken into account. (The upgrade costs are the extra costs for upgrading a lock to an increased capacity, say 25 years after it was built, instead of when the lock functions for its full design live.) The minimum net value is reached when only a limited amount of locks can be replaced through this same project and when Multiwaterwerk is deployed suboptimal due to constraints, and when savings on upgrade costs are not taken into account. How Multiwaterwerk came to these estimates can be seen in Appendix D.

In contrast to the value estimated by Multiwaterwerk, Slijk [7] shows that the net benefits of standardizing locks may as well be zero in terms of net present value. The difference can be found in their respective estimates of savings on maintenance and upgrading. According to Slijk [7], they are around €16 million while the estimates by Multiwaterwerk are ranging from €35 million to €140 million [5] – see Appendix D – not including upgrading estimates.

Hence, the magnitude of the savings by standardization seems to be quite uncertain. Both studies however, conclude that standardization is the way to go because of an overall increase in predictability and therefore an increase in availability. Even if the net benefits in terms of currency are zero, neither Multiwaterwerk nor Slijk [7] think that it will result in more costs.

Another benefit of standardization of locks indicated by RWS is that it lowers the capacity pressure of the construction industry. It is questionable whether there are enough specialists, or is enough capacity at contractors to actually replace these 52 locks before 2040. As standardized elements are potentially quicker to build and install, partly due to a learning curve [8], they can help reduce the required capacity.

Hence, in the report from Multiwaterwerk and predecessors thereof, it becomes clear that Rijkswaterstaat wants to standardize locks. The standardization of locks will herein mean that the amount of lock types and sizes are reduced and the locks – or certain parts of locks – will be build according to generally accepted and uniform designs, in type as well as in size.

In conclusion, Rijkswaterstaat – in collaboration with other companies involved in MWW – concluded it can save a lot of money by standardizing locks, while Slijk [7] found the effect of saving money to be only zero to marginal but stated that the other benefits for standardization could still set the balance in favour of standardizing. This idea that standardization will have an overall positive effect – if done in the right way – will be the starting point of this study. One of these ways will be elaborated in this report and several parts where another way of standardizing can be taken will also be discussed.

1.2 PROBLEM ANALYSIS

1.2.1 PROBLEM DESCRIPTION

Over-dimensioning is one of the main drawbacks of standardization, it is estimated to cause extra costs in the order of €10 million - €20 million over all locks to be replaced [5], [7]. For instance, a set of locks is designed with one standard design that fulfils the highest requirements present in the set. That design could be optimised for the locks with lower requirements with loss of the standard. The other choice is to keep the standard and use the more expensive choice, e.g. heavier doors, thicker walls, different hinges etc. This is the type of over-dimensioning that causes these extra costs.

Over-dimensioning may however not be a big disadvantage; it may even become an advantage if it is done for the whole waterway. This would cause the waterway to become accessible to bigger ships, if the channel is (made) wide enough. The investments – made by the government – required for making these bigger locks including widening and deepening the waterways will primarily flow back as profits for owners of the bigger vessels. It will also make local economy more accessible and reduce the amount of trucks required to supply this local economy. This results in a balance between the increasing investments for bigger locks and waterways and the increasing net worth of the named advantages.

Over-dimensioning can also happen on a smaller scale where it has no positive effect on the capacity of the lock. Namely the structural aspects, like how much material is used in each element of the lock, are prone to this type of over-dimensioning. A standard will require an element to meet the highest requirements in the series where the standard is applied, while a specialised element may, on its own, be much cheaper when designed specifically for the lower requirements that are present for another lock in the series.

Another set-back of standardizing locks can be the reduction in innovations. When a standard is developed, it generally does not allow for a lot of innovations outside of it. It is harder to compete with new innovations from outside of the standard because applying new technologies is often more expensive than existing ones due to for example, a learning curve. These new technologies still have potential to become cheaper on the long run.

From the perspective of standardization, innovation in itself also brings a difficulty. When the 52 locks that need to be replaced are replaced in the coming 25 years, and each few years some new

ideas appear that are integrated in the newer locks, possible standards become hard to maintain and the arsenal of different lock types will be as big as it is now. So each innovation needs to be assessed on its expected net worth with respect to the loss of the standard.

To get the best of both worlds, a good balance between innovation and standardization is required. If a standard allows for too much innovation, the benefits of maintaining a standard become nihil. If a standard allows for too little innovation, we will keep using the same locks for years after a standard is set, which may be much more expensive than new state-of-the-art locks.

So from this, the question arises if a standard lock can be designed that has limited extra costs from over-dimensioning and allows for innovation. It should be noted that an innovation should add value to something, either through cost reduction or through added functionality. This is an addition to the basic meaning of an innovation where it just means ‘something new’, that is also adapted by Businessdictionary.com [9]. This addition prevents the discussion that innovations should be done to add value and not just to be innovative and instead defines an innovation as such.

1.2.2 STAKEHOLDERS

Rijkswaterstaat

In general the goal of Rijkswaterstaat is to prevent congestions and improve accessibility in order to let people and goods reach their destinations in a safe and fast manner [10]. They also need to protect the Netherlands against high water and make sure enough clean water is available. Maintaining, upgrading and replacing locks are part of this job. For this goal, Rijkswaterstaat has a limited amount of money available.

So their main interest in lock standardization is to reduce the life cycle costs (LCC) of locks. Also improving the predictability of the LCC of locks is an important aspect. Some of their studies – through Multiwaterwerk [4] – have concluded that standardization of locks will result in reduced LCC. Hence the wish for standardization comes from Rijkswaterstaat.

Provinces

Counties also have water management – including that of waterways – in their portfolio. This means that their interests are the same as that of Rijkswaterstaat, or at least comparable. As counties have a smaller arsenal of locks to maintain, they may not have found a problem with all the differences between locks. They are also less interested in a corridor as a whole.

Municipalities

Even some municipalities have locks in their arsenal. Their main job is to do the tasks that are directly in the interest of their population. Their concerns will thus probably be whether their population has any hindrance from the new lock with respect to the old ones, or from the construction itself. Also municipalities do not have such a big arsenal of locks that standardization becomes part of their agenda.

Engineering firms

They want to show that they can design the most efficient locks in terms of costs (mainly construction but dependent of the contract, also maintenance costs or even the LCC), least amount of hindrance and ship passing times. Their motivation towards being the best on any of those aspects is still greatly dependent on the way the project is tendered. E.g. if the contract automatically goes to

the cheapest tender while there is only a requirement that states that ships need to be able to pass in an x amount of time, the engineering firms will come up with the cheapest lock that can lock a ship in x amount of time, hence innovations on locking times are not stimulated. However, by designing a new innovative lock they may be able to draw attention towards them to get more interesting assignments.

Engineering firms will probably be against standardization of locks. Each time a new lock can be designed, they get the possibility to compete with others and prove themselves as the best. When locks are standardized, fewer designs have to be made and thus less work for- and less potential for innovative ideas from, the engineering firms.

Contractors

During the tender process contractors want the construction costs to be low and the predictability of the costs to be good with respect to other competing contractors. If they also need to maintain the locks, they would want the maintenance costs to be low (and predictability of the costs to be high) too. Lowering these costs gives them a competitive advantage over other contractors. Standardisation is an aspect that can help with lowering these costs and improving the predictability, though with national/global standardisation this goes for all contractors, so with respect to each other no one gets the advantage.

So contractors will only really benefit from standardisation if they get several similar projects so that they can themselves apply a standard and use it in their construction process. This would give the bigger contractors a competitive advantage over the smaller ones because they have the capacity to do more projects in the same time frame and thus have a bigger use of the economy of scale.

After winning the tender process and signing the contract, applying an innovation or even finding cheaper components and/or producers may lower the LCC. This increases the profits from the project and it gets them a competitive advantage over other contractors when tendering the next projects. This freedom to apply an innovation or looking for other producers and components will be gone when the standard is to be maintained.

Contractors are thus expected to only want a standard when they get some guarantee that they can also do future projects, or a compensation for using the, for them, more expensive standard.

Government

As the final payers representing the whole country, they want a good balance between LCC, reliability, innovation and trade within the country. In this, innovations could and should in future projects increase reliability and reduce the LCC.

A good standard can improve this balance by lowering the LCC and improving the reliability and by improving the reliability of locks, the trade within the country.

Shippers/users

They want hindrance to take as short as possible. Their interest will be in short construction times, reliable locks, low locking forces and fast passage times for the completed locks. Hence, shippers will advocate everything that results in more cost effective transport.

Through standardization, a learning curve in construction may appear, reducing construction times after some locks have been built. However, a standardized design may also be less optimal in construction time (but also locking forces and passage times) than a lock specially designed (including its construction sequence) for that location.

The preference on the shippers will therefore depend on the balance between standardization and optimised design.

1.2.3 PROBLEM DEFINITION

Too many different types of locks are recently built. 52 Older locks are in need of replacement. A good lock standard that does not undermine innovation or competition is lacking.

1.3 GOAL

The goal is to design a lock gate that can be used as the future standard of lock gates. A lock gate design that fulfils this goal, will be one that has a wide application range and causes limited extra costs from over-dimensioning, making the LCC of all locks combined lower. As a secondary goal, the lock gate needs to be innovative.

These goals do not solely result from the problem definition, as then, before deciding to design an element (such as the lock gate) one would first need to make an estimate of where the most value can be gained from standardisation and innovation. The reasons to zoom in on the lock gate and to make it innovative, will be explained in the next sections.

1.3.1 LOCK STANDARD -> LOCK GATE STANDARD

Slijk [7] already made an estimate of where the most value from standardisation can be gained. His thesis work resulted in the conclusion that standardising movement equipment is most desirable, followed by the control system and the gates on a shared second place.

The Eindhoven University of Technology also has a project running called the Lock system analysis project [11]. This project consists of identifying lock objects that have a significant impact on reliability and availability; and identifying lock objects and interfaces that are candidates for standardization.

Hence, in expectation of the results from the study from the Eindhoven University of Technology the focus is set on the lock gate here, partly from personal preference and partly because Slijk [7] concluded the lock gates to be a fairly desirable element of standardisation. Also my expertise and master track is neither on the movement equipment nor on the control system.

1.3.2 INNOVATIVE

Because it is often said that innovation should not be the goal but instead should be the means to reach a goal, it is somewhat peculiar to state as the secondary goal that the lock gate design should be innovative. It is also said that the lock building industry is usually quite conservative. So either there is no goal (or problem) in place that requires innovation, or the current lock designs cannot be improved upon. This means here that there are no innovations that would result in an upgrade from the perspective of the stakeholders that have a say in the design.

This whole thought process about innovation results in an downwards spiral: when there is no innovation there is no means to realistically set progressive goals and when there are no progressive

goals there is no reason to innovate because there is no problem (i.e. the goals are automatically reached). To break this spiral and to challenge my creativity the secondary goal is set to design an innovative lock gate.

1.4 RESEARCH QUESTIONS

1.4.1 *WHO WANTS TO HAVE A STANDARDIZED LOCK DESIGN AND WHY?*

The answer gives the reason for achieving the standardisation part of the previously set goal and knowing who would be seeing the most value in it. And thus for who and why the goal should be reached.

Answering this question was a great part of Sections 1.1 and 1.2. Therefore it can be concluded here already that having a standardized design is a wish from the big governmental bodies that have to manage a large arsenal of locks. In the Netherlands that would be Rijkswaterstaat. The wish comes from estimates that concluded a reduction in LCC and an increase in reliability.

1.4.2 *CAN CHANGES TO THE NETWORK OR CORRIDORS IMPROVE THE ABILITY TO STANDARDISE?*

This question will be answered in Chapter 2. From a top-down analysis of how to standardize locks, the network/corridor level is the first part. The current network consists of many different locks, for a great part (but not exclusively) because the boundary conditions vary per location. To name a few: a different rise¹, different traffic intensities, different soil conditions, different ship sizes etc. So: can we make changes to (some of) these conditions to make it more feasible to have a standardised lock?

1.4.3 *WHAT SHOULD BE STANDARDISED ON LOCK LEVEL AND HOW?*

This question will be answered in Chapter 3. This is the second step of the top-down analysis. The background behind this question is that even when different locks are subject to comparable boundary conditions, they may still vary in dimensions (less likely) and design (more likely). These variations can have several reasons ranging from functional reasons, like variations in prices over time and optimization of the design for each project to reduce the LCC on these projects; to non-functional reasons like different project teams with different preferences. To give a (fictional) example of the last reason: one team can tender in a way that favours durability of the structure more, while another team at the same client tenders in a way that favours sustainability of the project more.

To remove these reasons for having different locks, even with comparable boundary conditions a certain awareness of the advantages of standardisation and how it can be done needs to be created. Leaving the quantification of the advantages in terms of LCC of the whole arsenal of locks to the cost experts and the previously mentioned estimates from Multiwaterwerk [4]. The awareness of how to standardise will be created here by answering what to standardise (dimensions, certain elements/components) and how to do it.

¹ The rise is the change in water level over the lock. It is also often called the lift or head difference. The rise causes a hydraulic head over the lock/lock gate.

1.4.4 TO WHICH BOUNDARY CONDITIONS AND REQUIREMENTS WILL THE STANDARDISABLE LOCK GATE BE SUBJECTED?

This question will be answered in Chapter 4. It is stated in the Goal already that it is a personal choice to design a standardisable innovative lock gate. The first step in the design process is to know what the design is for. By getting to know the boundary conditions and requirements the design process is started. Appendix E shows a flowchart of the design process for the preliminary design as sketched in source [12]. The flowchart is accompanied by commentary indicating which parts of the process are a part of this thesis and which are not.

1.4.5 WHAT ARE THE CURRENT CONCEPTS FOR LOCK GATES AND HOW CAN THEY BE USED TO CREATE AN INNOVATIVE STANDARD FOR A GATE (A.K.A. TO REACH THE GOAL)?

These questions will be answered in Chapter 5. The second step in the design process is to determine and compare the several alternatives, which is done by answering what lock gate concepts there are and comparing them on the aspects of innovativeness and possibility to standardise. The result is a choice to further develop a certain concept.

1.4.6 HOW CAN THE CHOSEN CONCEPT BE IMPROVED?

This question will be answered in Chapter 6. The third step in the design process is to evaluate the chosen concept. This is done by asking experts what they think about said concept and evaluating the strong and weak points of the concept. The result is knowledge on how to develop the concept further.

1.4.7 HOW IS THE CONCEPT TO BE DEVELOPED FURTHER?

This question will be answered in Chapter 7. Here the lock gate and its surroundings will be designed and materialised, the fourth step in the design process.

1.4.8 HOW CAN THIS STANDARDIZED DESIGN BE IMPLEMENTED?

This question will be answered in chapter 8. When having made a new standard element, the problem arises that it must be implemented in the upcoming 52 lock projects. With the current design & build contracts being used that only specify functional requirements to tender; and where the projects get a lot of different contractors that do not share information a standard cannot be implemented without additional measures. So what methods can be used to still implement the standard? Three methods will be listed and compared in Chapter 8 to answer this question.

1.5 REPORT STRUCTURE

In the report some choices will be made as presented in Figure 1. Chapters 1, 2, 3 and 5 are represented by a choice tree. The choices that are made in this report are green. They will be discussed in their respective chapters. The goal that is set in Section 1.3 is already based on the choice to standardize the lock gate.

Chapter 4 describes a case on the basis of which the boundary conditions on the lock gate are set, which helps on the decision for a gate type in Chapter 5. In Chapters 6 and 7 the conceptual design and a more detailed design are made respectively.

Chapter 8 is the final chapter that discusses how the standard, which this report will help develop, could be implemented.

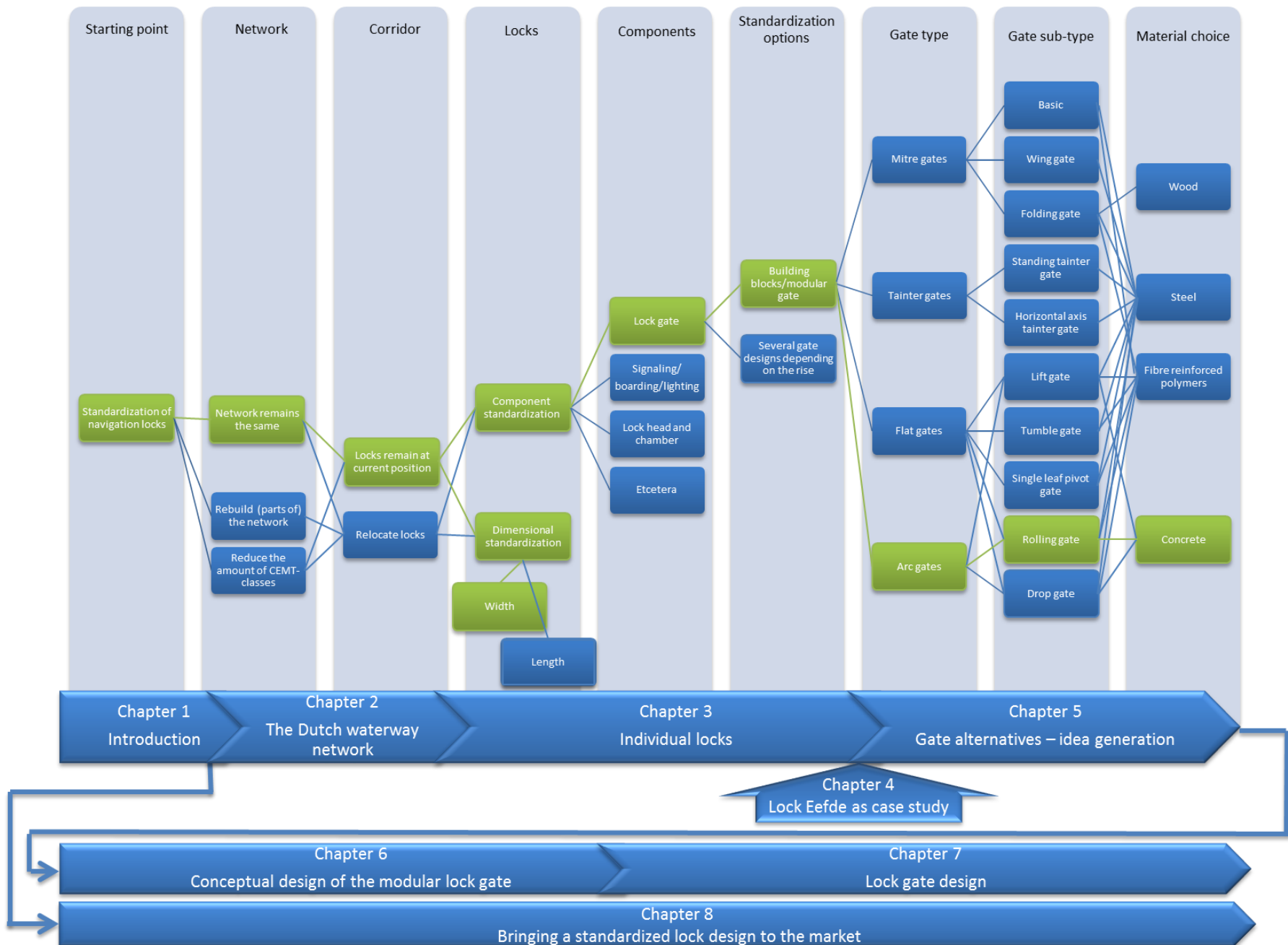


FIGURE 1 – REPORT STRUCTURE

2 THE DUTCH WATERWAY NETWORK

2.1 INTRODUCTION

This chapter will describe the current waterway network. It also discusses the effect that large and small scale changes in this network will have on the water management and infrastructure in the Netherlands. With large scale changes, the re-arrangement of the waterways is meant in order to come to a situation where less locks are needed or where locks can become much more similar; while with small scale changes, the changes on corridor level are meant: mainly changes in locations and numbers of locks.

2.2 NETWORK CHANGES

Currently, the Dutch waterways look like in Figure 2. This is a network that developed naturally over time through interactions between nature and humans. First only rivers were present around which villages and cities emerged. Those natural waterways were the only waterways present at that time. Over time people started improving this network by creating short connections between those natural waterways. Later, people also started creating longer channels that functioned as shortcuts in rivers or as completely new waterways. [13]

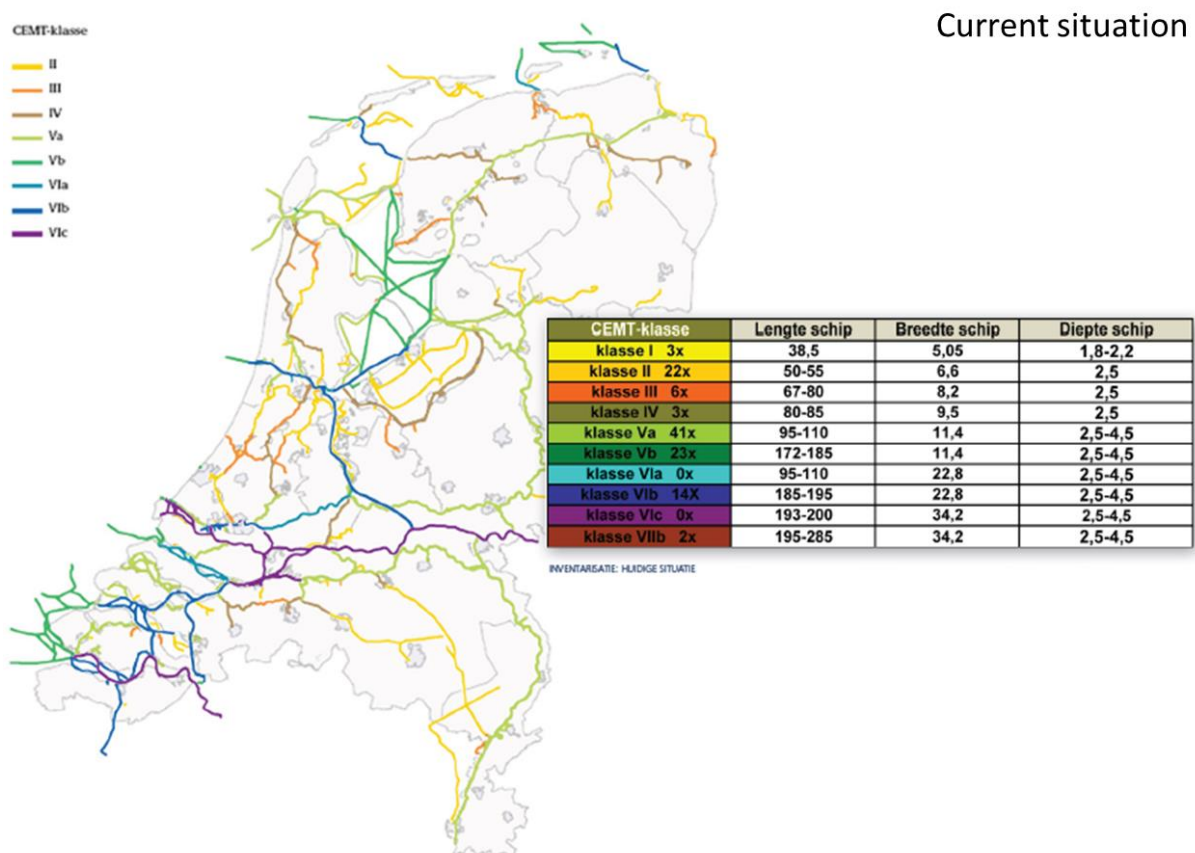


FIGURE 2 – CURRENT SITUATION DUTCH WATERWAYS, SOURCE: [4]

A major change in the system that is proposed by MWW [4] is a reduction in the amount of CEMT-classes to which the waterways will be dimensioned. This will result in something like is shown in Figure 3.

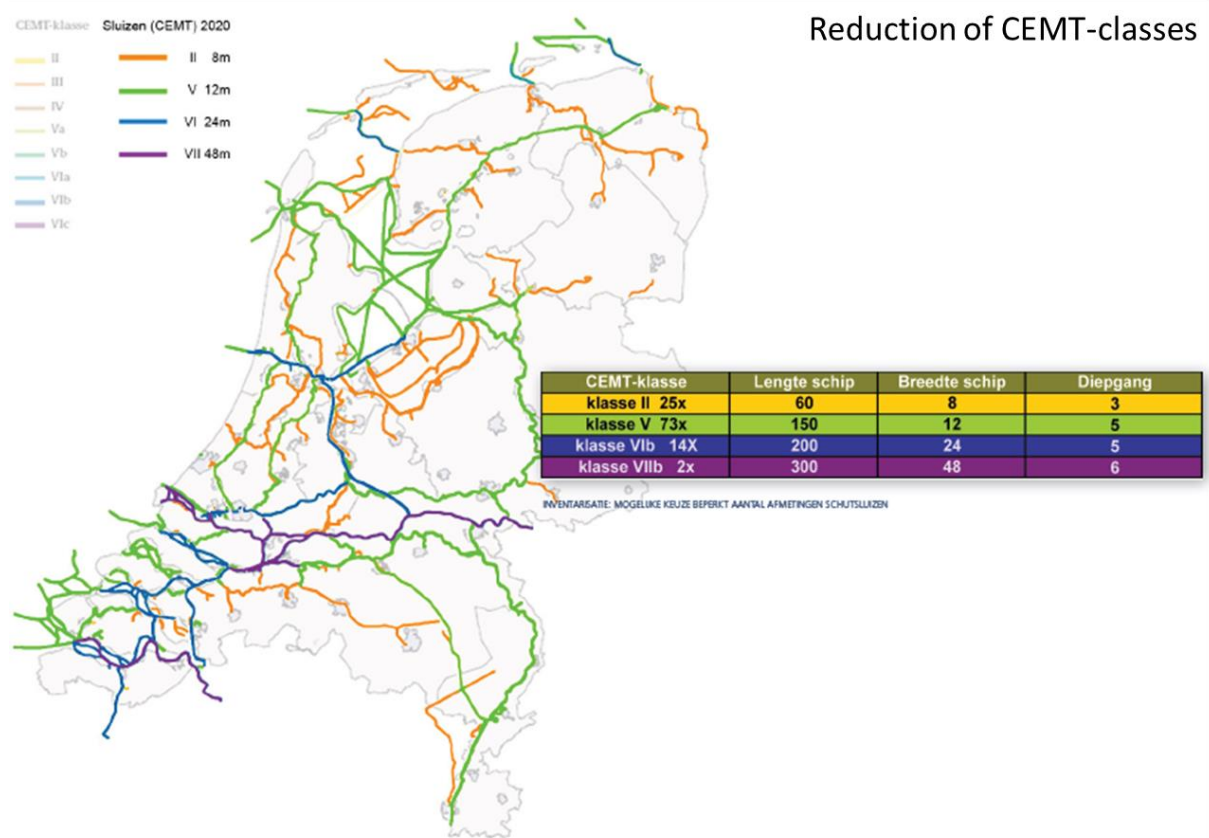


FIGURE 3 – POSSIBLE FUTURE SCENARIO AFTER REDUCING THE AMOUNT OF CEMT-CLASSES, SOURCE: [4]

Changes on this scale require the greatest amount of financing. One of the main costs factors will be over-dimensioning of locks. In the example from the figures, a large part of the 52 locks will eventually be replaced by locks of a bigger CEMT-class. This results in extra construction costs, maintenance costs and higher amount of locking water which can also negatively influence the passage times for ships.

The waterways in which the locks go up one or two CEMT-classes also need to be adapted to those bigger ships, which is the other main cost factor. This is in order to at least make use of those bigger locks and have the advantage for shippers that they can make use of more waterways within the network to reach their destinations with bigger ships.

A project of this scale will require a thorough cost/benefit analysis. The costs will be the extra costs to install bigger locks with respect to installing the minimum required lock for its life cycle. Besides, the widening of the waterways will result in a large sum of investment costs. For the benefits (i.e. more waterways available for bigger ships) a market research needs to be done to see if shippers really have need for these extra waterways. Part of this will be to express time and fuel savings for the shippers in financial gain. Also, the potential reduction of road traffic through increasing the waterway capacity is an important benefit.

Such an investigation will be outside the scope of this graduation work but is a recommendation for future projects.

Another large scale change one might think of, is rearranging the waterway network in a way that less locks are required or that more waterways will have the same requirements for their locks and thus can have the same locks.

Rearranging the waterways is done in the past to connect rivers and it is still done for other reasons too. A Dutch example is the Zuid-Willemsvaart [14]. The reasons for rearranging the waterways are in these cases far greater than reducing the amount of locks. In cases where rivers are connected for transportation purposes, even some locks need to be added.

In the case of the Zuid-Willemsvaart the two main reasons were to: 1. Make local industry more accessible over water by also making the new channel wider and deeper. 2. Get the bigger ships out of the city 's-Hertogenbosch and in this way prevent congestions due to open bridges. Widening the channel would also be near impossible inside the city. Reducing the amount of locks or creating a project in which standardization of locks is searched through creating several locks with the same rise is thus not even mentioned as a reason. It can however still turn out to be a positive side-effect.

This kind of change will be extremely expensive and is hardly applicable when applied solely for the reasons of going to a situation where less locks are required, or where a LCC reduction of the locks can be created through building several of the same lock. This is because the waterway network is closely linked to other infrastructure, cities and villages around it. So changes to a waterway should have a positive effect on the (link to) other infrastructure, cities and villages first, before considering applying those changes for the purpose of LCC reductions of the total arsenal of locks.

2.3 CORRIDOR CHANGES

On a smaller scale, one can think of replacing 3 locks with a different rise to 3 locks with the same rise (Situation 2, Figure 4) or 2 locks with the same rise (Situation 3, Figure 4). In this case the boundary conditions will be the water level and bed level on the sides.

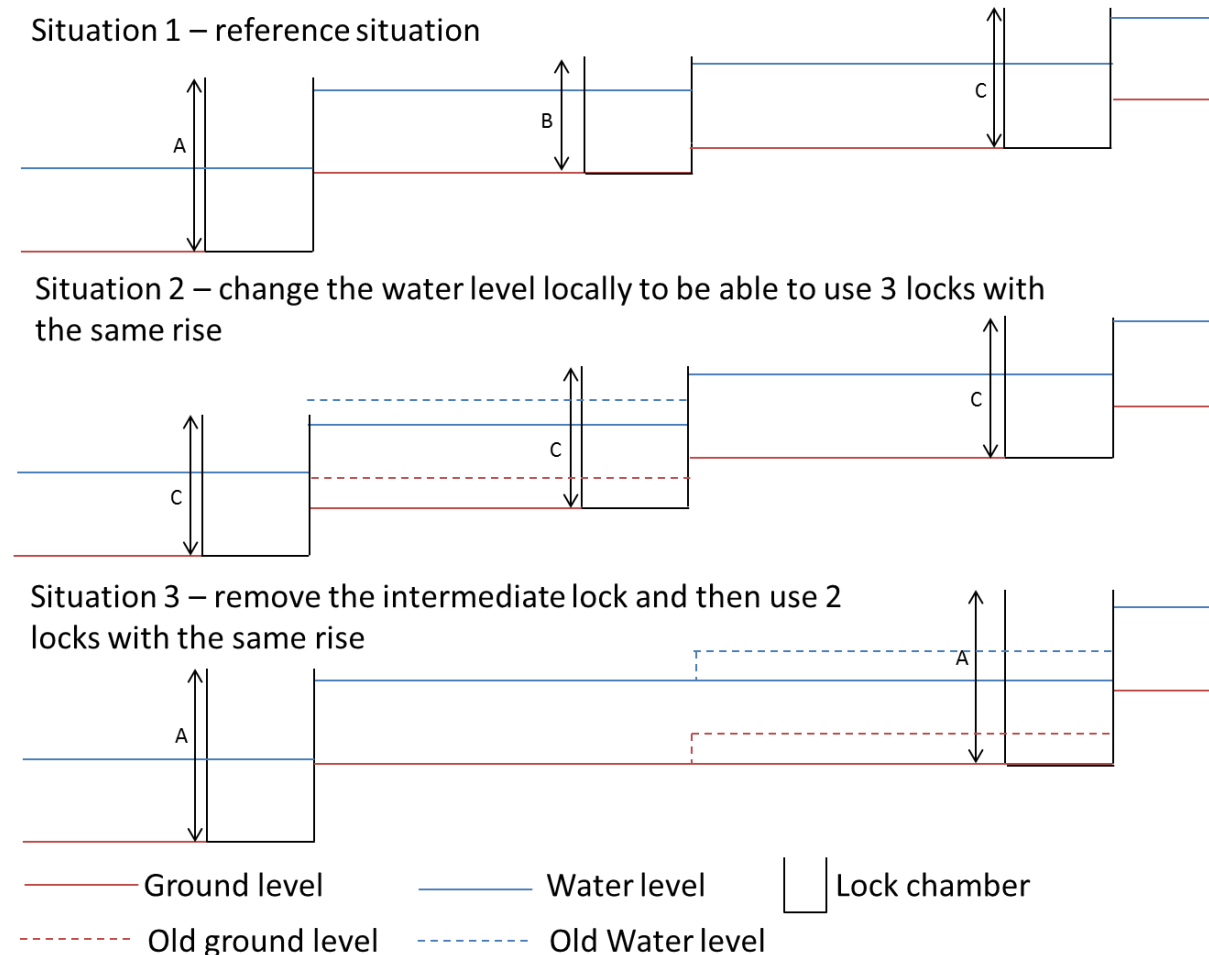


FIGURE 4 - CHANGES IN WATER LEVEL AND NUMBER OF LOCKS, SIDE VIEW OF A WATERWAY; THE SAME LETTERS INDICATE A COMPARABLE DOOR HEIGHT

In this example, in Situation 2, a higher rise is bridged at the middle lock and a lower rise is bridged at the left lock. This will result in a lower water level between the left and the middle lock. Situation 3 results in a lower water level between the original middle lock and the right lock. The difference in water level in comparison to the reference situation is bigger in situation 3.

Such water level changes can negatively affect the surroundings. For instance one can think of foundations of structures near the waterway that are sensitive to water level changes or the local flora and fauna that requires a certain water level to be maintained.

It may be worthwhile to investigate the possibilities for these water level changes, as especially in Situation 3 a lot of value may be gained from reducing the number of locks. Savings can come from less maintenance, less construction costs, increased standardization and increased reliability. Also shippers have to go through less locking cycles. Disadvantage is that less water is saved in the upper waterways.

An example of the application of situation 3 is Verbreiding Wilhelminakanaal [15]. Here, two existing locks are replaced with 1 lock with a higher rise. The one difference with situation 3 as is shown in Figure 4, is that the remaining locks do not have the same rise.

When looking into this example, one can find out the problems that can arise due to the water level changes, actually do arise. To mitigate those effects, a water infiltration system will be built in such a way that current ditches, canals and ponds are supplied with as much water as they lose through seepage. At present this water infiltration system turned out not to mitigate the described negative effects enough – a new study found that there was more seepage than expected from an earlier study – so other alternatives are investigated.

Due to the significance of the negative effects induced by changes in water levels, it can be concluded that these types of solutions can only incidentally help to reduce the amount of locks and/or standardize (the remaining) part of the lock arsenal. If (parts of) locks that are directly dependent on the rise are standardized nonetheless, this standard will need to be flexible for the purpose of varying head differences because changes in the water level are normally not feasible.

2.4 CONCLUSION

Changes in the network or corridors cannot be used to improve the ability to standardize locks. They are expected to be much more expensive than what they may save in costs through standardization. However, when changes to the network or corridors need to be made on the basis of other argumentation, it is helpful to check if they can be made in such a way that several of the same locks can be built.

Chapter 3 will go more into detail on the standardization options of locks.

3 STANDARDIZATION OF LOCKS

3.1 INTRODUCTION

Chapter 2 discussed methods of standardizing lock design that made changes to the whole network or (parts) of corridors. This would result in creating the same boundary conditions in which to create the lock at several locations and in this way standardize locks (creating the same lock over and over again by making changes in the environment).

It is probably much easier (and cheaper) to either standardize only the parts of the locks that are not so much influenced by the environment, or to also standardize also the influenced parts but make that those standards are flexible. E.g. the height of the lock chamber is dependent on the rise, but one could make standard lock chambers of different heights varying in steps of 1 m.

This chapter will discuss how these locks can be standardized and which parts may benefit the most from standardization.

3.2 DIMENSIONAL STANDARDIZATION OF THE LOCK

In a natural design process, the lock dimensions and number of chambers would be determined according to these parameters [12]:

- The intensity of navigation volume (navigation supply and pattern)
- The assignment of vessels over the lock complex
- The dimensions of the normative vessel
- The fleet composition.

In theory the passage time of ships is also part of the considerations for the dimensions of locks. In practise this does not vary enough to have a significant impact on the lock capacity. So normally when designing a new lock the capacity is increased by increasing the dimensions of the lock chamber and thus the number of ships that can pass through in one locking cycle. After that, this capacity may be fine-tuned by reducing the passage time through either a faster closing mechanism of gates, improving the filling times through the use of culverts or applying mechanisms that make it easier and thus faster for ships to navigate in, moor and navigate out of a lock.

There are several methods for dimensional standardization of locks. The grid and the building blocks will be discussed.

3.2.1 GRID

A grid can be used on the scale of the full lock in order to come to a smaller amount of differently sized locks. By using a grid, dimensions can be set, e.g. at squares of 75 m by 6.25 m – based on half the width and half the length of a lock dimensioned solely based on the dimensions of the governing CEMT-class Va ship [16]. Such a grid will make sure that the elements and components within the lock can be standardized to match the steps by which the lock can be dimensioned larger.

A grid will also allow for some flexibility with respect to setting the dimensions of the full lock as a standard. One could – with the example grid – decide to make the lock 3 blocks wide and 2 blocks long in order to facilitate small ships next to the class Va ship, as can be seen in Figure 5. When only one class Va ship needs to be facilitated at the same time, the lock will be built 2 blocks wide and 2 blocks long.

Possible lock dimensions when based on a grid of 75 m by 6.25 m

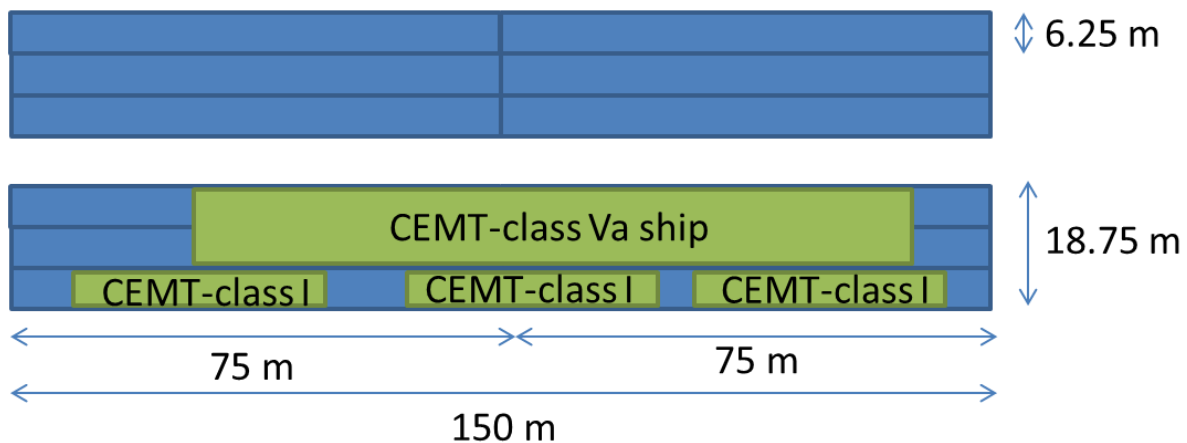


FIGURE 5 – A LOCK DIMENSIONED WITH THE EXAMPLE GRID IS IDEAL FOR A CEMENT-CLASS VA SHIP AS WELL AS WHEN IT WOULD NEED TO FACILITATE CEMENT-CLASS I SHIPS NEXT TO IT

Disadvantage of a grid, especially of this size, is over-dimensioning. Say, on another location a 14 m wide lock is required. Through the standard this example grid forces, the resulting lock will be 18.75 m ($3 \times 6.25 \text{ m}$) wide, which is much wider than actually required. This over-dimensioning reflects back on the gate size, lock head size, the amount of locking water required, etc. This somewhat extreme example intuitively shows that such a standard grid of this size is not feasible.

A much smaller grid can also be used, say a grid of $100 \times 100 \times 10 \text{ mm}^3$. The advantage of this grid will not directly result in the standardization of a lock. It can however result in a reduction of construction errors due to differences in the size of elements being easily recognizable. It is recommended to weigh the benefit from a reduction of construction errors against potential over-dimensioning caused by a grid before choosing to apply it.

3.2.2 BUILDING BLOCKS

Building blocks will mean that an element of the lock (e.g. the lock chamber) can be built from specialized modules. The modules or building blocks will all have the same size and are interchangeable over different locks. So as example, in one lock it could be possible to stack 2 of these modules to create a lock chamber wall. While in another lock that is twice as high, it could be possible to stack 4 of these modules. For an impression of a lock build from building blocks, one could take a LEGO lock as an example, see Figure 6.

The advantage is that those blocks can be placed in mass production which will give advantages on construction time through a learning curve and the re-usability of equipment (and possibly even of the blocks). Two aspects that combine into a disadvantage are that the connections between those

blocks may form a weak spot in the design; and transportation and installation of big blocks (reducing the amount of connections) is fairly difficult.

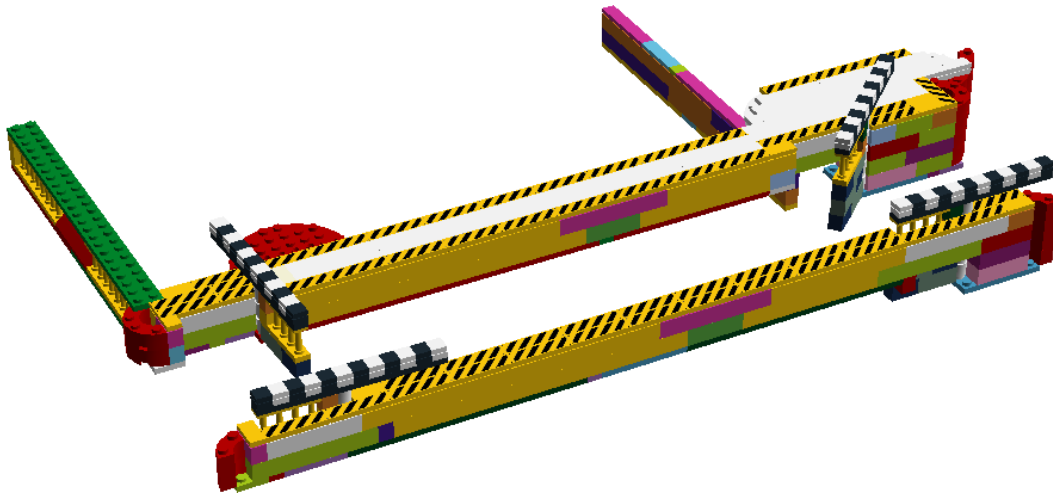


FIGURE 6 – LEGO LOCK CONSISTING OF BUILDING BLOCKS, SOURCE: [17]; NOTE THAT THIS EXAMPLE IS IN NO WAY MEANT TO MAKE BELIEVE THAT AN ACTUAL LOCK COULD BE BUILD OUT OF LEGO STONES

Hence, when building blocks are chosen as a way to standardize locks, an optimization will need to be done between the risk of leakage between those blocks on one side and transportation, production and installation costs dependent on the shape and dimensions of those blocks on the other side.

When the shape is determined while the scale is not, such an optimization will look as shown in Figure 7 (example not based on any data). Depending on the quantification of this optimization the result may look very different. The graph represents the costs of the whole element depending on the size of the building blocks with respect to the element size (blue vertical line). When the building blocks become too small, the costs rise due to high production and installation costs and due to the risk of leakage of the element (every block has to be connected with each other). When the blocks become too big, the costs may rise again due to installation costs because of heavy equipment that may be needed to carry and connect them.

When the element in a different lock has the need for 2.5 blocks instead of 2 or 3, such an element is most likely more expensive than an element build out of 2 or even 3 blocks, because the production needs to be adapted to building half blocks. These inconsistencies are left out of the graph. When choosing to build the element out of blocks, it is probably best to over-dimension the element instead of building blocks in multiple scales to fit each element perfectly. So the graph is only made to be able to fit considerations of whole blocks, without inconsistencies due to the creation of scaled down blocks.

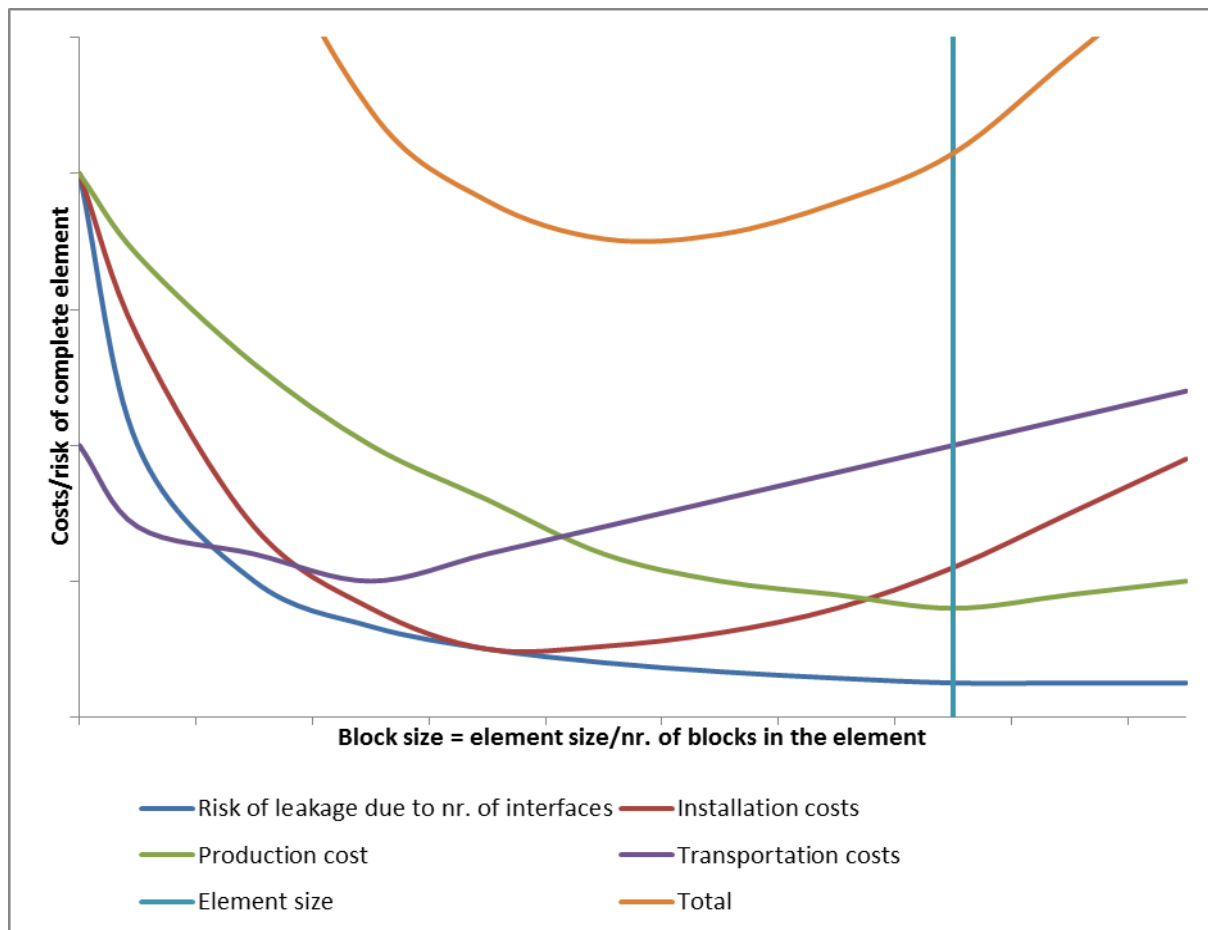


FIGURE 7 – OPTIMIZATION OF BUILDING BLOCK SIZE – THE VERTICAL LINE INDICATES WHERE THE ELEMENT CONSISTS OF 1 BLOCK; THE HORIZONTAL AXIS HAS AN INCREASING BLOCK SIZE AND THUS A DECREASING NUMBER OF BLOCKS THAT AN ELEMENT IT BUILD OUT OF WHEN GOING TO THE RIGHT

3.3 COMPONENT STANDARDIZATION

The components of a lock can be listed as is done by MWW: in classes depending on whether the component could be integrated as a standard; or should be an option; or be part of the integration of the lock on its site and thus be fully customizable (Table 1). The following sections will list if, how and why standardizing some of those elements is beneficial.

TABLE 1 – OBJECT CLASSIFICATION MWW, SOURCE: [5]

Standard	Options	Integration
• Heads • Gates • Walls • Floors • Cable housings • Levelling system • Control • Steering • Guidance • Lighting • Signalling • Boarding • Energy supply • Mooring facility in lock chamber • Mooring facility outside lock chamber	• Pumps • Sluice • Fish migration • Energy production/turbine • Fresh-/salt water separation • Control building • Remote control • Shorepower • Recreational facilities • Collision prevention system	• Outport • Berths • Fendering • Crossing dry infrastructure • Screens

3.3.1 STANDARD

Under the standard, the facilities are listed that are present in (almost) every lock.

Heads

A navigation lock has two lock heads. The lock heads facilitate the gate and its moving mechanisms. The lock gates determine the design of the lock head. On the basis of the dimensions of the lock gate and the forces that it introduces into the lock head from the loads on the gate, the dimensions and required strengths of the gate recesses, the gate moving mechanism and the lock head are determined.

Two lock head construction methods can be distinguished:

- In-situ construction of the lock head creating one element, this method can benefit from dimensional standardization with reusable formwork, thus saving costs on formwork.
- Construction of a precast element that is the whole lock head. This method can benefit from a well settled dimensional standard.

Though, because the lock head facilitates the gate; a consequence is that if the gates are not standardized, the head needs to be flexible (and the other way around). So one cannot be standardized (or designed) without the other.

Gates

Slijk [7] concluded in his report that the most value of standardization can be found in the lock gates and its moving mechanics. The mechanics are also heavily correlated with the gates. Three options to standardize lock gates can be distinguished:

- Construction of multiple gates with the same dimensions – only possible if the requirements (the rise and lock head width or minimum passage width) are the same or if the different requirements can be matched with the same gate. For instance, by over dimensioning for the less governing requirements.
- Design multiple gates with intermediate steps in its height and width that match different requirements in the rise and the lock width.
- Construction of a modular gate: modules made of a standard shape form the basis, by joining them, higher and/or wider gates can be built.

Dimensional standardization of the lock (head), namely its width, helps to limit the amount of different gates or modules required for the second and third option. But there are still many variations in the rise of a lock, which as discussed in Chapter 2, is not (likely) feasible to adapt. Hence, it is more important for the gate standard to allow for different heights than for different widths.

A relatively big (high) gate cannot be fitted in a small lock and the economies of scale become relatively small when designing and building multiple gates at intermediate steps of the gate height. Therefore the third option, where building blocks can be stacked to match different gate heights seems the best.

Guidance

The guidance works are strongly related to the gates. It is therefore only possible to standardize the guidance if the gates are standardized.

Lock chamber (walls/floors)

The lock chamber is the part in which ships are moored when they are levelled. It lies between the lock heads. As with the lock heads, two construction methods can be distinguished:

- In-situ construction of the chamber, creating one element, this method can benefit from dimensional standardization with reusable formwork, thus saving costs on formwork.
- Precast elements that cover the functions of the lock floors and walls, several of those elements put together along the length will create shorter and longer locks. This method can benefit from a well settled dimensional standardization, especially concerning the width of the lock.

The lock chamber may however be built wider than the entrance at the lock head to increase the capacity. Though this is not usual practise because it increases the time it takes for ships to sail in, to be moored and to sail out. In contrast, when the lock gate is as wide as the lock chamber, sailing in and sailing out can be done in one straight line without a lot of steering movements.

A reason to still build a wider lock chamber with a narrower entrance occurs when a lot of relatively small ships need to be locked. They need a small entrance and thus the expensive lock head and gate can remain small, while the cheaper lock chamber is build wider. Hence, the lock chamber has more

size variations than the lock head and also not the same interaction with the lock gate, which makes that the benefits for standardizing the lock chamber are a lot smaller.

Cable housings

This is a small component with respect to the lock and consists of multiple connectable parts. It is intuitively suggestable to make these parts fully interchangeable and maintainable with the same tools and procedures to come to optimal LCC. Having standardized cable housings is therefore seen as a must.

Levelling system

Levelling systems are fairly situational and often integrated into the lock gate. Few locks have the same volume that needs to be locked and when optimizing on costs one could opt for the cheapest levelling system that only just meets the requirements. On the other hand one could also standardize the levelling systems where each lock has the same system. This will have the following consequences:

- Over-dimensioning of material which results in extra material costs.
- Over-dimensioning and/or under-dimensioning of the openings which results in either longer- or shorter locking times.
- Savings on maintenance costs because the same tools and procedures are applicable on every lock.
- Savings on production (excluding material) because the same equipment can be used for each system.

Control/Steering

Control and steering systems of a lock should be standardized for the following reasons:

- Possibility to remote control several locks from the same building.
- Personnel from one lock can be easily moved to another one.
- Potential flaws and their solutions will sooner be known.

Lighting, signalling and boarding

The output of these aspects already is standardized. This is important to prevent errors in interpreting the signals and boards. Further standardization of the structures that hold the boarding, lighting and signalling should be easily possible. Savings from it are estimated to be minimal however.

Energy supply

The cables to supply energy with could easily be standardized (if not already done). However, as more sources become available to locally generate energy (solar, wind, water power), it should be noted that these sources should also be included in the energy supply of the lock when they become feasible (or are part of an innovation project).

Mooring facilities

For mooring facilities, a standard exists that determines how much load the bollards can take.[18] There is no standard however to how they should look like or work. Some savings in maintenance and production can be expected due to economies of scale when these are standardized.

On the other hand, there is a development of automated mooring facilities that could shorten the locking cycle and hence improve the capacity of locks, reducing the need for bigger or more locks. Here is referenced to the automated mooring systems. [19]

So when opting for standardization there are three options.

1. Standardizing a certain non-automated mooring system – consequence is that locks either have longer waiting times for ships or the need to have bigger/more locks. As the capacity per chamber per m^2 will be smaller than with automated mooring systems.
2. Standardizing a certain automated mooring system – consequence is that locks that will never have capacity problems even with manual mooring, will have expensive and maintenance heavy equipment.
3. Have both previous options as partial standards depending on the situation – consequence is smaller savings on economies of scale, but it gives the option to choose the cheaper of the 2 previous options depending on the situation.

As bollards are also used in harbours the increase in economies of scale for the production is small. Bollards also do not require a lot of maintenance so standardizing those seems superfluous. When opting for automated mooring systems however, standardization could significantly reduce maintenance costs because those systems need specialised maintenance.

3.3.2 OPTIONS & INTEGRATION

Options and integration parts can have a significant impact on the possibility and feasibility to standardize locks. If there is a lot of variation as to which options are needed amongst the arsenal of locks and if these options influence the ‘standard’ parts described above.

When there is a lot of variation in the options it is recommended that the standard can easily integrate the frequently used options if this can be done without making the standard much more expensive. Otherwise a balance should be made between the advantages and disadvantages of a standard with respect to the possibility of varying the options.

3.4 DETERMINATION OF THE LOCK GROUP TO BE STANDARDIZED

The previous sections give several options of standardization. One of the options is to standardize lock dimensions by applying a grid. In this way the same elements can be used in different locks because they are of the same size (if the grid size is large enough so that it has many locks within the range of one step in the grid size).

Another option was to make building blocks. When building blocks can be standardized on a large scale, this may save money and time on the production and installation through economies of scale.

The final option was to standardize only certain elements and components in the lock. Some of those component types can already be standardized. Other component types will require a grid or building blocks in order to allow for a standard, because those are dependent on the boundary conditions.

The most interesting standardization possibilities lie in the latter component types, where it is not as easy as saying: ‘from now on we will be using this cable housing’. In accordance with the conclusions of Slijk [7], concluding that the most value (greatest reduction of costs through economies of scale)

of standardization can be found when standardizing lock gates, and from a personal preference to design a lock gate, it will be chosen here to focus on the design of a standardisable lock gate.

When the lock system analysis project [11] from Eindhoven University of Technology is done, one can find from its conclusions whether standardizing the lock gate is the 'best' choice. Though standardizing any part of the lock is the right choice if it can be proven to be beneficial in the long run.

To allow the lock gate to be standardized, the gate will become modular, as this seems intuitively more feasible than having a whole range of gates with different dimensions depending on the situation. This modular standard is expected to have the following benefits:

- Easy transportation: the modules can be made small enough to be transported by road
- Only one reserve gate: making the modules transportable by road will make it possible to only have one set of modules that could be used for a reserve gate in every future project with the same modules; in the current situation each lock has 2 reserve gates
- Easy installation: the modules can be made light enough to install with lightweight cranes, making the use of specialised equipment unnecessary

The possible disadvantages are:

- Over-dimensioning: when the standard is set to 2 m high modules, and a 7 m high gate is required, the resulting gate will be 8 m high. Also the modules need to be able to bear high loads on some locations, but will also be used in locations with lower loads. The result is a higher material usage than without the standard
- Leakage: any interface between modules is prone to leakage
- Lock downtime: relatively big modules will still need to be transported to the lock and connected there. The downtime of the lock will therefore be larger than in the case of reserve gates that are placed adjacent to the lock.

In the following chapters, the design process of this modular lock gate will be started. Starting with Chapter 4, where the requirements are listed.

4 LOCK EEFDE AS CASE STUDY

4.1 INTRODUCTION

To determine to what boundary conditions and requirements the standard lock gate needs to be designed (the first step in the design process), an existing lock is chosen as an example. The choice is lock Eefde because this lock is built for a CEMT-class Va ships like many other locks in the Netherlands which is helpful to create a good economy of scale. Besides the lock Eefde project – which will expand the lock complex with a second lock – is currently well under way and the second lock is expected to be designed by engineering firms and contractors shortly. This will make it possible to compare the designs from this report and the engineering firms in the future.

Also, lock Eefde has a relatively high rise (7.3 m), so when a standard is developed based on that boundary condition, it can follow up in robust modules for the lock gates (with a smaller rise) of future projects. There are however locks with a higher rise than lock Eefde, like sluis Maasbracht, which has a rise of nearly 12 m which is the highest rise in the Netherlands for a navigation lock. Because many locks also have a rise of less than 2 m, the disadvantage of over dimensioning becomes very significant with an increasing design rise.

Hence, also in modular design, a balance will need to be found between over dimensioning on the one hand, and an increased economy of scale on the other hand. For the design in this report, lock Eefde is used. For standardisation projects using modular design, it is recommended to find this balance. It could be better to make a more specialised design (or an adapted standard) in the high rise locks while focusing the standard on the more often occurring low rise locks.

Lock Eefde is a lock located in Twenthekanaal (Zutphen – Enschede) near Eefde, see Figure 8. The lock maintains the rise between the IJssel and Twenthekanaal in which the high water level is in the Twenthekanaal.

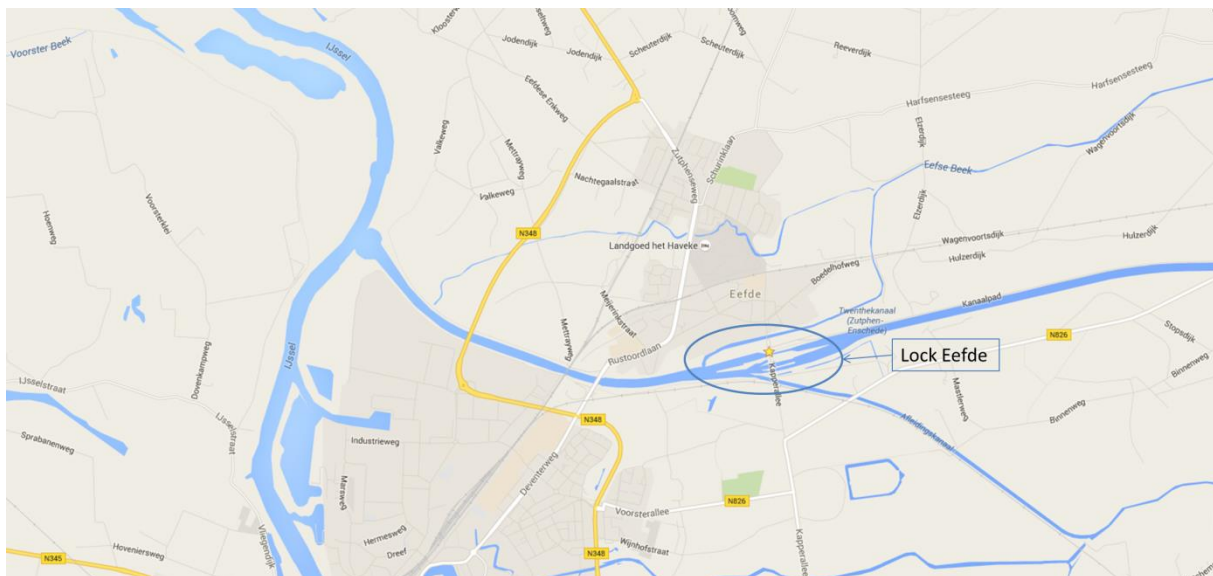


FIGURE 8 – LOCATION OF LOCK EEFDE

Lock Eefde will be expanded with a second lock because the current waiting time for ships exceeds the 30 minute limit. This limit is set in the Netherlands for shippers in order to maintain a predictable travel time. Besides, the presence of just 1 lock makes that the complex is susceptible to maintenance and calamities; the complex is too small for the expected growth of transport by water and a second lock will improve the reachability of Twente and is expected to stimulate the local economy. [20]

Firstly a qualitative list of requirements will be shown as set by Rijkswaterstaat in current navigation lock tender processes. Because the project involving lock Eefde is classified during writing of this report, a quantification of these requirements cannot be shown in detail. Whether and how these requirements influence the design of a modular lock gate will be discussed. Secondly the requirements that can and must be quantified will be listed and where needed an estimate is made. Those will be used in the design.

4.2 LOCK REQUIREMENT LIST USED FOR TENDERING

The basis of this section is a list of requirements made for an unnamed lock, the exact requirements for lock Eefde are protected and therefore cannot be given. The requirements are provided with commentary, stating whether they are relevant in the next step of the design process.

4.2.1 FUNCTIONAL REQUIREMENTS

Locking of ships

The lock should be able to lock shipping traffic in a safe and fast manner (safe and fast were not quantified in the available requirement specification) given the governing water levels and rise in accordance with the hydraulic boundary conditions. This requirement is of primary influence to the gate design and consists of 5 parts.

Part 1 – Dimensions

The most important requirement is that the lock has certain minimum dimensions. These consist of the effective length of the chamber, the effective width of the chamber and the entrance at the lock head, the sill depth and the headway (clearance above the ship). The required dimensions of the chamber have no influence on the gate dimensions, though usually the lock chamber has the same effective width as the lock head. The required sill depth, the headway and the effective width of the lock head at lock Eefde, will determine the dimensions of the lock gate.

Part 2 – Locking time

The locking time consists of:

- Sailing in and mooring
- Closing gates
- Levelling
- Opening gates
- Unmooring and sailing out

The locking times will partially be influenced by the choice for the gate and its drive mechanism. The greatest part of the locking time however, either comes from levelling times or from ship movement and mooring.

Hence, the amount of time within which a ship is locked, often depends on the rise which influences the levelling time. This levelling time is often required to be in the order of 10 minutes. Whether a requirement on the levelling time has an influence on the lock gate design depends on whether (sluices in) the lock gate is (are) used to level the ship. If it is chosen to level the lock around the gate (through culverts), the locking time requirement still influences the gate design somewhat through the time it takes to open and close the gates as one can opt for faster drive mechanisms and faster to open and close gate types.

This choice for the gate type will be made in Chapter 5 and the choice between culverts and filling through the gates will be made in Chapter 6. This means that the design process here differs from the usual design process indicated by the flowchart in Appendix E [12]. In this chart the choice for the intake- and discharge system is made before the choice for a certain gate type. This should not cause any problem because the relation between the intake- and discharge system and the gates occurs only what the gates are dimensioned. The choice for a gate type does not influence (most of the times) the choice for culverts versus filling through sluices in the gates.

The locking time requirement will, in the scope of the preliminary gate design, be added as a qualitative requirement where the choice for a gate type can also depend on opening and closing times. The dimensions of the filling system in the gate (if applied) will be determined through required locking times.

Part 3 – Ship movement and locking forces

The water level in the lock chamber should be levelled in such a way that a steady position of the ships can be guaranteed in the lock chamber as well as in the outports. This means that the longitudinal forces on vessels in the lock during levelling may not exceed a specified restriction. This restriction is mostly in the order of 1‰ of the ships' weight/water displacement. Besides, the direction in which the resulting locking force acts, is not allowed to change more than once or twice during a locking cycle. This part influences the intake- and discharge system design but has no influence on the gate (if culverts are used).

Part 4 – Finishing

The lock should prevent ships and hawsers from getting stuck or damaged by means of a proper finishing of the structures. This means that there should not be any protruding parts, like boulders or stairs. Those parts should always be recessed when required in the lock chamber. A ship is normally not close to the lock gates during locking. So this requirement does not influence the lock gate design.

Part 5 – Gate movement

It should be possible to open, close and hold the gate in a controlled manner, given the load combinations from the hydraulic boundary conditions and in case of any accumulation of debris and/or sediment around the gate. This part influences the gate design.

Letting water through

Some locks should be able to drain water with a certain (adjustable) flow rate. These locks should obtain the function of a draining facility within a certain amount of time (e.g. 5 minutes) after giving the command.

When the choice is to level the lock through the gates this can influence the design of the gate sluices which need to be placed in some of the modules and may need to become wider to obtain the required draining capacity. Nevertheless it is assumed that this requirement is either automatically met when levelling requirements are met and if not, a separate draining channel will be required.

This assumption is made because the two functions of locking ships and draining water influence each other. When a ship is still locking and the lock is emptied to match the downstream water level, the lock cannot start draining water from upstream without either increasing forces on the ship or slowing down the locking process. But if the lock can drain enough water with the installation that is used for levelling ships in-between and/or during locking cycles without neglecting requirements with respect to the locking of ships these two functions should be combined.

Thus by choosing to design gate sluices only for the requirement of locking of ships and stating that drainage of water should go through a separate system if this cannot be handled with the already required system, the subject of letting water through is put out of the scope of the gate design.

Allowing the passage of ships

The lock should be provided with marker lights and markers:

- On protection facilities in the lock chamber to make the border between water and the protection facility visible.
- Visible and illuminated stop line for the purpose of lock operation.

This requirement has no influence on the design of the lock gate.

Retaining high water

The lock should be water retaining within 2 minutes of Control Command: Close Water Retaining Structure. (Bediencommando Sluiten Waterkering in Dutch). This needs to be possible in the operation phase as well as the realization phase (which usually means that the lock remains closed and is high water retaining during all phases of construction). For a lock gate, this means that the gate should be able to move from a fully opened to a fully closed position within 2 minutes (allowing some slack for a ship that may still be sailing in) and be able to bear the hydraulic loads. A requirement like this is not necessary for all lock gates but for the sake of a broad applicability of the standard lock gate, it will be used in the design phase.

Ship collision

A scenario not specifically mentioned in the requirements, that could reduce the ability of the lock to retain high water, is the collision of a ship against the lock gate. Unless a collision prevention system is in place, the gate will need to be able to retain high water – until the other gate can be closed – after being subjected to the loads caused by a colliding ship.

Maintain the rise

The leakage rate of the lock may at maximum be $1 \text{ m}^3/\text{s}$ (as example). As a great part of this leakage rate flows between the gate and the lock head, this is an important requirement for the design of the lock gate with the accompanying lock head. In the scope of this preliminary design this will be taken into account by the choice for a gate and detailing the shape of the interface between the lock gate and lock head.

4.2.2 ASPECT REQUIREMENTS

Safety and security

The lock should meet the minimum requirements regarding exposure to risks from physical agents. This requirement has no influence on the lock gate design because it is not expected that usual construction materials and techniques cause a high exposure risk of physical agents.

The lock should be hydraulically safe conform [NEN-EN-ISO 4413]. This is a code describing general rules and safety requirements for hydraulic fluid power systems and its components. This requirement follows from a demand or assumption that the lock will be fitted with hydraulic driving mechanisms; it is therefore just an example requirement that is in the list when the lock is actually fitted with hydraulics. Also because this requirement is about rules for the driving mechanism, in itself it will not have an influence on the gate design.

The lock has to be provided with firefighting resources. This has no influence on the lock gate design.

The lock should meet a certain safety specification named: '*Specificatie veiligheidsfuncties schutsluis*' in Dutch.

The lock should be fitted with safety- distances and fencing. This requirement has no influence on the lock gate design.

The lock should be seen as a Composite Machine consisting of the following Machines conform the Machine guideline:

- Both lock gates
- De-icing systems in both lock heads
- Emergency power supply

This requirement will not be used in the scope of the preliminary design phase.

Serviceability

The lock has to be fitted with safely walkable lock gates fitted with handrails and toe board. This requirement will have an influence on the design of the top of the lock gate. Because either the gate needs to be fitted with attachment points for some sort of bridge on top of it or the shape of the gate itself needs to fulfil the need to walk over it. In the context of the gate design in this report, the walking deck will not be included because it is not part of the primary functions of a lock gate and will not have a big influence on the rest of the design.

The lock should be fitted with ladders and hand braces. This is a requirement that will need to be met in the lock chamber and will thus not influence lock gate design.

4.3 LOCK GATE REQUIREMENTS

In this section an overview of the requirements from Section 4.2 that are relevant for the lock gate will be given, including a quantification of these requirements. This quantification will be in accordance with (estimates of) requirements for lock Eefde.

4.3.1 DIMENSIONS

The minimal functional dimensions of the lock are (see Figure 9):

- Lock width 12.5 [m]
- Lock length 125 [m] (not relevant for the lock gate)
- Sill depth 4.2 [m]
- Clearance (above water level) 8.8 [m]

These dimensions are set for the second lock at lock Eefde. They originate from the dimensions of the minimum capacity lock (i.e. one governing ship per locking cycle) [21]. The governing ship is given by CEMT-class Va with dimensions:

- Beam 11.4 [m]
- Length 110 – 135 [m] (not relevant for the lock gate)
- Draught 3.5 [m]
- Height above water line¹ 7.1 [m]

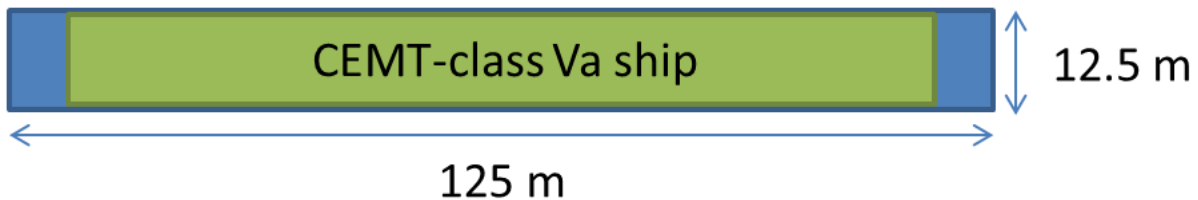


FIGURE 9 – TOP VIEW OF THE MINIMUM FUNCTIONAL LOCK DIMENSIONS WITH THE GOVERNING SHIP

Note that only the shorter CEMT-class Va ships can be locked at lock Eefde. This choice is likely made because longer ships cannot be facilitated at other parts of the Twenthekanaal either, which would make longer lock redundant.

4.3.2 LOCKING OF SHIPS

The sum of the time taken for closing the gates, levelling and opening the gates should be in the order of 10 minutes. The time requirement for opening and closing the gate will be set at 30 seconds each, giving enough time for levelling.

Locking forces may not exceed 1‰ of the ships weight. Only relevant for the gate design when the levelling system is integrated into the gate.

It should be possible to open, close and hold the gate in a controlled manner, given the load combinations from the hydraulic boundary conditions and in case of any accumulation of debris and/or sediment around the gate.

4.3.3 RETAINING HIGH WATER

The lock gate should be water retaining within 2 minutes of Control Command: Close Water Retaining Structure. Hence, the required closing time will be under 2 minutes. The 30 seconds requirement for opening the gate, set in the previous section, should make that this requirement is also met. Ships that are still busy sailing in or out will then get a time of 90 seconds to either stop before the gate or finish sailing in or out before the gate should be closed after the control command.

¹ This height is not exceeded by 90% of the empty container vessels

Ship collision

The gate needs to bear the load of a colliding ship and still be able to retain high water for 2 minutes after that (until the other gate can be closed). The relevant parameters of this ship are:

- Ship mass $3.0 \cdot 10^6$ [kg]
- Sailing speed 0.20 [m/s]
- Ship length 110 [m]
- Ship draught 3.5 [m]

These parameters are based on the short CEMT-class Va ship that the lock is designed for. The speed is based upon the mooring speed of a ship, assuming that a shipper would never sail near a closed gate at higher speeds, as the ship is in the process of mooring.

4.3.4 MAINTAIN THE RISE

The leakage rate of the lock may at maximum be $1 \text{ m}^3/\text{s}$.

4.3.5 HYDRAULIC BOUNDARY CONDITIONS

The water levels occurring at the lock are:

- Maximum upstream water level 10.15 [m + NAP]
- Minimum upstream water level 9.75 [m + NAP]
- Minimum downstream water level 2.9 [m + NAP]
- Average downstream water level 4.3 [m + NAP]
- Maximum downstream water level 8.75 [m + NAP]

These water levels are shown in Figure 10.

Side view of the hydraulic boundary conditions

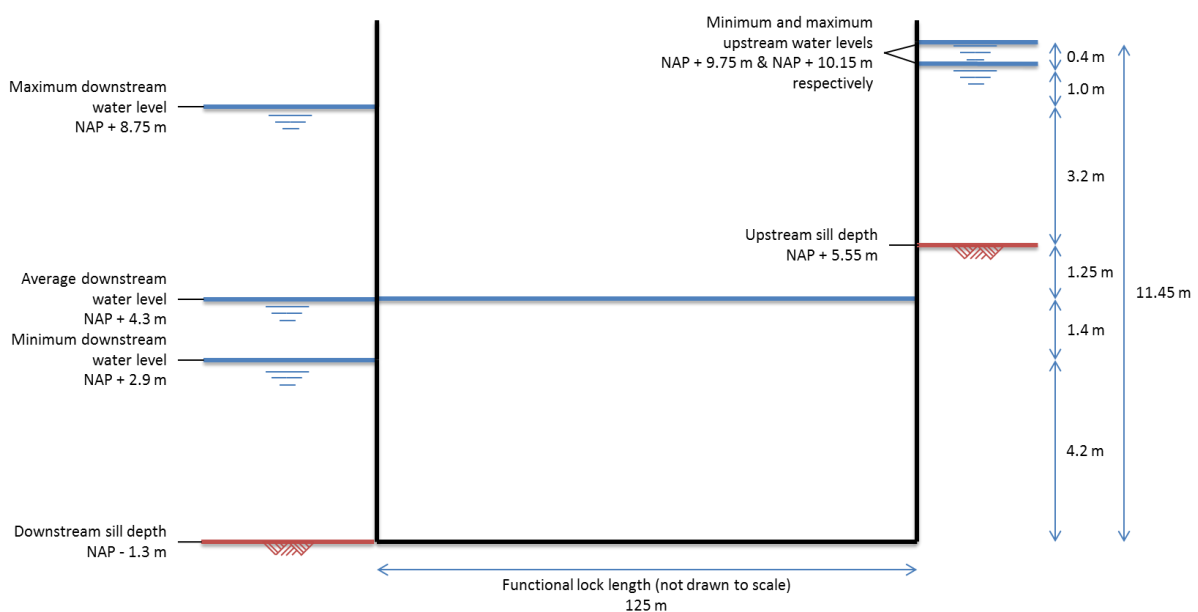


FIGURE 10 – SIDE VIEW OF THE HYDRAULIC BOUNDARY CONDITIONS – THE BLACK BOX REPRESENTS THE LOCK

5 GATE ALTERNATIVES – IDEA GENERATION

5.1 INTRODUCTION

This chapter will be about generating new ideas. It is the second step in the design process where ideas for lock gates are generated and compared to each other. First the main functions of a gate and its (inseparable) operating mechanisms are listed because these have to be taken into account for every concept. Secondly, the classic path of choices made to choose a gate is shown and commented upon. Thirdly the criteria by which a gate concept will be chosen will be listed. Fourthly many of the possible concepts with their pros and cons will be described. Lastly a gate concept is chosen and the theory of its workings is described.

5.2 FUNCTIONS OF A LOCK GATE AND ITS OPERATING MECHANISMS

The functions of a lock gate and its operating mechanisms are listed from source: [12]. These functions are the basis of every gate design and therefore also this one.

- The gates have to move from a closed to an open position and provide unimpeded passage to vessels entering or leaving, in a length of time that is in relation with the required duration of the lock cycle. This length of time is set to 30 seconds in Section 4.3.2.
- The gates have to move from an open to a closed position and then be able to absorb the subsequent hydraulic loads.
- If so required, the gates have to be equipped with lockable openings for the filling or emptying of a lock chamber. The speed with which the sluice gates move have to, in conjunction with the size of the openings, bring the vessels to the required water level in a responsible manner (with regard to safety and duration).

5.3 CLASSIC CHOICE DIRECTORY FOR GATES

To determine how gates are now chosen, a book that is often used as reference material by Dutch engineers when designing locks is used. The translated version is called *Design of Locks* [12]. From the source text, Figure 11 is created which gives an overview about the sort of gate that is used in each situation.

Notable about this tree (Figure 11) is that the gate choice is, according to the source, in no way dependent on the rise of the lock, but only dependent on the width combined with the direction of the rise. This can be explained by noting that this design guide originates from the Netherlands where the rise does not deviate as much. The maximum rise that occurs is at Sluizencomplex Maasbracht with a rise of 11.85 m, at which mitre gates are applied, just like Figure 11 would suggest. So the rise is not of a big influence.

The amount of space available in the vicinity of the lock is also of influence on the lock. In such cases it is found that lift gates (guillotine gates) require the least amount of space along the length and width of the lock. The double rolling gate is also quite exceptional. The reason for going for two rolling gates in each lock head is an extremely high demand on the availability of the lock. By having two lock gates, maintenance can be carried out on one of the gates while the other is still functioning. The second lock gate also acts as reserve gate in case of accidents. Locks of 24+ m wide are usually

sea locks and part of a route that is important for the national economy, which results in the high demands on the availability.

Also, as will be seen in Section 5.5 where old and new gate concepts are explored, the resulting flowchart lists only few of the existing lock gate concepts. This can be the result from having no 'need' of other gate types because the listed types are already the most economical in the range of lock requirements encountered in the Netherlands. It can also be caused by having no experience with the other concepts and not wanting to take any risk by putting one of them in trial, possibly unknowing of their potential; combined with a conservative industry.

Which lock gate should I use? Based on the text from *Design of Locks part 1*

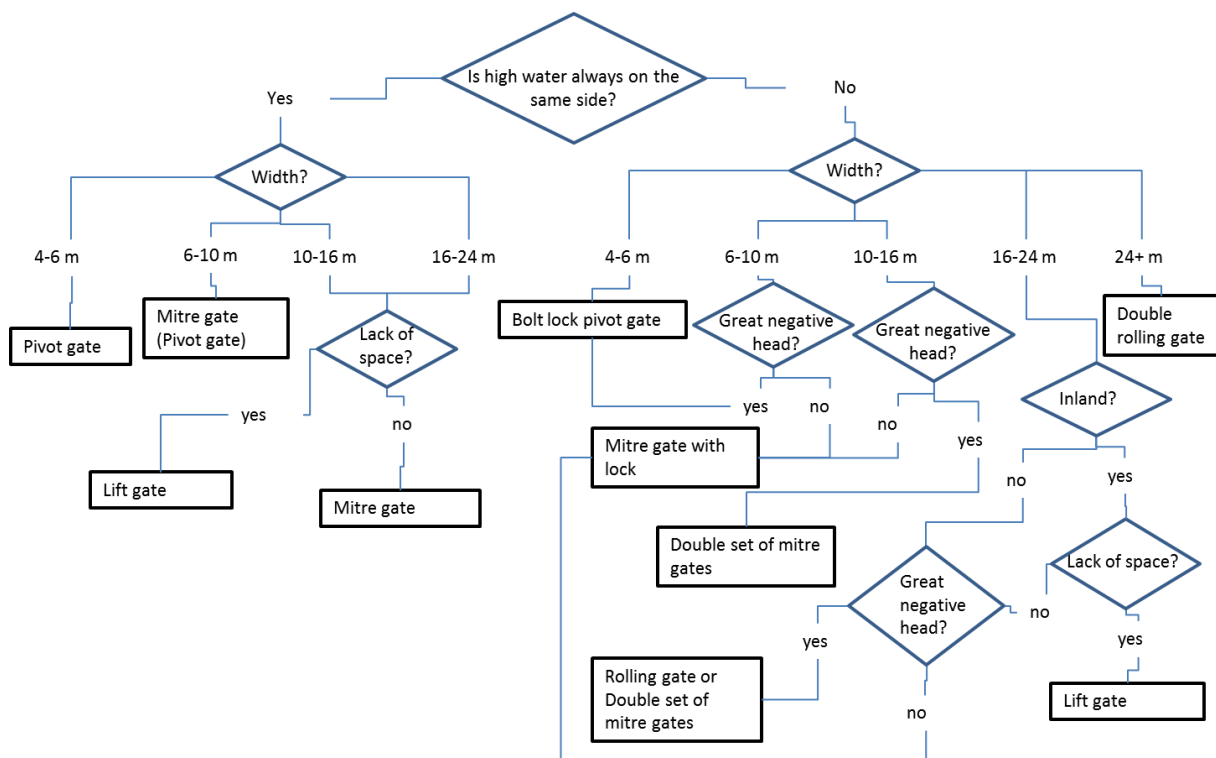


FIGURE 11 – CHOICE TREE FOR A LOCK GATE, BASED ON THE TEXT FROM SOURCE: [12]

One way or the other, the limited set of gate types and specifying quite clearly in a design guide when to install which type does not support innovative ideas. For means of standardization it is however an almost ideal scenario, except that each gate still has its own unique dimensioning.

Because a modular gate, as decided upon in Section 3.4, is different from the regular gate, Figure 11 may not apply anymore when finding the best concept. To explore whether other gate concepts could fit the modular design better and to find out if there are some innovative gate concepts with high potential with respect to the currently used gate types. The next section will determine new criteria that will be used in this thesis work to decide on a gate concept.

5.4 CRITERIA FOR THE IDEAS

From far in the past up to now, locks are fitted with mitre gates almost exclusively. This is a good thing for standardizing lock design, as one can choose to, not only install the same mitre gates everywhere, but also make them have exactly the same dimensions, or at least interchangeable.

The interchangeability of lock gates is something that is usually not considered, or at least, nothing is done with it and this is at least one of the factors that causes that a standard cannot reach its full potential. The non-interchangeability of the gates can be seen from the reserve gates that are unique for nearly every lock.

Only in some cases where several locks are built in the same channel during the same project, it may occur that one (set of) reserve gate(s) can be used for several locks. Also in cases where the rise is small, it is chosen to have the same gate height in both the lower- and the upper head of a lock. This makes the gates interchangeable between the 2 lock heads and only one (pair of) reserve gates is required.

The cause for the different non-interchangeable lock gates is that each project is seen as a single project and, more importantly, each lock has different water levels and often different lock widths are chosen.

However, through the interchangeability of the gates, several advantages can be reached (see also Section 3.4):

- Reduce the amount of reserve gates and thus the investment costs
- Better predictable downtime during replacement
- Better predictable replacement costs
- Only one set of modules is required as reserve gate

Hence it will be tried here to increase the scale of this interchangeability from a few 'incidents' where it was made possible by combining several projects or where the upper and lower head of a lock have been built identically; to a scale where a lock gate in e.g. Limburg could be replaced with a reserve gate located in Utrecht. This will be done through a combination of modularisation of the gate and a gate type where this is easy to achieve.

Through modularisation of the gate as decided upon in Section 3.4, this interchangeability can be increased. When one uses a small set of different modules, preferably as few as possible, this set can be used to build lock gates of several heights with the same/interchangeable modules. Hence, the criterion that the gate heights need to be the same to create interchangeable gates will be removed when the gate is built from modules.

Hence, the possibility of modularizing the concept and thus making gates more interchangeable will be one of the criteria when choosing a gate type.

From far in the past up to now, only few revolutionary innovations in lock gates have taken place. Before the invention of the mitre gate by Leonardo da Vinci 1480 and the application of the first 6 mitre gates in 1487, locks were built with guillotine gates (also called lift gates). [22] Since the invention, mitre gates have become the most used gate type for one-way water retaining. The only revolutionary innovation after that which also found such a wide application, was the use of steel instead of wood in lock gates.

In the meantime, also other gate types have been invented and put to use. Some of them are situational (high rise locks, 2-sided turning), other types were simply too expensive with respect to their competition. For a more extensive list of past and present lock types the thesis of Doeksen [23] is

referenced. He listed many of those gate types with their application and why they are (not) used (anymore).

More recently, some new developments are taking place with respect to gate design. Rolling-/sliding gates are put to use in small locks instead of only the 16+ m wide locks (see also Figure 11 where the application of these types start at 16+ m wide locks that are double sided retaining). One of these small sliding gates is even built in concrete in 2010, named *Sluis 124* [24], which is the first concrete lock gate to be build. Also, composite gates made of Fiber Reinforced Polymers (FRP) are being researched and made, for example at the Golbey Gate Replacement and at a composite lift gate in France [25]. Another example of a composite gate is the upcoming composite lock gate in the Wilhelminakanaal near Tilburg [15].

Despite these developments, the business of designing and building locks is still very conservative in comparison to other industries as many voices from inside and outside of Rijkswaterstaat say. This is most likely caused by the high investment costs for each single navigation lock. The result is that risky ideas that may lead to revolutionary innovations are easily abandoned for the risk of becoming too expensive due to unforeseen circumstances. Evolutionary innovations may however still take place.

To be able to reach revolutionary innovations one should, during this second step of the design process, look into as many solutions as possible and try to see if there are gate types that have not been used or designed yet. Because “opportunities (for innovations) often lie outside of the boundaries where others typically explore.” [9]

Innovation will thus be one of the criteria when choosing the gate type

5.5 EXPLORATION OF IDEAS/CONCEPTS

5.5.1 INTRODUCTION

Ideas are explored through a series of images with accompanying advantages and disadvantages. An overview of the lock gate types, distinguished by their way of bearing the loads, is shown in Figure 12. Figure 13 up to Figure 18 show a further subdivision of the concepts (mostly based on the way they move) in which the advantages and disadvantages of each concept are displayed.

There will be no MCA (Multi Criteria Analysis), as is usually taught in project education, to choose the best gate design because doing this objectively requires knowledge about the LCC and about values (in terms of currency) that can be assigned to the benefits of each gate before and after standardization. This knowledge is not present for the more unusual concepts (in which innovations may be hidden), which would mean that the LCC and the benefits of the lock gates will be based on estimates.

The focus of this thesis will be laid on designing the gate. Making these estimates for all usual and unusual concepts in order to find the innovation with the highest potential does not fit in the time frame. However, the book *Design of Locks – Part 1* [12] does such a MCA to compare mitre gates with pivot gates and rolling gates. The conclusion in the case for an inland navigation lock with a width ranging from 10 m to 16 m (lock Eefde is one of many locks in this category), is to choose a mitre gate. Though it is stated there that the result varies depending on which aspects are emphasized and on the principal's preference even though these are the types of gates of which the LCC should be well known, given that those are the more well-known gate types.

Hence, instead of using a MCA to compare the gate types, the gate type will be chosen on the basis of personal preference and comparing the advantages and disadvantages with respect to the modularisation possibilities and the innovativeness of each gate. The aim is hereby to explore an innovative gate type.

Figure 12 shows the main categories that will be discussed, based on how the gates are stressed: combined compression and bending, pure compression/tension, pure bending. Even having no gates at all seems to be technically feasible and is added for reference to stimulate innovative thinking. [26]

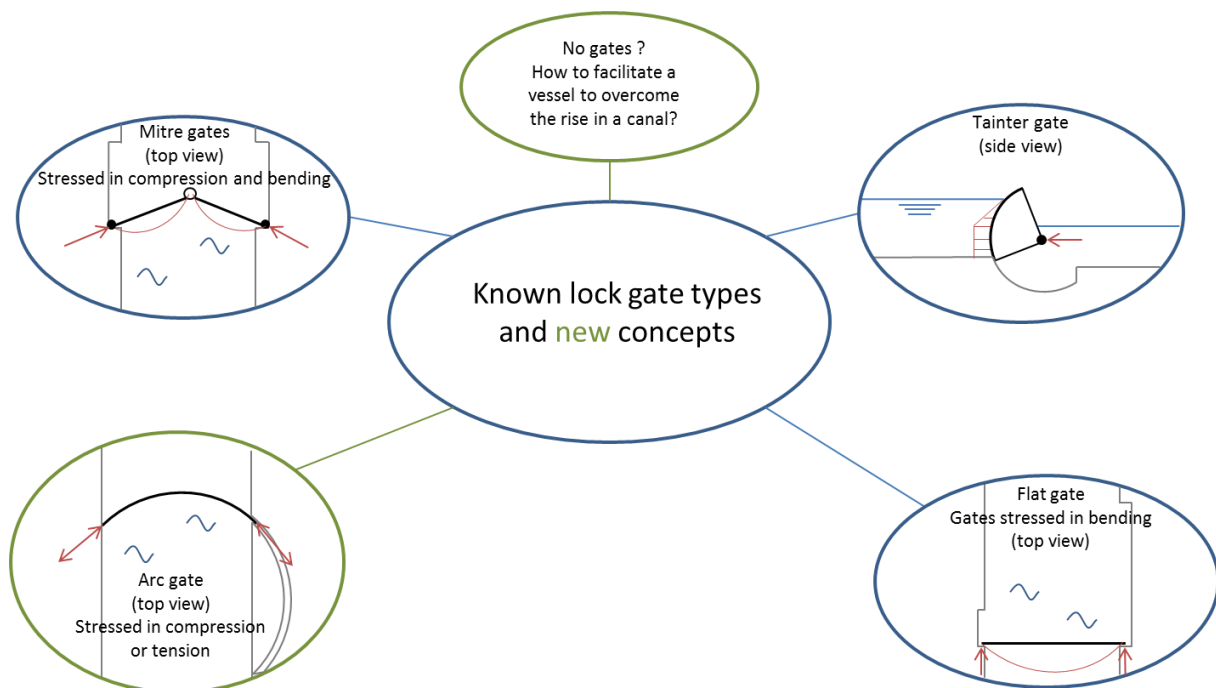


FIGURE 12 – MAIN CATEGORIES OF THE KNOWN LOCK GATE TYPES AND NEW CONCEPTS

5.5.2 MITRE GATE

Figure 13 shows the different mitre gate concepts: arc mitre gate, wing gate, standard mitre gate and folding gate. The basic mitre gate is praised for its simplicity, closing speed, low usage of space, and the economic use of door material, which results in a low mass. The wing gate adds some functionality to the mitre gate (2-sided retaining) while becoming more expensive.

The arc mitre gate and folding gate (a concept by van Stralen [27]) aim to be cheaper and lighter by a more economic use of material through following the shape of the forces. However, they also add costs through a more complicated to build shape. The folding gate also has the disadvantage of an extra hinge, which results in more moving parts and a more complicated operating mechanism.

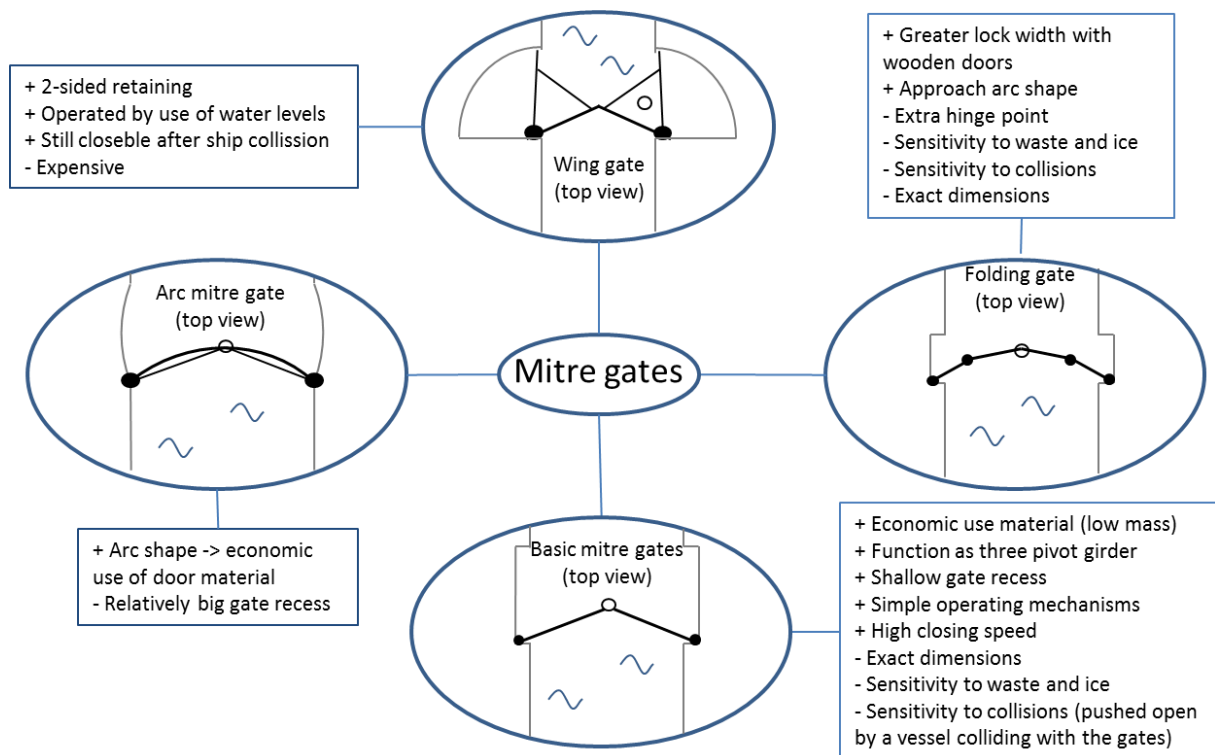


FIGURE 13 – MITRE GATE TYPES

The mitre gate is the most basic gate and thus does not score well on the part of innovation (exceptions are the arc mitre gate and the folding gate). Also, modularizing mitre gates which need to hinge around a certain point is relatively difficult. As it means that either each module needs its own hinges, or the modules need to be connected in such a way that they work as a single plate.

So the mitre gates are not chosen based on the criteria of innovation and modularization. It needs to be acknowledged however that mitre gates are the most widely used gates (at least in the Netherlands) and that this is not without reason. It is still the cheapest (LCC) and/or most reliable gate according to many; besides, few (are able to) take the risk of trying something new that is completely different but could become cheaper and more reliable in the long run.

This does make the mitre gate a good reference structure when analysing other gate types.

5.5.3 TAITNER GATE

Figure 14 shows the tainter gates. The tainter gates with a horizontal axis are often in the upper head of navigation locks while the standing tainter gates are often found in water defense structures, but also in locks. The strengths of tainter gates are to be 2-sided retaining, being able to operate in flowing water and in the case of the horizontal axis tainter gate to have very little use of space side-ways. Tainter gates are however very expensive and operation in flowing water is not as important in navigation locks as it is for water defense structures.

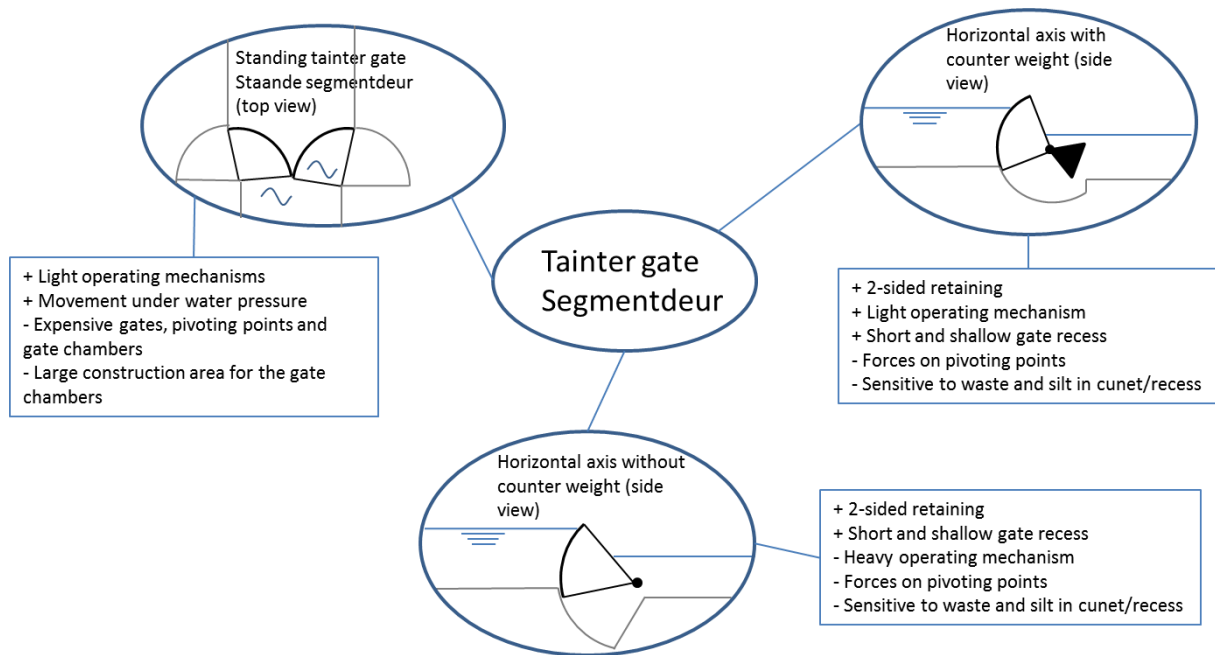


FIGURE 14 - TAINTER GATES

Because tainter gates are relatively new in respect to other gate types, originating in the 20th century, they can be seen as fulfilling the innovation criterion. The innovative part however is where they are good at operation in flowing water. This advantage is however of little use in navigation locks, where at least one gate is always closed. Also, the complicated structure of a tainter gate (a curved water retaining part plus braces that hold it) makes it hard to modularize the gate.

Hence, the tainter gate types will not be chosen.

5.5.4 FLAT GATE

Figure 15 shows the flat gate types. Their strength is in the simplicity of the gate structure and the shape of the gate recesses. There are many ways in which to open and close the flat gates: pivoting to- and from the side, pivoting to- and from the bottom, lifting, sinking and moving sideways. Each one has its own pros and cons as is summarized in the figure.

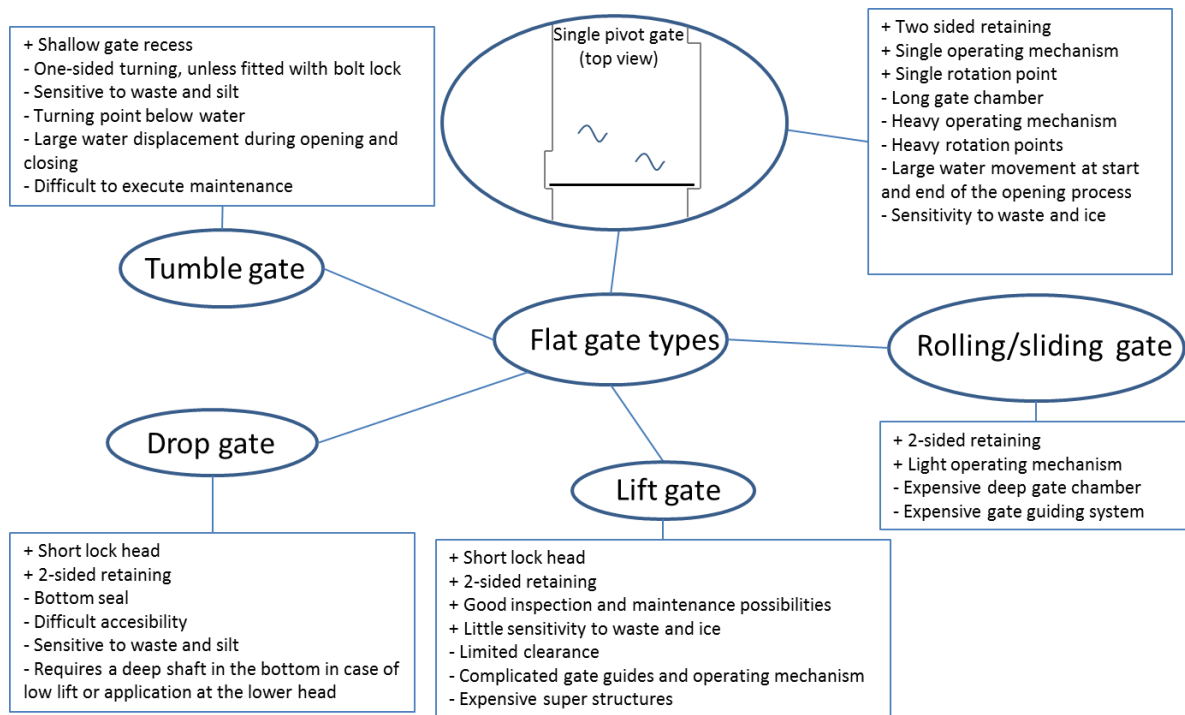


FIGURE 15 - FLAT GATES

The flat gate category has both the oldest (lift gate or even further back the stop logs) and the newest gate types (tumble gate, drop gate). This could mean that the flat gate category has potential for many innovations. Also, some of the flat gate types can easily be built of stackable modules. These are the rolling/sliding gate, the drop gate and the lift gate, making the gate (modules) employable at many different rises.

Hence, the flat gate type is one of the choices that fits the criteria.

5.5.5 ARC GATE

Overview

Figure 16 shows the arc gates. A distinction is made between arc shaped gates which function still like flat gate types and arc shaped gates that really function like an arch through compression and tension. This causes transversal as well as longitudinal loads on the lock head. The latter will be called an arc gate here. So a drop gate with a curve on one side is still a flat drop gate and not an arc drop gate.

In the arc gate category, the drop-, lift- and rolling gate are also present like in the flat gate category. The drop- and lift gate will require changes in the lock head with respect to the flat gate types in order to bear the transversal forces but function otherwise in the same way. For the arc rolling gate a circular gate recess is required instead of a straight one like for flat rolling gates, see Figure 16.

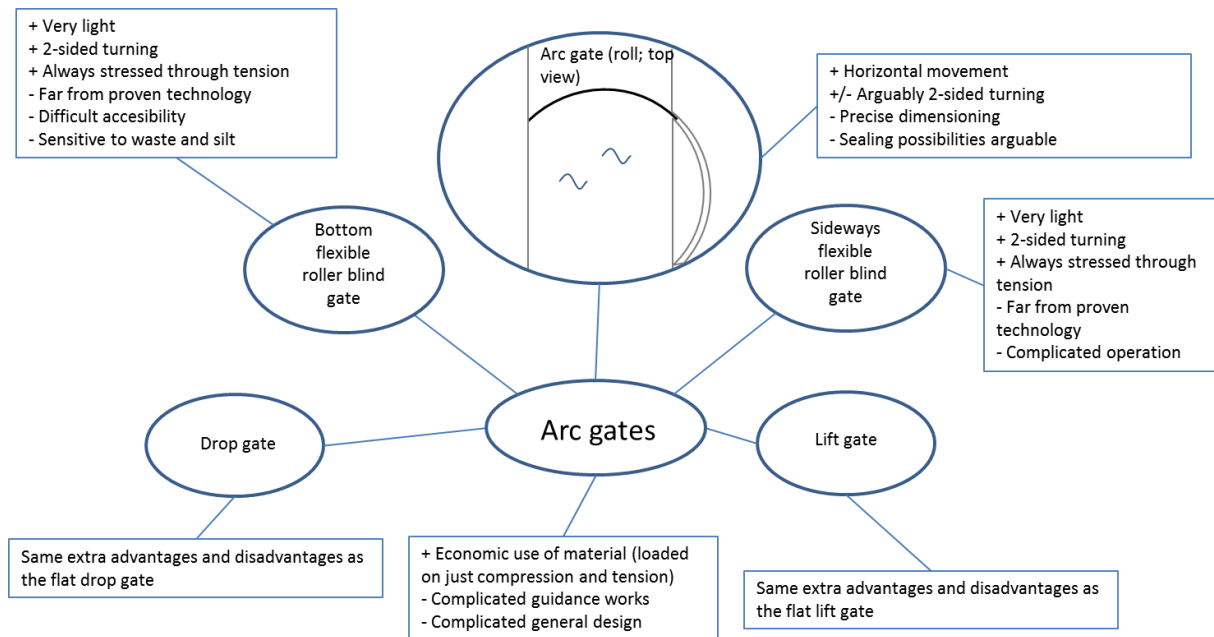


FIGURE 16 - ARC GATES

In the next subsections the roller blind gate and the rolling gate will be elaborated upon.

Roller blind gate

The two other gate types in Figure 16, the roller blind gates with either a bottom or a side recess are a personal idea of which no other reference was found, but are listed like the Gelsluis (Figure 18) to stimulate innovative thinking.

The idea came when thinking about the Ramspol barrier, a barrier made of flexible material. One should think that it is also possible to create a flexible lock gate. Because filling a balloon-like shape with a mixture of water and air takes too much time for the purpose of a navigation lock, a mechanical mechanism of opening and closing is most likely required: hence the roller blind. This will also require much less material for the gate because of the flat cross section instead of the circular (balloon-like) cross section.

The advantage of the flexible material is that it is always stressed in tension. A water level on one side causes the gate to become concave in one direction and a high water level on the other side causes the gate to become concave in the other direction (the same as wind on a roller blind). So there are no problems with buckling and bending and this will make the required cross section very thin and light-weight.

The trouble with a roller blind as lock gate is that it needs to be water tight. Hence it must be carefully guided through a rails like with blackout roller blinds. These rails need to: hold the flap when the gate is closed, be water tight when the gate is closed and also be able to guide the roller blind when it moves without much friction.

If it is possible to create rails that function like described above, a roller blind gate can potentially become an innovation that adds a lot of value. It can be cheap, lightweight, easily replaceable and thus maintainable due to its lightweight and it can potentially dissipate some energy from ship impact due to its elasticity. However, such claims cannot be made without further elaboration of the

concept. Because another concept was already elaborated upon during this graduation work (this idea came to mind later), the roller blind gate idea is put aside.

Otherwise, it would have scored high on innovation due to above mentioned estimated potential. It would have scored low on modularization as one can imagine it is hard to create a roller blind (gate) out of modules and add value to it in the process (i.e. making it more widely useable). However, the roller blind itself is quite flexible. One can use a long roller blind (meant for a high rise) in locks with a low rise. Or one can use the same moving parts and shorten the flap of the roller blind. Thus the roller blind gate would also have been the chosen one on interchangeability as replacement for modularization.

Rolling arc gate

One can also have an arc shaped rolling gate without it being an arc gate. The arc shaped rolling gates are actually of the flat gate category as described earlier in the *Overview*, because they bear the loads mainly through bending stresses in the structure instead of normal stresses. However, the arc shaped rolling gate will also be described here because it has exactly the same extra disadvantages with respect to other gate types when opening and closing as a rolling arc gate.

The rolling arc gate and the arc shaped rolling gate are gates that have the shape of a quarter circle, see Figure 17. Any other shape will make that the gate recess fits less elegantly alongside the lock chamber, causing a wider space to be occupied. When closed, the 2 edges fit in a notch in the lock wall like with the rolling gate. When opening the gate, it rolls into a gate recess along rails. These rails form half a circle with the same radius as the gate. Half the rails (a quarter circle spanning the lock width including the notch and gate recess) is used for a closed position, the other half (a quarter circle next to the lock chamber in longitudinal direction) is used for the opened position. This means that the radius (r) of the rolling arc gate and the arc shaped rolling gate are determined by the width of the lock, through the required span of the gate (l).

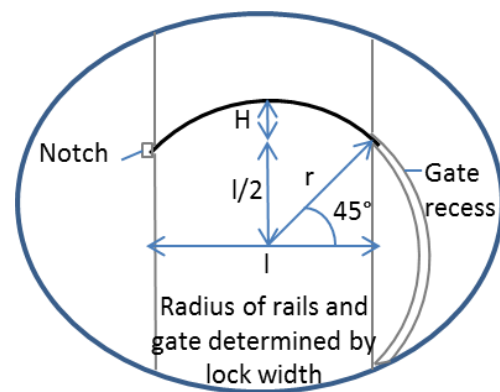


FIGURE 17 – SHAPE OF THE ROLLING ARC GATE

The relation between the radius of the rolling arc gate and the lock width is:

$$r = \frac{l}{2 * \sin 45^\circ} \quad [1]$$

In which:

- r Gate radius [m]
- l Gate span (the functional lock width including a part sticking into the gate recess and notch) [m]

The arch height is then given by:

$$H = r - l/2 \quad [2]$$

In which:

- H Arch height [m]

The rolling arc gate and arc shaped rolling gate have several disadvantages. The circular shape causes extra friction when moving the gate because the centripetal force required to move the gate along a circle is (partly) coming from sideways contact with the rails. Also, the construction and installation of curved gates (in general) is more difficult which may cause more flaws and make it more expensive.

The main advantage of both the arc shaped rolling gate and the rolling arc gate is the saving of space with respect to flat rolling gates. Parallel locks could be built closer to each other because the lock gate does not extend sideways as much as with the flat rolling gates.

The rolling arc gate gets its potential with respect to the arc shaped rolling gate from being lightweight due to material savings. Thanks to this, the gate is more cost-effective, easier to maintain and has less friction in the opening process. However, the lock head will be more expensive because it needs to be able to bear lateral forces besides the longitudinal forces.

The rolling arc gate scores high on innovation because it has yet to be build and because of its potential to build it in more locations than a standard rolling gate. This also makes the rolling arc gate better when standardizing lock gate design as it has a wider application range. As with the flat gate types, the rolling arc gate can be made relatively easy of stackable pieces that can be easily transported. This also makes the gate score good on the modularization criterion.

5.5.6 NO GATES: GELSLUIS

To get a wider view, one should also discuss the possibility of not applying a gate at all. It is found technically feasible to pull ships through a gel across a head difference that is maintained by the gel [26].

Impression



No
gates:
Gelsluis

- + No gates
- + No waiting time for shippers
- + Limited loss of freshwater
- Very long (requires a lot of space)
- Ships need to be pulled through and cannot use their engines
- Requires collection and recirculation system for the gel

FIGURE 18 - NO GATES

The main disadvantage of this type of navigation lock, is that it needs to be very long. The main advantages are that ships have no waiting times in theory and this type of lock completely separates fresh water and salt water.

The survivability of this concept will in the end depend on the LCC and the total time it takes to lock a ship with respect to a normal lock (including waiting times). The long structure makes that the initial investment costs are probably very high. The devices that will need to pull the ships through the gel

and the ones that will recycle the gel will also add up a lot on maintenance and investment costs. The capacity this lock has may be able to compensate for these extra costs.

Hence, this lock scores high on innovativeness. It will however not be part of this graduation work as the goal is to design a lock gate.

5.6 CHOICES

In Section 5.5 a lot of gate concepts were shown and their advantages and disadvantages were stated. It was also stated qualitatively if the gate would be innovative and whether it could be build up from modules.

The choice in the end is to design a rolling arc gate and to design it in concrete. The following sections will explain why. Section 5.6.1 will also discuss the theory of an arc and the practise of applying it in an rolling arc gate.

5.6.1 Rolling arc gate

The reasons to choose for the rolling arc gate are:

- There are less space requirements between parallel locks than for a flat rolling/sliding gate
- Aesthetics
- In lock design the shape is innovative (never before build)
- Effective use of material in the gate (the use of an arch shape)
- The gate can be built from modules quite well, which helps standardizing the lock gate
- 2-sided retaining (given that the supports can be designed in such a way that they hold the gate in 2 directions)

The arch will have the shape of a quarter circle. The reason for this is that a circular shape is the most effective in bearing water pressure loads; it has the same radius everywhere in contrast to any other arc shape and can thus be easily manoeuvred over a track or rails; and when opened the gate will fit right next to the lock, as can be seen in Figure 17.

Arc in theory

An arc gate has a theoretical effectivity of material in bearing the forces like an arch. The material effectivity of an arch is originates from bearing the loads solely through axial compression or tension. The quarter circle makes it relatively simple to calculate these axial forces, see Figure 19.

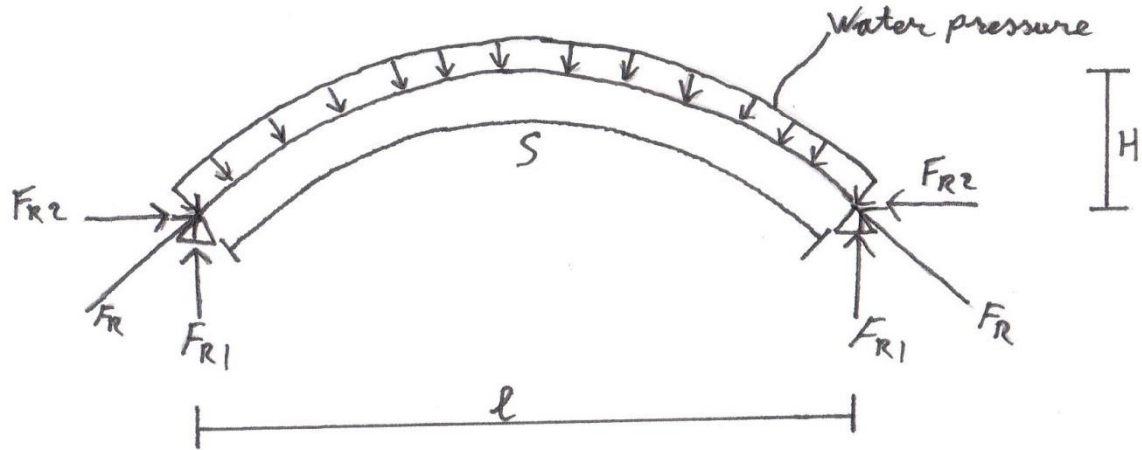


FIGURE 19 – AXIAL FORCE IN QUARTER CIRCLE ARCH – TOP VIEW

The angle with the support of the arch is 45° . This makes that in a perfect arch, $F_{R1}=F_{R2}$. F_{R1} can be calculated as if it is a simply supported beam with the projection of the water pressure on the plane between the supports. This means that $F_{R1} = F_{R2} = \frac{1}{2}ql$. F_R and with it the compression force in the arch can then be calculated with:

$$F_R = \sqrt{2 * F_{R1}^2} = \sqrt{2 * \left(\frac{1}{2}ql\right)^2} = \sqrt{2 * \frac{1}{4}q^2l^2} = \sqrt{\frac{1}{2}} * ql \quad [3]$$

In which:

- F_R Axial compressive or tensile force in the lock gate [kN]
- F_{R1} Support reaction parallel to the gate longitudinal axis [kN]
- F_{R2} Support reaction perpendicular to the gate longitudinal axis [kN]
- l Span [m]
- q Line load resulting from the hydraulic head [kN/m]

In the case of arches loaded under compression, buckling is the most relevant failure mechanism. The buckling length of an arch (l_0) is approximated with $l_0 = 1.25 * \frac{s}{2}$ in which s is the arc length. This is applicable for curves with $0.15l < H < 0.5l$, in which H is the height of the arch. [28]

The maximum buckling load can then be estimated through the Rankine Gordon Formula:

$$\frac{1}{F_{max}} = \frac{1}{F_e} + \frac{1}{F_c} \quad [4]$$

In which:

- A Cross sectional area [m²]
- E Young's modulus [kN/m²]
- F_c Maximum compressive load calculated from the material compressive strength = $f_{cd} * A$ [kN]
- f_{cd} Design compressive stress [kN/m²]
- F_e Euler buckling load = $\frac{\pi^2 EI}{l_k^2}$ [kN]
- F_{max} Buckling capacity of the arch [kN]
- I Second moment of area [m⁴]

One can use topological optimization programs as a confirmation whether the material is used in the most effective way. In Figure 20 Topostruct is used to create one of the modules of the arc shaped gate. It shows that when the volume surrounded by the grey lines needs to be effectively used to bear the loads (blue) towards the supports (red), the volume will be filled with 2 parabolic lines.

In this program it was not possible to simulate a water pressure and hence, the pressure on the structure is a line-load that is perpendicular to the line between the two supports. This causes the structure to become a parabola. In the case of a water pressure where the pressure will always be perpendicular to the structure itself (pointed towards the centre of the curve), the curve will become circular.[29]

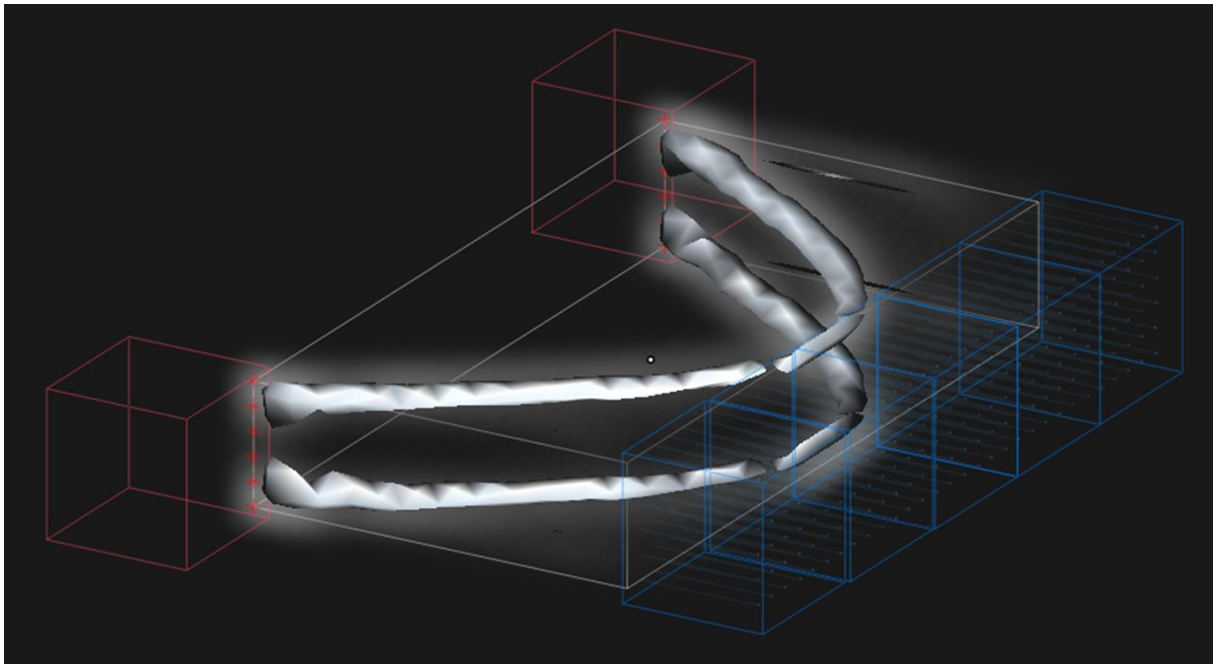


FIGURE 20 – TOPOLOGICAL OPTIMIZATION THROUGH TOPOSTRUCT; SUPPORTS IN RED, WATER PRESSURE IN BLUE, MATERIAL IN GREY.

Arc in practice in a rolling lock gate

When the supports can move freely parallel to the gate span, a beam that spans the distance between the supports underneath the arch (a drawbar) is required to prevent the supports from moving (which would result in a collapsing arch), see Figure 21. For lift- and drop gates this would be a cost/benefit consideration between this extra material in the gate, or bearing those loads in the support. With rolling- and sliding gates this drawbar will not fit in the recess, as can be seen when looking back at Figure 17.

The result is that the lock head will need to bear the lateral forces. It will thus become a more massive structure. Obtaining a water tight closure with a curved gate is also more difficult. It is also hard to design a lock head structure that can bear the lateral forces and is able to move the gate in- and out of the gate recess. Doeksen [23] analysed three alternatives for this: hooks, wedges and pins. These alternatives all have the same disadvantage: an extra mechanism is required that can lock and release the gate while it is also strong enough to bear the forces acting from the gate on the lock head.

Here another alternative will be designed to get rid of these extra mechanisms. The lock head will be designed such that one side of the recess bears the longitudinal forces (acting along the locks' longitudinal axis) and the other side of the recess bears the lateral forces, see Figure 22.

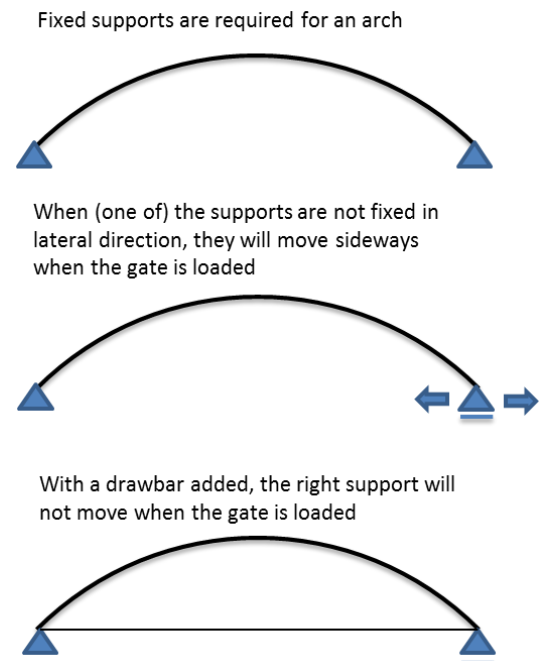


FIGURE 21 – CONSIDERATION BETWEEN A FIXED SUPPORT AND A DRAWBAR

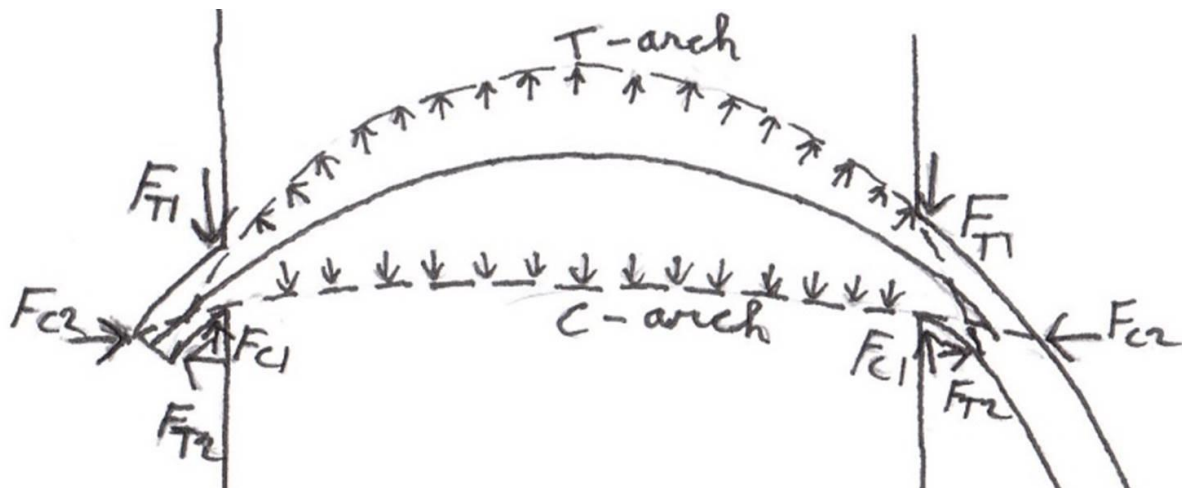


FIGURE 22 – LOCK HEAD BEARING LATERAL FORCES – F_T INDICATES THE SUPPORT REACTIONS WHEN THE ARC IS LOADED IN TENSION; F_C INDICATED THE SUPPORT REACTIONS WHEN THE ARC IS LOADED IN COMPRESSION; T-ARCH AND C-ARCH INDICATE THE GATE SHAPE (EXAGGERATED) WHEN THE ARCH IS EITHER IN TENSION OR IN COMPRESSION RESPECTIVELY

Two scenarios are possible and hence which side of the gate recess bears the longitudinal forces and which side bear the lateral forces can turn around. The first scenario is when the gate is loaded in

tension; this is indicated by the T-arch in Figure 22 and happens when the high water level is at the concave side of the arch. The second scenario is when the gate is loaded in compression; this is indicated by the C-arch in Figure 22 and happens when the high water level is on the convex side of the arch.

Support reactions F_{C1} and F_{T1} are the main support reactions resulting from the gate pressing on the lock head, comparable to when a flat rolling gate is loaded – the longitudinal forces. Support reactions F_{C2} and F_{T2} stop the gate from moving further outward (or inward) at the support as a result of bending. These are the lateral forces the gate has on the lock head. At the spots of these load bearings, as drawn in Figure 22, the lock head will need specific detailing to be able to bear those forces. This will be elaborated further in Chapter 7.

5.6.2 MATERIAL SELECTION

There are many materials to choose from in civil works. The basic materials are steel, concrete, wood and polymers. For lock gates wood and steel were until recently, the only used materials. Wood is the older one of the two and has its limits with respect to the lock width; hence steel has taken over the position of the main material for lock gate design.

Currently however, a development is taking place where locks (though very few) are fitted with doors of the other 2 types of materials. One example of a concrete gate is Sluis 124 in Amsterdam [30], where concrete was used in the form of high performance concrete, HPC. One example of the polymers is the new lock being built for the project Verbreding Wilhelminakanaal [31]. Here the polymers are used in the form of fiber reinforced polymers, FRP.

Staying at the innovation side of the spectrum, one of the latter two material types is chosen. Both FRP and HPC (or even ultra-high performance concrete, UHPC) are practically maintenance free. Their main mechanical material properties are shown in Table 2. Three types of FRP are shown and both, HPC and UHPFRC, are shown, besides steel is shown as reference.

TABLE 2 – MATERIAL PROPERTY COMPARISON; SOURCE: [32-34]

Material	Ultimate strength	Elastic modulus	Failure strain
Glass FRP	517 – 1207 MPa	30 – 55 GPa	2 – 4.5 %
Carbon FRP	1200 – 2410 MPa	147 – 165 GPa	1 – 1.5 %
Aramid FRP	1200 – 2068 MPa	50 – 74 GPa	2 – 2.6 %
HPC	>70 MPa / N/A*	N/A**	N/A**
UHPFRC	170 MPa / 8 MPa*	50 GPa	2.3 – 2.6 ‰ / 5 – 25 ‰*
Steel	483 – 690 MPa	200 GPa	>10 % (after yielding)

* Before and after the '/' are the compressive and tensile situation respectively

**For HPC, the elastic modulus and failure strain are not defined because HPC can have many different properties depending on the application

Of the FRP's, the carbon FRP gives the best properties in the table above and also on the aspects such as durability, fatigue and alkaline resistance. The price is comparable to the aramid FRP and higher than that of glass FRP. [32]

Concrete is much heavier than any of the FRP's and a lot more material will be required for the same load bearing capacity because concrete has a far lower ultimate strength. This gives FRP the

(dis)advantage that it floats much earlier in a submerged hollow structural application. The mechanisms to move the gate have to bear less weight this way but it may cause troubles through water leakage.

With respect to other concrete types, UHPFRC has an extra advantage. It has an extremely low porosity and permeability. This makes it possible to use a very minimal concrete cover in the order of 10 mm [35]. Also, Piérard, et al. [36] determined that the concrete cover of UHPC could be as small as 5 mm when subject to carbonation for a lifetime of 100 years, while conventional concrete would require a cover of 65 mm.

There is also a difference in price. Concrete has lower costs per m^3 than FRP or steel but FRP and steel are stronger and can be used with much thinner profiles. Hence, the prices (of the structure as a whole) are expected to be in the same order of magnitude. Though accurate estimates of these prices could not be gotten because the modular rolling arc gate is never designed before and prices of the materials are not available.

The material choice is therefore based on personal preference and its innovative character. This will be UHPFRC. If comparable designs are made from the other materials, including the accompanying lock head designs, it will become possible to compare prices of each of these designs. This thesis will however only focus on the design of one gate.

5.7 CONCLUSIONS

This chapter started with naming the basic functions of a lock gate. After this the classic choice direction for choosing a gate type was shown, the nature of which is very conservative. Which does not stimulate engineers to come up with innovative ideas.

To come up with new ideas and choose a different gate, other criteria for choosing a gate were set. These criteria were: the possibility of modularisation and innovation. The first criterion originated from Chapter 3 where the choice for making a modular gate was made to reduce the amount of reserve gates that are needed and ease the construction process. The last criterion (together with the first) was (further) explained in Section 5.4.

A broad spectrum of gate types was then described and their main advantages and disadvantages investigated. Based on these advantages and disadvantages, with respect to the choice criteria the rolling arc gate became the chosen concept. This is different from the mitre gate that would normally follow, mainly because it is sought after to do something different to find if it is still possible to innovate on gate types used. Whether the rolling arc gate is really an innovation (an invention that adds value) is still to be shown.

Finally some materials are compared and UHPFRC is the chosen material to design the rolling arc gate with.

In Chapter 6 the conceptual design is made and evaluated.

6 CONCEPTUAL DESIGN OF THE MODULAR LOCK GATE

6.1 INTRODUCTION

After choosing the rolling arc gate in Chapter 5, a conceptual design will be drawn here and evaluated, as third step in the design process (after setting the requirements and choosing a gate concept). The evaluation will be used in Chapter 7 for further improvement and detailing of the concept.

6.2 METHODOLOGY

Chapters 3 to 5 resulted in choices that will be combined into a concept of a lock gate. Namely:

- The gate will be modular
- The gate will be a rolling arc gate
- The gate will be build out of UHPFRC

The drawings of this concept are made with Sketchup. This was followed by a discussion of the concept with experts:

- At Rijkswaterstaat the concept was discussed in a brainstorm session with several experts mostly from the hydraulic engineering department to find the pros and cons of the modular lock gate
- A meeting was arranged with the supplier of FRP mitre gates for the lock in the Wilhelminakanaal near Tilburg to discuss how a FRP modular lock gate would compare to an UHPFRC modular lock gate and whether it would be feasible to build an FRP lock gate from modules
- A meeting was arranged with two of the advisors at the lock in the Wilhelminakanaal near Tilburg, mainly to discuss the problems with the water levels around the project there, but also some time was available for a quick discussion on the feasibility of the curved modular lock gate
- A meeting was arranged with the lockkeeper at lock Eefde to discuss any general problems that may occur at lock Eefde.

Their views on the concept will be taken into account when designing the lock gate in more detail.

The discussion was left as open as possible, which means there was no list of questions that was consistently asked to each expert. The reason was to analyse what are the first things that come to mind when discussing such a new lock gate concept.

6.3 CONCEPTUAL DESIGN OF THE GATES AND HEADS

The first conceptual design is shown in Figure 23 and Figure 24. In Figure 23 it can be seen that the gate in the upper head has high water on the convex side while the gate in the lower head has high water on the concave side. In this way the structure of the lower lock head gate recess will be fully build at parts where the ground level is still high. Otherwise (when the gate at the lower lock head also retains high water on the convex side) the gate recess will be shaped in such a way that it will stick out away from the lock chamber, rising far above the local ground level and polluting the view.

The result is that the rolling arc gate and its supports in the lock heads need to be designed in such a way that it can retain high water in both directions. Though, the ability to do this, will make the lock

gates applicable over a wider range of locks, namely also the locks where high water can come from both sides of the lock, resulting either from a tide or a separation between two rivers that have varying water heights.

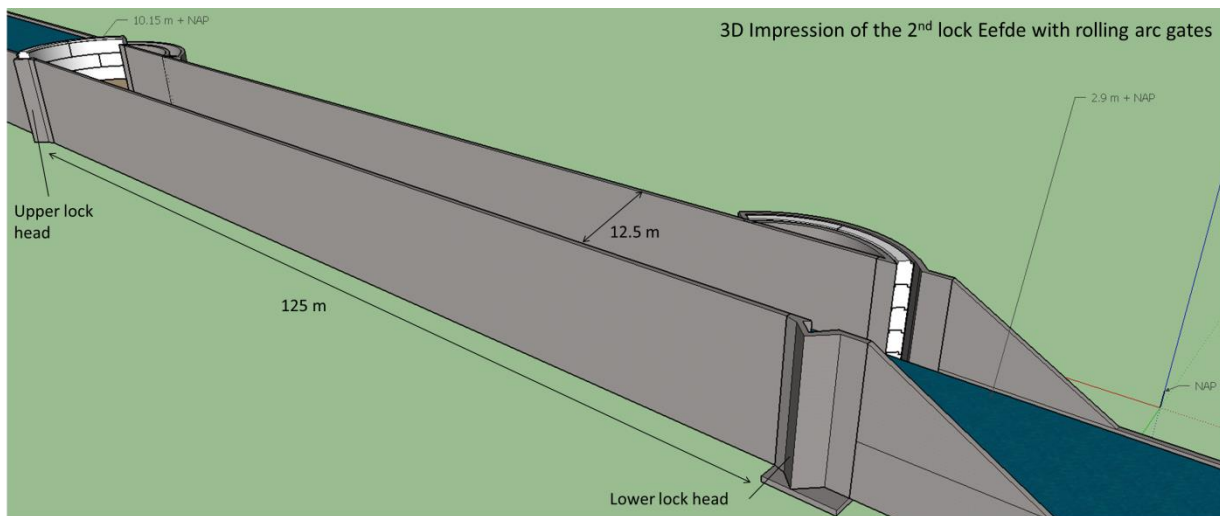


FIGURE 23 - OVERVIEW OF LOCK EEFDE WITH THE ROLLING ARC GATES

An aspect that can be seen in Figure 24 is the brick-wise build-up of the gate as it was in the conceptual design. This was the result of an idea to create blocks that are transportable by road with the advantage that less reserve gates were required, while still being able to get a new gate on location within a day in case a fast replacement should be required. Another advantage is that lighter equipment can be used to install the gate, which is often cheaper and has a better availability.

It is assumed that the optimum for the module size (see Section 3.2.2) is at modules that can be transported by road without the need for additional licenses or restrictions with respect to normal road traffic. The best way of transporting these modules is assumed on their side, while supporting the higher parts of the arch, so it cannot slide off. The height of the module is then restricted to 2.5 m, so that it will not exceed width limits as a truck load.

The span of the gate is 13 m. This covers the 12.5 m functional width of the lock and gives a 0.25 m long part of the gate in each recess to guide the loads towards the supports.

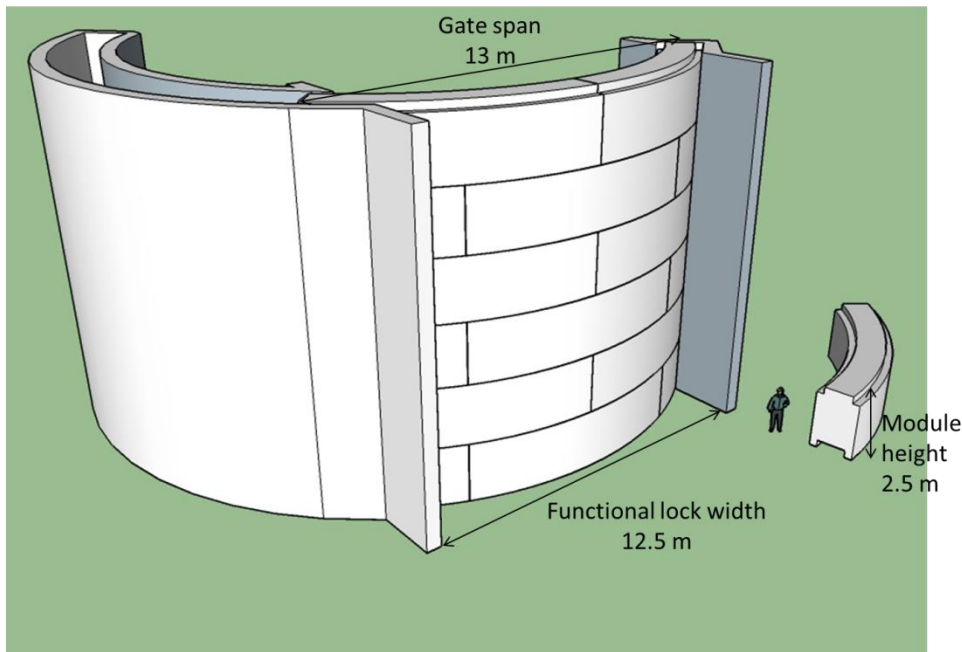


FIGURE 24 - LOCK GATE IN ACCOMPANYING HEAD

6.4 EVALUATION OF THE EXPERT INPUT

During the discussion with experts, a lot of questions and comments were made. They are categorized here and will be a guide in the next stage of the design process.

6.4.1 LEVELLING

In the category of the levelling system the following comments were given and noted:

1. How would the lock be levelled?
2. Levelling through the gates is a lot cheaper than through culverts.
3. Levelling through the gates was never a consideration in the design process for Sluis 124 in Amsterdam as there was enough space available to build culverts.

Comment 1 is an obvious result of the conceptual design that was made. Neither culverts nor holes in the gate were shown. This was a method to elicit the experts to think about the levelling system without directly using holes in the gates.

This resulted in the knowledge from comments 2 and 3. Most believe that levelling through the gates is cheaper and culverts should only be applied when levelling through the gates is not feasibly possible anymore. This (non-)feasibility is caused by a requirement on the combination of forces acting upon a vessel in the lock resulting from [37, 38]:

- Translation waves
- Flow reduction longitudinal to the lock, hence a gradient in the water level
- Friction (of minor importance with respect to the other aspects)
- Fill ray against bow
- Water level drop above the fill ray

When the combination of these forces exceed 1 ‰ of the ship's water displacement with a maximum of 100 kN the requirement is not met and another solution should be found. This requirement exists

to protect mooring lines of ships from high forces. Another solution is usually found by redesigning either the opening scheme or the openings in the door. When either of those do not sufficiently reduce the mooring forces, culverts are used.

As a test to know if culverts are really that expensive, and to opt for faster locking schemes without increasing the locking forces on ships, the design choice for culverts is made here.

6.4.2 MODULES

In the module category the following comments were given and noted:

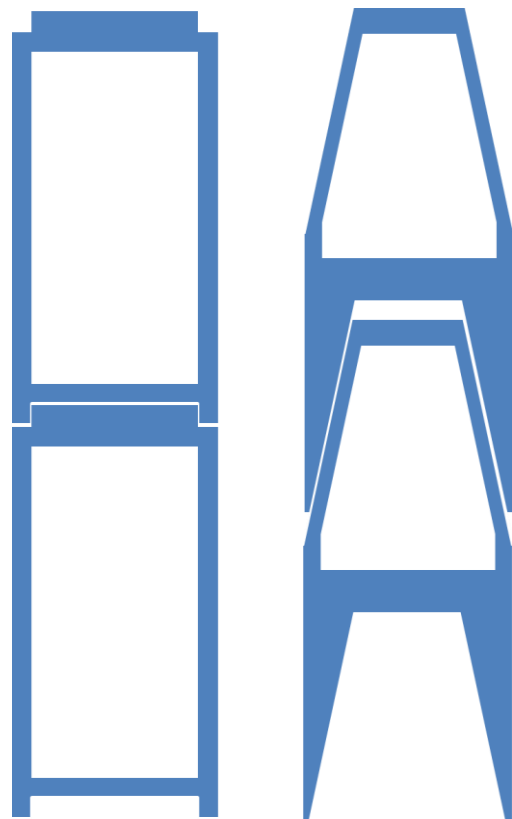
1. The modules should at least cover the full gate width instead of this brick-wise build-up.
2. In FRP the modules would look somewhat differently, as presented on the right in Figure 25. The surface area by which the modules can be connected will then be greater, which improves the strength of the gate as a whole and reduces the risk of leakage between the modules.
3. In FRP the production of modules would be far more expensive and time consuming than building the whole gate at once.

The first of these comments will be taken over in the final design for the following reasons:

- The intersections between modules are prone to be less water tight.
- Special measures need to be taken to allow tension in the arch at those intersections, such as a tension cable.
- The brick-wise module build requires 2 different sized modules.
- Modules covering the full width of the 12.5 m wide lock are still transportable by road.

So there will be no brick wise build-up of the gate and the modules will, from the next design stage on, cover the full width of a 12.5 m wide lock. The modules remain 2.5 m high.

The second and third of these comments are noted for the case of a FRP door. The main design alternative will remain to be an UHPFRC door as discussed in Chapter 5.



**FIGURE 25 – CROSS SECTIONS OF THE GATE
LEFT: UHPFRC AS SHOWN IN FIRST CONCEPT;
RIGHT: FRP**

6.4.3 *SHAPE*

In the shape category the following comments were given and noted:

Sealing between the lock gate and lock head will be more difficult with curved gates than with flat gates.

From this first comment it becomes obvious that the sealing of the gates is an important detail. This will be detailed best by creating a support in the lock head that has the same shape as the displaced door (from bending) when closed as to increase the contact area. Also a somewhat more flexible material than concrete can help to improve the sealing of the gate.

This gate uses a lot of space next to the lock.

This comment is true with respect to a mitre gates as these gates have their thickness and width occupying the space next to the lock, besides, the lock head needs a part to facilitate lateral forces coming from mitre gates. This combination is a lot less wide than the combination of a curved lock gate and its recess. However, when mitre gates need to retain a large negative head, a second set of gates is required behind the first set, greatly increasing the required length of the lock which cannot be used to increase the functional length (support the locking of longer ships).

With respect to flat rolling gates the gate also requires somewhat more area next to the lock. But in terms of width of the lock facility, a lot of space can be saved. Because flat rolling gates require that the lock head is at least twice the width of the navigation lock so that the gate can fit in the recess when opened. This also makes that locks built with the rolling arc gate can be built in closer proximity to each other than locks fitted with flat rolling gates.

A lock gate that fits barely in its recess is sensitive to getting stuck due to waste and ice.

This comment is indeed very much applicable to the curved rolling gate. This means that the gate recess needs to be built such that it can be easily cleaned of waste and ice. Also measures should be taken to reduce waste and ice accumulation.

One can think of air bubbles and heating systems around the water level as means to reduce/prevent ice accumulation. Track clearers in front of the carts can prevent the gate from getting stuck due to waste. Waste and ice also give troubles at mitre gates, rolling gates and probably many (if not all) other gate types. Systems to prevent this are in place and already known at these other gates and it is therefore expected that it is at least technically feasible to prevent the rolling arc gate from getting stuck.

One of the ways that could ease keeping the gate recess ice and waste free is to open it not only on the side of the gate but also where it touches the wall of the lock chamber. This will be done in the next design phase (Chapter 7).

A curved rolling gate can give a lot of friction on the rails during movement.

A gate not only has to translate to the side of the lock, but also has to turn around the centre of a circle. To accommodate this rotation the rails need to apply a centripetal force on the gate while moving, which gives some extra friction. The curvature is however also used to design a lighter gate. By making use of the arch, the design will be such that mainly normal stresses are present in the gate and bending stresses will be reduced to a minimum. Hence a smaller cross section is required and the gate will be lighter. This can compensate some of that extra friction.

7 LOCK GATE (MODULE) DESIGN

7.1 INTRODUCTION

The concept made in and discussed in Chapter 6 has resulted in more insights about how to design the curved modular lock gate. For the next (and fourth) design step this chapter will analyse the forces that work on the gate modules and then design these modules accordingly.

The focus of this chapter will be on the bottom module because this module is subject to the highest water pressure, see Figure 26. The idea is that modules on top will be the same so that a standardized construction process can be set up and no mistakes can be made where a module meant for the top will be put on the bottom in the lock gate. Hence, dimensioning of the bottom module will be assumed normative.

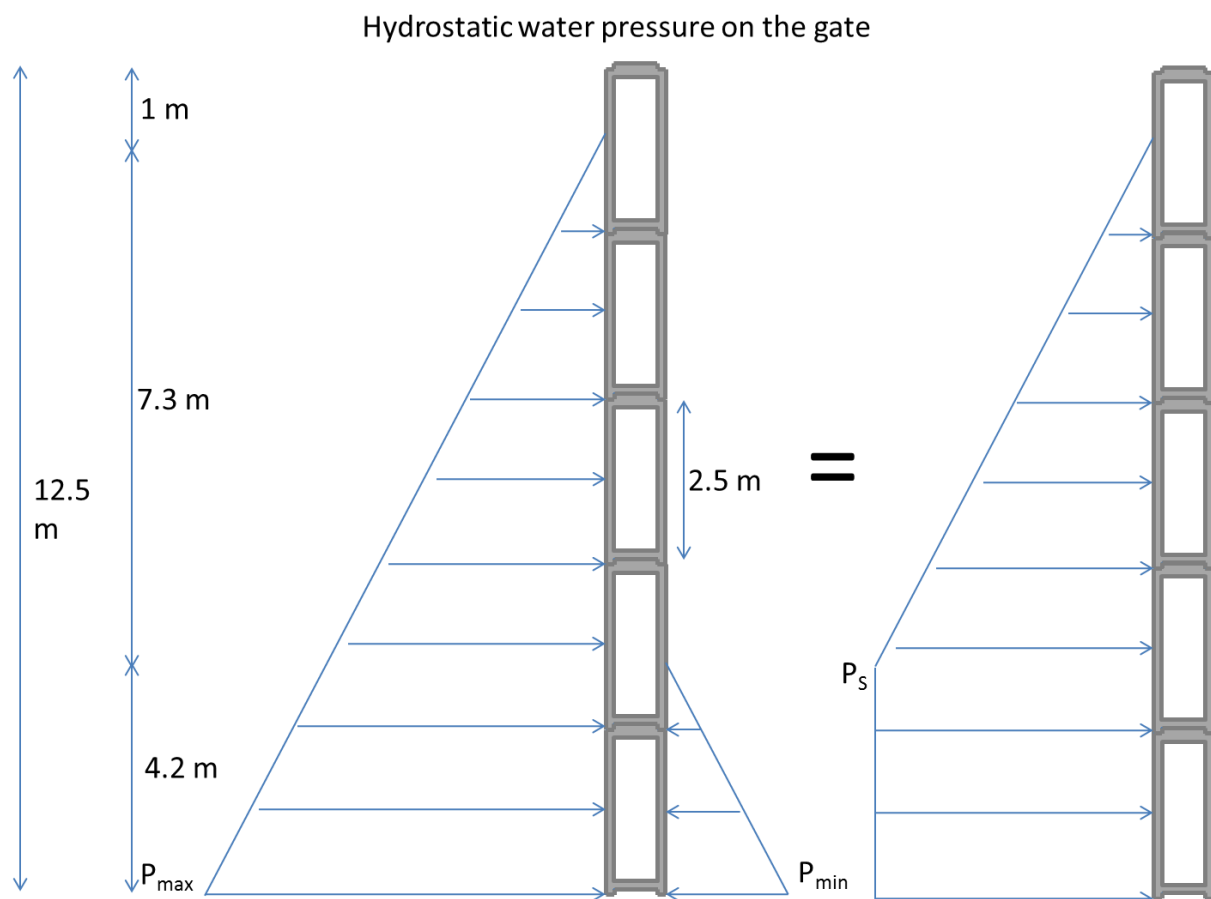


FIGURE 26 – HYDROSTATIC WATER PRESSURE ON THE GATE; CROSS SECTIONAL VIEW

The dimensions of the modules are given by (see relation between the gate span and the radius in Section 5.5.5):

- Span (l) 13 [m]
- Radius (r) 9.7 [m]
- Arch height (H) 2.7 [m]
- Module height (b) 2.5 [m]

This chapter will begin by defining the loads that act on the module in Section 7.2. Section 7.3 then discusses the interaction between the gate (modules) and the lock head through a series of computer models. In Section 7.4 the modules will then be designed based on the model that comes closest to simulating an arc gate. The end result of this chapter will be a module design that should be able to handle the loads that act on it given the lock gate requirements from Section 4.3.

7.2 LOADS ON THE GATE (BOTTOM MODULE)

7.2.1 HYDROSTATIC WATER PRESSURE

The main load is a positive and negative hydraulic head (resulting from the rise over the lock) over the gate of 7.3 m. This gives a resultant pressure on the bottom module of (see Figure 26):

$$P_s = \rho g \Delta H = 1000 * 9.81 * 7.3 = 71 \text{ kN/m}^2 \quad [5]$$

Because the sections are hollow, the high pressure from the high water side of the gate, not reduced by the low water level at the other side, has also to be accounted for. This pressure is given by:

$$P_{max} = \rho g H_1 = 1000 * 9.81 * 11.5 = 112 \text{ kN/m}^2 \quad [6]$$

The gate must be able to bear this rise on its convex as well as its concave side. No density differences will be taken into account for now. When the gate will be designed in more detail, and is assumed to be feasible for both inland as sea navigation locks, a check for density differences should also be applied.

The gate might be opened when there is still a little bit of a head difference present. This could be in the order of 0.1 m. In this case the gate would be supporting in only one of its gate recesses and should be able to remain stable.

7.2.2 SELF-WEIGHT

Each module weighs about 60 kN (appendix B). This load is dependent on the cross section of the modules, which are calculated in Sections 7.4.3 and 7.4.4, giving a first estimate based on global buckling of the gate and the hydrostatic water pressure on it. A material density of the cross section of 2500 kg/m^3 was used. The self-weight will be governing when the lock head is empty and all modules are stacked on top of each other. In the lock Eefde example this – with 5 modules stacked – means that a total of 295 kN needs to be supported by the carts standing on the rails.

This load could be reduced by demanding that the lock head needs to stay submerged when maintaining and/or replacing the modules, discarding the need for stop logs. However, also the lock head (especially the rails) requires maintenance. So designing for a situation where the lock head is never dry is only possible when maintenance and inspection is possible (and feasible) in a submerged situation. For now it will be assumed that this is not possible and one of the load situations will be when the lock head is dry and all modules are stacked.

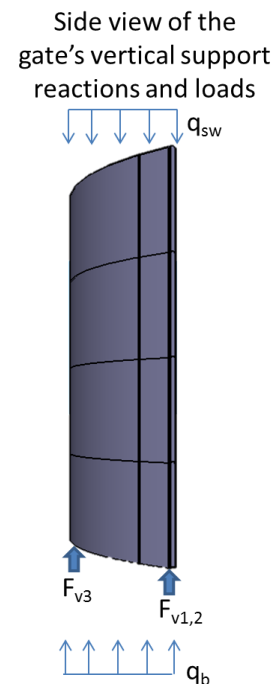


FIGURE 27 – GATE SUPPORTS AS SEEN FROM THE SIDE. $F_{sw1,2}$ INDICATES 2 SUPPORT REACTIONS, ONE AT EACH SIDE OF THE GATE

7.2.3 BUOYANCY

Each module has a water displacement of 58 kN when fully submerged. With the self-weight this results in a submerged net-weight of 2 kN, see Figure 27.

7.2.4 WAVES

A maximum wave height of 1 m will be assumed at the level of the highest water level. The gate has 1 m of freeboard in the current case (Figure 26). When a wave hits a vertical wall like a lock gate it is fully reflected and the wave height will be twice as high (Figure 28).

The force on the gate will be calculated with a Sainflou approximation (Figure 28).

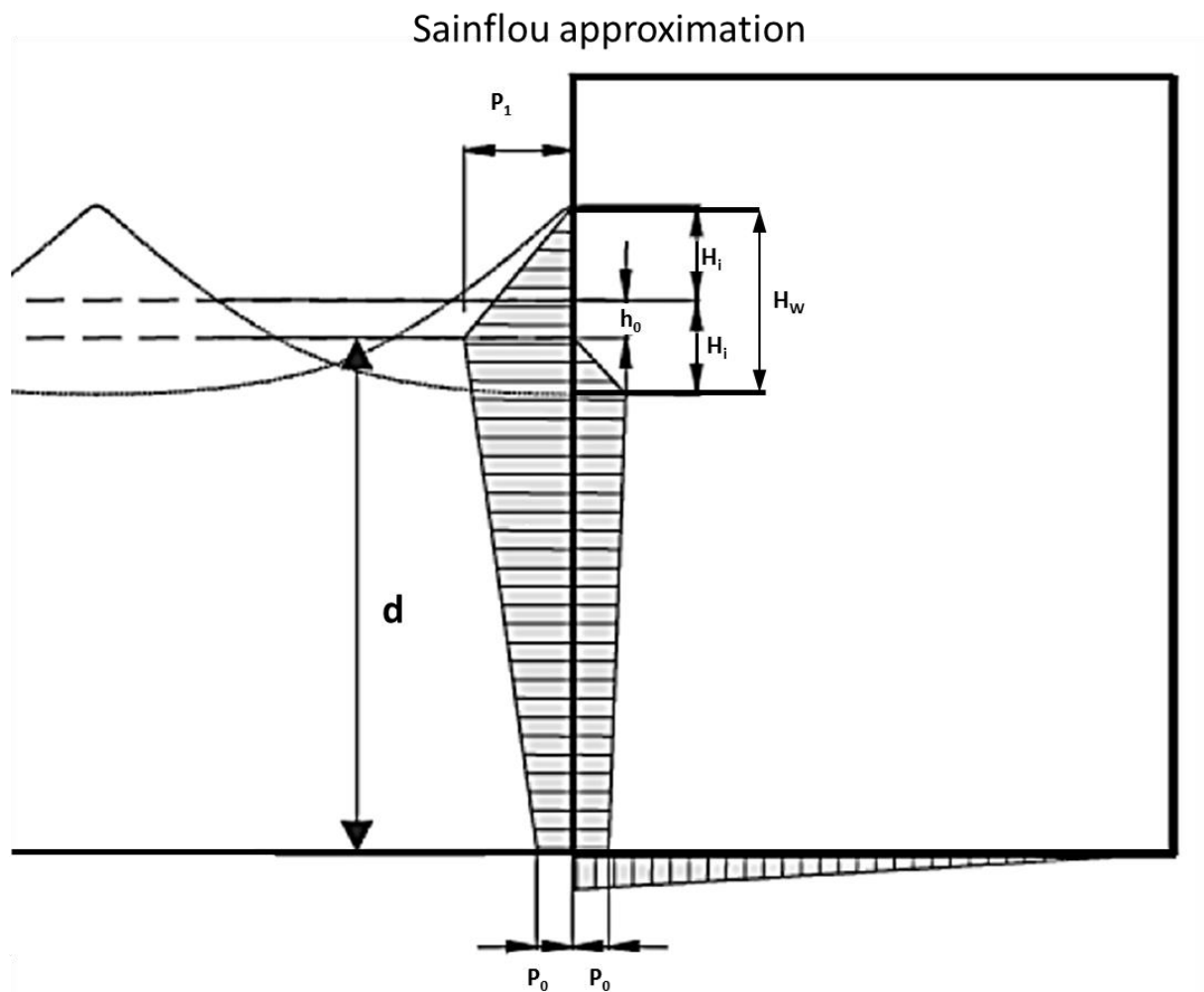


FIGURE 28 – SAINFLOU APPROXIMATION OF A WAVE LOAD ON A VERTICAL WALL

The approximation starts by an increase in the water level by:

$$h_0 = \frac{1}{2} * k * H_i^2 * \coth(kd) \quad [7]$$

In which:

- h_0 An increase in the mean water level [m]
- H_i The wave height of an incoming wave [m]
- k The wave number of an incoming wave = $\frac{2\pi}{L}$ [m⁻¹]
- d Water depth [m]

The wave length first needs to be estimated. The First estimate is that of the wave period, through which the wave length can be calculated. A typical wind wave of 1 m in height has a wave period (T_w) of about 3 seconds [39]. This period will thus be assumed. The waves may however also occur due to translation waves of filling/emptying the lock (or from an upstream lock) or from ship movement.

With the period of 3 s, the wave length (L) and the wave number (k) can be calculated (L_0 and k_0 are initial estimates; at least one extra iteration is required to find more accurate numbers for the wave length and the wave number):

$$\begin{aligned} L_0 &= \frac{g * T_w^2}{2\pi} = \frac{9.81 * 3^2}{2\pi} = 14.1 \text{ m} \\ k_0 &= \frac{2\pi}{L_0} = 0.45 \text{ m}^{-1} \\ L &= \frac{g * T_w^2}{2\pi} \tanh(kh) = \frac{9.81 * 3^2}{2\pi} \tanh(0.45 * 4.2) = 13.4 \text{ m} \\ k &= \frac{2\pi}{L} = 0.47 \text{ m}^{-1} \end{aligned} \quad [8]$$

In which:

- L Wave length [m]
- L_0 Initial estimate of the wave length [m]
- k_0 Initial estimate of the wave number [m⁻¹]
- T_w Wave period [s]

Now h_0 becomes:

$$h_0 = \frac{1}{2} * 0.47 * 1^2 * \coth(0.47 * 4.2) = 0.24 \text{ m} \quad [9]$$

And P_1 and P_0 are calculated through:

$$\begin{aligned} P_1 &= \rho * g * H_i = 1000 * 9.81 * 1 = 9.8 \text{ [kN/m] (line load)} \\ P_0 &= \frac{\rho * g * H_i}{\cosh(kd)} = \frac{1000 * 9.81 * 1}{\cosh(0.47 * 4.2)} = 2.7 \text{ [kN/m] (line load)} \end{aligned} \quad [10]$$

7.2.5 WIND

The wind force is taken as negligible. The gate is for a great part surrounded by the lock chamber, the lock head and by water. Only a small part of the gate may still be in a situation where it needs to overcome a wind force at certain times. This part will also be loaded by waves, either from filling/emptying the lock, from approaching or leaving ships or from the wind. These wave forces are greater than the wind force. Also the wind cannot hit the gate at the same time when a wave is al-

ready pressing against it, hence the wind will also not be present in a load combination. However when the design will be done in more detail, it is advisable to also check for wind loads.

7.2.6 GATE MOVEMENT

Mechanism pull force

The gate will be moved by mechanics on top of the lock head that pulls in the direction of the local gate axis with force F_w . This force is counteracted by rolling resistance $F_{f1,2,3}$ (see Figure 29). The force also introduces possible tilting of the gate. Hence the weight of the gate minus its buoyancy force may not be too small.

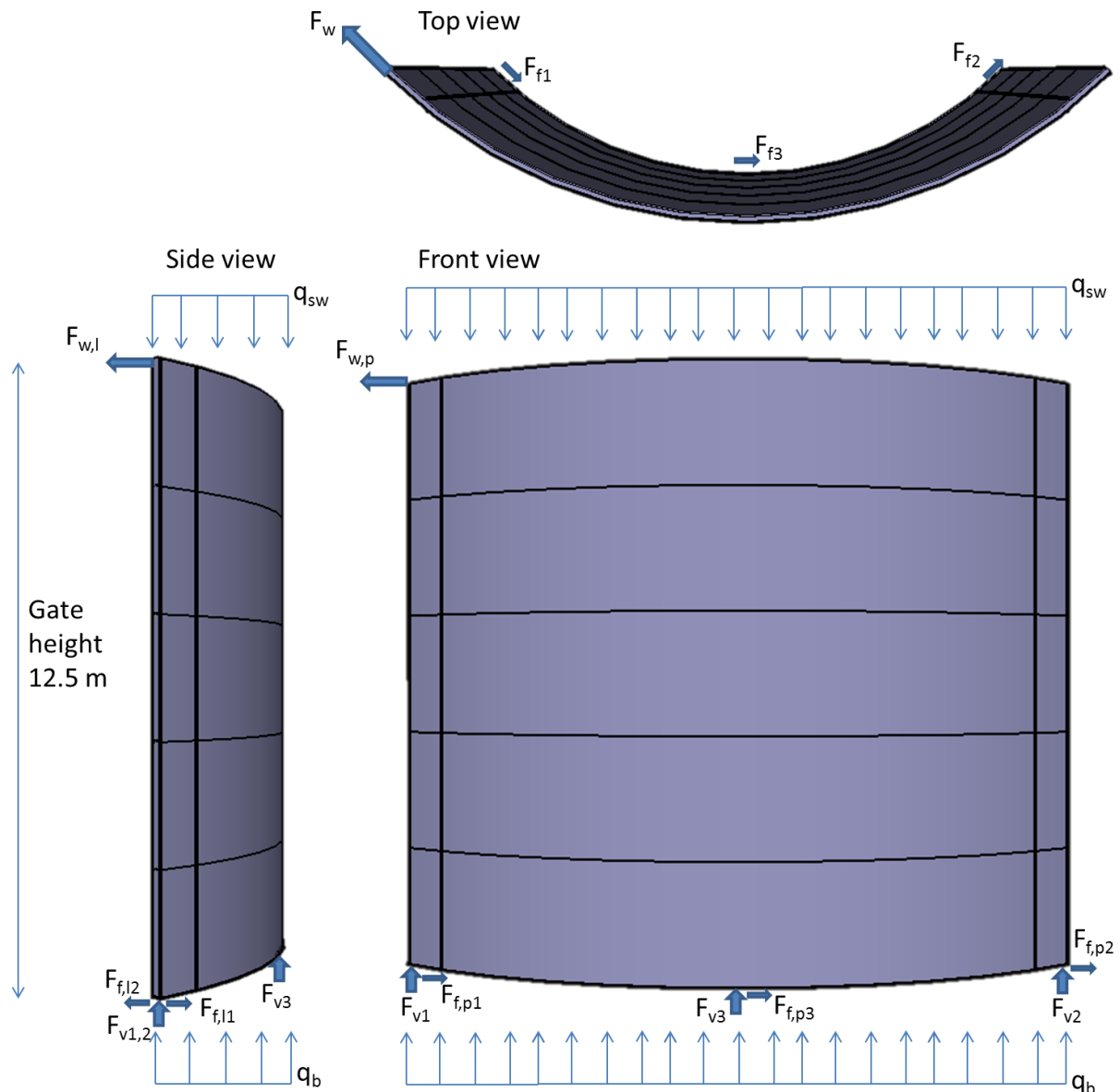


FIGURE 29 – GATE FORCES RELEVANT WHILE OPENING AND CLOSING THE GATE; THE L AND P SUFFIXES REPRESENT THE FORCE IN LONGITUDINAL AND PERPENDICULAR DIRECTION TO THE LOCK AXIS RESPECTIVELY

The pulling force of the mechanism (minus the rolling resistance) should result in comfortable opening and closing times that do not take up a lot from the total locking time. For this an opening/closing

time of about 30 seconds will be used. In this time the gate will have to accelerate to a maximum opening speed and then decelerate.

An acceleration time of 10 seconds and a deceleration time of 5 seconds will be assumed reasonable in these 30 seconds of moving time. The remaining 15 seconds, the gate will move at its top speed. This will result in the graph of Figure 30.

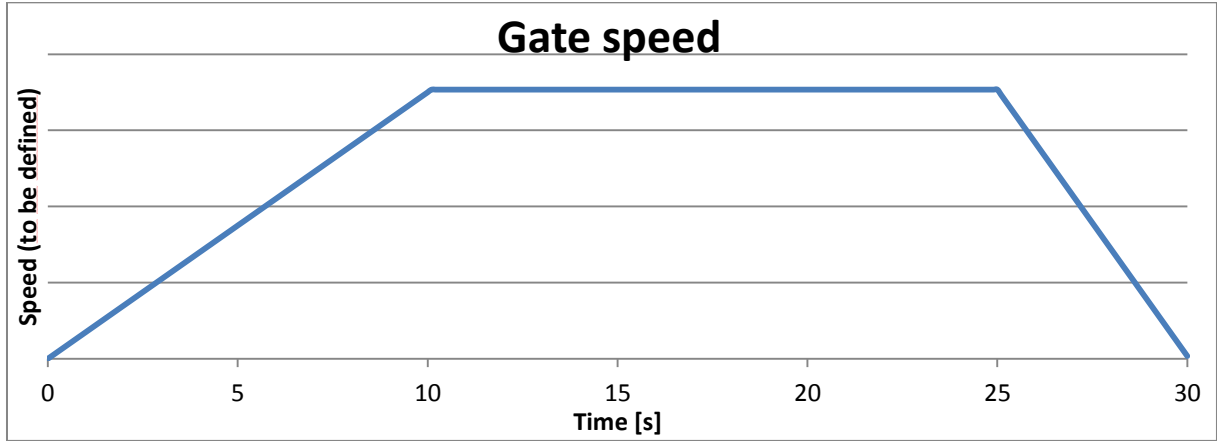


FIGURE 30 – GATE SPEED OVER ITS MOVEMENT PERIOD OF 30 SECONDS.

Within this 30 second time laps the gate has to move over a distance of 15.6 m (which is the curved length of the gate). The required top speed of the gate, and from that the acceleration and deceleration can be calculated with the following equations:

$$\begin{aligned}
 s &= 0.5 * v_{max} * 10 + v_{max} * 15 + 0.5 * v_{max} * 5 = 22.5 * v_{max} \\
 v_{max} &= \frac{s}{22.5} = \frac{15.6}{22.5} = 0.7 \text{ m/s} \\
 a^+ &= \frac{v_{max}}{10} = 0.07 \text{ m/s}^2 \\
 a^- &= \frac{v_{max}}{5} = 0.14 \text{ m/s}^2
 \end{aligned}
 \tag{11}$$

In which:

- s Length of gate curvature and distance it has to translate [m]
- v_{max} Gate top speed [m/s]
- a^+ Gate acceleration [m/s²]
- a^- Gate deceleration [m/s²]

The deceleration will be done by a bumper that could be on the rails to stop the roller carts or could be somewhat higher in the lock head, so that the gate bumps against it. The acceleration will be done by the engine through the pull force (F_w). This force can now be calculated using the mass of the gate ($M_{gate} = M_{module} * 5$) and its acceleration (a^+):

$$F_w - F_{total} = M_{gate} * a^+ = 6000 * 5 * 0.07 = 2.1 \text{ kN} \tag{12}$$

This can be translated to a force parallel (suffix l) and perpendicular (suffix p) to the lock longitudinal axis:

$$F_{wl} - F_{ftotall} = F_{wp} - F_{ftotalp} = \sqrt{\frac{1}{2}} * (F_w - F_{ftotal}) = \sqrt{\frac{1}{2}} * 2.1 = 1.5 \text{ kN} \quad [13]$$

Rolling resistance

The rolling resistance of the carts on the rails can be calculated using the following formula:

$$F_f = C_r * W_{net,gate} = 0.002 * 10 = 0.02 \text{ kN} \quad [14]$$

In which

- C_r Coefficient of rolling resistance = 0.002, using the railroad steel wheel on steel rail coefficient

Stability due to tipping of the gate

The pulling force of the mechanism plus the rolling resistance it has to overcome, may cause the gate to topple over, or at least be unstable during movement. This is because the moment caused by the pulling force can exceed the stabilizing moment from the weight of the gate. This can happen parallel or perpendicular to the lock longitudinal axis (Figure 29):

$$\begin{aligned} M_l &= (F_{w,l} + F_f) * (b * 5) - W_{net,gate} * \frac{H}{2} = 1.52 * 12.5 - 10 * \frac{2.9}{2} = 4.5 \text{ kNm} \\ M_p &= (F_{w,p} + F_f) * (b * 5) - W_{net,gate} * \frac{l}{2} = 1.52 * 12.5 - 10 * \frac{14}{2} = -51 \text{ kNm} \end{aligned} \quad [15]$$

In which:

- | | | | |
|------------------|--|-----|-------|
| • b | Module height | 2.5 | [m] |
| • $W_{net,gate}$ | Total weight of the gate minus the buoyancy force | 10 | [kN] |
| • H | Arch height | 2.9 | [m] |
| • l | Span | 14 | [m] |
| • M_l | Moment around the bottom left corner of the gate parallel to the lock longitudinal axis | | [kNm] |
| • M_p | Moment around the bottom left corner of the gate perpendicular to the lock longitudinal axis | | [kNm] |

A positive moment would mean an unstable situation, the gate will turn around the bottom left corner of the gate seen in Figure 29. A negative moment would mean that it will be compensated by the vertical support reactions on the gate to become 0. Hence, these calculations indicate that the stabilizing moment from the weight of the gate, parallel to the lock longitudinal axis, is too small (the lock will lift at support 3, turning around the supports 1 and 2). The stabilizing moment perpendicular to the lock longitudinal axis is on the safe side.

The solution will be reducing the acceleration of the gate and increase the time it takes to open and close. Whether this is acceptable will depend on gate opening times of other gate types and whether the lock itself can stay within required locking times. Increasing the weight of the gate is not a solution because this would also increase the force required to open it.

Another solution is to reduce the moment caused by the pulling force by lowering the mechanism, or at least the location at which it pulls at the gate, into the lock head. Lowering the mechanism is however unwanted as this will mean more moving parts under the water level.

Lowering the point at which the mechanism pulls, as is sometimes done with straight rolling gates through cables, could not be found a solution for in the case of the curved rolling gate. The cable will need to be guided around a curve without the guidance mechanism of the cable impeding gate movement.

So it can be concluded that another disadvantage of the curved gate is found here. Namely the instability of movement because the opening force of the gate needs to be applied at an angle. This may cause that opening/closing times of the gate are somewhat slower than they could be for a straight rolling gate.

7.2.7 SHIP COLLISION

Ship collision will be a force that the lock gate, given its slenderness most likely cannot bear. For reference, the force is calculated here. This is done through calculating the amount of kinetic energy that needs to be absorbed by the structure [39]. The kinetic energy of the ship is given by the following formula:

$$E_{kin} = \frac{1}{2}(m_s + m_w)v_s^2 C_E C_s C_c \quad [16]$$

In which:

- E_{kin} Kinetic energy [kNm]
- m_s Mass of the ship (= $3.0 \cdot 10^6$ kg) [kg]
- m_w Mass of the water moving with the ship (= $\rho L \frac{1}{4} \pi D = 3.0 \cdot 10^5$ kg) [kg]
- v_s Velocity of the ship (0.20 m/s; assuming that a shipper would never sail near a closed gate at speeds higher than this, a design velocity for mooring structures) [m/s]
- C_E Coefficient of eccentricity (1 at a frontal collision)
- C_s Softness coefficient (1 because of negligible deflection of the ship's hull)
- C_c Configuration coefficient (1, no hydrodynamic damping assumed)
- L Ship length (=110 m) [m]
- D Ship draught (=3.5 m) [m]

So the kinetic energy becomes:

$$E_{kin} = \frac{1}{2}(3.0 \cdot 10^6 + 3.0 \cdot 10^5) \cdot 0.20^2 = 66 \text{ kNm} \quad [17]$$

The collision force can then be estimated with:

$$F_{collision,0} = \sqrt{2k_{fender} * E_{kin}} = \sqrt{2 * 14000 * 66} = 1.4 \cdot 10^3 \text{ kN} \quad [18]$$

In which:

- $k_{fender,0}$ An assumed stiffness example from source: [39] – $1.4 \cdot 10^4$ [kN/m]

The estimate of this force was then put into the model of Method 1 (which will be defined in Section 7.3.2) as a point load in the middle of the gate to determine the deflection. The result can be seen in Figure 31.

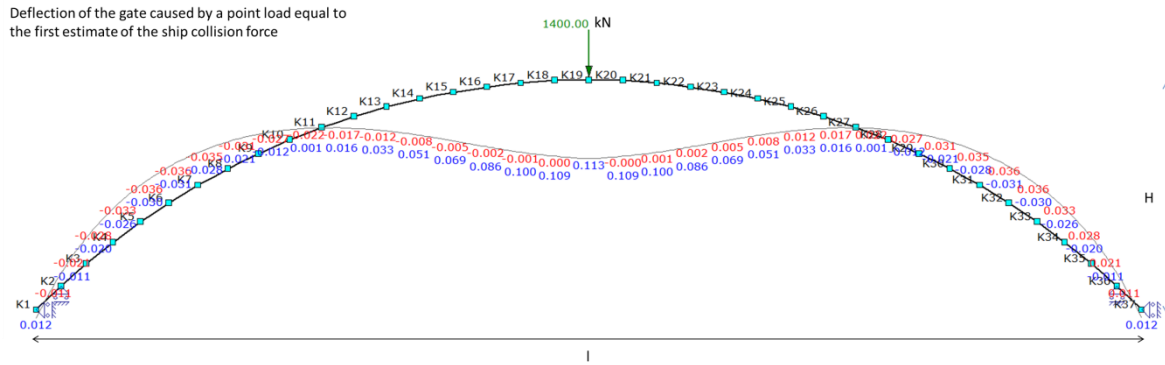


FIGURE 31 – DEFLECTION OF THE GATE CAUSED BY THE SHIP COLLISION FORCE – DEFLECTIONS IN [m]

The load and the deflection can then be used to define the stiffness of the gate when subject to a point load in the same order of magnitude:

$$k_{fender} = \frac{F_{collision,0}}{w_0} = \frac{1400}{0.113} = 1.2 * 10^4 \text{ kN/m} \quad [19]$$

In which

- w_0 Deflection in the middle of the gate [m]

Which is not that far off from the first estimate. Hence, the collision force can now be calculated:

$$F_{collision} = \sqrt{2k_{fender} * E_{kin}} = \sqrt{2 * 1.2 * 10^4 * 66} = 1.3 * 10^3 \text{ kN} \quad [20]$$

As a comparison, the hydraulic pressure causes a total load on one module of:

$$\begin{aligned} F_{ps} &= b * l * P_s = 2.5 * 14 * 71 = 2.5 * 10^3 \text{ kN} \\ F_{p1} &= b * l * P_1 = 2.5 * 14 * 112 = 3.9 * 10^3 \text{ kN} \end{aligned} \quad [21]$$

In which:

- F_{ps} The total load on a module as a result from the hydraulic water pressure [kN]
- F_{p1} The total load on the wall of a module as a result from the hydraulic water pressure [kN]

Because the loads from the hydrostatic water pressure are much greater than the collision load of a ship, it may be possible for the modules to bear the collision force ($F_{collision}$) as is estimated above. The loads from the collision of a ship and the hydraulic head, do not occur at the same time at the same place on the gate structure. Hence it is not a load combination for one of the modules in the gate.

The gate may however, fail more locally because the ship collides with its front, probably giving a relatively small impact area. On top of that, an analysis of cases where a ship collided with lock gates may be required to get a better estimate of the speed. Working out the collision force of the ship is not done in great detail due to a lack of time, instead this estimate of the ship collision force is made.

7.2.8 SUMMARY

The forces that the gate (module) is subjected to are summarized here:

• Resultant hydrostatic water pressure	(P_s)	71	[kN/m ²]
• Hydrostatic water pressure on the module walls	(P_{max})	112	[kN/m ²]
• Self-weight (per module)		60	[kN]
• Buoyancy force (per fully submerged module)		58	[kN]
• Top wave pressure	(P_1)	9.8	[kN/m]
• Bottom wave pressure	(P_0)	2.7	[kN/m]
• Mechanism pull force	(F_w)	2.1	[kN]
• Rolling resistance	(F_f)	0.02	[kN]
• Ship collision	$(F_{collision})$	$1.3 \cdot 10^3$	[kN]

For the purpose of testing the concept (by first only designing the bottom module and determining its interaction with the lock head when closed), only the resultant hydrostatic water pressure is taken into account in the next section.

This hydrostatic water pressure is assumed governing (on the bottom module) and when the concept can bear this load with some redundancy, the other loads (self-weight of the gate, wave pressure etc.) and load factors should not cause big problems.

7.3 INTERACTION BETWEEN GATE AND LOCK HEAD

7.3.1 INTRODUCTION

In this section a computer model will be set up to be able to calculate the stresses in the arch and the support reactions in the lock head. Because it is unknown how the gate will really act on its supports in the lock head, several models and their results will be analysed. Based on the results concerning the stresses, support reactions and displacements, one of the models will be chosen and used for further calculations and dimensioning of the lock gate.

First a calculation is made based on the normal arch situation as is shown in Figure 19 (Section 5.6.1). This will give a reference for the order of magnitude of the forces in the structure and on the supports. The reference is based on the bottom modules of the gate, where the hydraulic head is fully present. The axial force in the arch and the support reactions are then given by Equation [3] (Section 5.6.1):

$$F_{R1} = F_{R2} = \frac{1}{2} * P_s * l * b = \frac{1}{2} * 71 * 13 * 2.5 = 1.2 * 10^3 \text{ kN}$$

$$F_R = \sqrt{\frac{1}{2}} * P_s * l * b = \sqrt{\frac{1}{2}} * 71 * 13 * 2.5 = 1.6 * 10^3 \text{ kN} \quad [22]$$

Given the hydrostatic water pressure:

$$P_s = \rho g \Delta H = 1000 * 9.81 * 7.3 = 71 \text{ kN/m}^2 \quad [23]$$

In which:

- | | | | |
|---|----------|--|---------|
| • | F_{R1} | Support reaction parallel to the gate longitudinal axis | [kN] |
| • | F_{R2} | Support reaction perpendicular to the gate longitudinal axis | [kN] |
| • | l | Module span | 13 [m] |
| • | b | Module height | 2.5 [m] |

The support in the lock head however, looks more like in Figure 22. This means that the structure will be statically indeterminate. Also, there is a little displacement and bending even before the lock gate moves to its final position and presses against its supports.

The combination of the curved structure of its statically indeterminateness, makes that hand calculations are insufficient. The structure will thus be calculated using a FEM program. The only known program available for free to students, and thus the only program that could be used here is Matrixframe. This limits calculations to a 2D situation and this makes it impossible to simulate the interaction between the modules. In Section 0 a qualitative explanation of this interaction between the modules will follow.

In the next section, 3 methods will follow to simulate the interaction between the gate and the lock head in Matrixframe. It is yet unknown how to model the gate given the concept of clamping the gate as discussed in Section 5.6.1. The results in terms of the displacements of the gate and the internal forces may give an indication which of these methods comes closest to the actual situation.

7.3.2 METHODS

Each method will simulate the 2.5 m high UHPFRC module that spans 13 m of width. This module will be hollow and has a thickness of 0.15 m and a wall thickness of 0.03 m, see Figure 32 and Figure 33. The module cross section was based on a calculation that used global buckling as a failure method and the hydrostatic water pressure as the load, a presented in Section 7.4.3¹. This gave a first estimate of the required cross section. The global module dimensions were defined in Chapter 6.

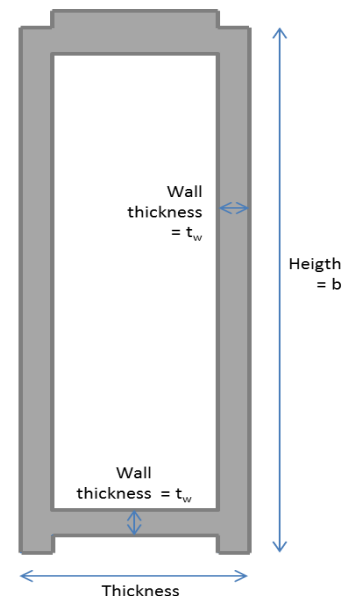


FIGURE 32 GATE MODULE CROSS SECTION

¹ Sections 7.3 and 7.4 were done simultaneously and in the report the order will either be defining the cross section before the internal forces are defined, or defining the internal forces before the cross section is defined. It is chosen to do the latter by giving an overview of the simultaneously defined cross section beforehand.

To summarize the dimensions from Figure 32 and Figure 33:

- B 2.5 [m]
- H 2.7 [m]
- l 13 [m]
- R 9.7 [m]
- t 0.15 [m]
- t_w 0.03 [m]

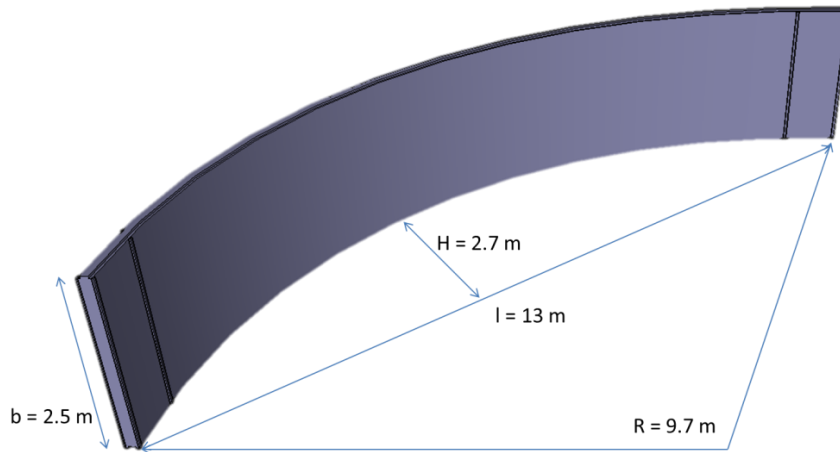


FIGURE 33 – SKETCH OF THE GATE MODULE AND ITS DIMENSIONS

The force in each method will consist of the hydrostatic water pressure with a hydraulic head of 7.3 m and over a height of 2.5 m. This will cause a line load in the model of:

$$q = P_s * b = 71 * 2.5 = 177.5 \text{ kN/m} \quad [24]$$

The given cross section gives a cross sectional area of:

$$A = A_{outer} - A_{inner} = 2.5 * 0.15 - 2.44 * 0.09 = 0.16 \text{ m}^2 \quad [25]$$

It gives a 2nd moment of area (for uncracked concrete) of:

$$\begin{aligned} I &= I_{outer} - I_{inner} = (b_{outer} * t_{outer}^3)/12 - (b_{inner} * t_{inner}^3)/12 \\ &= \frac{2.5 * 0.15^3}{12} - \frac{2.44 * 0.09^3}{12} = 5.5 * 10^{-4} \text{ m}^4 \end{aligned} \quad [26]$$

And the material has a Young's modulus of $E = 44 * 10^6 \text{ kN/m}^2$.

Method 1

Method 1 shows the same support reactions as Figure 22 (Section 5.6.1) in the case of a compressive arch force. The gate moves against the longitudinal supports (pointing vertically in Figure 34) and then, after it bends a little, also presses against the transversal supports (pointing horizontally in Figure 34). When this stage is reached, there is no further movement and the arch functions as it should. This model assumes a combination of friction and pressure to support the gate in its closed position because the support reactions are not perpendicular to the local gate axes.

To simulate the initial bending of the gate, the outer roller bearings will get an initial displacement of 0.03 m. This spacing is assumed to be sufficient to allow the gate to open and close, while also sufficiently small to allow the gate to reach its supports without excessive bending.

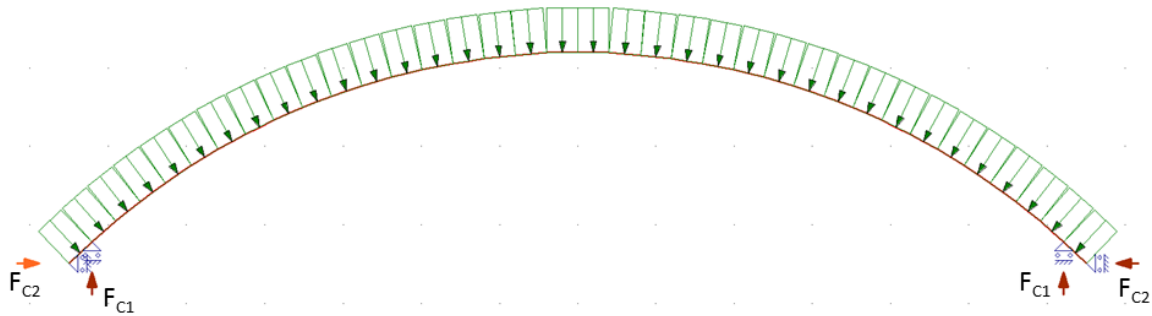


FIGURE 34 – TOP VIEW OF THE CLOSED GATE WITH 2 ROLLER BEARINGS PARALLEL TO THE LONGITUDINAL LOCK AXIS AND 2 ROLLER BEARINGS PERPENDICULAR TO THE LONGITUDINAL LOCK AXIS, THE LINE LOAD SHOWN IN THE FIGURE WILL BE DEFINED AS THE LINE LOAD CAUSED BY A POSITIVE HYDRAULIC HEAD

Method 2

In method 2 the emphasis in the model is put on the clamping nature of the gate recess and the fact that it can move into the recesses. It is shown in Figure 35. The clamping roller bearings can move in the direction of the local gate axis.

This model only works if translations are small because in the actual situation the gate recess curves inward whereas translations at the support in the model are not curved.

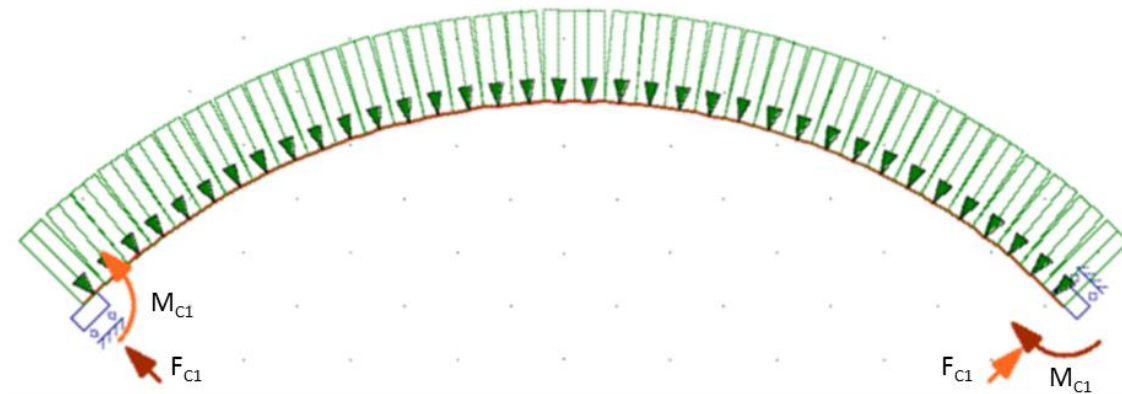


FIGURE 35 – TOP VIEW OF THE CLOSED GATE WITH CLAMPING ROLLER BEARINGS AT THE EDGE OF THE GATE, THE LINE LOAD SHOWN IN THE FIGURE WILL BE DEFINED AS THE LINE LOAD CAUSED BY A POSITIVE HYDRAULIC HEAD

Note that in Matrixframe the supports cannot be placed at an angle. They can either be placed vertically, or horizontally. To have the supports in the angle shown above, the structure was turned 45° with the left support as turning point. This was done by converting the coordinates of each point in the model to polar coordinates:

$$R = \sqrt{x_1^2 + y_1^2} \quad [27]$$

$$\varphi_1 = \tan\left(\frac{x}{y}\right)$$

Then the polar coordinate ϕ_1 was changed by 45° :

$$\varphi_2 = \varphi_1 + 45^\circ \quad [28]$$

After which the coordinates were changed back to a Cartesian coordinate system:

$$\begin{aligned} x_2 &= \cos(\varphi_2) * R \\ y_2 &= \sin(\varphi_2) * R \end{aligned} \quad [29]$$

The result is that one side of the gate was now vertical in the model, and the other side of the gate horizontal, ensuring that the supports could be placed in such a way that the translation is possible in the direction of the local gate axis.

Method 3

Method 3 is the intermediate variant, combining the 2 roller bearings from Method 1 and the direction in which they can translate freely from Method 3. The combination of the 2 roller bearings clamps the gate in the recess, like in Method 3, but a little bit more away from the edges of the gate.

Like with Method 2, this method only works if translations are small.

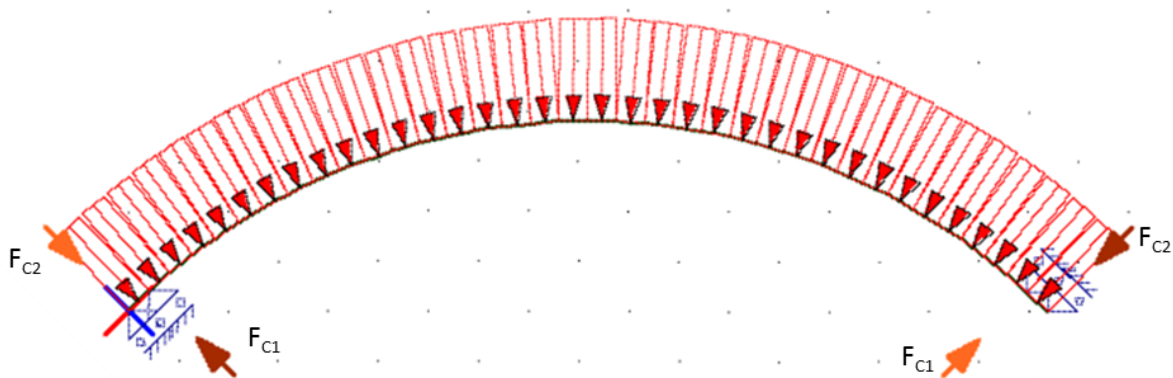


FIGURE 36 – TOP VIEW OF THE CLOSED GATE WITH TWO ROLLER BEARINGS PERPENDICULAR TO THE LOCAL GATE AXIS AT EACH SIDE OF THE GATE, THE LINE LOAD SHOWN IN THE FIGURE WILL BE DEFINED AS THE LINE LOAD CAUSED BY A POSITIVE HYDRAULIC HEAD

7.3.3 RESULTS

The results will start with showing the bending and displacements of the gate globally and in detail in the gate recess. This will be done for the compressive and the tensile situation (a positive as well as a negative hydraulic head).

Displacements

Compression

Figure 37 shows the gate in a compressive situation for each of the methods described in Section 7.3.2. As expected, Method 2 and 3 are not that much different from each other. Method 1 however displaces a lot less along the longitudinal axis. This is because the supports in Method 1 fix the gate along the longitudinal axis (as well as the transversal axis). In Method 2 and 3, the displacement of

the support is in longitudinal as well as transversal direction due to the angle in which it is directed. While in Method 1, the gate only got an initial transversal translation, simulating the initial bending without being supported. Hence, there is no longitudinal displacement of the support and thus the gate itself displaces a lot less in this direction.

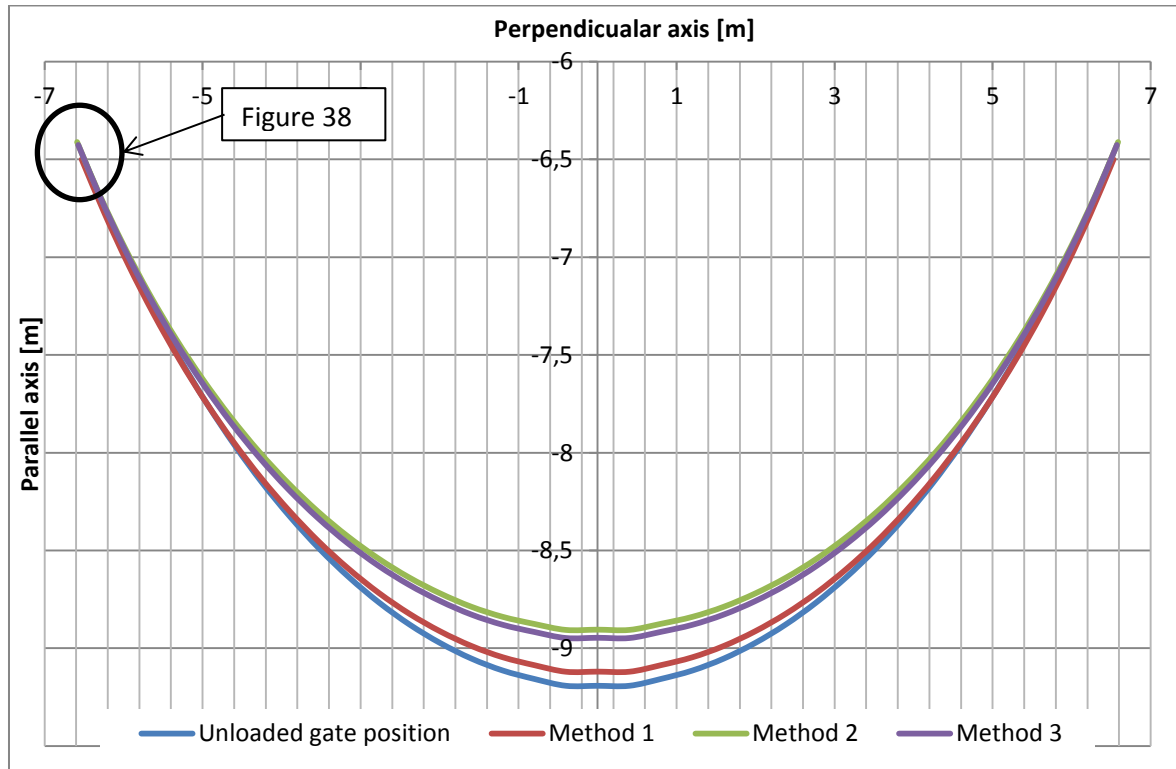


FIGURE 37 – GATE DISPLACEMENT OF THE 3 METHODS WITH A POSITIVE HYDRAULIC HEAD WITH THE UNLOADED GATE AS REFERENCE SITUATION

When zooming in on the support, one reaches the image of Figure 38. The gate is just a line in this figure and does not indicate the gate thickness. To indicate when the gate ‘reaches’ its supports (the gate recess) as shown in Figure 22 (Section 5.6.1), two lines are added. They will be called the gate recess tolerance. They are about 0.02 m on the inner side (above) and outer side (below) the gate, constructed using a curve of a circle that has a radius which is 0.02 m smaller or greater than the radius of the gate respectively. Hence, a 0.02 m tolerance on each side of the gate is used here. Because anything smaller can make gate operation practically impossible, this is seen as the limit where the theory of the gate clamping between the 2 sides of the recess should be tested.

The effect of the outward movement by 0.03 m of the gate in Method 1 can be seen clearly in Figure 38 because the gate is in contact with the outer parts of the gate recesses. Despite Method 1 having a clearly flatter curvature than the unloaded gate position seen from Figure 37, it clearly does not curve inwards towards the inner part with respect to the gate recess in Figure 38. So the clamping of the gate in its recess is not reached.

Method 1 should curve at least a little bit inwards, but in Figure 38 it looks as if the gate curves outwards, indicating a less flat curvature. It is known from Figure 37 that this is not true. This is because of the supports: the inner supports support the gate parallel to the gate axis and the outer supports support the gate perpendicular to the gate axis. The parallel (inner) supports move a little bit outwards when the gate is loaded, but the perpendicular (outer) supports cannot move in this direction

(see also Figure 34). This makes that the gate is more inward oriented to the left in Figure 38 and more outward oriented to the right in the figure.

Method 2 and 3 stay very much in the middle of the tolerance lines. Although they can be seen to be curving inwards with respect to the gate recess (in contrast to Method 1), they stay so much in the middle that a situation where the gate clamps between the recess walls is not reached.

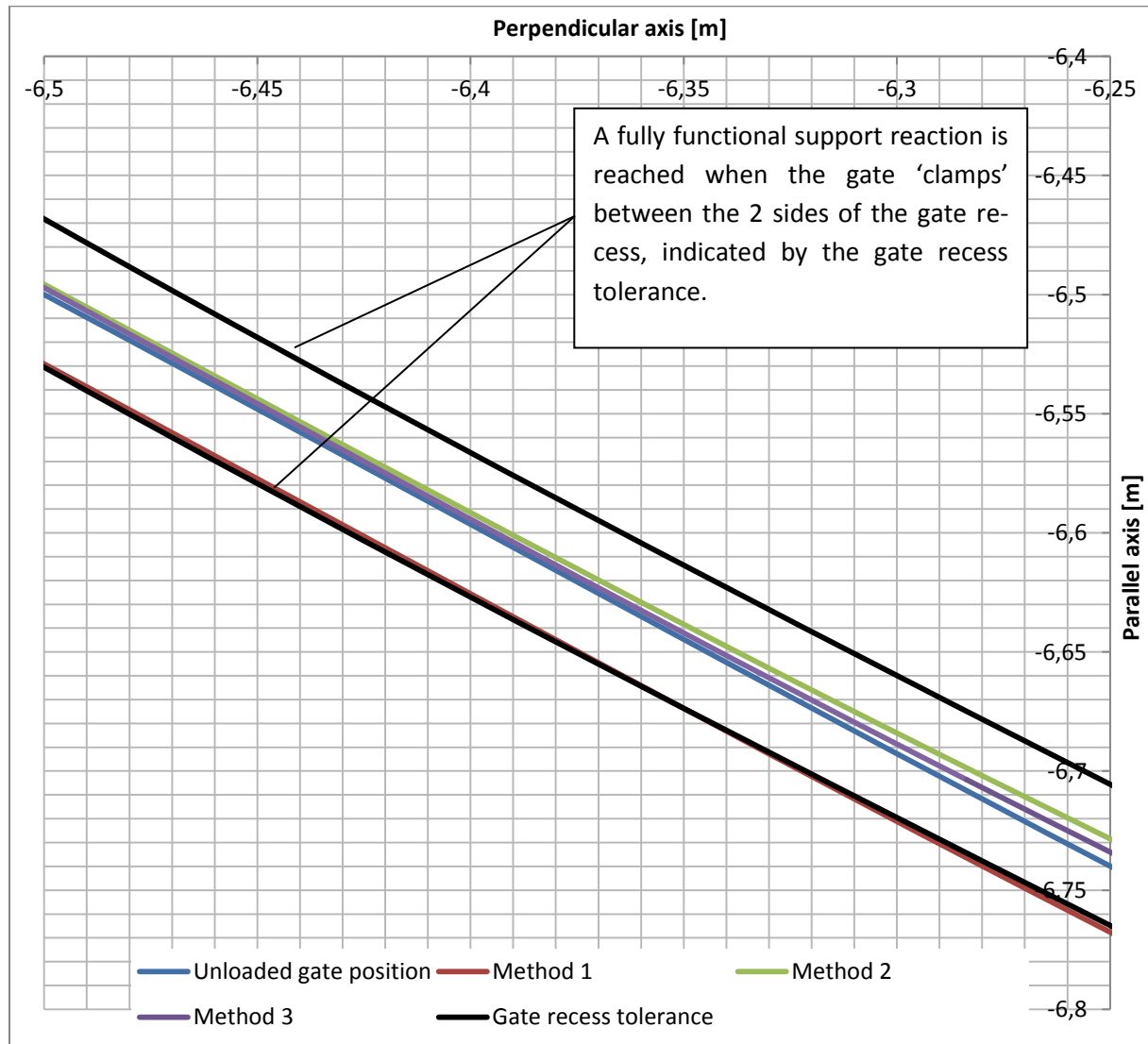


FIGURE 38 – ZOOMING IN ON THE GATE DISPLACEMENT IN THE RECESS; THE TOP GATE RECESS TOLERANCE LINE INDICATES THE INNER SIDE OF THE GATE RECESS IN THIS FIGURE WHILE THE BOTTOM GATE RECESS TOLERANCE LINE INDICATES THE OUTER SIDE OF THE GATE RECESS

Tension

Figure 39 shows the gate in a tensile situation for each of the methods described in Section 7.3.2. The tensile situation does not differ from the compressive situation when looking at how the gates displace with respect from each other. The only difference is that the gates curvatures are now less flat than in the unloaded situation and the gates support situation in the recesses should be mirrored.

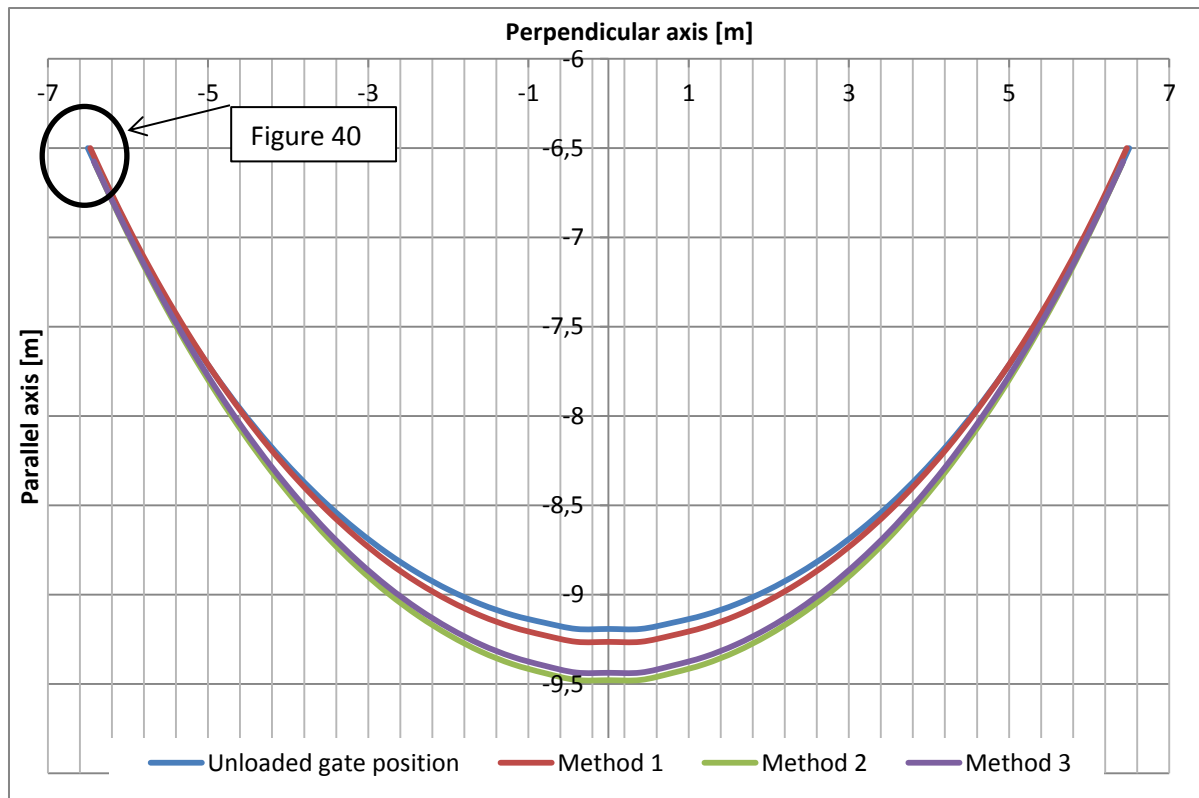


FIGURE 39 – GATE DISPLACEMENT OF THE 3 METHODS WITH A NEGATIVE HYDRAULIC HEAD WITH THE UNLOADED GATE AS REFERENCE SITUATION

When zooming in on the support, one reaches the image of Figure 40. It is made in the same way as Figure 38 and the same lines are shown, except now the gate is loaded in tension. In contrast to Method 1 in the compressive situation, the gate now curves within the gate recess as expected from the global image (Figure 39). It presses against the inner side of the recess on the left side and then has a less flat curvature and curves (by far too little) to the outer side with respect to the recess curvature. Hence, also in this situation the clamping of the gate in its recess is not reached.

Method 2 and 3 are practically in the same situation as when in compression. They stay in the middle of the tolerance and only a slight difference in curvature can be seen. Also making supporting of the gate within the recess by a clamping mechanism impossible.

The good part is that in each method, the gate stays within the reach of the gate recess and is not pulled out of the recess into the lock chamber, which starts on the perpendicular axis at -6.25. Though this could be caused by the combination of supports used in each of the methods still being too 'fixed' with respect to the actual situation, where the gate is not supported until it bends and moves against both gate recess walls.

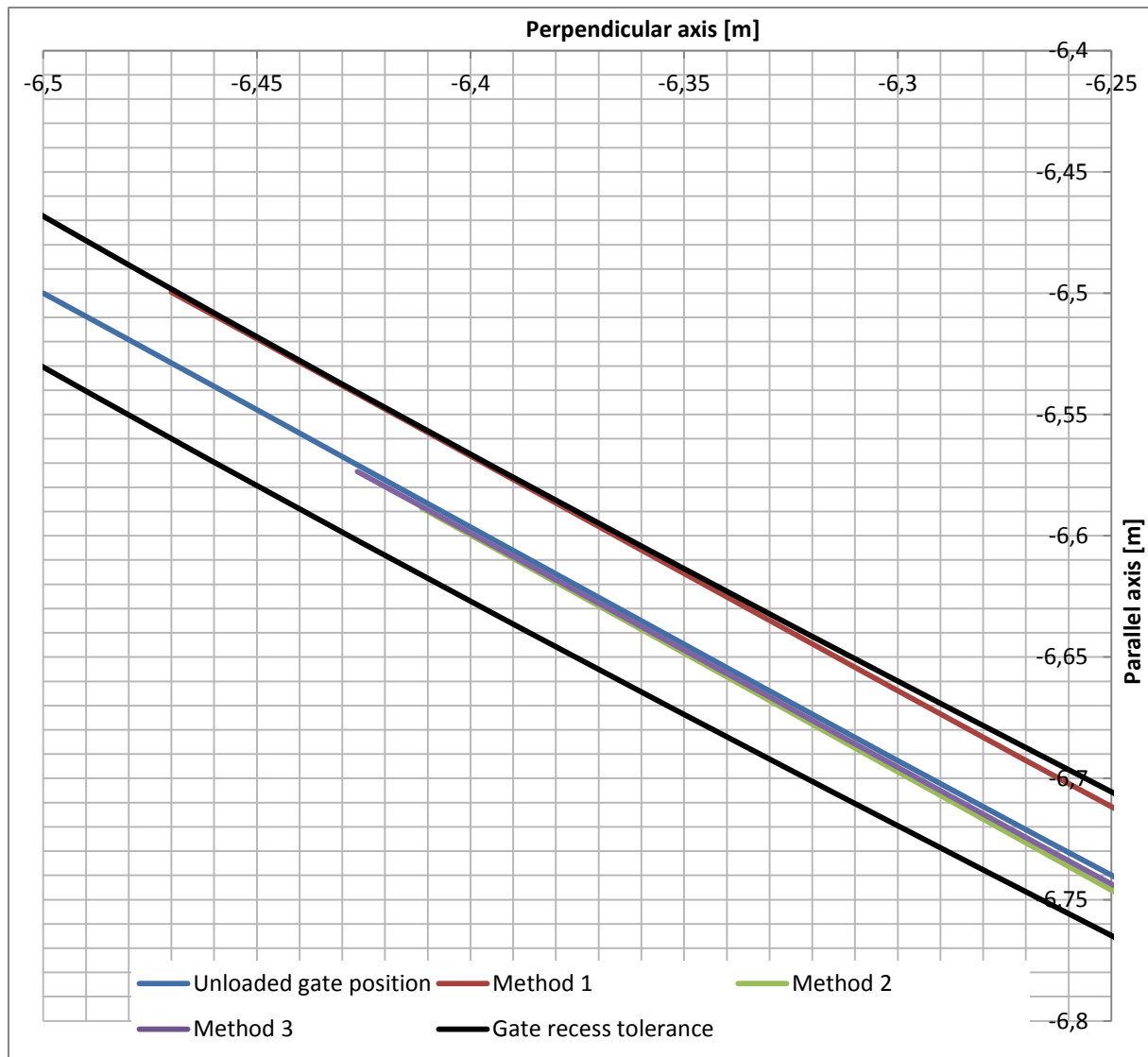


FIGURE 40 – ZOOMING IN ON THE GATE DISPLACEMENT IN THE RECESS; THE TOP GATE RECESS TOLERANCE LINE INDICATES THE INNER SIDE OF THE GATE RECESS IN THIS FIGURE WHILE THE BOTTOM GATE RECESS TOLERANCE LINE INDICATES THE OUTER SIDE OF THE GATE RECESS

Forces

Support reactions

The support reaction forces in compression and tension are shown in Table 3 and Table 4 respectively. With the help of the support reaction calculation in Section 7.3.1, it is possible to check the order of magnitude of the support reactions of each of these methods. A support reaction of about 1600 kN was found there.

TABLE 3 – SUPPORT REACTIONS OF THE 3 METHODS WHEN THE GATE IS UNDER COMPRESSION (A POSITIVE HYDRAULIC HEAD)

Method	F_{c1} [kN]	F_{c2} [kN]	M_{c1} [kNm]
1 (Figure 34)	1154	971	-
2 (Figure 35)	1634	-	4104
3 (Figure 36)	10614	8980	-

The two support reactions from Method 1 can be combined to find the following resultant force:

$$F_R = \sqrt{F_{c1}^2 + F_{c2}^2} = \sqrt{1154^2 + 971^2} = 1508 \text{ kN} \quad [30]$$

Which is in the same order of magnitude to the support reaction found in the introduction.

Method 2 has a moment force as one of its support reactions (on each side). The other support reaction (F_{c1}) is a force that is comparable to the support reaction found in the introduction.

In method 3, when support reaction F_{c2} is subtracted from F_{c1} (they are directed in opposing directions, resulting in a couple and a force), the same force as F_{c1} from method 2 is found, as expected. The couple from Method 3 also results in the same moment as in Method 2.

TABLE 4 – SUPPORT REACTIONS OF THE 3 METHODS WHEN THE GATE IS UNDER TENSION (A NEGATIVE HYDRAULIC HEAD)

Method	F_{c1} [kN]	F_{c2} [kN]	M_{c1} [kNm]
1 (Figure 34)	-1154	-971	-
2 (Figure 35)	-1634	-	-4104
3 (Figure 36)	-10614	-8980	-

The support reactions found with a negative hydraulic head (Table 4) are – as expected – the same as the ones found with a positive hydraulic head (Table 3), but in opposite direction.

From the support reactions it can already be concluded that the way of supporting the gate modelled through Method 2 and Method 3 is unwanted. They both create a high bending moment in the gate: Method 2 through a high moment at the support and Method 3 through a couple with support reactions that are 10 times as high as the ones found in Method 1.

This makes Method 1 the best situation that may be reached through ‘clamping’ the gate between the gate recess walls. Though the displacement figures from the previous sections do not support the idea that clamping occurs with any of these methods. Which makes that a final conclusion cannot be made as to how the clamping of the gate in its recess should be modelled, if at all possible with the current (conceptual) design.

Internal forces

The forces within the gate are made visible by showing the moment line, the normal force line and the shear force line in Figure 41, Figure 42 and Figure 43 respectively.

In the moment line the high moments from the support reactions from methods 2 and 3 can be seen again. To get an indication of high these moments are for this type of structure, the moment for a simply supported straight beam 13 m in length (the same as the total span of this curved structure, except it is longer due to the curve) is given by:

$$M_{max,span} = \frac{1}{8} * q * l^2 = \frac{1}{8} * 177.5 * 13^2 = 3.7 * 10^3 \text{ kN} \quad [31]$$

When the gate is supported like modelled in Method 2 and 3, the moment very close to (Method 3) or even exceeds (Method 2) the moment when it would have been a straight simply supported

beam. This causes that the (extra) advantage, of material efficiency and the possibility to create an even lighter gate that an arch gate could have, is lost.

Method 1 however, makes it clearly visible that it is possible to support the gate in such a way that the moment line is clearly reduced to a minimum without having fixed supports by placing the roller bearings in a 90 degree angle with respect to each other.

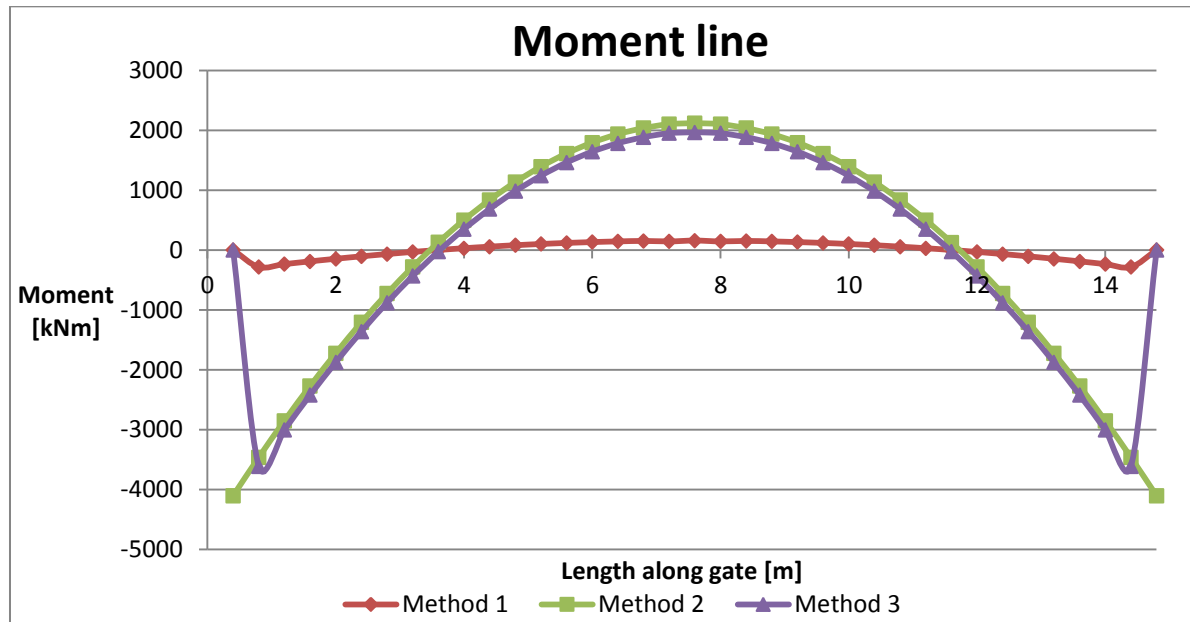


FIGURE 41 – MOMENT LINE WITH A POSITIVE HYDRAULIC HEAD

The idea that Method 1 really works like the intended arch gate can be confirmed from the normal force in it. This is much higher and consistent in magnitude over the full mid-section of the gate (Figure 42: red line), while also in the same order of magnitude as calculated in Section 7.3.1.

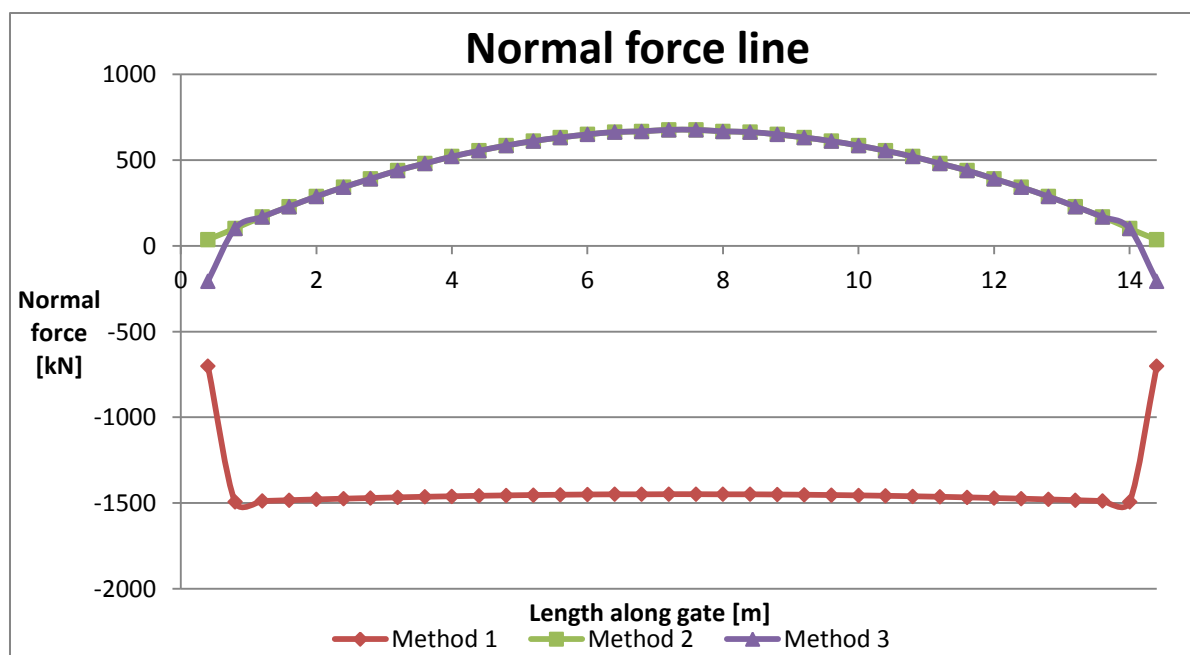


FIGURE 42 – NORMAL FORCE LINE WITH A POSITIVE HYDRAULIC HEAD

The normal force in Method 1 is also the only one that is in compression, which is rather unexpected (it was implicitly assumed that the gate would be stressed in compression when loaded from the convex site, independent of the Method used to model its support). An explanation can be found in the displacements of the gate. In Methods 2 and 3 the support is free to move in the direction in which the arch would be loaded. So the gate can extend a little, which would cause a tensile stress in it.

Method 2 and 3 have, besides a moment that is as large as if the gate was a straight simply supported beam, also a normal force in them that is of a significant magnitude. This even gives them an extra disadvantage over the straight rolling gates. (Of course they still have the space saving advantage as discussed in Section 5.5.5.)

The shear force line from Figure 43 adds to the realisation of what the 2 opposite directed supports, at each end of the gate (from Method 3), do to the shear force present in the gate. This is out of proportions with respect to methods 1 and 3, in which Method 3 is already over twice as bad as Method 1. This makes that Method 3 is by far the worst situation (also in combination with the normal force and moment) possible of those 3 methods.

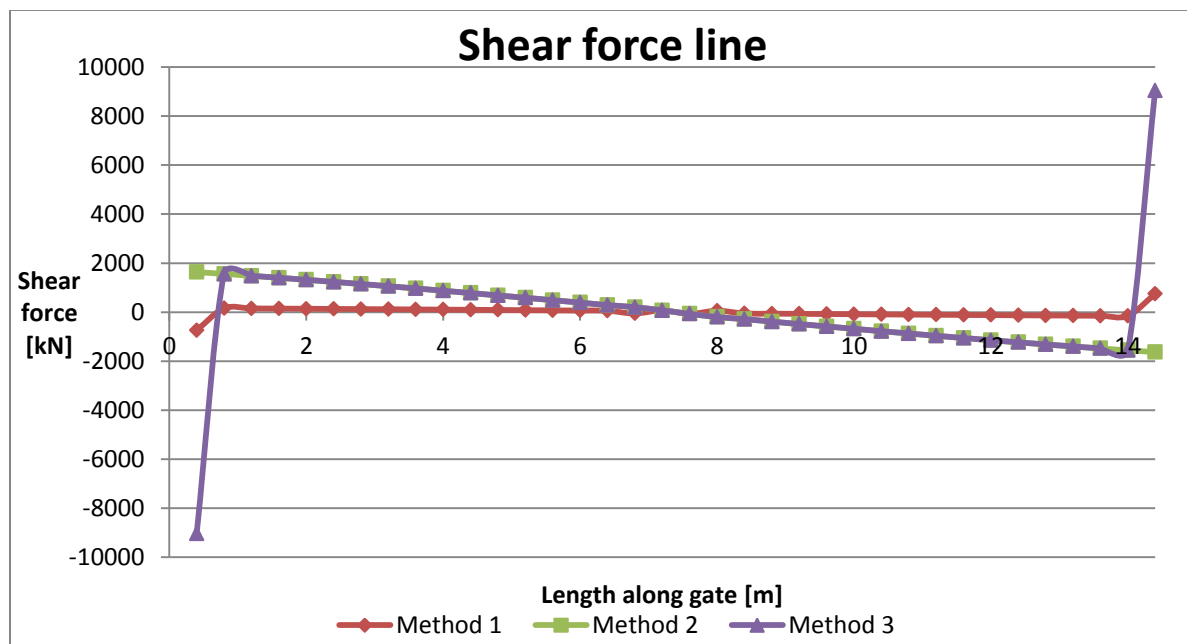


FIGURE 43 – SHEAR FORCE LINE WITH A POSITIVE HYDRAULIC HEAD

The hypotheses was that one of these Methods could now (knowing the resulting differences in support reactions, moments and normal forces) be chosen as the most accurate for the situation that was illustrated in Figure 22 (Section 5.6.1). In hindsight it is not really possible to say anything about which of the methods best represents the situation from Figure 22.

It is however possible to state that only in Method 1 the gate acts as the intended arc gate, whereas Methods 2 and 3 act as arch shaped flat gates. So the situation must be turned around. Now there are three methods that may represent the situation as sketched in Figure 22 in an accurate way. But only one of them is desired (Method 1). Hence, the gate and lock head will be designed for Method 1.

This means that either scale model tests will be required to confirm that the gate acts as represented by Method 1; or the shape of the gate and lock head should be designed in such a way that it ‘helps’ the gate into the Method 1 situation.

7.3.4 SENSITIVITY ANALYSIS TO DIFFERENCES IN THE CROSS SECTION

Because each of the 3 methods is statically indeterminate, the internal forces and support reactions are sensitive to changes in the cross section. It is important to know how much this matters because the cross section used in the models is now only based on a preliminary buckling equation (Section 7.4.3). Hence, it is prone to changes.

Method 1, being the desired situation, will be checked again with a positive hydraulic head, but with varying cross sections. The results will be shown with the displacement graphs, the moment line and the normal force line. The module thickness will be reduced in 2 steps by 0.04 m per step, and also increased in 2 steps by 0.04 m per step. The wall thickness remains unchanged. This results in the following cross sectional properties:

TABLE 5 – CROSS SECTIONAL PROPERTIES RESULTING FROM CHANGING THE MODULE THICKNESS

Module thickness t [m]	A [m ²]	I [m ⁴]
0.07	0.15	$7.1 * 10^{-5}$
0.11	0.15	$2.5 * 10^{-4}$
0.15	0.16	$5.5 * 10^{-4}$
0.19	0.16	$9.8 * 10^{-4}$
0.23	0.16	$1.5 * 10^{-3}$

As can be expected the smaller cross sections have the flatter curves in Figure 44. The cross section with a thickness of only 0.07 m stands out the most, as it is not only flatter in the middle. It is also much wider at about a third of the way from the supports to the middle.

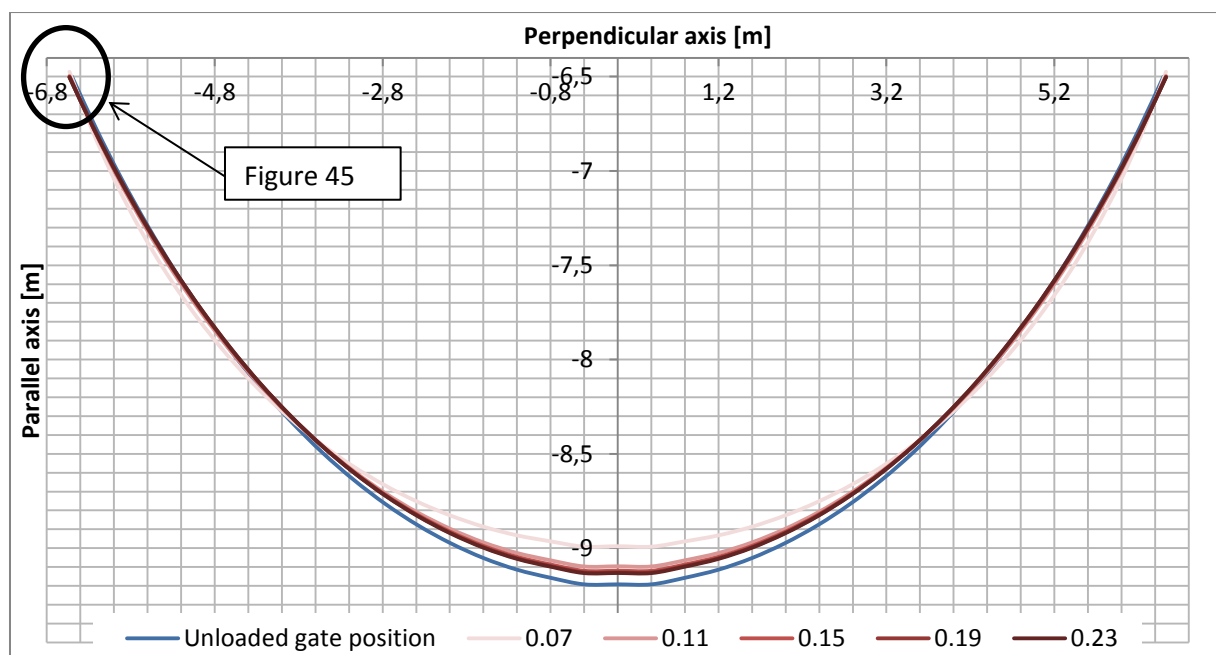


FIGURE 44 – METHOD 1 DISPLACEMENTS WITH CROSS SECTION OF VARYING THICKNESS INDICATED IN [M]

When zooming in on the displacement near the support (Figure 45), the results of the wider curve near the supports from the 0.07 m thick (least stiff) cross section can be seen clearly. It moves into the recess tolerance range from the outer side and then curves inwards much further than the thicker cross sections. As the cross sections become stiffer, they tend to have this effect in a lesser way, but it is still present. It is caused by the F_{c1} supports moving a bit outwards towards the F_{c2} supports when the gate is loaded, while the F_{c2} supports move a little bit parallel to the lock axis and away from the F_{c1} supports.

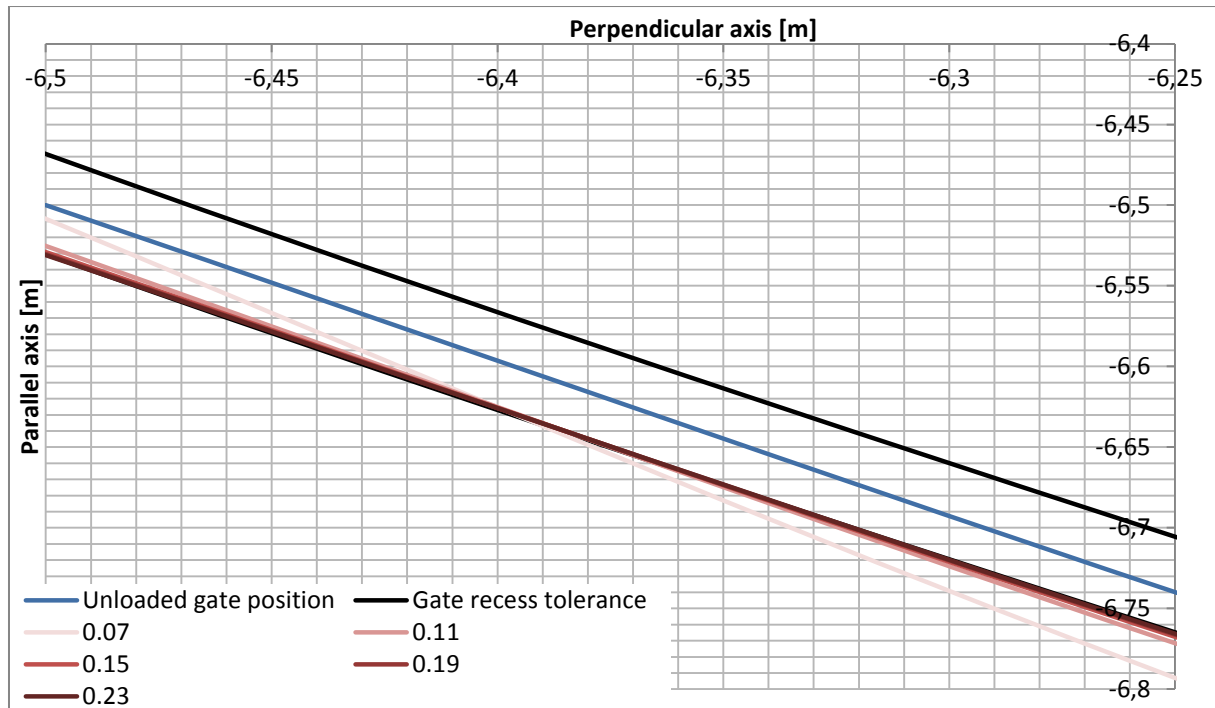


FIGURE 45 - METHOD 1 DISPLACEMENTS WITH CROSS SECTION OF VARYING THICKNESS INDICATED IN [M] ZOOMED IN ON THE LEFT GATE RECESS; THE TOP GATE RECESS TOLERANCE LINE INDICATES THE INNER SIDE OF THE GATE RECESS IN THIS FIGURE WHILE THE BOTTOM GATE RECESS TOLERANCE LINE INDICATES THE OUTER SIDE OF THE GATE RECESS

It becomes clear that, to properly model the gate when it is bending in a position where it becomes clamped between 2 supports that are directed perpendicular to each other, some form of conditional support reactions are required. Due to a lack of this luxury at present, the hypothesis that this way of supporting a curved gate is possible remains unproven.

Nevertheless, it is assumed that at least the support reactions and internal forces following from Method 1, are at least somewhat accurate. Because Method 1 and the situation that is aimed for are both arc gates and hence, in both situations, most of the loads are carried through the gate to the supports by normal forces. Also, Method 1 seems to be corresponding quite well with the forces calculated in Section 7.3.1.

In Figure 46 the moment line is shown. Here, it is visible how an increased thickness of the cross section causes higher field moments. The moment at the supports is however relatively unaffected by a difference in the cross section and is the biggest moment present in the gate module. Because the weaker cross section still has to be able to bear the same moment as the stronger cross section, the strength of the weaker cross sections will probably not be sufficient.

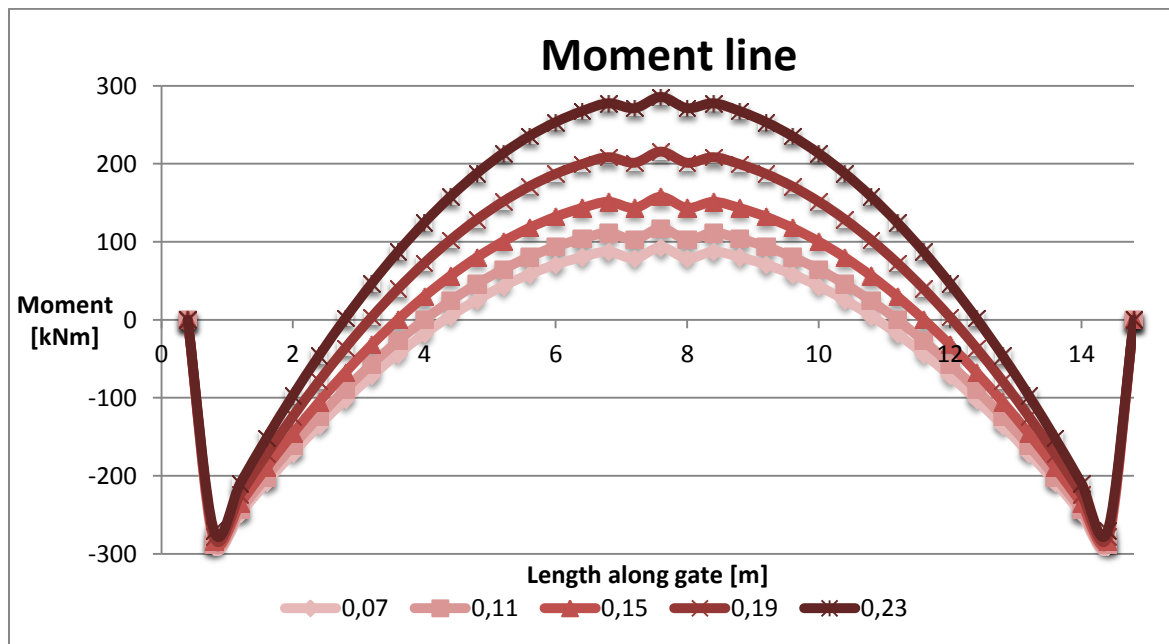


FIGURE 46 – METHOD 1 MOMENT LINE WITH CROSS SECTION OF VARYING THICKNESS INDICATED IN [M]

In the normal force line from Figure 47 it is even so that the weaker cross sections get higher normal forces to bear. This will make them even more prone to buckling than the stronger cross sections than they would normally be.

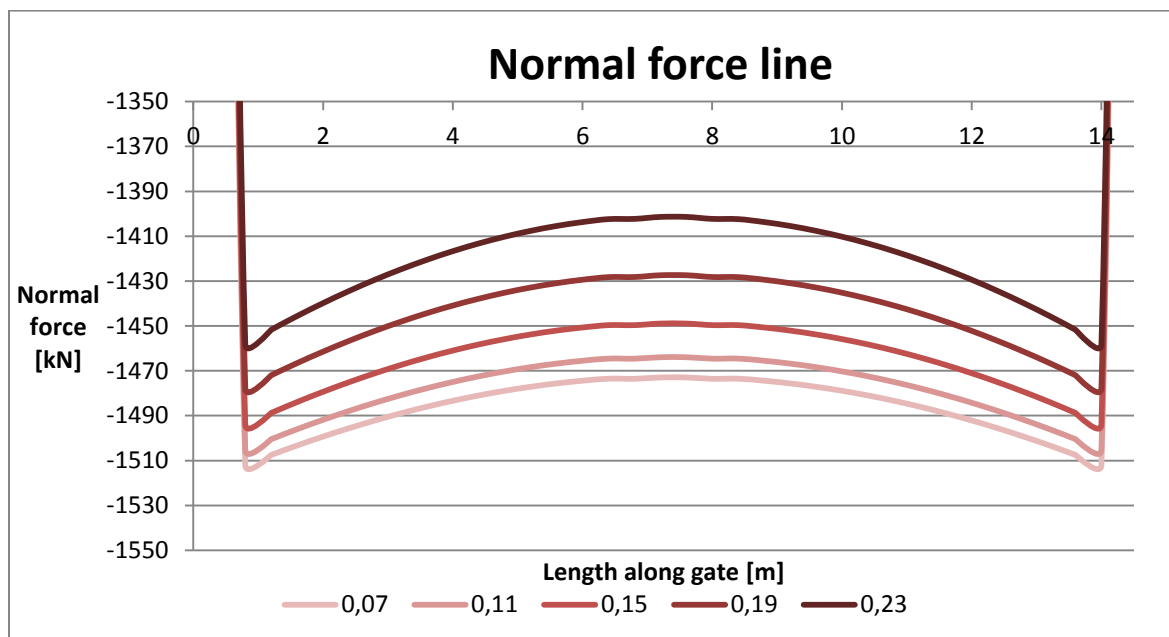


FIGURE 47 – METHOD 1 NORMAL FORCE LINE WITH CROSS SECTION OF VARYING THICKNESS INDICATED IN [M]

In the shear force line from Figure 48 barely any difference can be seen between the weaker and the stronger cross sections. Hence the only effect of going for a smaller cross section will be the strength of this cross section and its ability to bear this shear force.

The bulging of the shear force line in the middle (and the moment line of Figure 46), which appears only in Method 1 in Figure 43, but becomes more visible here due to the scale of the graph is most

likely just some inconsistency in the calculation. Maybe this is caused by the curve being built up from 36 straight 'beams'.

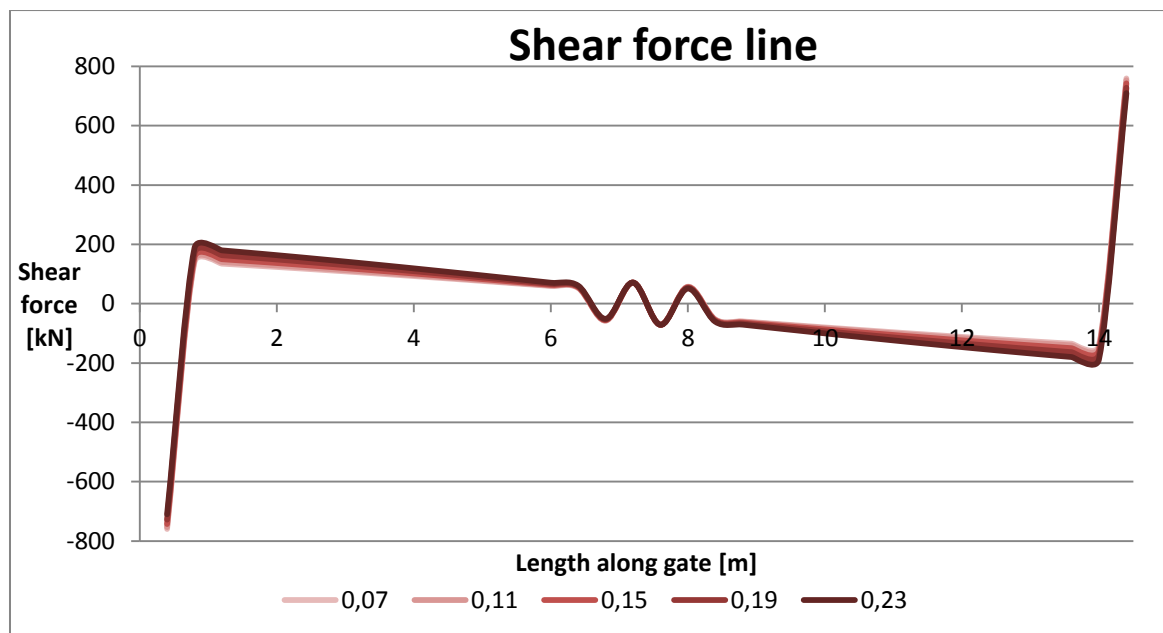


FIGURE 48 – METHOD 1 SHEAR FORCE LINE WITH CROSS SECTION OF VARYING THICKNESS INDICATED IN [M]

7.3.5 CONCLUSIONS

Neither of the 3 above described methods had a satisfactory displacement graph that could confirm that the gate would clamp between the walls of a gate recess.

Methods 2 and 3 did not function as the intended arc gate, which could be seen from the relatively high moments and low normal forces. They even had a tensile force in them where a positive hydraulic head would introduce a compressive normal force on an arc gate.

Method 1 was thus investigated further to see the effects of the gate becoming more- or less flexible. The gate was expected, when becoming more flexible, to rest on the outer side of the recess with the convex end of the gate and to rest on the inner side of the recess with the concave side a bit away from the end of the gate (Figure 22). However, the direction in which the gate enters the gate recess as seen in Figure 45 indicates the opposite.

This was explained by how the supports may have worked in Method 1. It is most likely required to have conditional support reactions. The F_{c2} support reaction would then be given the condition to support nothing unless the gate curvature is bended so flat that (with respect to the gate recess), the convex end of the gate actually rests against the outer side of the gate recess. The available tools did not make it possible to create such a support reaction.

The forces resulting from Method 1 do match the expected forces to occur in an arc gate from an introductory hand calculation. Hence these forces are expected to be helpful in dimensioning the gate modules. This will be done in Section 7.4.

Seeing how much the gate bends with respect to the gate recess, even if it is in the 'wrong' direction, a measure will be taken as precaution. The modules themselves will become a bit wider than used in

the 3 Methods. They will have a span of 14 m instead of 13 m. This extra length will give an extra 0.5 m of the gate ends spanning into the recess, which makes the gate more able to reach its supports.

7.4 GATE MODULE DESIGN

7.4.1 MODULES

The modules will span 14 m, have a height of 2.5 m and a radius of 9.9 m (Figure 50). These dimensions depend on the functionality of the modules as explained in Section 5.6.1. Dimensions like the width of the cross section, the thicknesses of the flanges and the web depend on the forces, material strength and stiffness, see Figure 49.

The notch on top of the modules ensures water tightness, in combination with a rubber-like material on top of it. It also bears shear stresses present between the modules.

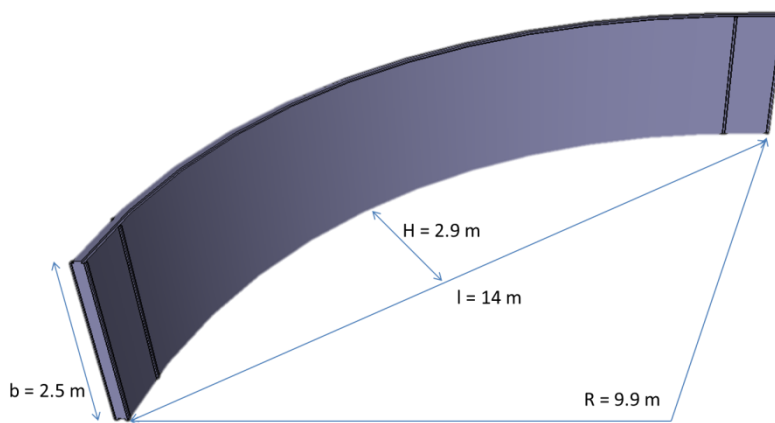


FIGURE 50 – GATE MODULE DRAWING

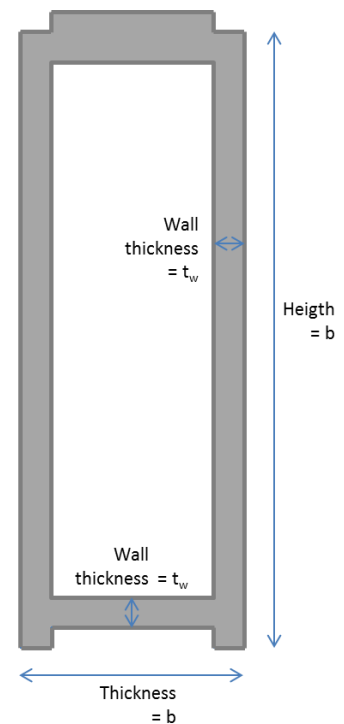


FIGURE 49 – CROSS SECTION PROPERTIES

7.4.2 SUPPORT

The arc gate should make sure that all forces flow through the gate towards its side. There the forces will be guided into the walls of the gate recess through the (assumed) support reactions as seen in Method 1 in Section 7.3.2, see also Figure 51.

To make sure that the Method 1 support reactions happen, and not the ones from Method 2 and 3 (which resulted in much higher moments in the gate), notches could be added to the gate and to the recess like shown in Figure 51.

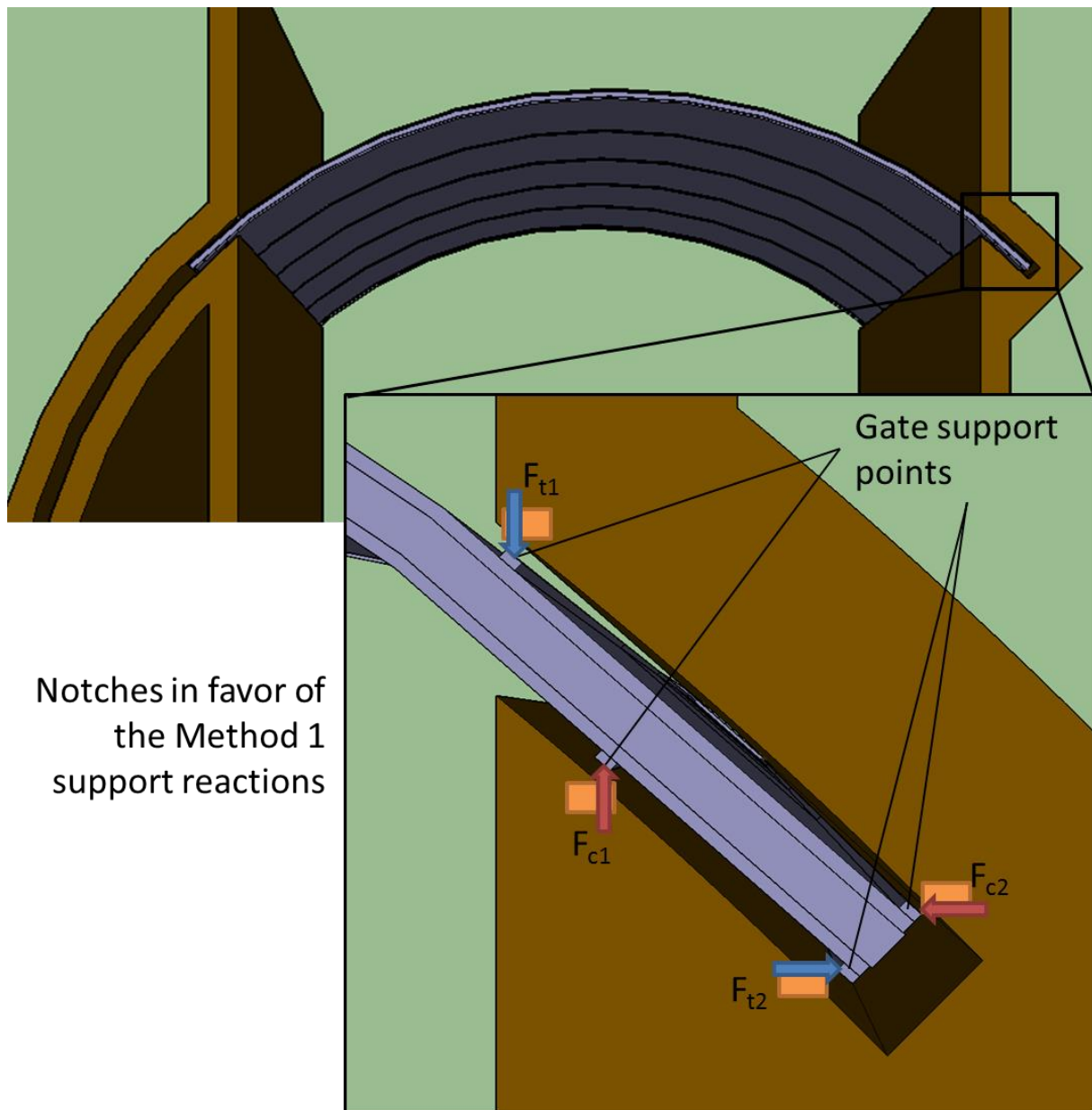


FIGURE 51 – TOP VIEW OF THE GATE; NOTCHES ARE ADDED TO THE GATE AND THE LOCK HEAD IN FAVOUR OF THE SUPPORT REACTIONS AS MODELLED IN METHOD 1

These notches need to be big enough to clamp the gate as soon as it bends. However, due to the need for the gate to also move back and forth between the notches, they will also need to be small enough so that the gate will not get stuck during movement. This is most likely the biggest disadvantage of supporting the gate in such a way in order to make it lighter than an arch shaped rolling gate.

The forces in these notches have been calculated in Section 7.3.3 and can be found under Method 1 in Table 3. They are (per module):

- F_{c1} 1154 kN
- F_{c2} 971 kN
- F_{t1} 1154 kN
- F_{t2} 971 kN

7.4.3 ARCH STRENGTH

When the arch is in compression the slenderness of the cross section makes that the main failure mechanism is buckling. The buckling capacity is calculated as a function of the buckling load related to the stiffness of the arch, i.e. the Euler load and as the capacity of the material compressive strength. This is shown already in Equation [4] and rewritten here to directly solve for F_{max} :

$$F_{max} = \frac{1}{\frac{1}{F_e} + \frac{1}{F_c}} = 2.5 * 10^3 \text{ kN} \quad [32]$$

In which:

- $F_e = \frac{\pi^2 EI}{l_k^2} = \frac{\pi^2 * 4.93 * 10^7 * 5.55 * 10^{-4}}{9.7^2} = 2.9 * 10^3$ [kN]
- $F_c = A * f_{cd} = 0.16 * 113.3 * 10^3 = 18 * 10^3$ [kN]
- A Surface area of the cross section [m²]
- E Young's modulus [kN/m²]
- I Second moment of area in m⁴ calculated from an RHS-like shape with t=0.15 m; b=2.5 m; t_w=0.03 m [m⁴]
- t Module thickness [m]
- t_w Module wall thickness [m]
- l₀ Effective buckling length [m]
- f_{cd} Compressive design strength [kN/m²]

Through Equation [32] a cross section was defined that could bear the water pressure with a relatively high redundancy, as at this point only the hydraulic head is taken into account. The variables in these equations were the module thickness and the wall thickness (see Figure 49), which are input for the surface area and the second moment of area of the cross section. Appendix B gives the calculation form that is used.

7.4.4 REINFORCEMENT

The modules require longitudinal and vertical reinforcement, which will be calculated in the next sections.

Longitudinal reinforcement

The longitudinal reinforcement is designed to make the modules able to bear tensile forces up to the same value as compressive forces. The required amount of steel in the cross section then becomes:

$$A_s = \frac{F_{max}}{f_{yd}} = \frac{2.8 * 10^6}{435} = 6.4 * 10^3 \text{ mm}^2 \quad [33]$$

This is done with Ø8 mm rebars with a spacing of about 35 mm. Each side of the cross section then has $\frac{2500}{35} \approx 70$ rebars. This results in a steel cross sectional area of $2 * 70 * \pi * 4^2 = 7037 \text{ mm}^2$.

Vertical reinforcement

The module walls also require reinforcement to bear the loads (for now, only the water pressure is taken). This can – in UHPFRC - be calculated according to a procedure made by P.P.F. van Rijen [40] (Appendix C). This resulted in Ø6 mm rebars with a spacing of 25 mm, placed near the hollow side of the wall.

The total cross sectional area of the rebars per meter module length per wall is then given by:

$$A_s = \frac{1}{0.025} * \pi * 0.003^2 = 1.1 * 10^{-3} m^2 \quad [34]$$

Module wall buckling

The walls of the module could also buckle due to high normal forces in it. To check for this strength the elastic bifurcation load can be calculated using formula from source: [41]. The buckling stress is calculated through:

$$N_{buckII} = \frac{E * \pi^2}{12 * (1 - \nu^2)} * \left(\frac{t_w}{l_{kw}}\right)^2 * \frac{3}{4} = \frac{49 * 10^6 * \pi^2}{12 * (1 - 0.15^2)} * \left(\frac{0.03}{1.6}\right)^2 * \frac{3}{4} \quad [35]$$

$$= 1.1 * 10^4 kN/m^2$$

In which:

- ν Poisson ratio
- l_{ow} Effective buckling length of the wall assuming spacers every 2.5 m (the same as the module height)

This results in a buckling capacity of the cross section (2 walls combined assuming the same normal force in both walls) of:

$$N_{Rd,buck} = N_{buckII} * A = 1.1 * 10^4 * 0.16 = 1.8 * 10^3 kN \quad [36]$$

Hence, the local buckling strength is somewhat lower than the global buckling strength. It is still able to bear the normal force present in the structure, which is about $1.5 * 10^3$ kN (Figure 42).

Moment resistance

The maximum moment present in the cross section is about 300 kNm (Figure 41). Before doing any extensive moment resistance checks, one can already estimate that this moment will cause failure in the wall buckling calculation from the previous subsection because of the following: this moment can be translated into a couple with an additional compressive force in 1 side of the module and an additional tensile force in the other side of the module. This force is given by:

$$F_m = \frac{M}{t} = \frac{300}{0.15} = 2.0 * 10^3 kN \quad [37]$$

Each wall already has a compressive (or tensile, depending on the direction of loading) force in it of $\frac{1.5 * 10^3}{2} = 0.75 * 10^3 kN$ (based on the normal force from Figure 42 divided by the 2 walls). Added (or subtracted) to this is the couple force (F_m) of $2.0 * 10^3$ kN. Giving a total force in the walls ranging from a tensile force of $2.8 * 10^3$ kN to a compressive force of $-2.8 * 10^3$ kN.

Hence, this load exceeds the local buckling strength, which is $0.9 * 10^3$ kN for one of the module sides ($= N_{Rd,buck}/2$). This local buckling strength can still be increased by adding spacers. However, it is probably best to decide upon increasing the thickness of the whole cross section including wall thicknesses, given the magnitude of this exceedance of strength. A module thickness of 0.2 m and a wall thickness of 0.05 m were found to be able to bear the combined compressive and moment force, see Appendix B.

Nevertheless, the moment resistance and required reinforcement can be calculated. A concrete compressive zone (x_u) of 0.03 m (the wall thickness) is assumed. The compressive zone can then resist a force of:

$$N_c = \alpha * b * x_u * f_{cd} = 0.56 * 2.5 * 0.03 * 113300 = 4.8 * 10^3 \text{ kN} \quad [38]$$

In which:

- N_c Force in compressive zone [kN]
- α Surface factor of the compression zone (assumption based on strength class C90/105)
- x_u Height of compressive zone [m]

The reinforcement steel needs to be in balance with this force:

$$A_s = \frac{N_c}{f_{yd}} = \frac{4.8 * 10^3}{435000} = 1.1 * 10^{-2} \text{ m}^2 \quad [39]$$

It should be noted that this is more than the longitudinal reinforcement required over the full cross section to take the pure tensile forces as calculated a few subsections back, while this reinforcement should be present in each wall. The moment resistance becomes:

$$\begin{aligned} M_{Rd} &= A_s * f_{yd} * \left(t - \frac{t_w}{2} - \beta * x_u \right) \\ &= 1.1 * 10^{-2} * 435000 * \left(0.15 - \frac{0.03}{2} - 0.34 * 0.03 \right) = 594 \text{ kNm} \end{aligned} \quad [40]$$

The reinforcement ratio is then given by:

$$\rho = \frac{A_s}{A} = \frac{1.1 * 10^{-2}}{0.16} = 7.0 \% \quad [41]$$

The moment capacity of the concrete with the given reinforcement would be redundant to resist the 300 kNm moment in the cross section. However, this is done through a very high reinforcement ratio as seen above. Besides, a high normal force is also present. No moment and normal force interaction diagrams were found however, for hollow cross sections, so this could not be checked within the time frame.

One could opt for filling the hollow part of the cross section. This would give some more redundancy for the normal force and the reinforcement ratio will be smaller. The gate will however become much heavier. Another option is to increase the module thickness and wall thicknesses of the module. This would introduce the possibility to use concrete of a weaker concrete class, which would also need a thicker cover for the reinforcement.

Also, a smaller assumption of the compressive zone height (x_u), up to the point where the 300 kNm moment can just be resisted would introduce smaller reinforcement ratios. A combination of a thicker cross sections and a relatively smaller compressive zone height is recommended. With the cross section mentioned above (a module thickness of 0.2 m and a wall thickness of 0.05 m) and a compressive zone height of 0.03 m for example, a reinforcement ratio of 4.2 % was found with a moment resistance of 784 kNm.

Result

The resulting cross section from the normal forces (the ideal arch situation) is shown in Figure 52. This is an example of how the gate cross section could look. Some detailing and adaptations are required when going to the final design of the modules. For instance the reinforcement for the moment resistance is not added (as this also requires a thicker cross section – as mentioned above and shown in the calculations in Appendix B – because of the high reinforcement ratio). Also for the interaction between the modules and making sure that they are water tight, a rubber like material could be added around the top notch of each module.

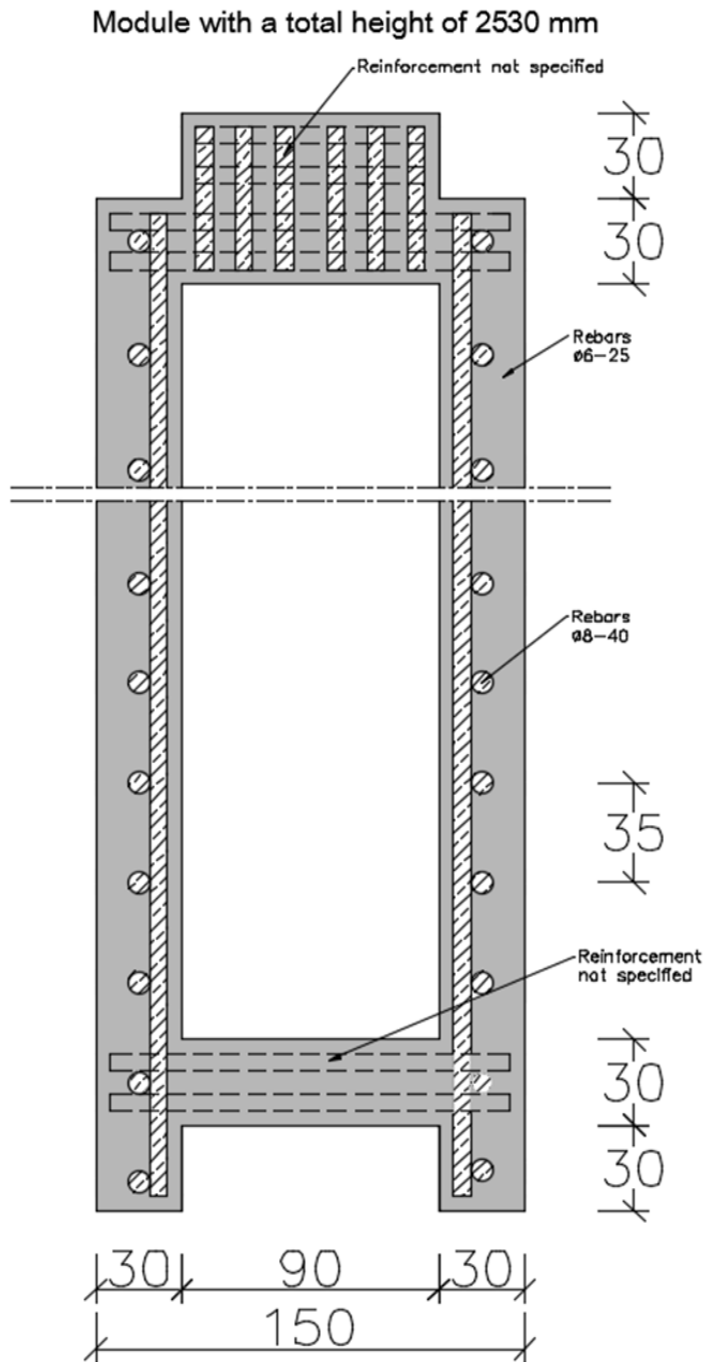


FIGURE 52 – CROSS SECTION OF A MODULE – UNITS IN MM

7.4.5 SEALING

The sealing at the sides of the gate is done through the gate notches pressing against the lock head notches through the support reactions. The sealing at the bottom of the gate is made through some sort of sill extending over a flexible plate that is attached at the bottom of the gate, see Figure 53. Water from the high water level side will enter the empty space under the gate, the pressure will then press the sealing material against the sill, creating a water tight sealing at the gate bottom.

In Figure 53 the sill lies above the lock bottom, however it could of course also be deepened into this empty space under the chamber.

An idea on how the roller carts of the lock gate could look like can also be seen in Figure 53. This is however just a concept at this point. The main goal was to design the lock gate and the focus has been going towards the civil engineering parts of it. In a lock gate the mechanical engineering parts are however also of importance, hence the concept to get an idea of how big such a part could be in the current design.

Side view of the bottom of the gate

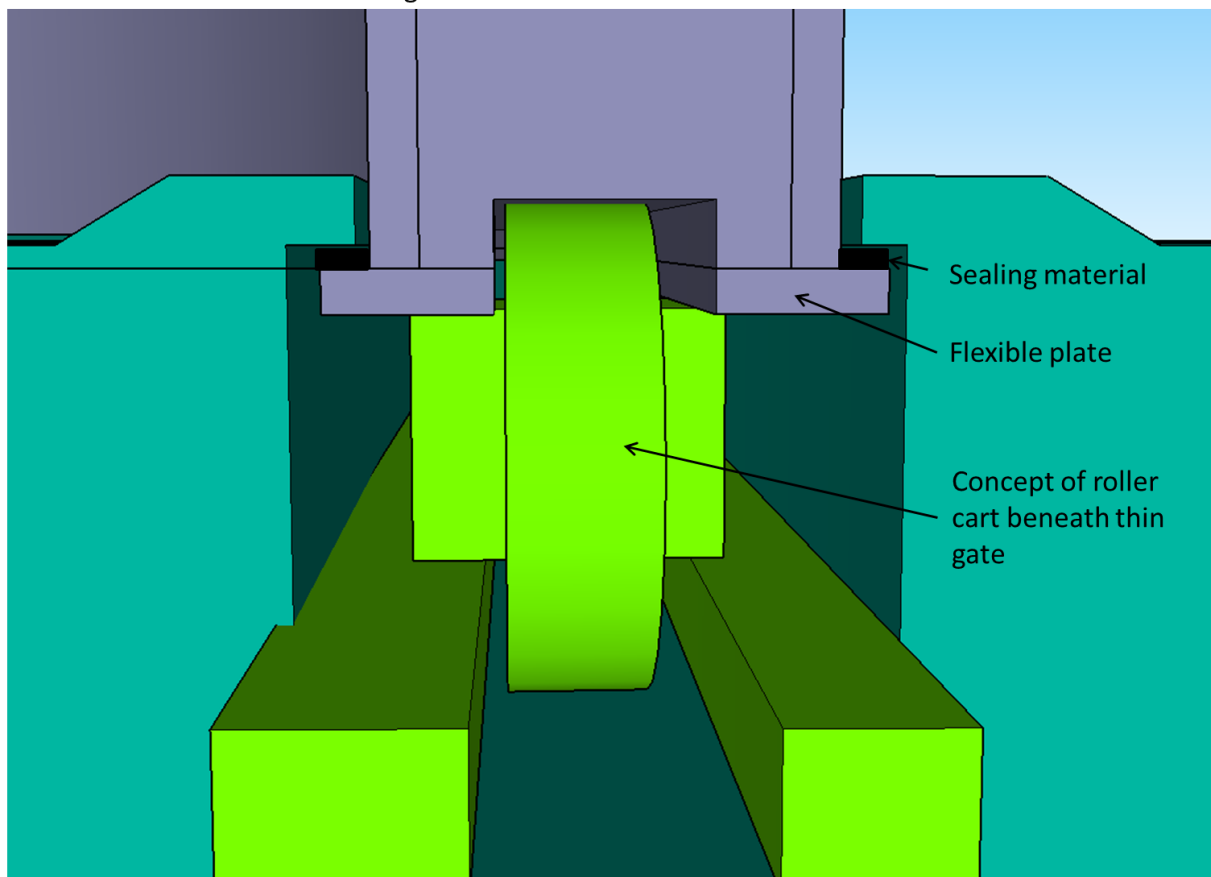


FIGURE 53 – GATE BOTTOM SEALING

7.5 COMMENTS & CONCLUSIONS

In this chapter the lock gate was further designed and dimensioned. 3 Methods were created to check the forces in the gate and the support reactions. Only Method 1 was found to be simulating an arc gate. It could however, with the available recourses, not be confirmed whether this method (or Method 2 or 3) would be the real situation when the gate was clamped between the 2 walls of the gate recess. This is because neither of the methods resulted in a gate that displaced in such a way that it would clamp between the gate recess walls.

In order to help the idea of the support reactions (the direction in which the roller bearings act) set in Method 1 and thus to increase the likelihood that an arc gate is designed, notches were added to the gate and lock head. These notches should make it possible for the gate to press against the gate recess walls in the direction of the assumed support reactions. Still, it is advisable to use a computer program that has conditional support reactions and to build a scale model to test what happens when (if) the gate is forced in the clamping position by water pressure.

The module cross section that was designed based on its global buckling strength with respect to the normal force that would be present should suffice, including its longitudinal reinforcement to bear the compressive and tensile loads present. However, 'even' Method 1, which came closest to the theoretical arch had a moment present in the gate. When designing for this moment, a relatively high reinforcement ratio was required within this cross section.

This could be reduced by increasing the thickness and wall thickness of the cross section. However, this reduces the flexibility of the arch and thus the ability of the gate to clamp within the gate recess. Hence, the requirement to increase the strength of the modules cannot be matched with the high flexibility of the gate that is needed to clamp within the gate recess and form an arch in this way. Making the concept technically unfeasible.

This final conclusion might change when other methods to simulate the gate are found that could be more realistic (conditional support reactions), though there is no evidence yet to support this claim.

8 BRINGING A STANDARDIZED LOCK DESIGN TO THE MARKET

8.1 INTRODUCTION

The result of the previous chapters is a design of the lock gate that could help to standardize all future lock gates. The concept was chosen in Chapter 5 to fit in as much situations as possible (given that completely new locks are built) and further developed in Chapter 6 & 7. Now it needs to be implemented and further developed.

This chapter will treat several of the ideas that could help to introduce (and maybe develop) such a standardized design on the market. A standardized design will be defined as a design with generally accepted and uniformly categorized dimensions and materials [42].

Standardized design

A design with generally accepted and uniformly categorized dimensions and materials

This may either be possible by doing something completely new to civil engineering like designing in the open, or by going back to older contract forms known to civil engineers like the ‘bestek’ in which the client specified all relevant details about the structure to be build, or something in between.

8.2 IMPOSING (PARTS OF) A DESIGN

As client, it is possible to force a design in a certain direction. Some parts are already imposed by law or codes, like signalling and boarding, which need to be executed according to the Police Regulations on Inland Navigation and the Rhine Navigation Police Regulations [12]. In Dutch, they are called the Binnenvaartpolitiereglement and the Rijnvaartpolitiereglement respectively [43, 44]. Most of the design of a lock and other structures is however, up to the designers and clients.

This section will discuss the concept, the benefits and drawbacks of imposing a design as a means of standardization.

8.2.1 CONCEPT

For each set of structures with comparable functional requirements, one design will be made that fits all. This can be done by either the client or several companies. This design will then be used to call for tenders. Much like what is done through a ‘bestek’ (a specification of a construction work to be performed, including the applicable administrative, legal and technical provisions, materials and performance stipulations [45]).

Imposing a design

Have a design of a structure that you require to be built. Others may not make adjustments to the design.

Standardization is then obtained by applying the same specification to as many projects as reasonable viable. These specifications may not be changed without the client’s consent to ensure the standard of the client.

8.2.2 *BENEFITS*

Easy to make designs a standard within the base of operations of the client

As a client, one can call for tenders with the same design over and over again, if it is a design that can be applied at several locations. Therefore it should be relatively easy to make one design the standard.

Does not require big changes in the philosophy of civil engineers

A method with specifications set by the client has already existed for a while. It is therefore a well-known way of working.

Simple contracts

The contractor is only responsible for building. Responsibilities over the engineering and maintenance parts do not have to be included. Contracts may however become complicated when other companies are hired for design and maintenance and responsibilities are to be divided equally.

Cheaper to call for tenders

It is easier and thus cheaper to call for tenders when the design is fixed. In that way only prices have to be compared to see who can build the design for the least amount of money. When also the design and maintenance part are done by the contractors, they may all have different advantages and disadvantages, like cheap maintenance versus higher functionality. All these designs have to be compared, which may make it more expensive for the client. It is also less expensive for a contractor to bid on a tender where the design is already made, which may be seen in the prices contractors come up with.

The design however, has to be made first. So the extra costs from making the design, or contracting a company for only making the design, should be less than the benefits from a cheaper comparison and cheaper bids from contractors. This could be reachable because only one design has to be made for several projects. While when calling for tenders in each separate project for a design and construct type of contract, each contractor is coming with their own design, resulting in several designs for only one of the projects.

8.2.3 *DRAWBACKS*

Contradictory to the 'markt tenzij' philosophy

The 'markt tenzij' philosophy means that practically everything from design up to maintenance can become the responsibility of the contractor through publiek-private samenwerking (PPS), which translates roughly to public-private partnership or [46]. When imposing a design like is done through specifications, that partnership could be gone.

The advantages from PPS projects are: they are often found to be done quicker; contractors get more responsibility over the process; because the contractors are also responsible for maintenance, their solutions could become more durable and maintainable; the client is not required to have expertise in engineering, they require less people for the same amount of projects [46]. Because imposing (parts of) a design is contradictory to this 'markt tenzij' philosophy, those advantages are also gone.

Reduced innovation

When imposing a design, that is made by the client, possible with the help of some other companies, relatively few parties are involved in the design. This reduces competition and the amount of people thinking it over. Therefore, less innovation is to be expected.

Nationwide (or even international) application is not possible

One cannot enforce that e.g. all locks are built according to a single specification on a nationwide scale, even if it does have additions for several sets of requirements. Mainly because this level of government interference in the industry is competition breaking and it is against what capitalism stands for.

8.2.4 CURRENT APPLICATIONS

STABU bestek

Probably the best example of the current applications where a design is imposed (by the client) is through a specification. For residential and commercial construction projects such a specification is standardized through a Stabu bestek. [47]

This is of course not a standardized design as is aimed at, but as a big client with a lot of structures to build, it is certainly possible to help standardizing the designs further through a standardized specification.

While the STABU is for residential and commercial construction, specifications are and were also widely used in all kinds of governmental projects. This includes locks, tunnels, bridges, dams, dikes etc. Also in these kinds of projects, it is not used as a means of standardizing the design. However, in some cases they could and maybe even should be.

8.2.5 SUMMARY

Imposing a design is used by the client as a means to standardize within their base of operations.

The benefits are:

- Easy to make designs a standard within the base of operations of the client
- Does not require big changes in the philosophy of civil engineers
- Simple contracts
- Cheaper to call for tenders

The drawbacks are:

- Contradictory to the “markt tenzij” philosophy
- Reduced innovation
- Nationwide (or even international) application is not possible

The effectiveness to come to a standardized design is high but a standard design on structure level is only possible on a company level.

8.3 ALLIANCE OF COMPANIES AND GOVERNMENTAL BODIES – A METHOD PROPOSED BY MULTIWATERWERK

The Multiwaterwerk project – a project by Rijkswaterstaat, Van Hattum en Blankevoort, Deltares and ipv Delft – has created a new process of calling for tenders that could be used to obtain a standardized design. [6]

This section will discuss the concept, the benefits and drawbacks of such an alliance as a means of standardization.

8.3.1 *CONCEPT*

The process starts with the application of all companies that want to participate in the alliance for the design and preparation part. After a selection based on their experience, expertise and finally a plan of execution, a sketch of the concept and their vision, 3 alliances will be formed that consist of the following companies: Rijkswaterstaat or more general: the client; an engineering firm; a contractor. [6]

In these alliances, the client (which is present in all 3 alliances) should bring knowledge about management and maintenance, the engineering firm should bring knowledge about structural design and the contractor should bring knowledge about constructability and cost efficiency. Together they should be able to design something that is widely applicable and thus a standardized design. [6]

Those 3 alliances also compete against each other for making the best design, as the reward will go to the best design, but some ideas from the other alliances may still be bought out [6]. This should create an incentive for innovation within the standardized design, but could also be an incentive to ‘simply’ use the best known technology.

8.3.2 *BENEFITS*

Room for innovation

Through design alliances that compete with each other, innovation is stimulated. Each team wants to get the best design. Although it is not the only way to reach the best design, innovation can help.

Prevent fragmentation in design, management and maintenance

By forming an alliance of companies with the given different backgrounds, everybody can have a say in the design. A design can be developed in which the management and maintenance aspects are better weighted against construction. The risks in management of water corridors and primary water defences are also said to decrease [6].

Sharing of knowledge

By sharing knowledge between the several companies in an alliance, some benefits can be reached that can be quite similar to benefits discussed in section 8.4. These are: gathering feedback from each other, communication of design decisions and sharing resources and techniques.

Several parties involved

By involving more parties in the decision making it is more likely that a standard that is reached by them will be accepted. This may make it possible to also sell this standardized design to other clients.

8.3.3 *DRAWBACKS*

Low design efficiency

Having several alliances do the same work parallel may be good for competition. A lot of double work is still done in the overall system, which makes it intuitively very inefficient.

Complicated contracts

It is hard to create contracts for which the outcome of the project is not known beforehand. Especially when one wants to use the main design from one design alliance, but some good ideas that came from another alliance, this can become complicated.

8.3.4 *SUMMARY*

Design alliances consisting of a contractor, an engineering firm and the client that work in competition on a standardized design.

The benefits are:

- Room for innovation
- Prevent fragmentation in design, management and maintenance
- Sharing of knowledge
- Several parties involved

The drawbacks are:

- Low design efficiency
- Complicated contracts

The design alliances have not yet been used in a project but they offer perspective for standardization on the same level as when imposing a design (as client) and also for innovation due to the competition between the alliances.

8.4 DESIGNING IN THE OPEN [48]

Designing in the open is a concept that is currently used in many web design projects. Here the following points will be discussed: what it is, the benefits and disadvantages of designing in the open and how they translate to river lock design (or civil engineering in general) and why it could help to standardize civil engineering works.

8.4.1 *THE CONCEPT*

The idea behind designing in the open is that work and/or the process will be shared publicly. This concept could help to standardize river locks because when a design process is publicly available and the design is publicly improved upon, it does not have to be re-done from the start each time another company is chosen to design and construct a lock. They can ideally just take the design that is there; make adaptations that may be needed for different boundary conditions and build the new lock. By making it easier/cheaper in this way to use a design of a lock, contractors may tend to do this instead of making a completely new design. This helps standardizing locks.

Designing in the open/Open design

Sharing (parts of) design work and/or the process of the design publicly.

There are several ways in which sharing is done for web design and their relevance to civil engineering will be discussed next.

Sharing artefacts

In web design, this means sharing “sketches, style tiles, mock-ups, prototypes and other tools/deliverables” [48]. This type of sharing may work in a restricted way for civil engineering purposes and standardization within it, mainly because sharing artefacts is easy. Sketches, scale models and prototypes are already widely used as a means of communication between client and contractor to discuss how a structure will function and look after it is build. The only thing that needs to be done is sharing them more publicly to increase the amount of people that can give feedback and tips to help improve the final design.

It is however, incomplete. Another company cannot build a design from sketches and random tools and deliverables. They need the full drawings. Therefore, sharing artefacts will probably only function as company advertisement for the company that is designing.

Bits and pieces

This type is comparable to sharing artefacts, but on a much smaller scale. Only previews and teasers of the project are shown in web design. This can be compared to showing a bird’s-eye view picture from a 3d model of a lock design. Feedback can only be given on how it looks in general but not on how it could function. The design itself is in this case already in a stage where the looks are not under discussion anymore, making feedback useless. This type thus only seems useful to get people interested in the end-results, which will not help in standardizing lock design.

Sharing stories

Progress is shared in web design “by telling stories of process, techniques and lessons learned” [48]. Although it is a way to share and get feedback on the design, it is not a very efficient way in itself because the easiest way to communicate how something will function is by showing. Also, a story is not a product from the designing process which only needs uploading; it is a piece of work that needs to be done on top of the process itself.

It may however work in combination with sharing artefacts, by telling about how other variants have been discussed, but not thought to be a proper idea before coming to the current sketches. Then the community to which the artefact is shared may have some extra inspiration for new ideas and will not come back with ideas that were already discussed.

Alphas

In web design this is a link to the most current state of the project. This can give people the most direct and detailed view on the current state of the design project. In theory, the most useful feedback can be given here because the community that is checking the progress has access to every piece of information about the project.

In civil engineering, this type of open sourcing will mean that all design steps from the first sketches up to the dimensioning of individual parts will be open. This will be farthest away from current perspectives on competition: why would somebody design something that cannot be sold because it is already open to everybody? It is however a good way to come to a standardized design that everybody can use and improve upon. Engineers and designers can fully focus on new ideas and improvements on current projects instead of designing the same things others designed.

Sharing tools

In web design this is sharing the code and toolkits that are used in the project. This helps when feedback is wanted on the coding only. How the website looks or should look is already given in such a case, but as a web designer you may want feedback on how to do it more efficient, e.g. to make the website load faster.

In civil engineering, this can be seen as sharing programs you developed, that help analyse the strength of a new design for example. Using the same programs as others is in some way standardization, but it is not on the level that is aimed for here, which is standardization of the design – and thus the structures made according to it – itself.

8.4.2 BENEFITS

The following points are benefits of designing in the open listed by Brad Frost [48], they will be translated to their impact on river lock design, and possibly civil engineering in general.

Gain resources, tips, and techniques from community

The design of river locks is very specialized work. At least part of the community therefor also needs to be on approximately the same level of specialization to be able to give resources and tips. This demands a lot from the community because they will also need to share things like tools they have to design the locks, while those things may help them in their competition against other companies in the community.

The community can also get some work done, the resource in this case being engineering time. Koch and Schneider [49] for example, confirmed the intuitive relationship between the number of active programmers and the output produced for an open source development project. This is an example from a completely different field. In the field of civil engineering it may not be as simple to get people motivated to work on your project. On the other hand, why would designing structures be so much different from designing code? Programmers are also highly qualified personnel who could also be designing in a closed project.

To help the process of going to an open design community going, it can help if clients create some incentive to share, as they gain the main advantages of sharing. As projects can be greatly helped if everybody helps each other.

Gather feedback

Gathering feedback from day one of the project can be very helpful in the design process. To come to a design that is wanted by all the stakeholders, it helps if they are all able to give feedback on choices that are made. Normally, on a project that includes all stakeholders from the start of it, a lot of feedback can already be gathered from stakeholders.

A bigger community can however be reached by designing in the open. Feedback can then also be gathered from students, non-anticipated stakeholders or just the local community. Not all of this feedback is wanted, but through a good filtering process and usage of this feedback, one may be able to reach a design that more people can agree upon as the best option.

Another advantage of this is that feedback can go directly to the designers. In a closed design environment where eventually a structure is placed, people may protest against it for several reasons. This protest will first go to the client as they are responsible, then the client may respond by asking the designers for other solutions, normally already very late in the design/construction process.

Build interest and community

Designing in the open helps to let the local people know about the project and get involved if they like. This can reduce opposition against the project. Sturzaker [50] has collected evidence on this for the case of rural affordable housing schemes in England. This may be helpful when opposition to the construction is to be expected.

Establish yourselves as leaders and innovators

This advantage is also achieved when the locks are built, and is only the case if you actually are building something innovative.

Have impact far beyond the scope of your project

Having impact beyond the scope of the project is helpful for others, but also for the designers. Contractors that want to construct a previously designed structure elsewhere will come to the original designers with questions and wishes for adaptation for that specific site, giving the original designers an advantage for jobs over others.

Lose the Big Reveal

On a big reveal, a lot of people can be unpleasantly surprised. By designing in the open you can let the community know beforehand what is going to happen and why. They can give feedback on how to reduce nuisance caused or on agreements that would compensate for it. Preventing potential hindrance caused by the community to stop or delay the project.

Communicate design decisions

Designing in the open automatically means constant communication between client and designers/contractors. This means that at each point in the design, the client can get inspiration for additional wishes. This makes it possible to apply them at an early stage in the design instead of at certain intervention points where the designer and client discuss current progress.

Commit to the project

When designing in the open, more people will know about the project, making you accountable to more people. This could be some sort of motivation to the people working on the project. For a civil engineering project however, there already should be enough motivation to see the project through without being accountable to a bigger community. Big investments are involved in such a project and they should be accounted for by gains for society, which brings enough motivation to do such a project.

Other contractors can take over the work of the first

When quarrels originate between a contractor and client and it even goes so far that the contractor quits the project altogether, another contractor can take over the project without much effort. They can pick up the design from the open source and then just continue work done by the previous contractor.

8.4.3 DRAWBACKS

The following points are drawbacks of designing in the open listed by Brad Frost [48], they will be translated to their impact on civil engineering.

It is uncomfortable to share works in progress [51]

This is something that everybody experiences, especially when you do not have enough experience to be comfortable with what you do. By trying to keep sharing your work in progress, one should be able to get over this discomfort sooner or later.

Un-experienced as well as experienced designers and engineers can benefit from tips, tricks and feedback from others when sharing their work publicly. The un-experienced ones can be helped by discovering bad choices in the design early. The experienced ones can be helped with breaking from conservative choices that are not ideal anymore.

Comments from the peanut gallery

Especially in engineering, a lot of decisions that are made are based on extended knowledge in the field. Companies with that knowledge may not want to help on the design (their work may not be rewarded), while the public often may feel the need to comment on stuff they do not know about. This means that a high rate of useless comments is to be expected with respect to useful input.

It will cost time to go through all the comments and it is not even sure whether there will be anything helpful in it. Those comments may however help to discover what the local population is worrying about. They may then be informed about how those worries are considered and where they can find them in the process of designing in the open.

“Other people will take our stuff”

For the case of web design, Frost [48] calls this a huge myth based on a blog article by Anderson [52]. The main arguments being: “most people may get excited about your idea, but very few of them would actually be willing to do all the work it would take to implement it” and “knock-offs are inevitable”. So what they are saying is: while the idea is still an idea, very few will actually try to compete with the person that is actually trying to make that idea come to life, but when the idea is implemented, it will eventually be copied anyway.

In civil engineering practice, knock-offs are indeed inevitable, because everybody can see how the structure globally looks like. It is another thing however, if others can see all the details and how they are designed. Maybe some companies have a huge hidden competitive advantage in some of the details that cannot be seen. This could cause them to be able to sell their expertise on the same project several times.

For the purpose of standardizing the design, it can almost be called a requirement that other people take our stuff. If a totally new idea is implemented and you want this to be the new standard, not only the first contractor that builds the structure needs to build it that way, but also all the contrac-

tors that follow. If others voluntarily use these designs, it also means that they are probably very effective.

Time

It takes time to share progress as you go on. However, it also takes time to discuss progress with client, supervisors and other stakeholders. If this is all done on a public domain, it should not cost any more time.

It may however cost time to set up a system where it is possible to share everything. Sharers need in some way to be or feel rewarded for their work so the system that is set up should be able to recognize who does what. Being able to change the course of designers/engineers at any point may however save a lot of time spend on changing the design when it is complete.

8.4.4 CURRENT APPLICATIONS

WikiHouse

WikiHouse is an open source construction system [53]. It is aimed at designing houses and the first thing you see when you open their website is: “Customised, in the 21st century, one size doesn’t need to fit all”. This indicates that open-sourcing here is used to do the contrary of standardizing designs. They aim at highly customized designs.

Why it still could help standardization is when people start browsing already designed houses, they may think some of them are already ideal as they are and just get one of those instead of making a new design. In lock design, this effect can be even stronger because the looks of a lock are much less important than the functionality with respect to a house and functionality can be objectively described. So, one of the designs in the ‘navigation lock catalogue’ that could be created over the course of several years has got to be the best.

8.4.5 SUMMARY

Open design helps by generating a standard because it is expected to be cheaper and/or easier to use and already existing design that is open source than to create one. Hence contractors are expected to use the open source of the design instead of coming up with a completely new one.

The benefits are:

- Gain recourses, tips and techniques from the community
- Gather feedback
- Build interest and community
- Establish yourselves as leaders and innovators
- Have impact far beyond the scope of your project
- Lose the big reveal
- Communicate design decisions
- Other contractors can take over the work of the first

The drawbacks are:

- It is uncomfortable to share work in progress
- Comments from the peanut gallery

- “Other people will take our stuff”
- Time

WikiHouse is a good example in how designing in the open can work. It is currently not used as a means to standardize designs, but it can probably be a helpful tool to achieve standardization nonetheless.

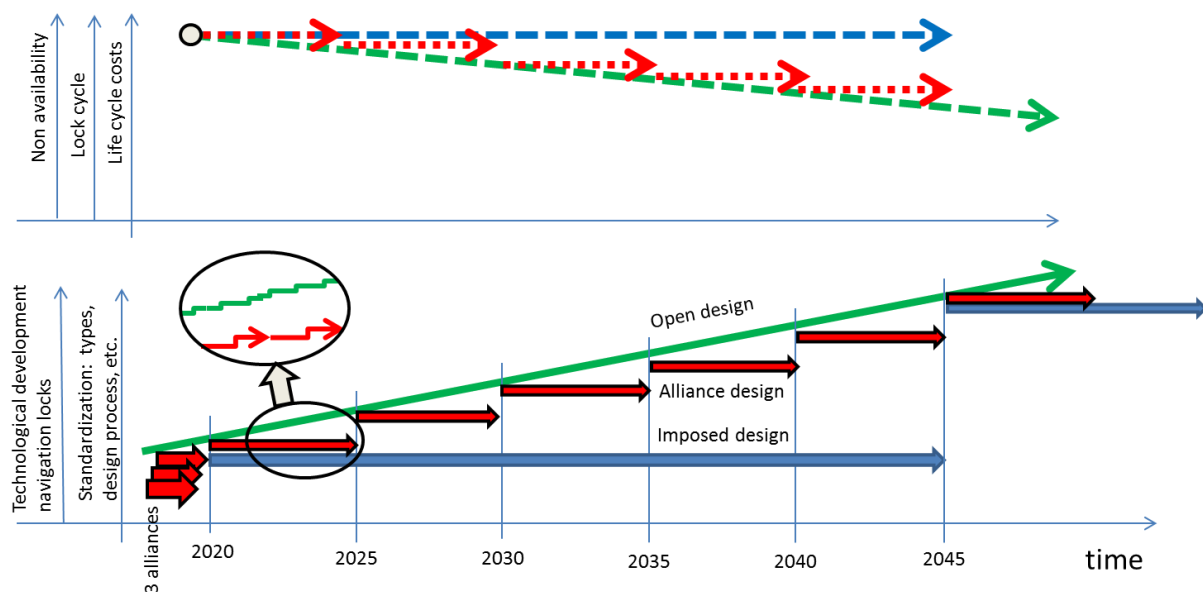
The effectiveness to come to a standardized design has yet to be proven. The drawbacks make it hard to fit designing in the open in current engineering practice. However, when it is applied, it may be possible for usage on a global scale.

8.5 COMPARISON

As a basis of comparison Figure 54 can help as a guide for the expected level of innovation and cost reduction caused by each of the previously discussed methods of getting a standard on the market.

If open design is used to its full potential, it can cause a continually evolving technology.

Standardization as an ongoing process



Ad van der Toorn, dec. 2014

FIGURE 54 – STANDARDIZATION AS AN ONGOING PROCESS

Table 6 gives a comparison between the 3 proposed standardization methods. It is based on the argumentation from the previous sections. For implementation the scores are based on how hard it is to implement the method in river lock design (and civil engineering). The scores of standardization are based on the scale of standardization that can be reached, just within the company or could it also reach further? Finally, the scores for innovation are based in how much room there is for innovation.

TABLE 6 – COMPARISON BETWEEN STANDARDIZATION METHODS

Method	Implementation	Standardization scale	Innovation
Imposing designs	+	-	-
Design alliance	0	0	0
Open design	-	+	+

Care must be taken that innovation can get in the way of standardization and the other way around. So with any one of these methods, one should always discuss whether current innovations are good enough to break standardization or whether the current level of standardization is good enough not to implement current innovations. Currently, from the assessments of Multiwaterwerk [4] and Slijk [7], standardization is the one that is expected to deliver.

From the comparison follows that it is relatively hard to implement open design, but it may be worthwhile in the long run. This method being worthwhile but on the other hand hard to implement, can be contributed to it not being directly as worthwhile for the people involved as it would be when they designed through classical methods and contracts.

It could thus be good to test out designing in the open on a small scale. One tool that may help therein for the case of navigation locks is SluisPedia [54], on which a lot of information regarding locks has already been shared. This could also help to further develop the curved modular lock gate designed in Chapter 7.

9 DISCUSSION

During this graduation work a choice diagram was created from the text in the book *Design of Locks – Part 1* [12] that shows the usual choices made when deciding on which lock gate type to use. Despite this choice diagram, which is quite clear on when to build which lock gate, no standard gate design originated. The current policy to outsource the design of locks to different contractors depending on who won the tender process of each individual project is the main reason behind that.

Rijkswaterstaat concluded in its investigations towards standardization that the LCC of locks would become cheaper when locks are standardized. During this graduation work, no studies from Rijkswaterstaat were found that would contradict this conclusion. However, there is still no consensus as to whether this is true, resulting (possibly) in the unchanged policy. When the studies can reach more detail about how the standard should look and be implemented, a higher level of consensus could be reached.

Such a clear view on when to use which lock gate as shown in this choice diagram (Figure 11) does not create a lot of room for innovative ideas about how a lock gate should look. Though, when going for a standard, having a clear view on which lock gate to use may not be as bad as it sounds. The current situation of how lock gates are built developed over hundreds of years and the resulting gates may as well be as good as lock gates get. One now only has to standardize the dimensions of those gates and the standard is set.

Nevertheless, sometimes a little ‘out of the box’ thinking could still result in innovations (nobody knew they ‘needed’ a phone until it was invented). In this graduation work the focus was therefore set on how the future standard lock gate should look by looking into innovative concepts. Which resulted in the concrete modular rolling arc gate. In which the ‘modular’ part is intended as a view on how the standard should look and the ‘concrete arc’ as a lock gate is intended as the innovative concept.

Other people may each come to a new idea or find a different concept to be better when attempting to innovate. Even if everybody uses a multi-criteria analysis (MCA) method, the numbers are still filled in by the person(s) choosing the gate. It is quite hard (if not impossible) to make an objective MCA when searching for innovative concepts. This is because each number indicating (parts of) the LCC or potential values of an innovation remains an estimate before the innovation is built. Only when built, the costs and benefits of an innovative gate type can be collected objectively. Hence, this graduation work focused on developing a concept first. The detailed analysis of its costs and benefits with respect to other gates is left open for when the concept is found good.

In the end, the rolling arc gate that clamps in its gate recess was not found technically feasible. But the idea of a modular gate design could still be tested on other gate types.

10 CONCLUSIONS

- The wish to have a standardized lock design originates from the big governmental bodies that have to manage a large arsenal of locks. In the Netherlands that would be Rijkswaterstaat.
- Changes in the network or corridors cannot be used to improve the ability to standardize locks. They are expected to be much more expensive than what they may save in costs through standardization. However, when changes to the network or corridors need to be made on the basis of other argumentation, it is helpful to check if they can be made in such a way that several of the same locks can be built.
- The best way of standardizing locks is by standardizing within each CEMT-class, those components that every lock has and do not depend on the hydraulic boundary conditions (e.g. signalling, boarding, cable housings etc.); and by modularizing the lock gates. There is not much value to be gained through standardizing the lock head and lock chamber, except when standardizing the width of the lock head, which may help by creating a higher economies of scale for the gate standard.
- By subjecting the lock gate to the boundary conditions as present at lock Eefde, the resulting design should be compatible with a large range of other CEMT-class Va locks with a lower rise.
- Of all the available lock gate types, the rolling arc gate was reasoned to match the criteria of innovativeness and the possibility to modularize the gate the best.
- The modular rolling arc gate works best if the modules span the full width of the lock head. Only the height of the gate will then be variable to match the different hydraulic boundary conditions at different locks. The gate standard will then benefit from a standardized lock head width within each CEMT-class.
- Building a modular rolling arc gate is technically feasible. Though the means of supporting this gate in the lock head (by clamping the gate in its recess through the use of the hydraulic head) that was designed in this thesis, is not found to be technically feasible. This is because the (magnitude of) the gate displacement in the recess did not result in a clamping situation.
- The standardized design can best be implemented through imposing the design. However, a wider application of the standard and more consensus among client and contractor may be reached through open design.

11 RECOMMENDATIONS

- Before standardizing lock gates it is recommended to investigate the use of other gate types and materials besides the steel mitre gates for the standard lock. As an example, Sluis 124 in Amsterdam is a concrete sliding gate. It is a lock that is about 6 m wide with a small (sometimes negative) rise. The involved parties concluded that the concrete sliding gate would be the cheapest alternative. In contrast, these boundary conditions would normally result in either a bolt lock pivot gate or a mitre gate with lock (Figure 11) while rolling/sliding gates would only be used in locks over 16 m wide.
- This graduation work used only qualitative argumentation as to why the gate was designed in modules. Namely the reduction on the amount of reserve gates that need to be stored near locks and more significant economy of scale of the standard versus over dimensioning and possible interface problems (e.g. leakage or a bad connection). Therefore it is recommended to investigate in more detail the costs and benefits of modular lock gate design.
- The conclusion that the gate is not clamped in the gate recess under the specified loads may be caused by the limits of the used finite element program. It is recommended to remodel the gate in a finite element program or in a scale model so that the support reactions can be modelled as conditional support reactions. I.e. the support reactions only appear after an initial displacement and bending of the gate. If the results are still the same, the rolling arc gate can be proven to be technically unfeasible.

12 APPENDICES

APPENDIX A – LIST OF LOCKS

This list is made from the sources: [55-58].

[illegible]

FIGURE 55 – SEE EXCEL APPENDIX FOR FULLY UPDATED AND VISIBLE VERSION

The different data sets used to create this document used different names and numbers for the locks, some locks even had different dimensions depending on the data set. Because of the different uses of the data sets they were for some parts of the information additions to each other. For the greater part (excluding name differences, which made it hard to find some locks from 1 set in another set) however, the data sets overlapped. It may thus be advisable to get rid of those differentiating names and combine all the data sets into one. From my involvement at some of the meetings involving the Multiwaterwerk project, I learned that some effort is already made regarding this, though this effort may not be as integrated in Rijkswaterstaat as it should be.

APPENDIX B – DESIGN CALCULATIONS

[illegible]

FIGURE 56 – SEE EXCEL APPENDIX FOR FULL CONTENT

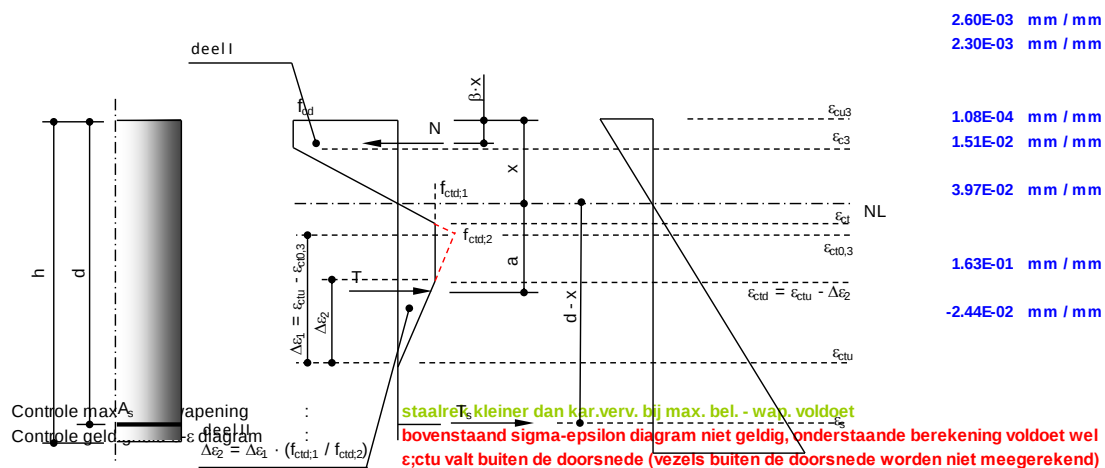
APPENDIX C – VERTICAL MODULE REINFORCEMENT



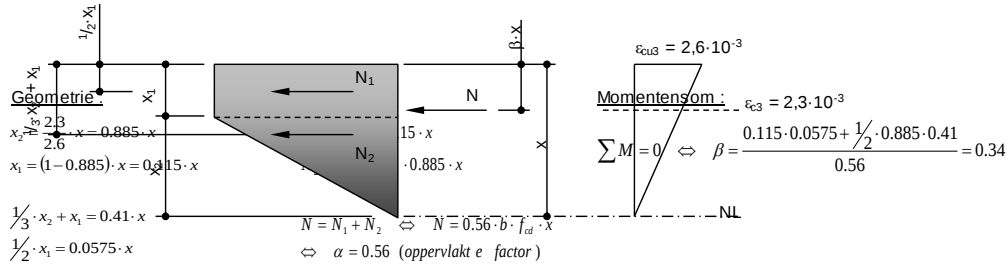
Project : Rekenvoorbeeld
Onderdeel : Balk 400x600

Auteur : Ing. P.P.F. van Rijen
Datum : 20-06-2011

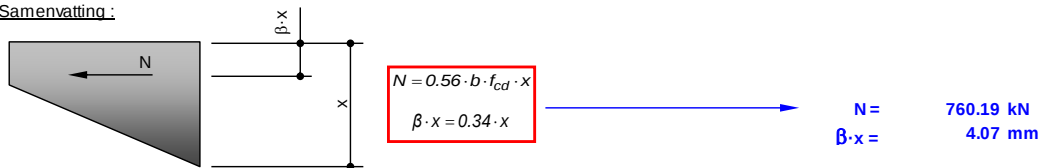
1. Algemeen	Breedte	: b	1000 mm
	Hoogte	: h	30 mm
	Nuttige hoogte	: d	27 mm
	Materiaalfactor t.b.v. betonspanning	: γ_c	1.5
	Materiaalfactor t.b.v. E-modulus	: γ_{cE}	1.2
	Reductiefactor t.b.v. vezeloriëntatie	: k	1.25
2. Staalvezels	Lengte staalvezels	: L_f	13 mm
3. Vezelbeton	Kar. Kubusdruksterkte	: f_{ckcube}	200 N/mm ²
	Kar. Cilinderdruksterkte	: $0.85 f_{ckcube}$	170 N/mm ²
	Rek. waarde max. drukspanning	: $f_{cd} = f_{ck} / \gamma_c$	113.3 N/mm ²
	Kar. waarde max. trekspanning	: $f_{ctk0.05}$	8 N/mm ²
	Rek. waarde max. trekspanning	: $f_{ctd} = f_{ctk0.05} / \gamma_c$	5.3 N/mm ³
	Gem. waarde elasticiteitsmodulus	: E_{cm}	58000 N/mm ²
	Rek. waarde E-modulus (secansstijfheid)	: $E_{cd} = f_{cd} / \epsilon_{c3}$	49275 N/mm ²
	Kar. waarde trekspanning bij w = 0,3 mm	: $\sigma_{(w0.3)}$	12 N/mm ²
	Rek. waarde trekspanning bij w = 0,3 mm	: $f_{ctd2} = \sigma_{(w0.3)} / (k \cdot \gamma_c)$	6.4 N/mm ²
	Betonstuk bij piekspanning f_{cd}	: ϵ_{c3}	2.30E-03 mm / mm
	Grenswaarde betonstuk	: ϵ_{cu3}	2.60E-03 mm / mm
	$\epsilon_{ct} = \frac{f_{ctd1}}{E_{cd}}$	: ϵ_{ct}	1.08E-04 mm / mm
	$\epsilon_{ct0.3} = \frac{w_{0.3}}{L_c} + \epsilon_{ct}$ waarin $L_c = \frac{2}{3} \cdot h$	: L_c	20.0 mm
		: $w_{0.3}$	0.3 mm
		: $\epsilon_{ct0.3}$	1.51E-02 mm / mm
	Grenswaarde rek vezelbeton	: $\epsilon_{ctu} = L_f / 4 \cdot L_c$	1.63E-01 mm / mm
4. Staalkwaliteit wapeningsstaal	B500 B		
	Rek.waarde vloeispanning	: f_{yd}	435 N/mm ²
5. Rekverloop	Kar. vervorming bij max. belasting	: ϵ_{sk}	5 %
	$\Delta \epsilon_1 = \epsilon_{ctu} - \epsilon_{ct0.3}$	: $\Delta \epsilon_1$	1.47E-01 mm / mm
	$\Delta \epsilon_2 = \Delta \epsilon_1 \cdot \frac{f_{ctd1}}{f_{ctd2}}$	: $\Delta \epsilon_2$	1.23E-01 mm / mm
	$\epsilon_{ctd} = \epsilon_{ctu} - \Delta \epsilon_2$	: ϵ_{ctd}	3.97E-02 mm / mm
	$\epsilon_s = \frac{(d-x)}{x} \cdot \epsilon_{cu3}$	: ϵ_s	-2.44E-02 mm / mm
			= -2.44 %



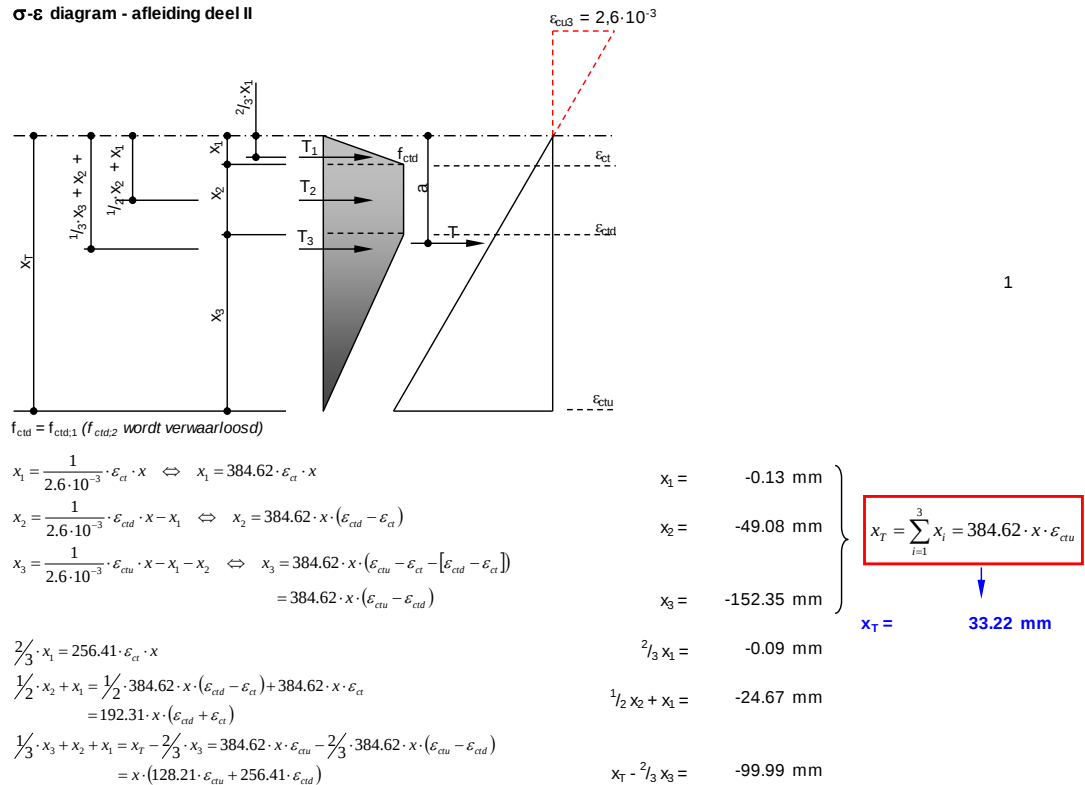
6. σ - ϵ diagram - afleiding deel I



Samenvatting :



7. σ - ϵ diagram - afleiding deel II



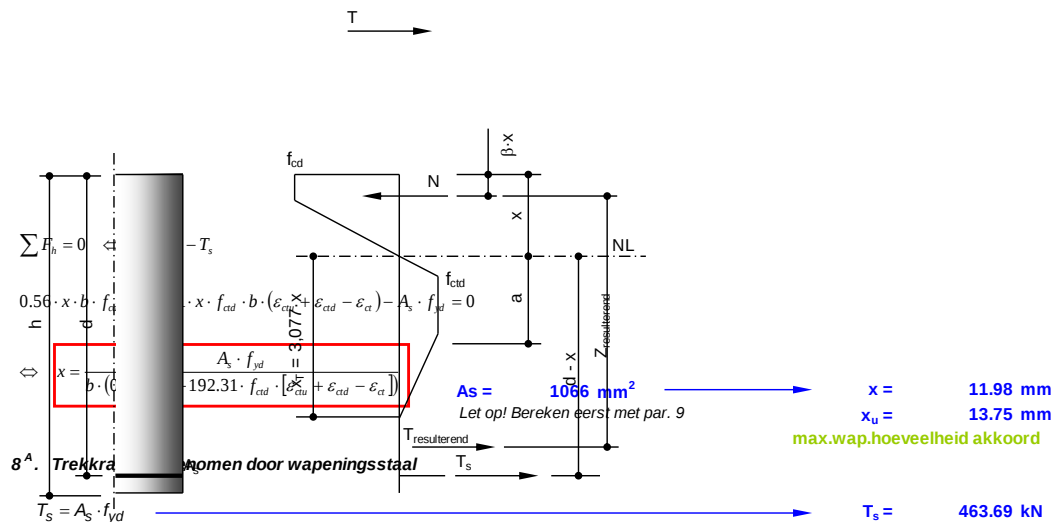
Trekkraft opgenomen door beton & vezels :

$T_1 = \frac{1}{2} \cdot 384.62 \cdot \epsilon_{ct} \cdot x \cdot f_{ctd} \cdot b = 192.31 \cdot \epsilon_{ct} \cdot x \cdot f_{ctd} \cdot b$
 $T_2 = x_2 \cdot f_{ctd} \cdot b = 384.62 \cdot x \cdot (\epsilon_{ctd} - \epsilon_{ct}) \cdot f_{ctd} \cdot b$
 $T_3 = \frac{1}{2} \cdot x_3 \cdot f_{ctu} \cdot b = 192.31 \cdot x \cdot (\epsilon_{ctu} - \epsilon_{ctd}) \cdot f_{ctu} \cdot b$

$T = \sum_{i=1}^3 T_i = 192.31 \cdot x \cdot f_{ctd} \cdot b \cdot (\epsilon_{ctu} + \epsilon_{ctd} - \epsilon_{ct})$
 $T = 296.50 \text{ kN}$

$a = \frac{T_1 \cdot \frac{2}{3} \cdot x_1 + T_2 \cdot (\frac{1}{2} \cdot x_2 + x_1) + T_3 \cdot (\frac{1}{3} \cdot x_3 + x_2 + x_1)}{T}$
 $a = 12.23 \text{ mm}$

8. Volledig σ - ϵ diagram



8^B. Resulterende trekkracht

$$T_{\text{resultierend}} = T_s + T \rightarrow T_{\text{resultierend}} = 760.19 \text{ kN}$$

$$Z_{\text{resultierend}} = \left(\frac{T \cdot a + T_s \cdot (d - x)}{T_{\text{resultierend}}} \right) + (x - \beta \cdot x) \rightarrow Z_{\text{resultierend}} = 21.84 \text{ mm}$$

8^C. Controle evenwichtsvergelijking

$$\sum F_h = N - T_{\text{resultierend}} = 0 \rightarrow \sum F_h = 0.00 \text{ kN}$$

evenwichts vergelijking voldoet

9. Wapeningsberekening

9^A. Wapeningshoeveelheid

Toe te passen wapeningshoeveelheid (start- en eindwaarde mm^2 wapening)
Rekenwaarde buigend moment

$$M_u = N \cdot Z_{\text{resultierend}}$$

gebruik oplosser	: A_s	1066 mm^2
	: M_d	55.6 kNm
	: M_u	55.5 kNm

Bepaal wapening

9^B. Maximum hoogte drukgebied

NEN-EN 1992-1-1, art. 5.5 :

$$\delta \geq 0.54 + 1.25 \left(0.6 + \frac{0.0014}{\epsilon_{cu3}} \right) \cdot \frac{x_u}{d} \text{ voor } f_{ck} > 50 \text{ N/mm}^2$$

$$\text{waarin: } \delta = \frac{M_{nhvd}}{M_{el}} = 1 \text{ en } d = 0.9 \cdot h$$

$$x_u = \frac{0.9 \cdot h}{0.54 + 1.25 \left(0.6 + \frac{0.0014}{\epsilon_{cu3}} \right)} \rightarrow x_u = 13.75 \text{ mm}$$

10. Conclusie

BEREKENING VOLDOET

APPENDIX D – DELTARES MODEL STORM SESSIE

Dashboard

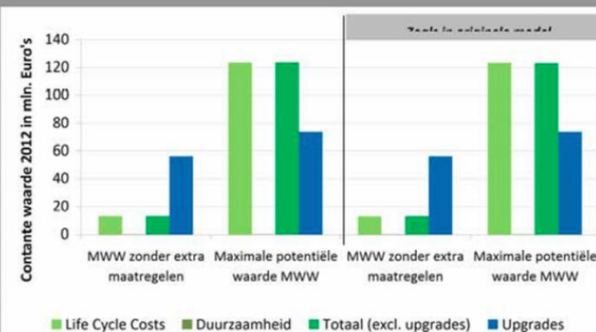
Deltares model STORM sessie

		Zoals in originele model	
		MWW zonder extra maatregelen	Maximale potentiële waarde MWW
Aantal sluisen			
Aantal klein dubbelzijdig kerende sluisen	70	70	
Aantal klein enkelkerende sluisen	100	100	
Fasering vervangingsopgave			
Begin jaar vervanging sluisen	2020	2020	
Eindjaar vervanging sluisen	2055	2055	
Vervanging met MWW			
% van de sluisen dat in 2020 al met MWW wordt vervangen	50%	50%	
Maximaal % van de sluisen dat uiteindelijk met MWW wordt vervangen	75%	100%	
Life Cycle Costs - Kosten ontwikkeling MWW			
Jaarlijkse kosten voor coördinatie en configuratie	€ 250.000	€ 250.000	
Life Cycle Costs - Kosten voorbereiding			
Voorbereidingskosten klein dubbelzijdig kerende sluisen als % van aanlegkosten (zonder MWW)	20%	20%	
Voorbereidingskosten klein enkelkerende sluisen als % van aanlegkosten (zonder MWW)	10%	10%	
Maximale besparing klein dubbelzijdig kerende sluisen door toepassing MWW	10%	10%	
Maximale besparing klein enkelkerende sluisen door toepassing MWW	10%	10%	
Life Cycle Costs - Aanlegkosten			
Aanlegkosten klein dubbelzijdig kerende sluisen (zonder toepassing MWW)	€ 50.000.000	€ 50.000.000	
Aanlegkosten klein enkelkerende sluisen (zonder toepassing MWW)	€ 50.000.000	€ 50.000.000	
Meerkosten klein dubbelzijdig kerende sluisen door toepassing MWW	1%	1%	
Meerkosten besparing klein enkelkerende sluisen door toepassing MWW	1%	1%	
Life Cycle Costs - Onderhoudskosten			
Onderhoudskosten klein dubbelzijdig kerende sluisen als % van aanlegkosten (zonder MWW)	3%	3%	
Onderhoudskosten klein enkelkerende sluisen als % van aanlegkosten (zonder MWW)	3%	3%	
Maximale besparing klein dubbelzijdig kerende sluisen door toepassing MWW	€ 109.500	€ 264.000	
Maximale besparing klein enkelkerende sluisen door toepassing MWW	€ 109.500	€ 264.000	
Life Cycle Costs - Exploitatiekosten (Energiekosten)			
Energieverbruik per sluis zonder toepassing MWW (kWh per jaar)	89.000	89.000	
Energiebesparing per sluis door toepassing MWW (kWh per jaar)	81.000	81.000	
Energiekosten per kWh	€ 0,20	€ 0,20	
Life Cycle Costs - Exploitatiekosten (Energiekosten)			
Energieverbruik per sluis zonder toepassing MWW (kWh per jaar)	89.000	89.000	
Energiebesparing per sluis door toepassing MWW (kWh per jaar)	81.000	81.000	
Energiekosten per kWh	€ 0,20	€ 0,20	
Life Cycle Costs - Upgradekosten			
% sluisen dat geupgrade moet worden (25 jaar na realisering)	10%	10%	
Kosten upgrade per sluis zonder toepassing MWW	€ 50.000.000	€ 50.000.000	
Maximale besparing per upgrade	30%	30%	

Uitkomsten

		Zoals in originele model			
	MWW zonder extra maatregelen	Maximale potentiële waarde MWW	MWW zonder extra maatregelen	Maximale potentiële waarde MWW	
Life Cycle Costs	13	123	13	123	
Kosten ontwikkeling MWW	-19	-19	-19	-19	
Voorbereidingskosten	6	11	6	11	
Aanlegkosten totale sluis	-17	-22	-17	-22	
Vervangingskosten elektro	5	5	5	5	
Vervangingskosten werktuigbouw	1	1	1	1	
Onderhoudskosten	35	146	36	146	
Operationele kosten (Energiekosten)	1	1	1	1	
Upgrade kosten	50	74	50	74	
Functionaliteit					
Hinder voor de scheepvaart	PM	PM	PM	PM	
Duurzaamheid					
Watermanagement	PM	PM	PM	PM	
CO ₂ uitstoot als gevolg van energieverbruik	0	0	0	0	
Totaal (excl. upgrade kosten)	13	123	13	123	
Totaal (incl. upgrade kosten)	69	197	69	197	

Contante waarden 2012 in mln Euro (afgerond op mln)



APPENDIX E – FLOWCHART PRELIMINARY DESIGN

[xx] commentary [xx]

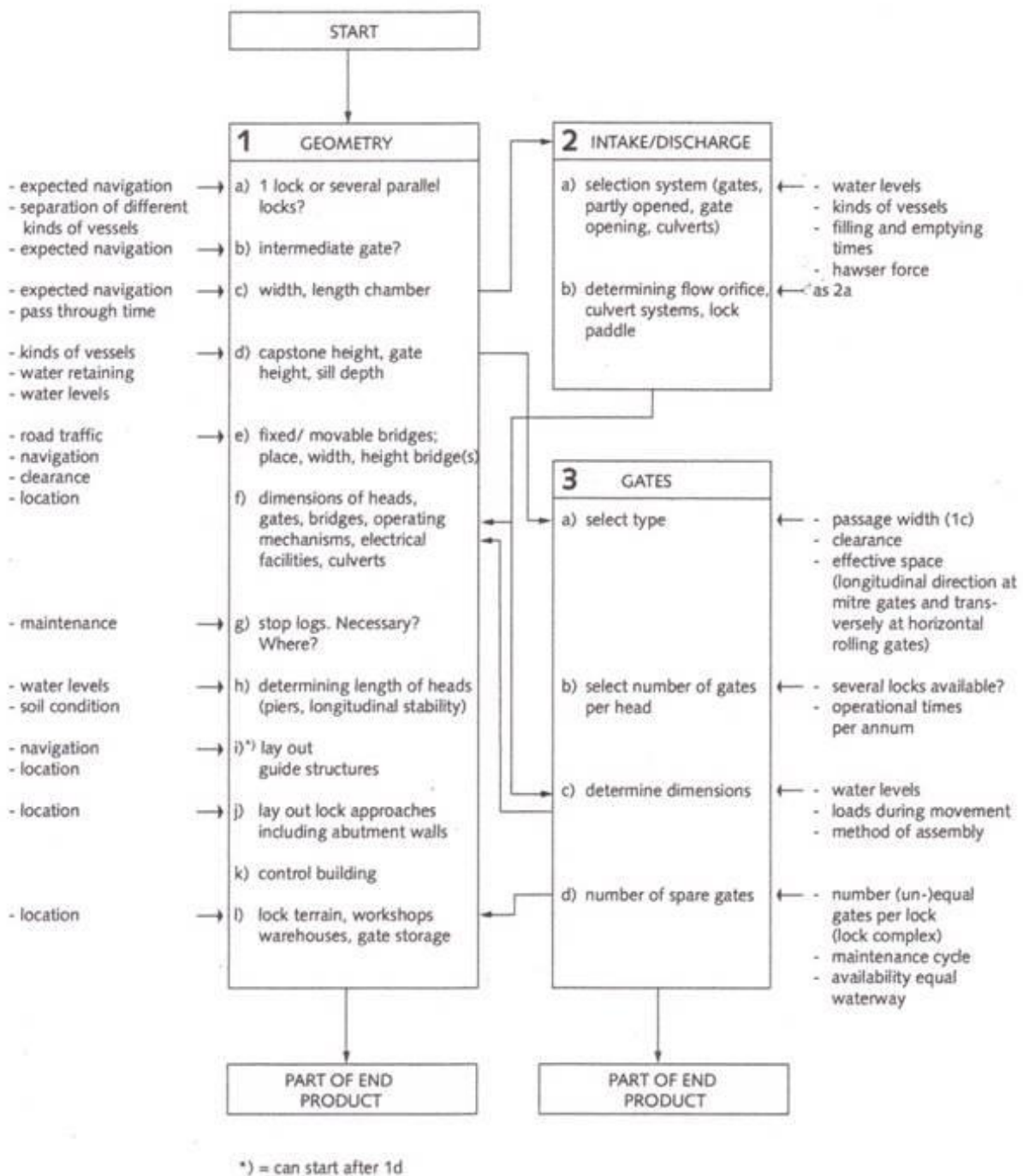
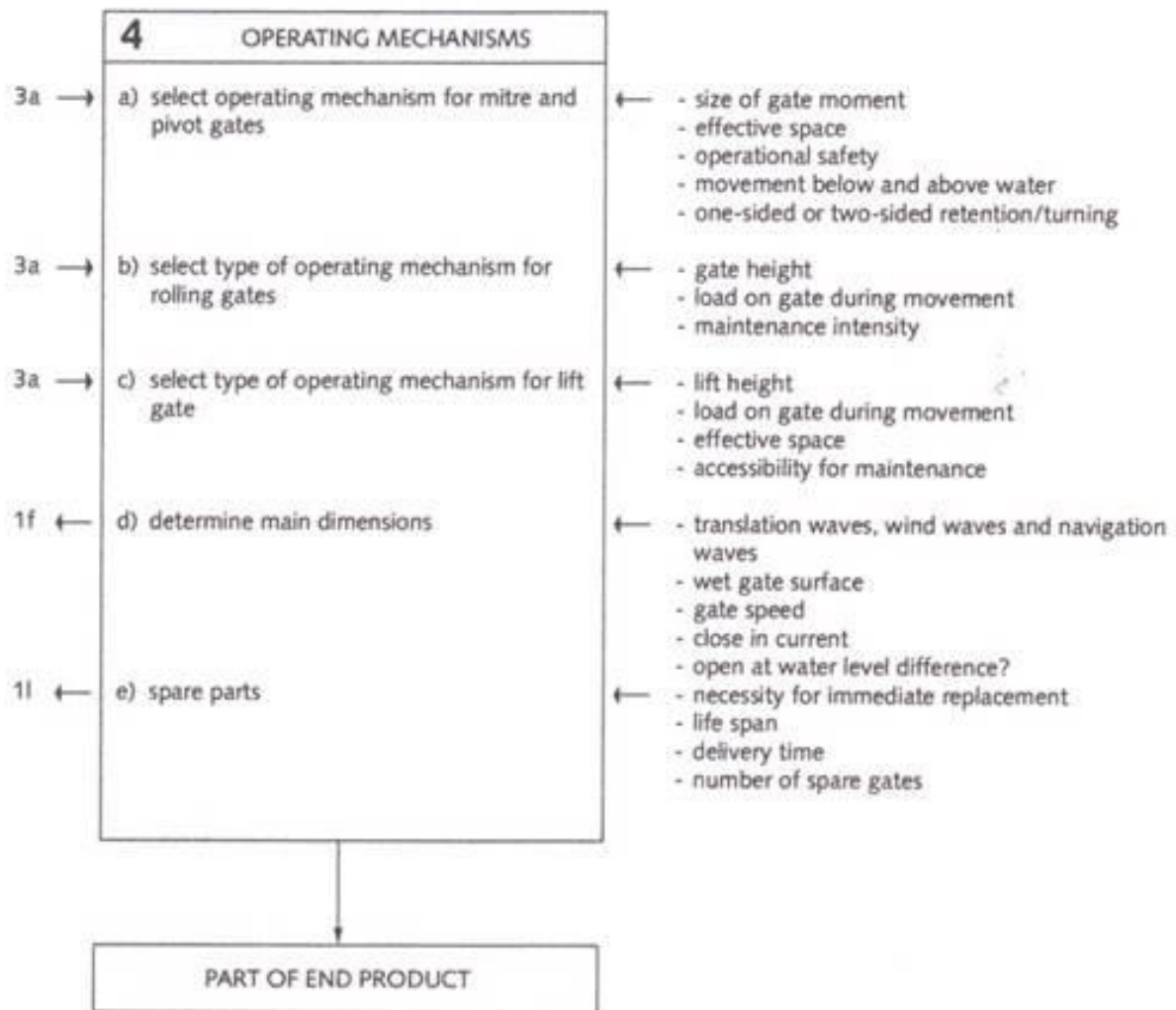


FIGURE 57 – FIRST PAGE OF FLOWCHART PRELIMINARY DESIGN – SOURCE: [12]

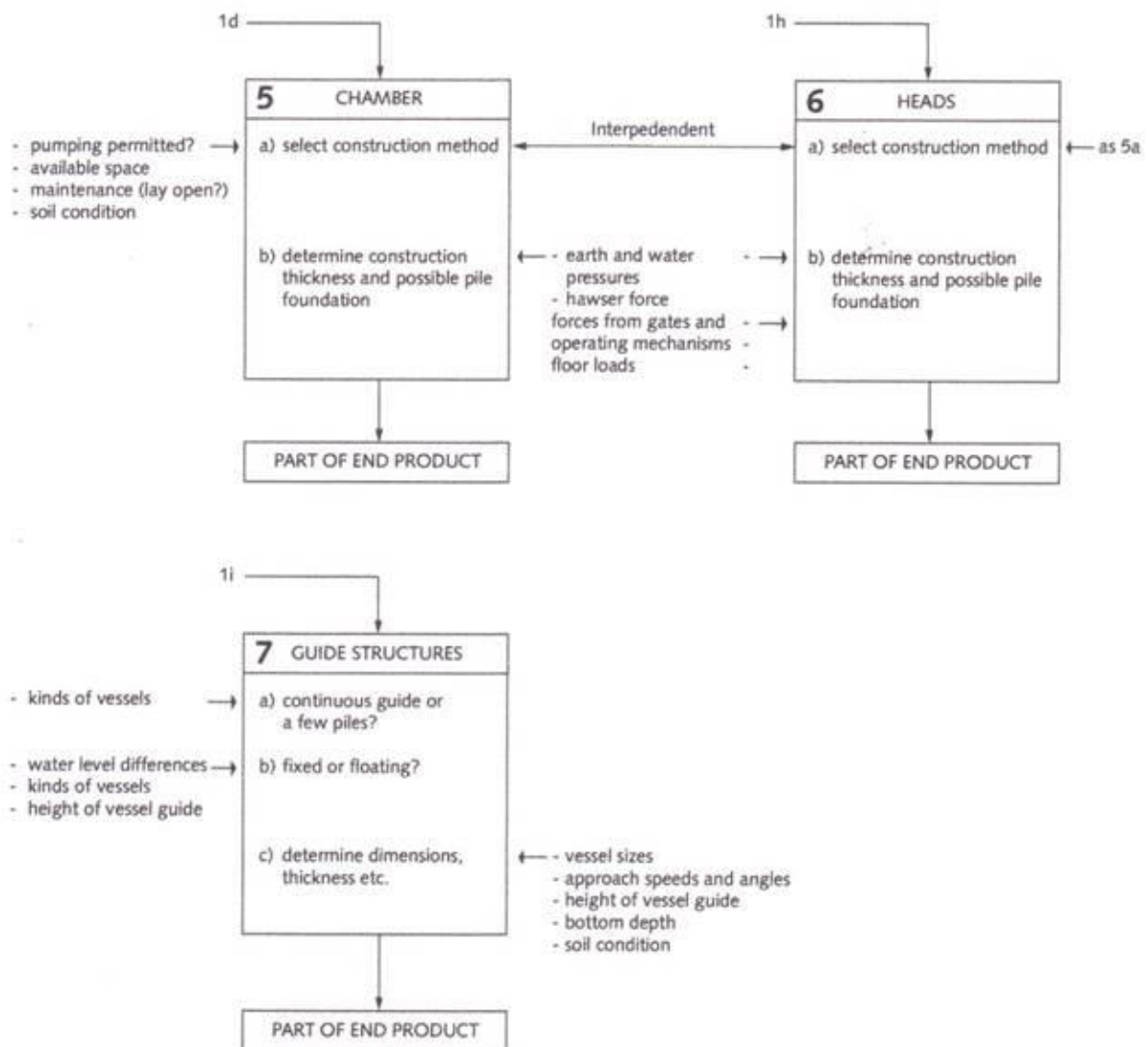


Legend:

3a → means: 4a to c is related to 3a from fig. 3.1

1f ← means: result 4d is required for 1f from fig. 3.1

FIGURE 58 – SECOND PAGE OF FLOWCHART PRELIMINARY DESIGN – SOURCE: [12]



Legend:

*1d → * means: block 5 follows after 1d from fig. 3.1

FIGURE 59 – THIRD PAGE OF FLOWCHART PRELIMINARY DESIGN – SOURCE: [12]

8 OUTFLANKING AND PIPING SCREENS

Connect : after 1 h
Intake from P.v.E. : - water level differences
- soil condition
Relation to : 1j (abutment walls)

9 ILLUMINATION, MARKING, SIGNALLING, BOARDING, MEANS OF COMMUNICATION

Connect : after 1i
Intake from P.v.E. : - regulations as to that (par. 2.4.8)
- location
Relation to : 1l (lock terrain)

10 BOTTOM LINING AND BANK REVETMENT OF LOCK APPROACHES

Connect to : after 1j
Intake from P.v.E. : - water levels wind waves
- waves and currents, turbulence due to navigation
- intake and discharge flows

11 POWER SUPPLY

Connect : after 9
Intake : - power requirements from 1e, 1k, 1l, 2b, 4 and 9
- connecting possibilities public network
- emergency power requirements
- execution requirements

Note: Sometimes the available power from the public net is the starting point (precondition) for the design and there is no "Connect : n 9"

12 OPERATING SYSTEM (ELECTRICAL INSTALLATIONS, SOFTWARE)

Connect : after 11
Intake from P.v.E. : - process descriptions (par. 2.4.6.1)

Note: Blocks 8 to 12 also end in a PART OF END PRODUCT

FIGURE 60 – FOURTH PAGE OF FLOWCHART PRELIMINARY DESIGN – SOURCE: [12]

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