INNOVATIVE HIGHLIGHTS – RENEWAL OF SÖDERTÄLJE LOCK
by

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Keywords: locks; lock gates; innovations in locks; inland navigation; structural design; mechanical design; duplex steel; segment gates; tainter gates

1. INTRODUCTION

The lock in the Södertälje Canal is situated between Lake Mälaren and the Baltic Sea. It was built in 1924 and with a chamber length of 135 metres and a width of 20 metres; it is the largest lock in Scandinavia. The average differential head is 60 cm.

The construction of a new lock is necessary to meet the growing volume and size of marine traffic. Over the years, not only the amount of shipping has increased but also the size of the seagoing vessels. The new lock will have a width of 25.3 metres and a length of about 170 metres. The renewal of the lock is part of the large-scale Mälaren Project.

The renewal project consists of the extension and widening of the lock chambers, the construction of two new lock heads and lock gates plus a new bascule bridge. The client is the Swedish Maritime Administration and the project is performed by Züblin Scandinavia AB partnering with the client. Design and engineering of the lock heads, including the sluice gates, are performed by joint venture S3P, consisting of the two Dutch engineering firms MH Poly and Iv-Infra.

As requested by the client, a special type of lock gate will be used: a segment (or: tainter-) gate made of duplex steel (a type of stainless steel). This type of gate is rarely used for locks in The Netherlands. Duplex steel is more expensive than regular carbon steel, but it has the benefit that maintenance during the structure life is minimised. The gates are partly circular, rotate around a horizontal axis and are also used for the levelling of the chamber. In addition, the gates can hold water in both directions and can be rotated up and above water level for inspection and maintenance.

Another unique feature of this project is that the lock heads will be built at the side of the existing canal, after which they will be moved to their final position as complete structures. As a result, the canal can, for as long as possible, remain available for shipping during the construction phase.

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**Figure 1: Visualisation of the future Södertälje lock
(Source: Swedish Maritime Administration through Sweco Architects)**

2. Structural and Mechanical Design

2.1.   Tainter Gates

2.1.1   Layout

A tainter gate consists of a leaf gate with arms connecting it to the horizontal axles. The leaf gate has a skin plate formed as a cylinder segment. The 2x2 radial arms connect the leaf gate to the two main axles situated in machine buildings on either side of the lock. At the back of the skin plate, two buoyancy chambers are integrated into the structure. Moreover, the structure is built up with main and secondary girders and stiffeners. The buoyancy chambers ensure that the gate will tend to close automatically, although, for safety reasons, it will be locked in position when opened or closed. The circular shape of the skin has the advantage that the line of action of hydrostatic pressures remains close to the main axles and that the arms can transfer the forces to them by the normal force. End stops integrated in the threshold secure the position of the gate in closed position. To avoid ships damaging the gate arms, a modular fender structure is mounted on the lock head and between the gate arms and the canal.
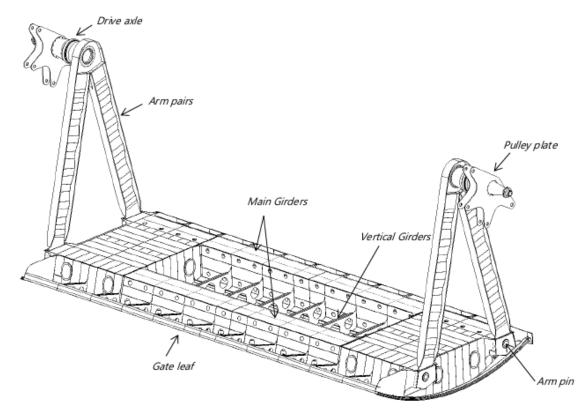
Figure 2: Structural design tainter gate

2.1.2 Buoyancy Tanks

The buoyancy tanks are fatigue sensitive due to the alternating position of the tanks relative to the water surface. This results in severe hydrostatic pressure differences between open and closed positions. Since a direct connection of skin-stiffeners against the tank skins leads to high stresses, they need to be disconnected from the tank plates or placed in line with the internal tank stiffeners. To reduce peak stresses on this type of connection, gusset plates are used.

With regards to fatigue, the internal buoyancy tank stiffeners are critical. The tank skin plates need to be properly supported so that bending stresses near internal bulkheads are kept to a minimum. Standard skin stiffeners like L-profiles or bulb flats have insufficient stiffness and result in poor fatigue life. Hence, continuous stiffener rings are used to support the tank skin plates. On the plates where continuous rings cannot be placed, stiffener plates with soft-toes are applied to minimise stress concentrations.

Manholes of 600x800mm are placed at the side of each tank. This allows for direct access to each tank.

2.1.3 Gate Arm Detailing

A common design approach for tainter gates is a rigid arm connection with the gate leaf and a flexible connection with the drive axles. During the design process, two major issues were found regarding the arm pairs and the connections to the gate leaf and drive axles:

- Due to global deflection of the gate leaf, bending is introduced through the rigid flange connection to the arm pairs. These bending stresses occur every cycle, resulting in fatigue near the flange connection.

- The flexible asymmetric connection of the axles to the arm pairs reduces the drive torque capacity of the arm pairs. The failure mode is a loss of stability. The design of this connection (regarding plate thickness and brackets to aid stability) will be governed by the emergency load cases "single sided drive" and "blockage". To increase stability and enhance the torque capacity of the connection, the plate thickness of the flexible plate needs to be increased and brackets need to be added. However, this eliminates the benefits of a flexible connection.

It can be concluded that the arm-drive axle connection is too flexible, and the arm-gate leaf connection is too rigid for an optimal design. To solve the issues described above, the arm pairs were redesigned. This redesign used a rigid arm-drive axle connection and a flexible arm-gate leaf connection. This alternative design adapts better to global deflections and reduces bending of the arms, improving fatigue life of the bolted connections and arm pair details. The flexible connection between the arm pairs and the gate leaf consists of a pinned connection, which is also helpful from the point of view of installation and maintenance.
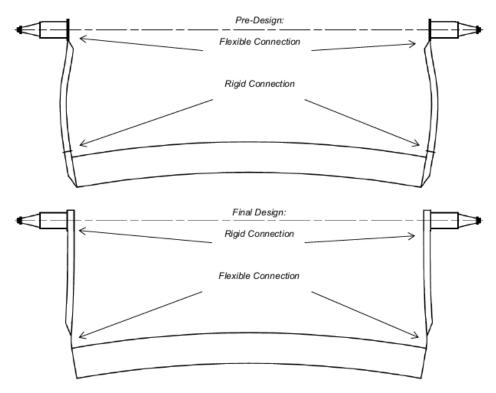

Figure 3: Arm detailing principles

2.1.4 Ship Collision

The sluice gate is checked for a 250t vessel collision at a speed of 1 m/s. The location of the impact, as well as the bow shape of the vessel, have major effects. Reaction forces are high, but local deformations are minimal.

The sluice gate, drive axles, bearing skids and concrete are designed to withstand these reaction forces. If a larger vessel impacts the gate, the weakest link is the pinned connection between the gate leaf and the arms, although the breaking load of the pins is uncertain due to a range in material properties.
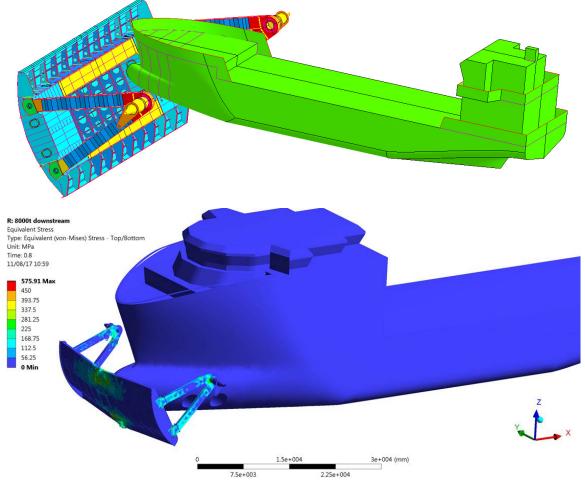

R: 8000t downstream
Equivalent Stress
Type: Equivalent (von-Mises) Stress - Top/Bottom
Unit: MPa
Time: 0.8
11/08/17 10:59

575.91 Max
450
393.75
337.5
281.25
225
168.75
112.5
56.25
0 Min

Figure 4: Ship collision analysis

2.1.5   Main Interfaces and Sealing Design

The interface between the gate seals and their opposite surfaces in the lock head requires specific attention. This is because of the circular shape at the sides and the fact that it needs to be both watertight and durable. While opening, due to the innovative arrangement, the side seals will move away from their contact surfaces instead of sliding along them, limiting friction and wear of the seals. While opening, the gate will temporarily be stopped at 5°, where an indented part of the skin forms a maximum opening to allow the water in the lock chamber to level with the water on the other side of the gate.

The sealing is arranged with rubber profiles on both sides and on the bottom of the closed gate. For the side seals, two mirrored self-activating seals are applied with a nominal (theoretical) compression of 10 mm when the gate is fully closed. The construction tolerances (based on DIN 19704-2) and structural deformations determine the sealing design. For the bottom seal, this leads to a total

compression capacity of 37 mm, with a nominal compression of 20 mm. Because of a relatively large deformation of the slender gate leaf, the contact area of the embedded plate in the threshold is perpendicular to the deformation direction.

Another important aspect is the compression stiffness of the bottom seal. In a closed position, the gate must make contact with the end stops and the bottom seal should be compressed. Both the buoyancy and the drive system are responsible for the forces that compress the bottom seal. For this reason, a double self-activating seal will be applied.

2.3   Drive System

2.3.1   Layout

Each gate is moved by two hydraulic cylinders located at each main axle. The main bearing positioned near the gates arms and a secondary bearing inside the machine building support each axle. Each axle assembly, the pulley plates, the main and secondary bearing, and the drive cylinder are integrated on one skid, which can be positioned and aligned in the desired position and direction, both at the start of the project and if necessary, adjusted in a later stage. This ensures that any eventual settlements over time will not lead to unnecessary high stresses, friction and wear in the main bearings.
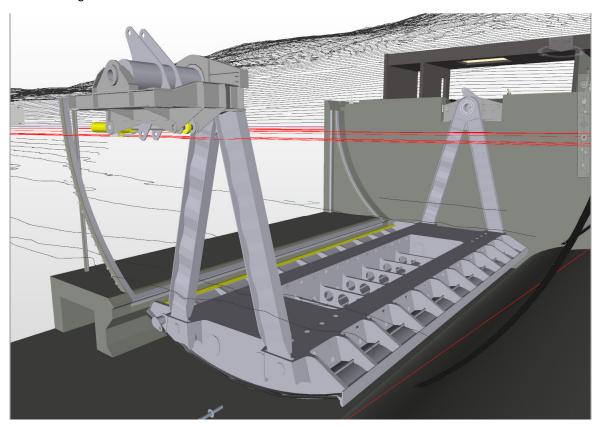

Figure 5: Gate and gate arms relative to drive system

2.3.2   Gate Positions

On each side of the sluice head, the tainter gate is equipped with a hydraulic cylinder to move the gate. These cylinders are connected to pulley plates and are welded to the gate axle. In the closed

position, the gate has an angle of 60 degrees to a vertical axis. In the opened position, this angle is 0 degrees. The position of the lock is regulated by the cylinders. A locking pin in an oblong hole in the pulley plates secures the position of the gate in both positions.
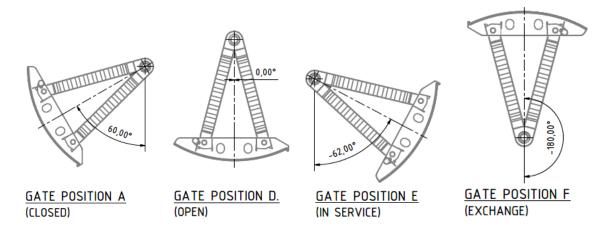

Figure 6: Gate positions (excl. position -120^0, in service)

For maintenance, the design allows for two gate positions. At an angle of -62 degrees the bottom seal is maintainable. By replacing the cylinder to another hole in the pulley plates, this position can be reached and locked with the locking pin. To put the gate with buoyancy tanks back into open position, the cylinder drive will be needed. For a complete inspection of the gate leaf and arms, a gate angle of -120 degrees is foreseen. Because of the weight of the structure without buoyancy, a mobile crane is needed to lift the structure. An additional support frame in both gate recesses can be rotated to support the structure vertically.

In vertical position (-180 degrees) the gate arms and gate leaf can be mounted and replaced if necessary. An extra gate leaf and a pair of gate arms will be fabricated and stored on site to increase availability in the case of major damage to the structure. The design also provides a second locking pin for this gate position.

2.3.3 Integrated Drive Skid

In the machine room, several mechanical components for the driving of the gate are foreseen, such as the bearings, hydraulic cylinder and two locking pins.

For the following reasons, a steel structure with all mechanical components included (drive skid) is designed to improve manageability of several interfaces.

- Avoids strict tolerances for all separate connections to the concrete structure.

- Provides optimal adjustability of the gate axles. The skid is supported is such a way that by customising the shim plate thickness, the axles can easily be aligned. This is important to be able to allow for any future movements of the sluice head due to settlements.

- Optimises transfer of loads. The forces generated by the drive cylinder must be in balance with reaction forces on the bearings. Embedded structures and local

reinforcement in the concrete structure are optimised when forces are internally transferred through the skid.

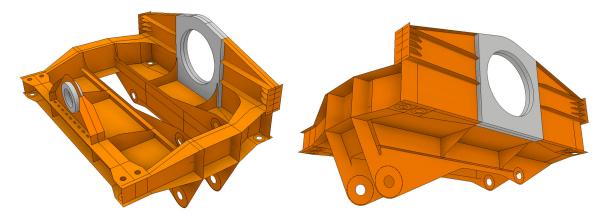- The drive system can be tested anywhere with several advantages.

Figure 7: Drive skid

2.3.4   Material Choices Drive System

Rather than a bronze bushing, a composite bushing has been chosen for the bearings. The lower stiffness of the composite material results in better stress distribution. The bearings will be placed in two parts meaning that both parts can be rotated should there be an occurrence of wear. Maintenance and replacement of the main bearings can be carried out in the machine room thanks to a separate watertight shield on the outside of the sluice head wall. In the design, a possible replacement of the gate axle from inside the machine room has also been taken into account.

Both the drive skid and the watertight shield will not be executed in stainless steel. The drive skid will never be in contact with water due to the presence of the watertight shield. The watertight shield is removable by use of a temporary shield which is situated between both structures.

The gate arms are connected to the main axles with a bolted connection. The main axle is supported by two bearings: the main bearing and a secondary bearing. To limit fatigue, loading a proper alignment of the bearings is required. This is crucial for the durability of the steel structures.

2.3.5   Fatigue analysis

The gate arms and axles are loaded by cyclic loading thus fatigue is a potential risk. The fatigue analysis needs to consider gate movements, drive forces and hydraulic loading. For each opening cycle, the buoyancy of the gate leaf results in bending moments in the gate arms and local bending in the buoyancy tanks.

For each opening cycle, a water level difference must be taken into account, including the dynamic forces due to levelling. In addition, the possible misalignment of the gate axles is considered in this analysis. Fatigue analysis is performed with a misalignment of 10mm for each support. The actual alignment of the gate axles will be measured during the inspection, mainly during the period when settlements of the sluice head are expected. The skid (including the gate axles) will be adjusted if necessary.
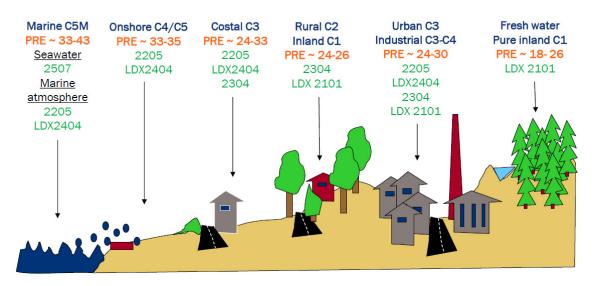
3. DUPLEX STEEL GATES

3.1   Material Selection

Contrary to common practice worldwide, the client, Sjöfartsverket, proposed a type of lean duplex rather than carbon steel as a base material for the lock gates and bridge. Although this material is more expensive than carbon steel, it has the advantage that an additional corrosion protection system would not be needed, which has a positive effect on maintenance costs and time. Various grades of stainless steel materials are available, each with different corrosion resistance.

Figure 8: Where to use which duplex grade

Corrosion resistance of stainless steel materials (Austenitic and/or Duplex Stainless Steels) is influenced by the following factors:

- Pitting resistance of selected material grade (PREN)

- Environmental conditions (presence of water, chlorine and other contamination, temperature)

- The effect of fabrication methods (welding and cold forming, flame straightening) on the stability of the microstructure

- Applied improvements of the fabricated finish

In the case of the Södertälje lock gates, the main driving factors influencing the choice of material are the submersion in brackish water and the risk of deposits and/or accumulation of contamination containing salts and bacteria in the open areas. Available materials vary with respect to the provided PREN (pitting resistance equivalent number) and CPT (critical pitting temperature), which both need to be considered. Eventually, Grade UNS S32205 / EN 1.4462 was selected for the lock gates. For optimal corrosion protection, aluminium anodes will also be applied to the gate.

3.2   Effects of Material Choice on Fabrication Methods

Welding affects the corrosion resistance of the applied material. As corrosion resistance is generally reached through a proper range for the austenite-ferrite ratio (phase) of the material, incorrect welding parameters and improper cooling rates can have a negative or even detrimental influence. A proper base material has a 50%/50% phase balance (A/F). To be able to properly weld, or apply other heat treatments (e.g. plasma cutting, preheating, flame straightening), specific attention needs to be payed to the heat input in relation to the thickness to avoid slow cooling rates and formation of detrimental phases such as Sigma phase. The welding parameters and welding conditions should be optimised to ensure a 40%/60% (A/F) phase balance in the heat affected zone. While in principle, all known welding processes can be used and appropriate welding consumables are available, specific welding qualification samples must be made for each specific grade and range of thickness and welders must be trained and qualified to reproduce these. All heat affected surfaces will require a good surface finishing followed by pickling and passivation.

In addition to heat treatments, cold deformation potentially also has a negative influence on the corrosion resistance. This is due to the phenomenon that an austenitic phase causes martensite at high deformation grades. In the design, specific attention is given to the extent of cold forming, the locations where it is applied and the presence of welds in these regions.

Fumes of (dry) plasma-cutting and welding of Stainless Steels is dangerous for the health of operators, welders and environment because of Cr6. Therefore, extraction of fumes and fresh air helmets for welders are required.

3.3   Fabrication Requirements for Use of Duplex Steel

There are specific requirements when building according to Eurocode and when using specific materials for construction. For this, a project specific fabrication specification had to be drawn up. This specification describes the specific coded requirements that need to be met when building with the prescribed materials for the structure. This Specification summarises the additional requirements for fabrication and assembly of the bridges, lock gate structures including related components and lists additional requirements based on SS-EN 1090-2, the National Annex (BFS 2015-6) as well as the contractor's requirements.

Several highlights of this specification are (the list is not complete).

- The fabricator, or his authorised representative established within the European Economic Area, is responsible for the affixing of the CE marking.

- Maximum carbon content and carbon equivalent (CEV) for weldability of carbon steels.

- Weldability properties, to be demonstrated by representative tests, which are to be executed on the maximum supplied thickness and for the lowest and highest anticipated heat input used during fabrication welding.

- Material testing requirements for through-thickness testing, ultrasonic examination, notch toughness, tensile, hardness and bend testing, Charpy V-notch testing,

examination of the micro-structure shall over the full thickness for detrimental phases and intermetallic phases near the centreline, the presence of pitting and weight loss, intergranular corrosion tests.

- Demonstration of weldability properties by representative fabrication welding conditions for both minimum and maximum product thickness and for each delivery source.

- Requirements with respect to the chemical composition of materials.

- Thickness tolerances and surface conditions.

- Requirements with respect to identification and traceability of essential fabrication history.

- Avoidance of contamination; requirements for lifting equipment and other tools.

- Requirements and test methods with respect to the applied heat straightening procedures and for cold deformation.

- Qualification of welding procedures and welding personnel.

- Processes to perform welding procedure qualification tests and ferric chloride corrosion tests.

- Requirements with respect to precautions for pre-heating, welding, cooling down after heat treatment, cleaning, blasting, pickling and Non-Destructive Testing (NDT).

4. INTEGRATED 3D MODELLING, STRESS ANALYSIS and BIM

For the structural analysis of the leaf gates, a direct link between 3D modelling software Inventor (used to generate drawings) and FEM analysis software, established Ansys Workbench. The FEM model was generated from the 3D design ('surface') model and any required changes and optimisations found in the structural analysis were fed back into the 3D model. This way the drawings are automatically consistent with the structural analysis, optimising time and quality.

To be able to do this, however, the model created in Inventor does not include the thickness of the materials, which is why it is called a 'surface model'. The final thicknesses as determined in the FEM analysis must be modelled in the 3D design, turning it into a 'solid model'. From this solid model, 2D drawings can be generated. The solid model can also be used as input to the Building Information Model (BIM) in which all the available building information can be integrated and all interfaces are made visible.
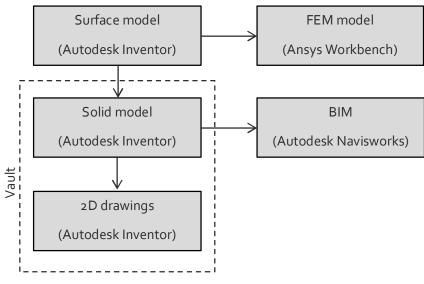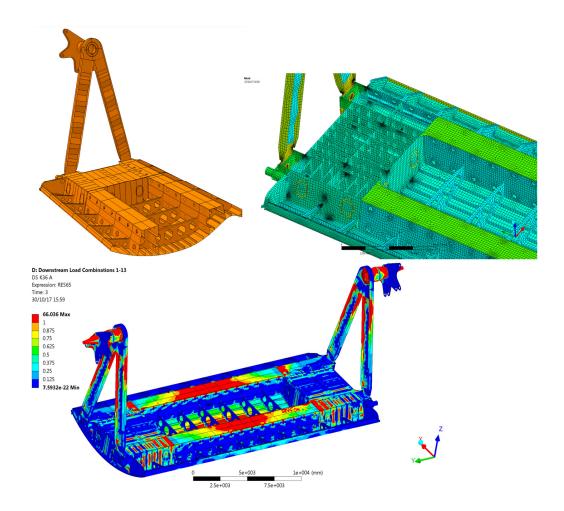

Figure 9: Modelling process

Figure 10: 3D model in inventor and FEM, mesh generated from it in Ansys Workbench and stress plot after FEM analysis

For the FEM analysis of details, such as the analysis of critical weld details, it is required to 'zoom in' and thus apply a finer element mesh. In Ansys Workbench it is possible to break a FEM model into sub-models or the reverse; combine separate detailed models generated by Inventor. These blocks are then analysed separately, each with their own model, but linked to each other by the overall geometrical environment. Since they are all linked, the data generated in separate blocks is automatically used by the other blocks.

In addition to the linking of models and sub-models, separate analysis types, such as linear, dynamic and elasto-plastic (collision) analyses can also be linked. Thanks to this structure, the overall design process is parametric and has a high level of integration. This allows for flexibility while designing and optimisation of the design.
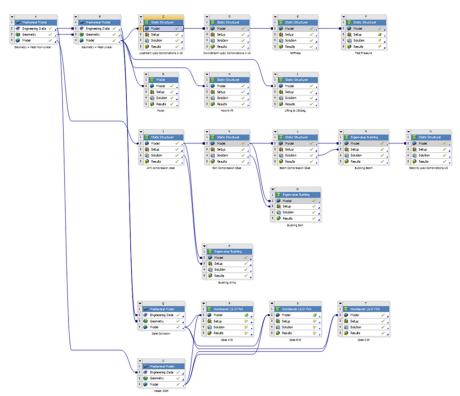
Figure 11: Process of FEM model integration

5. Construction Method

To allow ship traffic to continue during most of the construction phase, the lock heads are constructed in building pits at the side of the canal. Construction of the lock heads is thus carried out in dry conditions. The interface areas for the gate seals consist of embedded duplex steel and are prepared in a 2nd stage concrete cast so that they can meet the stringent geometrical tolerances required for such areas. Mock-up tests with the drive system and with dummy structures for the seals will be also carried out in these dry conditions.

The original plan was to move the lock head from the construction pit to its final position by skidding, but after an evaluation of schedule, risks and costs, the alternative, based on floating was chosen. When the lock head is in place, it will be temporarily supported by four jacks at the corners. Hereafter, the gap between the bottom of the canal and the lock head will be filled up with concrete. Moving and sealing the lock heads in their final position is to be carried out within a maximum of one week for each.

Building on top of the footprint of an already present lock and dealing with surrounding existing buildings and infrastructure means that the surrounding buildings, temporary structures and new structures which add to the lock function itself, like the bascule bridge, the moveable walkway and the machine buildings, all require specific attention to interfaces. There are many situations where interference can be critical, which requires the various design teams to work together seamlessly.

6. RISK MANAGEMENT

7.1   General

During the design process optimisations and possible risks were investigated. Maximal availability leads to a support system of the openable walkway (double rolling bridge at the upstream sluice head) without a support on top of the closed gate.

Natural frequencies are calculated by means of modal analysis using different amounts of added mass in various directions. Cylinder stiffness is included in this analysis and has a large contribution to the result. The rotational natural frequency range is between 0.25Hz and 0.55Hz. From the quasi-static CFD analysis, frequencies within this range are found. Due to the damping of the surrounding water and the non-linear spring characteristic of the cylinder, it is expected that resonance will not occur. For this reason, the design of the drive system is based on a larger hydraulic cylinder, with good damping properties and a higher capacity than minimally required cylinder diameter.
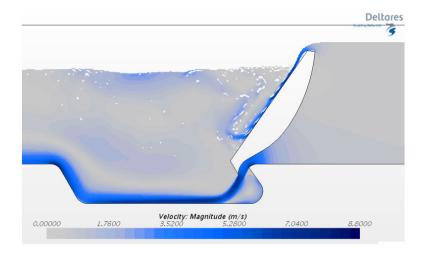

Figure 12: CFD-study

7. CONCLUSION

For the renewal of the lock in the Södertälje Canal, several innovative and state of the art design strategies, as well as construction methods, have been used.

During the design process, the integration of 3D surface models and FEM models allows for a high level of flexibility. Integration of the main axles and the drive cylinders on integrated skids, allows for a quick construction and adjustability when the positioning of the lock head changes over time due to settlements.

The choice for a duplex steel as a material for the gates and main axles is a relatively new approach to allow for lower maintenance costs and higher availability of the lock during its life. To be able to do so, however, specific precautions are to be taken in the manufacturing process.

Constructing the lock heads at the side of the existing canal and moving them to their final position as complete structures allows for a high level of availability of the lock during this large-scale renewal project.

In 2021 the new sluice will be opened. The design of the stainless steel tainter gate will be an interesting example for future sluice designs.