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LEVELLING THE NEW SEA LOCKS IN THE NETHERLANDS; INCLUDING THE DENSITY DIFFERENCE

#103

Wim Kortlever[1], A.J. van der Hout[2], T. O'Mahoney[3], A. de Loor[4], T. Wijdenes[5]

ABSTRACT

In the Netherlands two deep sea locks are being built, one at IJmuiden and one at Terneuzen. Since these locks maintain the transition between the fresh water in the canal and the salt water in the outer approach, density currents will occur in the lock during levelling. When designing the levelling systems of the new locks the additional forces on the moored vessel caused by these density currents have been taken into account. Extensive scale model studies have shown that for the IJmuiden Lock a system with openings in the lock gates is possible and safe, while for the Terneuzen Lock a more complex system is needed which fills and empties the lock through separate grids in the lock floor.

1 INTRODUCTION

To allow larger sea-going vessels to call in at the main ports of Amsterdam and Ghent, two deep sea locks are being built, the New IJmuiden Lock and the New Terneuzen Lock. The realization of the New IJmuiden Lock started in September 2016. According to the original planning the lock will be opened around the end of 2019. The New Terneuzen Lock will be built in the years 2017 to 2022.

This paper describes the design process which was followed to come to the reference designs of the lock levelling system that is safe for the vessels and at the same time allows for a short levelling time.

The IJmuiden locks are in the northwest of the Netherlands, at the entrance of the North Sea Canal, the canal which connects the Port of Amsterdam with the North Sea. The Terneuzen locks are in the southwest of the Netherlands, at the entrance of the Ghent-Terneuzen Canal, the canal which connects the Port of Ghent with the Western Scheldt Estuary and the North Sea. At both locations the new lock is built next to the existing lock for sea-going vessels. These two locks are the North Lock in IJmuiden and the West Lock in Terneuzen.

Firstly, in the next sections, the design and functioning of the levelling systems of the two existing locks are shortly examined, to find the reasons for choosing the specific type of levelling system. The North Lock uses short culverts in the lock heads, whereas the West Lock uses a bottom filling system. In the following section the design approach for the new locks is drawn up, which includes both numerical and scale modelling. In the last sections the resulting reference designs for both new locks are described following this design approach.

Principally, the choice of a type of levelling system is determined by the maximum head difference, the required levelling time, main vessel dimensions and mooring configurations. Since these locks maintain the transition between fresh (brackish) and salt water, density currents in the lock during levelling lead to additional hydrodynamic forces on the moored vessel. Therefore, this density effect must be included when engineering the levelling system.

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[1] Hydraulic Engineer, Rijkswaterstaat, Ministry of Infrastructure and Water Works, The Netherlands, wim.kortlever@rws.nl
[2] Researcher/consultant, Deltares, The Netherlands
[3] Researcher/consultant, Deltares, The Netherlands
[4] Researcher/consultant, Deltares, The Netherlands
[5] Hydraulic Engineer, OpenIJ, The Netherlands

2 IJMUIDEN NORTH LOCK

The North Lock was built in the nineteen twenties. The lock chamber is 400 m long and 50 m wide. The sill lies 15 m below mean sea level. At IJmuiden the head difference when levelling varies between about 4 m and -1.5 m. As the maximum head difference during mean springtide varies between only 1.6 m and -0.3 m, differences during normal conditions are relatively small.

The design of the levelling system for this lock was based on the designs of the German sea locks built at that time. A scale model study was carried out in Germany to study the behaviour of several levelling systems considering different culvert lay-outs (Ringers, J.A. and Josephus Jitta, J.P.,1927). In these model tests the density difference was not considered. Based on the test results, a system with short culverts in the lock heads was chosen (Figure 1). Levelling through gate openings was regarded as not feasible, mainly because of the impact on the steel construction of the gate, but also due to the expected flow forces on the moored vessel in the lock.

While the size of the vessels has increased by a factor of two (maximum blockage ≈ 0,8) since it was constructed, the levelling system works satisfactorily.

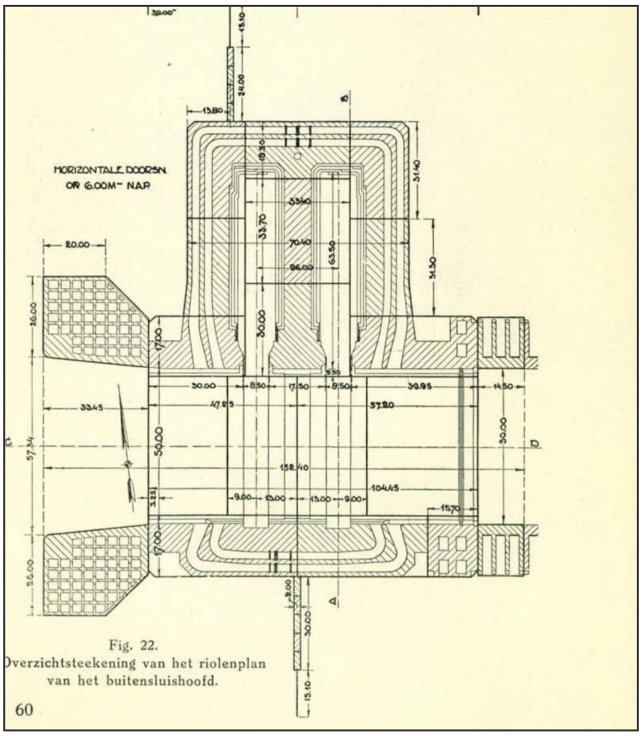

Figure 1: North Lock Outer Head: Horizontal Section of Short Culverts

3 TERNEUZEN WEST LOCK

The outlines of the West Lock, which was built in the nineteen sixties, are shown in Figure 2. The lock chamber is 355 m long and 40 m wide. The sill lies almost 13 m below mean sea level. The water level on the canal is about 2 m above mean sea level. The head difference when levelling varies between 1.5 m and -4.8 m. Compared to IJmuiden the daily maximum absolute value of the head difference is considerably larger, 4 m versus 1.4 m, corresponding to a mean water level on the canal of 2.1 m and mean low tide of -1.9 m outside.

Taking into account these higher head differences, it has been decided to fill and empty the lock through two bottom grids, located at about one quarter and three quarters of the chamber length (Philpott, K.L., 1961). By distributing the discharge over these two grids, the resulting translatory waves are significantly reduced, and the corresponding forces as well. This concept was originally worked out without considering the density effects. However, when this system was tested in a scale model, in a later phase also including a density difference, it showed that the density forces did not lead to extra-long levelling times. Not only the translatory waves are significantly reduced, but also the density currents. In practice, the levelling system at the West Lock has proven to be safe and reliable.

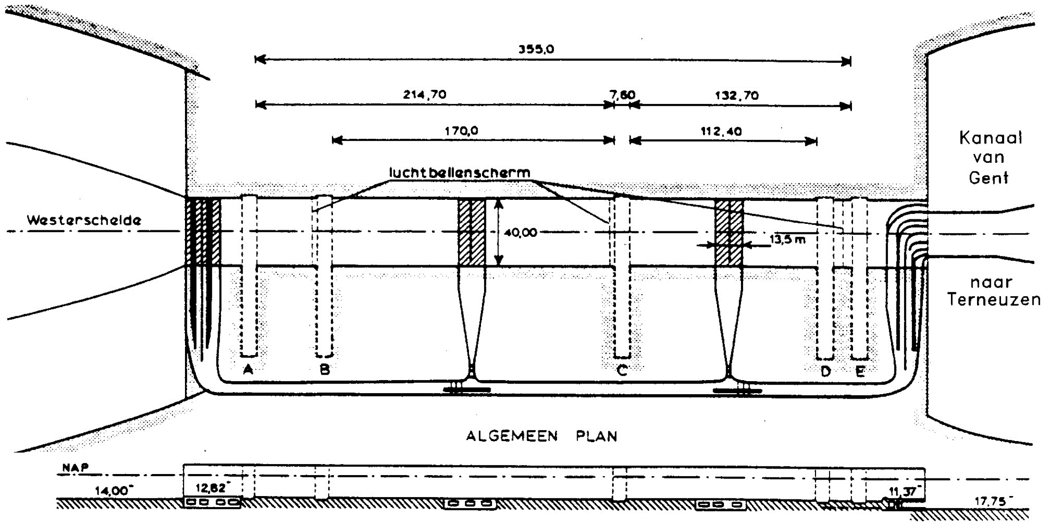

Figure 2: General Plan West Lock: Two Bottom Grids Centered Between Inner Gates

4 GENERAL DESIGN APPROACH

4.1 Choosing the Type of Levelling System

Several large sea locks have a levelling system which consists of short culverts in the lock heads, with culverts built around the gate recesses and culvert in-/outlets in the lock walls, like the IJmuiden North Lock and the Belgian locks with special outlets just above the lock chamber floor (Berendrecht, Kieldrecht). A through-the-gate filling system with openings or ducts in the gate, which is the most common for inland navigation locks, is the most simple system. Because of both the relatively high flow forces on the moored vessel and the impact on the gate structure, this system is less common for large sea locks (Kaiserschleuse, Zeebrugge). A more complex system is the longitudinal system, with culverts along the entire lock chamber and well distributed outlets or ports along the chamber wall or floor. This type of system has been chosen for the old and new locks at the Panama Canal. The levelling system of the Terneuzen West Lock is also a longitudinal system, but the outlets in the lock chamber are concentrated at the two bottom grids.

It is a well-known fact that for relatively low head differences and long levelling times a through-the-gate system may be sufficient. Although the lock is filled or emptied from one side the hydraulic forces on the vessel stay within acceptable limits. Compared to this gate system, a system with short culverts may be hydraulically advantageous when the jets from the outlets in the wall collide and lose their energy. However, using short culverts still means that the lock is filled or emptied from one lock head, leading to fluctuating water slopes along the chamber. Thus, short culverts are also only applicable for limited head differences. An important difference between a through-the-gate system and short culverts is the combination of functions when using the gate system, which may have consequences for the availability and maintenance of the gates. In the case of high head differences and/or short levelling times, a longitudinal system may be considered.

As the daily maximum head difference for IJmuiden and Terneuzen is 1.4 m and 4 m respectively, and the acceptable levelling time is about 15 to 20 min, the starting point for the design of the new locks was a through-the-gate system or short culverts.

4.2 Dimensions and Vertical Position of the System

If the lock chamber is filled or emptied at the lock head, through ducts in the gate or short culverts, the total cross-sectional area of these ducts or culverts can be determined by using the one-dimensional flow-force model LOCKFILL (Deltares, 2015), which includes the translatory waves, the effect of the jets and the force component due to the density currents (stratified flow). It has been assumed that the incoming flow from the ducts or outlets is well distributed over the width of the lock chamber. The chosen dimensions of the system and the valve opening program determine the flow curve and the levelling time. On the basis of this flow curve, LOCKFILL calculates the longitudinal hydrodynamic force on the vessel in the lock. The valve opening program is adjusted, resulting in a different flow curve, until the maximum hydrodynamic force meets the force criterion. The additional result is the attainable levelling time. As long as the force curve stays below the criterion, the levelling time may be shortened further by increasing the dimensions of the system.

A similar approach can be followed when choosing a longitudinal culvert system. First, after the dimensions and culvert losses (inlet, valves, bends, junctions, friction, outlet) have been estimated, the nonstationary flow through the culverts is calculated by using a one-dimensional flow model for nonstationary flow and pressures in closed conduits, e.g. WANDA (Deltares). The inflow in the lock will not only depend on the total resistance of the system but also on the inertia of the water in the system. Second, WANDA may be combined with a one-dimensional model for the flow in the lock chamber. With this combination, accounting for the blockage of the vessel in the lock chamber, a first estimate can be given of the water slopes in the chamber and the resulting horizontal forces on the vessel. As for filling, the effect of the density difference is not included.

Mostly, at the end of levelling, the gate is opened when the flow through the levelling system has decreased and the water level difference or the residual forces on the gate are below a certain threshold. However, when there is a density difference between the outer and the inner lock approach, the water level difference at the end of levelling will be determined by this density difference and the level of the openings of the levelling system. Naturally, the levelling stops when the pressure difference at the level of the gate openings or between the culvert inlets and the outlets is close to zero. Figure 3 shows the equilibrium state, with no flow.

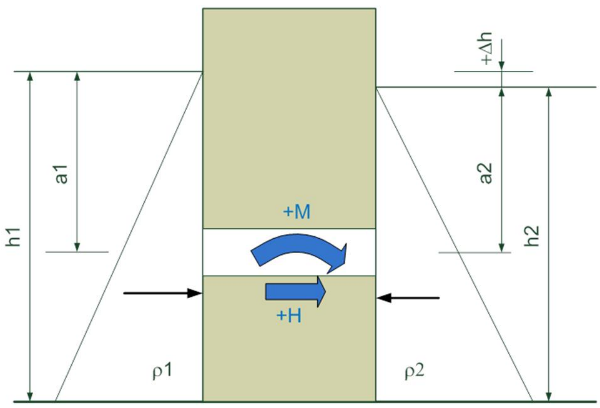

Figure 3: Water Level Difference at Equilibrium State; No Flow Through Openings

The water level difference is determining for the residual moment and horizontal force on the gate at the moment that the gate opening starts, and thus has an impact on the gate stability, the capacity of the gate opening system and the friction on the gate supports. Also, when opening the gate, the level difference can cause a translatory wave propagating into the lock chamber which exerts a short-lasting force on the vessel in the chamber.

It can be shown that both the residual horizontal force on the gate and the incoming translatory wave will be minimal if the level of the openings or the culvert in-/outlets is located at half the water depth at the end of levelling. It also follows that for a longitudinal levelling system with ports or outlets just above or in the chamber floor, one should take into account a larger level difference and higher residual forces on the gate. The drawback of a higher level of the openings or outlets in the chamber, when the vessel is moored close to the active gate, is the relatively high level of the incoming jets and the subsequent higher flow forces on the vessel. Balancing the forces on the gate, the incoming translatory wave and the flow forces on the vessel may lead to the choice of an intermediate location of the levelling openings, between half the water depth and the lock floor.

4.3 Hydraulic Design

When the layout and main dimensions of the levelling system are known, the next step is the hydraulic design, i.e. the streamlining and shaping of the system, especially the culvert systems. This is done on the basis of two-dimensional and three-dimensional flow models in CFD (Computational Fluid Dynamics), including turbulence, e.g. STAR-CCM+, Fluent, OpenFOAM. For a culvert system, it is possible to study a number of different culvert shapes by assuming stationary flow conditions, and neglecting any free water surface (‘rigid lid’) and the density difference. In the larger models the levelling system is combined with a part of the lock approach and the chamber. A vessel is not included. Attention has to be paid to the flow conditions in the culverts or ducts, the detachment points of the flow and the distribution of the incoming flow over the cross-section and length of the chamber. In this way, the loss coefficients of all specific parts of the system can be determined.

Using the more accurate loss coefficients resulting from the CFD, the LOCKFILL or WANDA one-dimensional calculations of the levelling process, which is nonstationary, can be repeated for a better prediction of the flow curve and the levelling times.

The hydraulic design is not always fully optimized, because of the interface between the hydraulic design and the steel or concrete structure of the gate or lock. Especially in the Netherlands where the lock is often not built in a dry building pit and lock walls are constructed with combi-walls or diaphragm walls there is usually a trade-off between the hydraulic design and the structural design.

4.4 Density Currents

It is emphasized that, when there is a density difference, density currents will develop in the chamber during levelling, and the entire flow pattern in the lock may be different. Because of the additional forces due to the density currents the maximum hydrodynamic force on the vessel will be larger than without the density difference. Additional longitudinal and transverse forces on the vessel will develop due to differences in stratification between fore and aft, and between port and starboard. It is advisable to carry out a CFD simulation of the density currents in the chamber for a first indication of the flow pattern. An example of the calculated flow through a gate with a density difference is shown in Figure 4 (De Loor, A., and O’Mahoney, T., 2014).

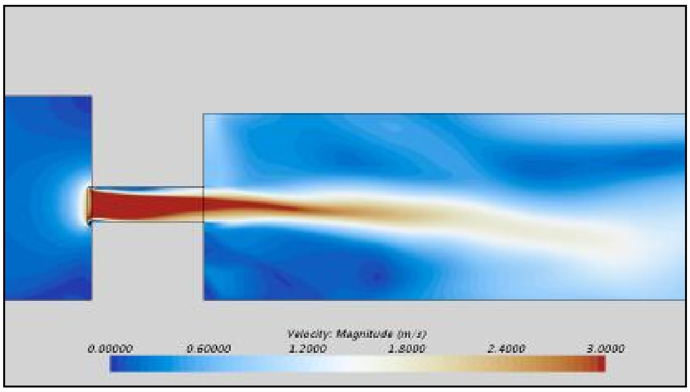

Figure 4: CFD Simulation, Flow Through Gate Ducts, Valve Fully Open, $\Delta\rho$ = 20 kg/m^3

Apart from levelling, when the density difference is large and the lock gate is opened to either of the sides, the water in the chamber starts to exchange with the water in the approach. These density or exchange currents are characterized by a fresh (brackish) water flow at the surface and a salt water flow below (stratified flow). Fresh water in the chamber will be exchanged for salt water from the outer approach, or salt water in the chamber will be exchanged for fresh water from the inner approach. The time needed for a full exchange is determined by the density difference and the length and the depth of the chamber. For the IJmuiden North Lock (Figure 5) the time needed for a full exchange is about 20 minutes. The exchange current will be delayed when a vessel with a large blockage is in the lock. When the gate has opened at the sea side, the outflow of fresh water from the stern is obstructed by the vessel. Thus, for a long time salt water is at the bow and fresh water at the stern (or vice versa). This condition creates a longitudinal force on the vessel, directed towards the sea side, and a transverse force, directed to the central axis of the lock, for a certain time (10-30 min for long locks).These forces will probably be higher than the forces due to the filling and emptying process.

Figure 5: Lock Exchange at the North Lock; Fresh Water Flowing out of the Lock

4.5 Scale Model

The layout, the dimensions and the shapes of the levelling system can be determined based on the results of the numerical models. However, it is recommended that for nonstandard locks the design of the levelling system is validated in a scale model of the lock, because in such a physical model all hydraulic phenomena may be included. In a numerical simulation it is practically not yet feasible to combine the nonstationary flow in the lock chamber, possible density currents, the rising or falling water level and the vessel present in the lock.

The locks and the levelling system for the Panama Third Set Locks had been built on a scale of 30 to 1. The effects of the density difference and density currents were not included. More recently, the new sea locks of IJmuiden and Terneuzen have been built on scales between 40 to 1 and 30 to 1. In these models the density effects are included. Given these scales, scale effects, which are related to the larger influence of the viscosity, are expected to be limited, when compared to the prototype.

The scale model that is used for the new locks of IJmuiden and Terneuzen is shown in Figure 6 (Nogueira, H.I.S., et al., 2018, Van der Hout, A. et al., 2018).

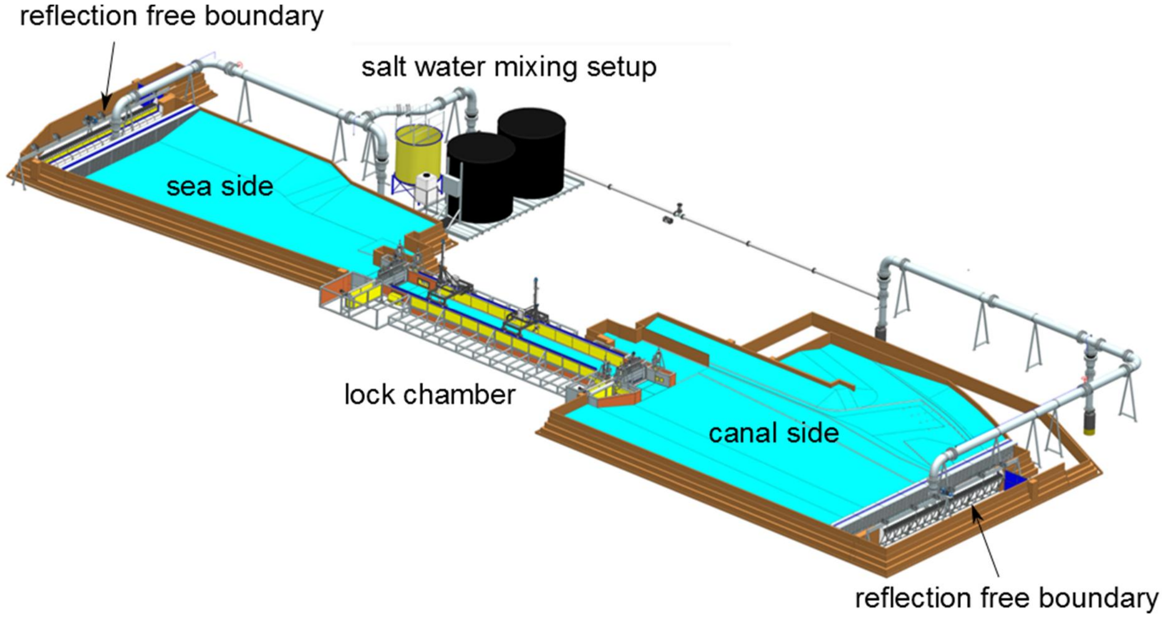

Figure 6: Scale Model Design IJmuiden Lock and Terneuzen Lock

The zigzag weirs at the model ends are used to adjust the water levels in the lock approaches. To avoid reflections of the translatory waves a constant flow is maintained over the weirs by using an adapted pipe system. The approaches in the model have been made approximately 600 m long (40 to 1), to avoid the disturbance of the measurements by the reflected density waves. To establish a density difference over the lock, the density of the water in the outer approach can be increased by mixing fresh water with brine.

Main parameters which are measured during the model tests: (1) water level; during levelling the water slopes in the chamber are a measure for the forces on the vessel, (2) water density; the density forces on the vessel are primarily determined by the differences in stratification between the sides of the vessel, between bow and stern, and between port and starboard, (3) force; the longitudinal force and the transverse forces on the bow and the stern of the vessel are measured, and the yawing moment can be derived from the transverse forces. The vessel is held still in the lock such that displacements in the horizontal plane are prevented.

In the scale model both the nonstationary levelling process and the lock exchange following after the opening of the gate can be simulated.

4.6 Hydrodynamic Force Criterion

In reality, the mooring lines have to withstand the hydrodynamic force on the vessel. When the forces in the lines become to high, the displacements of the vessel will be too large and the lines may break. In order to avoid this situation, the hydrodynamic force during levelling has to be lower than a certain force criterion. This force criterion is used to evaluate the results of the scale model tests.

Moreover, the mooring lines have to be handled to account for the vertical displacement of the vessel during levelling. If the lines are not slacked, then the forces in the lines due to the vertical displacement alone may already be higher than the maximum allowable force in the line. To evaluate the effect of different line handling scenario's and the changing water level on the line forces and the vessel displacements, numerical simulations have been carried out with a dynamic model, using the measured hydrodynamic force from the scale model as input (Rietveld, M.W.J., et al., 2016).

This dynamic model, called SCHAT, simulates the vessel movement and the forces in the mooring lines for a given input hydrodynamic force. For different head differences these line forces and the displacements of the vessel have been compared with the threshold values that were determined in advance. Thereby, not only different handling scenario's which were based on information received from the pilots, but also different mooring line configurations, line types and winch capacities have been considered.

5 NEW LOCK IJMUIDEN

5.1 Introduction

The reference layout of the new lock is shown in Figure 7. The entrance from the sea is on the west side, and the North Sea Canal to Amsterdam is on the east side. In this layout, the lock head at the sea side has two rolling gates, and the lock head at the canal side has one. The gate recess of the eastern gate in the western lock head is used as a maintenance dock. In the final design made by the contractor this maintenance dock has been removed to the canal side of the lock chamber.

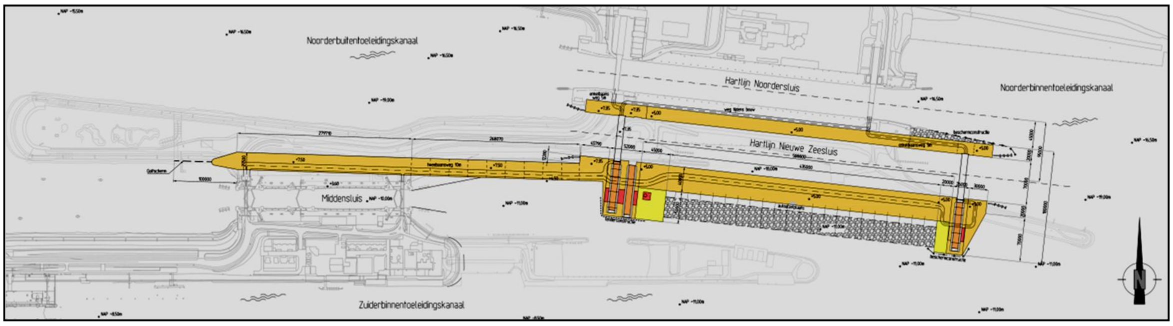

Figure 7: Reference Layout

The new lock chamber which is now under construction will have the following dimensions:

- Chamber length between outer gates: 545 m.
- Overall chamber width: 70 m.
- Sill level: NAP – 17.25 m (NAP: Amsterdam Ordnance Datum).
- Chamber floor level: NAP – 17.75 m.
- Design vessels: bulk carrier: Loa x B x T = 330 x 52 x 19 m, container vessel: Loa x B x T = 366 x 52 x 14.5 m.

The maximum allowable vessel draft in salt water is 13.75 m, due to canal restrictions.

Characteristic water levels:

- Mean high tide: NAP + 1.01 m (mean spring: NAP + 1.16 m).
- Mean low tide: NAP – 0.68 m (mean spring: NAP – 0.72 m).
- Lock closed when sea side above: NAP + 3.90 m.
- Lock closed when sea side below: NAP – 1.65 m.
- Target water level North Sea Canal: NAP – 0.40 m.

The maximum head during levelling, with the sea at high water and the canal at low water, is 4.95 m and the minimum head, with the canal at high water and the sea at low water, is -1.75 m.

The maximum water density difference between the approach harbours is about 20 kg/m^3. The average density difference may be estimated at 14 kg/m^3.

5.2 Type of Levelling System

While creating the reference design of the new lock, two types of levelling system were considered: a system with ducts and valves in the rolling gates and a system with short culverts in the lock heads. At the time of the construction of the North Lock it was not considered feasible to level with openings in the gates, because these openings would weaken the gate structure too much. Also, it was expected that during levelling the flow forces on the vessel in the lock might be too high. Now, based on the current state of knowledge in gate construction and lock hydraulics, and considering the daily maximum head difference of about 1.4 m, both options seem possible.

As mentioned before, hydraulically, the system with ducts in the gate and the system with short culverts are comparable, because the lock is filled or emptied from one side, leading to fluctuating water slopes along the chamber. The short culverts may be advantageous when the jets from the outlets in the wall collide and lose their energy. Being comparable, it was assumed that the development of the density currents during the levelling would not lead to a different behaviour between the two types of system. Therefore, it was likely that the levelling times of the gate system would only be longer to some degree than if short culverts were applied.

5.3 Dimensions and Vertical Position

For both types of system, ducts in the gate and short culverts, the initial one-dimensional LOCKFILL-calculations have resulted in a total cross-sectional area of 80 m^2: twelve gate ducts of b x h = 2.2 m x 3 m or four culverts (two on the south side, two on the north side) of b x h = 4 m x 5 m (Jongeling, T.H.G., 2014). To limit the residual horizontal force on the gate and the translatory wave, when opening the gate, it has been decided to put the ducts and in-/outlets near NAP – 8.5 m, halfway the mean water column of 17 m.

5.4 Hydraulic Design

Based on these dimensions of the levelling systems, a number of alternatives for the layout of the culvert system have been considered. At the sea side head, it is impossible to build the south side culverts around the gate recesses, due to a lack of space. It is regarded as not feasible to pass below these gate recesses, because of the soft soil conditions. As a consequence, all four culverts pass the gate on the north side of the gate (Figure 8). Two culverts come out into the chamber through the north wall, and two culverts cross below the chamber floor and come out into the chamber through the south wall. At the canal side head, two culverts pass the gate on the north side of the gate, and two culverts pass through the gate recess (Figure 8), comparable to the inner head of the existing North Lock.

The shaping and streamlining of especially the culvert system has been done on the basis of flow models in CFD, with STAR-CCM+ (De Loor, A. and O'Mahoney, T., 2014). The design of the north side culverts was adapted to decrease the difference in loss coefficients between the short north side culverts and the longer south side culverts. The culvert inlets in the lock chamber were enlarged to reduce the flow velocities and improve the flow distribution at the foremost position of the bow of the vessel. The openings between the beams and columns in the chamber inlets on the sea side have a cross-sectional area of about 80 m^2 (north) or 103 m^2 (south), and on the canal side a cross-sectional area of about 56 m^2 on both sides.

With respect to the gate ducts, 'breaking' bars have been placed at the end of all openings in the sea side gate, to improve the distribution of the inflow into the chamber when the valves are not fully open. In addition, the number of gate openings has been increased from 12 to 14.

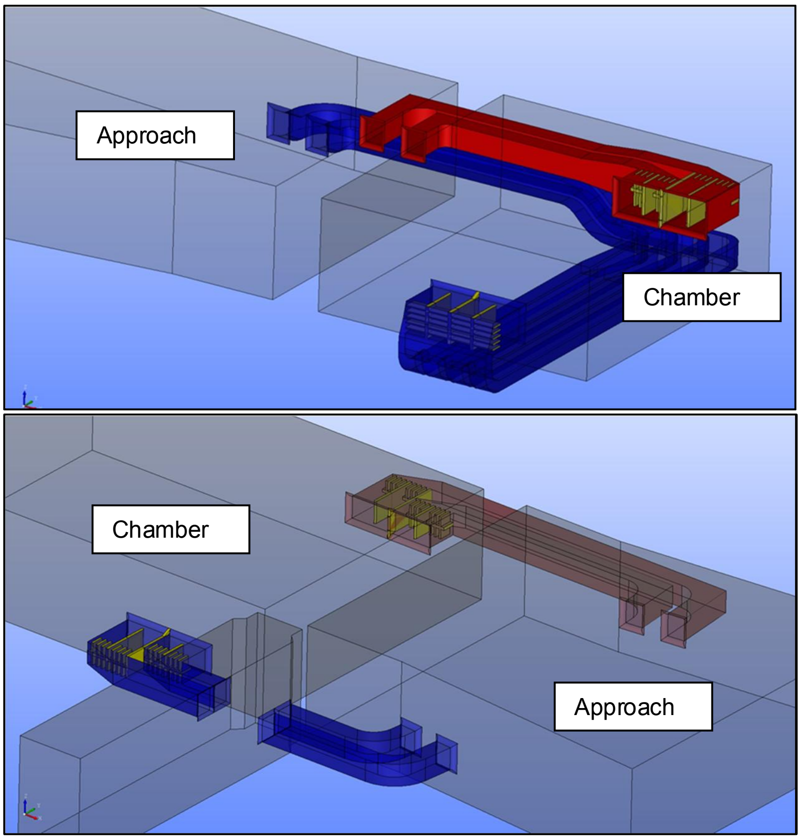

Figure 8: Reference Design of Short Culverts
Upper: sea side, lock lead, two short culverts (red), two long culverts (blue)
Lower: canal side, lock head, south culverts connected to gate recess

5.5 Scale Model

Based on the dimensions and the layout of the levelling systems resulting from the numerical models, a scale model of the lock has been built, on a scale of 40 to 1, including both systems (Figure 6). An extensive scale model study has been carried out (Nogueira, H.I.S., et al., 2018, Van der Hout, A. et al., 2018).

First, tests were carried out with a stationary flow to determine the loss coefficients of both levelling systems. Then, levelling tests were performed, in fresh water only and at a maximum density difference of 20 kg/m^3, with and without the main bulk carrier. In the levelling tests, both the levelling times and the hydrodynamic forces were measured. In a number of density tests, at the end of the levelling, the lock gate was opened to simulate the lock exchange.

It proved that the one-dimensional flow-force model LOCKFILL had to be adjusted to fit with the measurements of the forces on the vessel. The maximum force in the longitudinal direction at the moment of high flow rate was higher in the scale model. Also, it showed that the damping of the translatory waves in the chamber is less in the case of levelling through ducts in the gate than levelling through the culvert system. The influence of the density differences on the forces on the vessel is considerable. In the density tests, both the longitudinal and the transverse forces on the vessel in some cases exceeded the criterion as a result of this extra density component.

After levelling, when the gate is opened, the lock exchange flow, given the high density difference, brings about very high forces on the vessel, directed towards the side with the higher density. Then, both longitudinal and transverse forces are much higher than the criteria. These forces are independent of the type of levelling system.

5.6 Reference Design: Conclusion

After the model in LOCKFILL had been calibrated, this numerical model has been used to determine the maximum levelling times, allowing for the inaccuracy of the model (De Loor et al., 2015). It proved that these required levelling times are longer in case of levelling through the gate, when compared with levelling through the culverts. In consequence of the density difference the transverse forces during levelling may be higher than the criterion. The transverse forces prove to be higher for the gate system than the short culvert system.

The phase in which the vessel is leaving the lock, when the gate has been opened and the lock exchange results in very high forces on the vessel, is regarded as a special operational phase during which additional tug assistance should be available to assist the vessel (Van der Hout, et al., 2018).

5.7 Final Design by Contractor

On the basis of the results of the reference design the building consortium (OpenIJ) has chosen for the same gate system, though with 16 instead of 14 ducts, each with a net opening width of 2.2 m and a net opening height of 3.0 m (Van Lierop, 2018). These ducts are well distributed over the length of the gate, in order that the levelling discharge is evenly spread over the width of the lock chamber. The centerline of the gate openings is at NAP – 10.25 m, more or less at half of the water depth. This means that the residual horizontal force on the gate and the translatory wave, both related to the moment that the gate is opened, are limited.

The lifting valves, which are driven by hydraulic cylinders, are located at the center of the gate. To improve the distribution of the inflow into the chamber, breaking bars have been placed at the end of all ducts. Although these bars are more effective at the chamber side of the gate, the bars are installed on both ends of the ducts, so that the two operational gates are directly interchangeable with the only spare gate. Due to the symmetrical shape with respect to the center of the gate, the discharge coefficients for filling and emptying are equal. Figure 9 shows a cross-section of the gate.

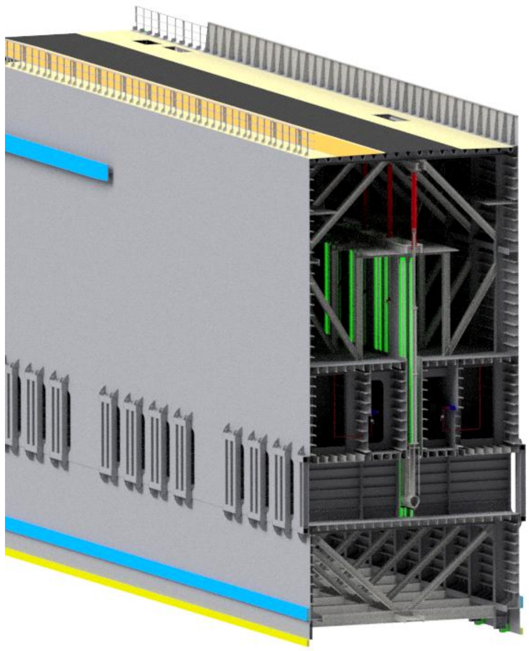

Figure 9: Cross-section Rolling Gate

To determine the discharge coefficient of the ducts, and to find the best shape and location of the breaking bars, OpenIJ carried out flow simulations with CFD, with package Flow3D (Figure 10, Van Goolen et al., 2017).

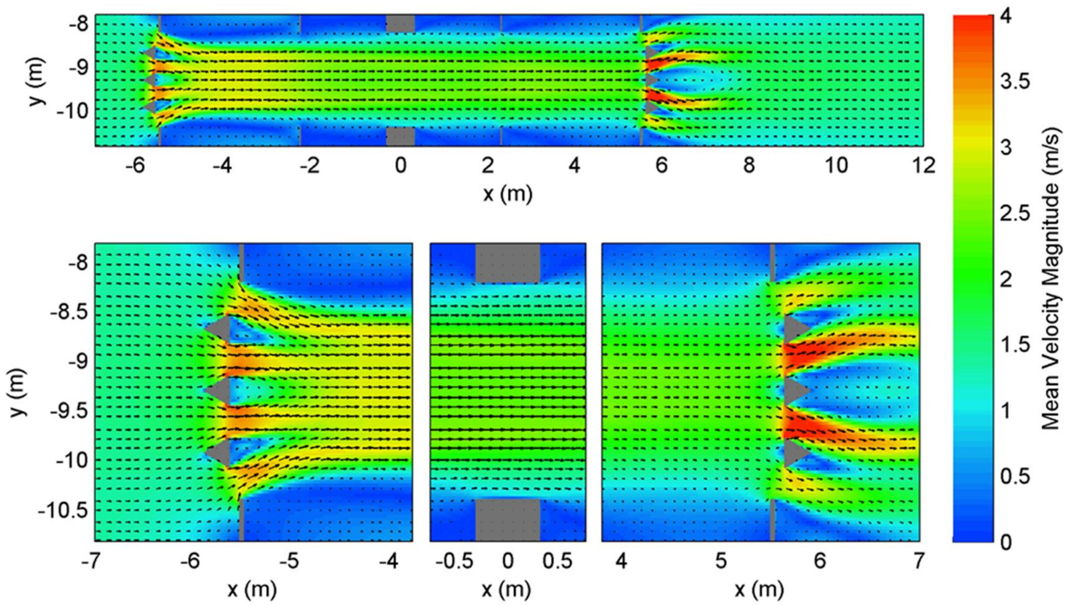

Figure 10: Horizontal Cross-section of Duct; Flow Pattern: Water Flows to the Right

It proved that the pattern of the inflow in the chamber improves when the breaking bars are placed just outside the gate and are given a triangular cross-section. The flow resistance in the ducts is mainly determined by the breaking bars at the entrance and the exit of the duct, the valve in the middle, the stiffeners at the valves, and the stiffeners in between the valves and the entrance or exit. Using the results of the numerical simulations the discharge coefficients have been calculated for different valve positions.

The final design has been assessed in the scale model which is shown in Figure 6. Again, the discharge coefficients have been determined accurately. It showed that the values resulting from the measurements correspond to the ones from the numerical simulations. With the valves lifted above the duct, the net discharge capacity (μA) is 44.4 m^2 (0.42 x 16 x 2.2 x 3 m^2). Subsequently, the valve lifting programs for the different head differences were determined based on the required levelling times and the maximum permitted hydrodynamic forces on the vessel. The tests showed that with the more extreme head differences the density currents during levelling produce the highest forces on the vessel.

The 1D flow-force model LOCKFILL was further calibrated with the scale model tests. Since it was not possible to carry out the scale tests over the entire range of head differences, the calibrated LOCKFILL was used to establish the intermediary valve programs. When emptying, the 16 valves will be operated simultaneously with a constant lifting speed or the valve speed will be varied in time. When filling, it will often be necessary to operate only 8 valves at a time, evenly distributed over the gate, except for the smallest head differences. Additionally, in the case of filling at more extreme head differences, the valves will be lifted in stages, which means that all valves will be stopped and remain standing for a specified period. This is due to the relatively high density forces in those circumstances.

When the gates are delivered, the final valve programs will be adjusted in accordance with a number of site tests of the levelling process. By means of measuring the levelling discharges against time the discharge coefficients will be validated and the levelling times will be verified.

6 NEW LOCK TERNEUZEN

6.1 Introduction

The building contract for the new lock has been awarded in the summer of 2017. The reference layout of the new lock is shown in Figure 11. The entrance from the sea and the Western Scheldt Estuary is on the north side (left), and the Ghent-Terneuzen Canal to Ghent is on the south side. The contract requires that each lock head will include two rolling gates. It has to be possible to carry out the maintenance to each gate in the own gate recess.

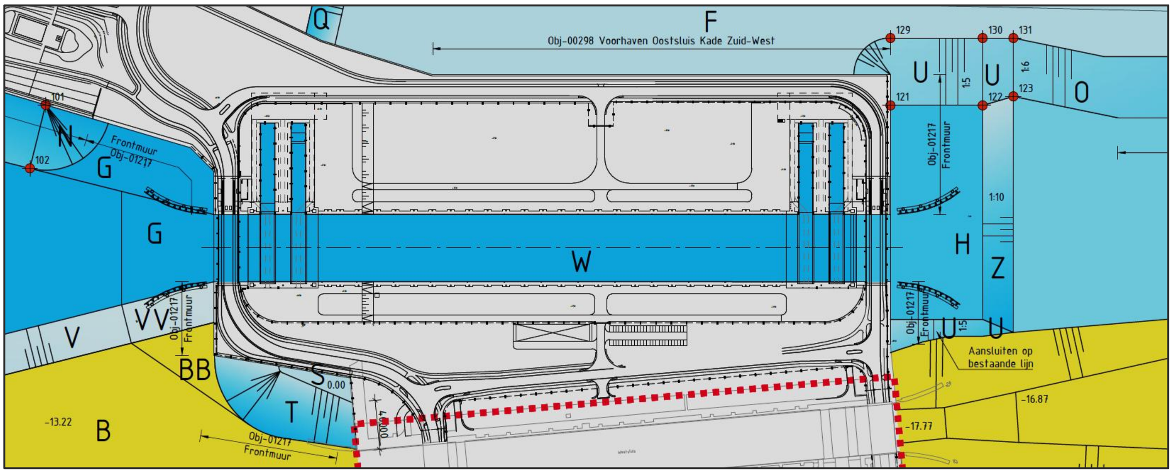

Figure 11: Reference Layout

The dimensions of the New Terneuzen Lock are:

- Overall lock length: 550.60 m.
- Chamber length between outer/inner and outer/inner gates: 452/427/402 m.
- Overall chamber width: 55 m.
- Sill level at outer head: NAP – 16.44 m, sill level at inner head: NAP – 14.12 m.
- Chamber floor level: NAP – 16.80 m.
- Design vessels with respect to levelling system design: bulk carrier: Loa x B x T = 257 x 40 x 16.3 m, container vessel: Loa x B x T = 366 x 49 x 14.5 m.

Given the sill level at the outer head and a minimum water level for locking of NAP – 2.69 m, a vessel can pass the lock irrespective of the tide level, when the draft of the vessel in fresh water is 12.50 m or less. A vessel with a draft of 14.5 m can pass the lock when the water level is NAP – 0.44 m or higher.

Characteristic water levels:

- Mean high tide: NAP + 2.29 m (mean spring: NAP + 2.67 m).
- Mean low tide: NAP – 1.89 m (mean spring: NAP – 2.13 m).
- Lock closed when sea side above: NAP + 4.60 m.
- Lock closed when sea side below: NAP – 2.69 m (LAT).
- Target water level Ghent-Terneuzen Canal: NAP + 2.13 m.

The maximum head during levelling, with the sea at high water and the canal at low water, is 2.72 m and the minimum head, with the canal at high water and the sea at low water, is -5.07 m.

The maximum water density difference between the approach harbours is about 20 kg/m^3. The average density difference may be estimated at 14 kg/m^3.

6.2 Type of Levelling System

Since it had been decided that the final design of the levelling system for the New IJmuiden Lock will be a through-the-gate system, this type of system has also been chosen as a starting point for the reference design of the New Terneuzen Lock. First, a comprehensive study has been carried out to assess the feasibility of a through-the-gate-system with 12 circular ducts, considering an absolute value of the daily maximum head difference of 4 m and an acceptable levelling time of about 15 to 20 min.

An important distinction has to be made between IJmuiden and Terneuzen, because the prevailing condition at IJmuiden is the filling of the lock with salt water from the outer harbour, and the prevailing condition at Terneuzen is the filling of the lock with fresh (brackish) water from the canal (Figure 12). Initially, it was assumed, also based on preliminary flow-force calculations with a 1D-model in LOCKFILL, that the different development of the density currents would not lead to significantly higher forces or longer levelling times for Terneuzen. An exploratory scale model study has been carried out to determine the shortest levelling times which could be attained, and to solve the uncertainty regarding the density currents. These model tests indisputably showed that the density forces when filling during low tide, i.e. filling with fresh water, could only be reduced by prolonging the levelling times outside the acceptable range.

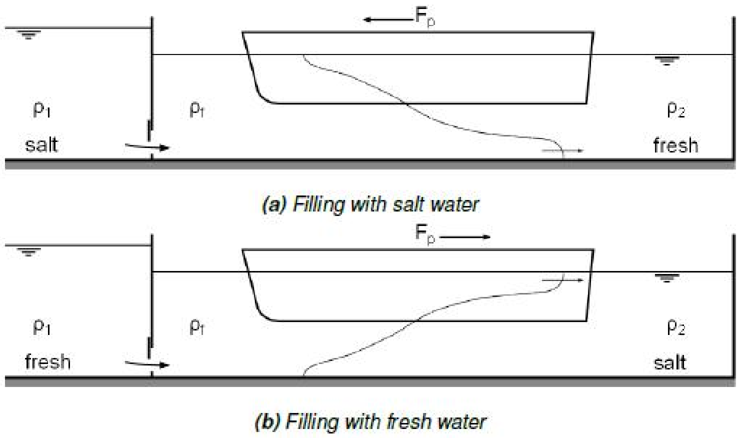

Figure 12: Force Due to Density Currents; Filling with Salt or Fresh Water

As a system with short culverts could be slightly advantageous, because of the colliding jets, additional tests were carried out with this type of system. It proved that even with shorts culverts it is not possible to meet, at the same time, the force criterion and the required levelling time.

Therefore, it has been decided to specify in the requirements for the tender a levelling system which is more comparable with the system of the existing West Lock. In the requirements two alternatives were specified: the West Lock System with two bottom grids, located at about one quarter and three quarters of the chamber length, and the Baalhoek System with four wall grids, two per lock head located in the walls, opposite each other. The Baalhoek System was subject of a scale model study, but has never been built. In both longitudinal systems the levelling discharge is distributed over two parts of the lock, thus reducing the hydrodynamic forces due to both the density currents and the translatory waves.

6.3 Dimensions and Vertical Position

In the preliminary case of the through-the-gate system consisting of 12 circular ducts the μA-value, i.e. the net discharge capacity, is about 28 m^2 for filling, which has been determined in the scale model. As a starting-point, the required dimensions of the reference system with bottom grids have been based on the capacity of the existing West Lock, adjusted for the width of the New Lock: $\mu A \approx 35\ m^2$.

The longitudinal culvert consists of two parallel culverts of 8 m x 4 m, which come together in one connecting culvert in between the bottom grids (Figure 13). In both lock heads, at the position of the gates, there is a valve house between the culverts and the outlet or inlet, having four valves, two valves per culvert. The maximum opening at each valve is b x h = 5 x 3 m^2, so that the total available area at the valves is 60 m^2. It has been decided to place the culverts within 25 m from the lock chamber wall to make it possible to combine the culverts and the chamber wall into one structure. As at the West Lock, the culverts connect to bottom grids, which are spaces under the lock floor with a perforated ceiling. The diameter of the holes is 0.3 m. Due to the relatively low position of the bottom grids, the residual horizontal force on the gate and the translatory wave, when opening the gate, have to be considered.

The second option, the Baalhoek system, with four wall grids is not considered in this paper, because the winning bid in the tender was based on the West Lock system.

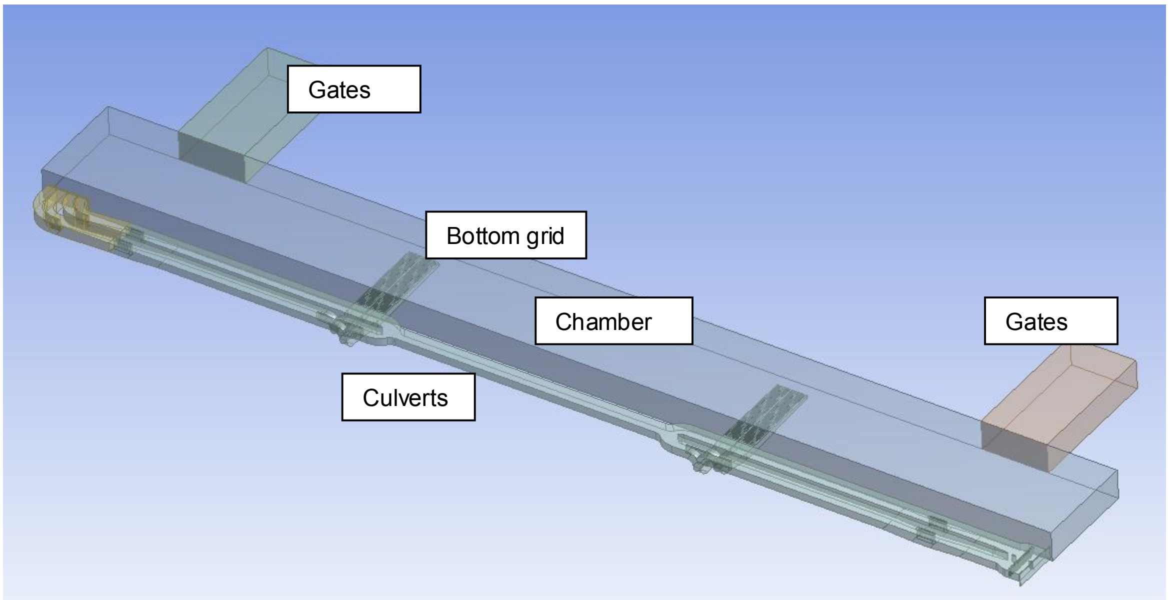

Figure 13: 3D CAD Rendering of Culvert System

6.4 Hydraulic Design

Given the dimensions, the next step focused on the hydraulic design of the bottom grids, the connection between the horizontal culverts and the bottom grids, and the in-/outlets. Again, the shaping and streamlining of the culvert system has been done on the basis of flow models in CFD, with STAR-CCM+ (O'Mahoney, T. et al., 2018).

The layout and the connection to the lock head of the in-/outlets have been varied to improve the distribution of the outflow when emptying and to direct the flow away from the approaches of the neighbouring West Lock, to limit the hindrance for vessels approaching this Lock. The emptying discharges will be higher at the outer lock head than at the inner lock head, because of the larger head differences at low tide. Furthermore, the lock may be used to discharge water from the canal. The fresh water flowing out of the lock to the outer harbour takes the form of a density current concentrated near the surface. Because of these conditions, the in-/outlet at the outer head has been given a 90°-bend towards the lock entrance.

Figure 14 shows the culvert connection to the bottom grid that has been chosen, based on the feasibility from both a hydraulic and a structural perspective. The CFD-simulations proved that a uniform flow distribution at the grid can be reached with a total area of the perforations of 60 m^2 per bottom grid, including a sloping bottom and a dividing wall in the longitudinal direction of the space under the grid.

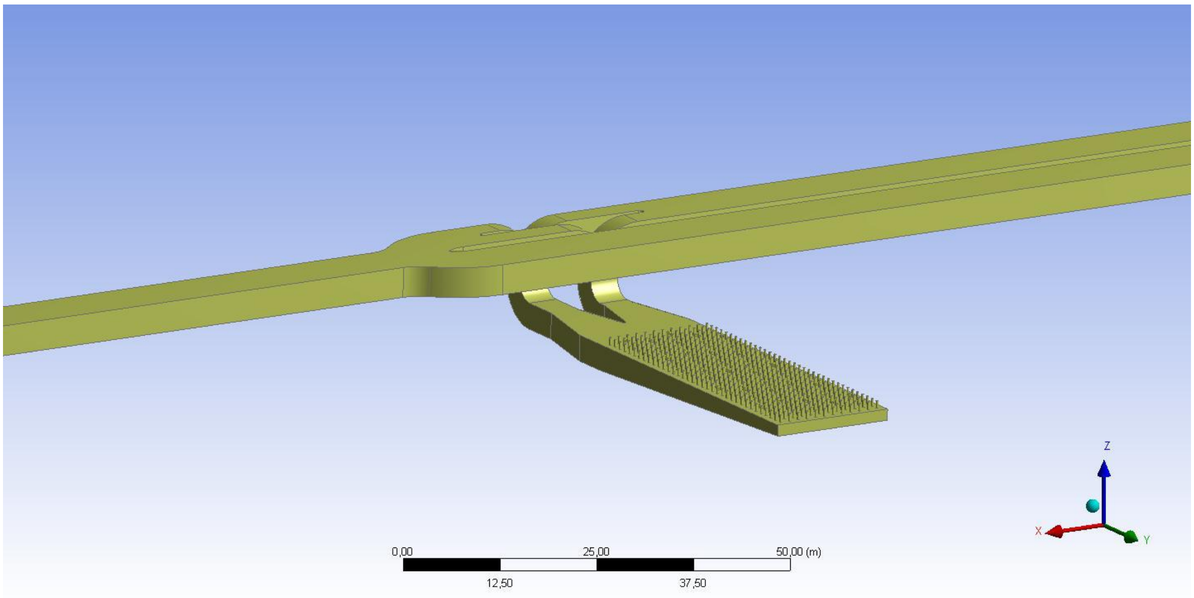

Figure 14: Culvert Connection to Bottom Grid

Based on the loss coefficients of all system components, the discharge coefficient of the total system was estimated. Next, simulations have been carried out with the one-dimensional flow model WANDA, intended for nonstationary flow and pressures in closed conduits, to provide an indication of the attainable levelling times and the evenness of the discharge distribution between the two bottom grids.

6.5 Scale model

The through-the-gate system was tested in a scale model, and subsequently rejected. Since there was insufficient time to test the longitudinal culvert system with bottom grids before the tendering process, it has been decided to prescribe the minimum net discharge capacities (μA), which had been determined in the CFD-study. The minimum μA-values for filling and emptying are 34.5 m^2 and 33 m^2 respectively. In addition, when filling the lock, during the 25% time interval around the maximum flow rate the ratio between the flow discharge through the nearby bottom grid and the far bottom grid has to be between 45/55 and 55/45. For emptying, the same ratio has to be applied, but then during the 15% time interval around the maximum flow rate. The skewness during emptying is less critical due to the absence of the density currents and the related force component.

Eventually, the final design by the contractor has to be verified in a scale model, which means that the net discharge capacity and the evenness of the levelling through the grids has to be proven. Then, given these required capacity and evenness of the levelling, the attainable levelling times while meeting the force criteria will be determined by Rijkswaterstaat, using the same scale model.

6.6 Reference Design: Conclusion

Since the daily head differences can amount to 4 m and the maximum levelling time should be approximately 20 min, a through-the-gate system is not feasible. Therefore, a longitudinal system has been considered, with two filling grids in the floor of the lock chamber or four filling grids, two per lock head located in the walls, opposite each other.

For the tendering-process, it has been decided to prescribe the minimum net discharge capacities (μA), which had been determined in the CFD-study. The minimum μA-values for filling and emptying are 34.5 m^2 and 33 m^2 respectively. Additional requirements apply to the skewness of the inflow along the lock chamber and the maximum overtravel at the end of levelling.

6.7 Final Design by Contractor

The contractor of the new lock has chosen for the West Lock System. As the layout of the in-/outlets and the bottom grids had been largely prescribed, except for the total area of the perforations in the grids, the main degrees of freedom in the design of the contractor were the dimensions and layout of the culverts, and the connections to the bottom grids and the valve houses. Now, the hydraulic design based on the numerical simulations is completed. In July 2018, the net discharge capacities and flow distributions will be verified in a scale model of this design. When the hydraulic design meets the requirements, the final scale model tests will be carried out, under the responsibility of Rijkswaterstaat, to determine the valve lifting programs and achievable levelling times, meeting the force criteria related to the vessel in the lock.

In essence, in the final design chosen by the contractor, the culverts are replaced by one large culvert, which is connected to both bottom grids. The flow into the lock can only be balanced as long as the flow losses are dominated by the losses at the perforations in the bottom grids and not by the losses in the in-/outlets, culverts and connections.

7 CONCLUSIONS

- Density currents in the lock during levelling lead to additional hydrodynamic forces on the moored vessel. Therefore, this density effect must be included when engineering the levelling system.
- The levelling systems of the existing large sea locks at IJmuiden and Terneuzen are a system of short culverts and a longitudinal culvert system with bottom grids respectively. At first, these systems were designed without considering the density currents during levelling. Practice has shown that for the occurring head differences these systems are adequate for these locks.
- When there is a density difference between the outer and the inner lock approach, the water level difference at the end of levelling will be determined by this density difference and the level of the openings of the levelling system. It can be shown that both the residual horizontal force on the gate and the incoming translatory wave will be minimal if the level of the openings or the culvert in-/outlets is at half the water depth at the end of levelling.
- Apart from levelling, when the density difference is large and the lock gate is opened to either of the sides, the water in the chamber starts to exchange with the water in the approach. This exchange flow creates density forces on the vessel, directed towards the salty side, which are most probably higher than the forces due to the filling and emptying process.
- It is recommended that for the nonstandard locks the design of the levelling system is validated in a scale model of the lock, because in such a physical model all hydraulic phenomena may be included.
- The scale model of the reference design of the New IJmuiden Lock proved that both a system of short culverts and a system of gate ducts are feasible, owing to the limited head differences, provided that the levelling times for the gate system may be longer to some degree.
- The final design of the gate system of the New IJmuiden Lock consists of 16 ducts (16 x 2,2 x 3 m^2), with breaking bars at both ends. When filling, it will often be necessary to operate only 8 valves at a time, evenly distributed over the gate. Additionally, in the case of filling at more extreme head differences, the valves have to be lifted in stages. This is due to the relatively high density forces in those circumstances.
- An important distinction has to be made; the prevailing condition at IJmuiden is the filling of the lock with salt water from the outer harbour, and the prevailing condition at Terneuzen is the filling of the lock with fresh (brackish) water from the canal. This fact, in combination with a daily maximum head difference of 4 m and an acceptable levelling time of about 15 to 20 min, meant that for Terneuzen a longitudinal levelling system is required, comparable to the system of the West Lock.
- The final design of the levelling system of the New Terneuzen Lock shows one large culvert along the lock chamber which is connected to two bottom grids. On the one hand the losses at the perforations in the bottom grids have to be dominant to balance the flow into the lock. On the other the total head loss has to be limited to meet the required flow capacity.

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