New Sea Lock of IJmuiden

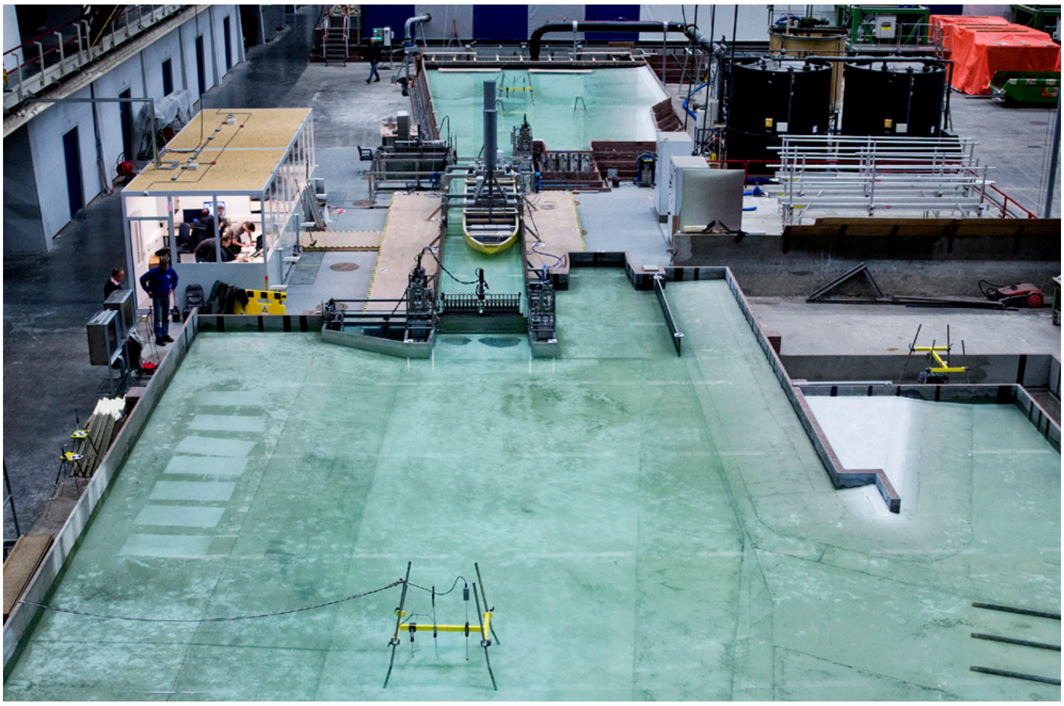
Hydraulic design of the levelling system

Assignment
Deltares carried out an extensive hydraulic study for the reference design of the levelling system for the new lock of IJmuiden. The main objective of the study was to determine achievable levelling times, on condition that the forces on the vessel remained within limits.

After almost 100 years the Noordersluis (Northern lock) in IJmuiden needs replacement. A new, larger lock will provide access to the Port of Amsterdam for larger sea going vessels and will thereby stimulate the economy in the region. Building of the lock started in the beginning of 2016. It is expected that the new lock will receive the first vessels in 2019. With a width of 70 m, a length of 545 m, and a depth of 17.75 m the new lock will be the largest lock in the world.

Client
Rijkswaterstaat – Ministry of Infrastructure and the Environment

Period
2014 – 2015



Overview of the physical scale model of the new sea lock of IJmuiden.

Keywords:
lock, density effects, ships, physical scale model, CFD, mathematical models

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Background

To accommodate the trend towards increasing vessel dimensions and to ensure that the Port of Amsterdam remains accessible for the new generation of vessels, it was decided to replace the Noordersluis of the IJmuiden lock complex. Rijkswaterstaat, in cooperation with the Port of Amsterdam, defined a reference design for the new sea lock. Deltares was involved as a consultant for the hydraulic functioning of the levelling system. One of the main challenges in the hydraulic design of a lock is to ensure a safe locking operation with a minimum delay for navigation. This means that the filling and emptying of the lock chamber should occur as fast as possible, provided that the hydrodynamic forces acting on the vessel remain acceptable. The prediction of these forces is not straightforward and depends on several factors, of which the difference in density over the lock complex is one of the most important for sea locks. In this context, Deltares performed several studies, including desk studies, detailed numerical computations and an extensive scale model study, aiming at obtaining a good insight into a number of hydraulic aspects relevant to the functioning of a levelling system.

In the physical scale model study a total of seven test series were performed, in which two levelling systems were tested - a system of short culverts in the lock heads and a system of openings in the lock gates.

The tests focussed on the following aspects:

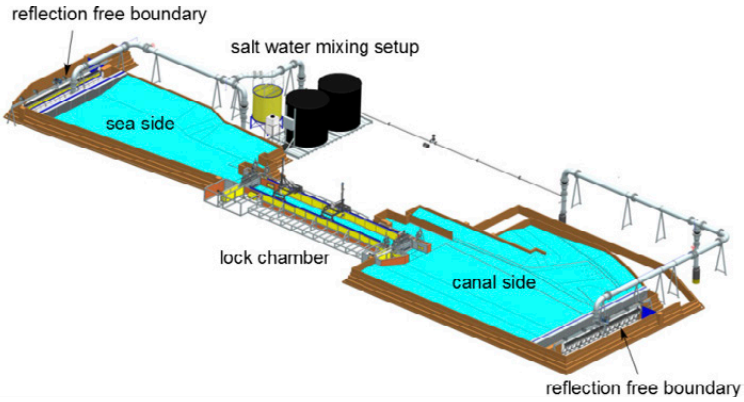
1. Hydraulic resistance and flow patterns associated with each levelling system;
2. The effect of seiches, translatory waves and lock exchange;
3. The levelling process with both levelling systems, with and without the ship in the lock, and with and without a density difference.

In parallel to the scale model research, numerical modelling of the levelling process was performed using LOCKFILL (an in-house developed, one-dimensional mathematical model) and detailed three-dimensional flow computations (CFD). The results obtained in the physical scale model were used for validation of the numerical models, such that a well-calibrated modelling toolbox was created, which could be used for interpolation of different hydraulic conditions. Based on the results of this work, advice was given to the Client on contractual requirements for the levelling duration and acceptable hydrodynamic forces.

Scale model

The scale model was built geometrically similar at a scale 1:40. The complete levelling process is simulated in the scale model, including the lock exchange flow after opening of the gate.

In the model, water levels are adjusted by using labyrinth weirs at the end of the lock approaches. The lock approaches have been made large enough, that reflections of density currents off artificial model boundaries do not affect the levelling process. In addition, to avoid reflections of translatory waves, a constant flow is maintained over the weirs. The maximum water level that could be achieved in the model is NAP+4 m and the minimum water level is NAP-1.75 m. The maximum head over a gate



Three dimensional drawing of the scale model.

that has been considered for levelling is 4.74 m. To establish a density difference over the lock, the density of the water in the outer approach is controlled by mixing fresh water with high density brine.

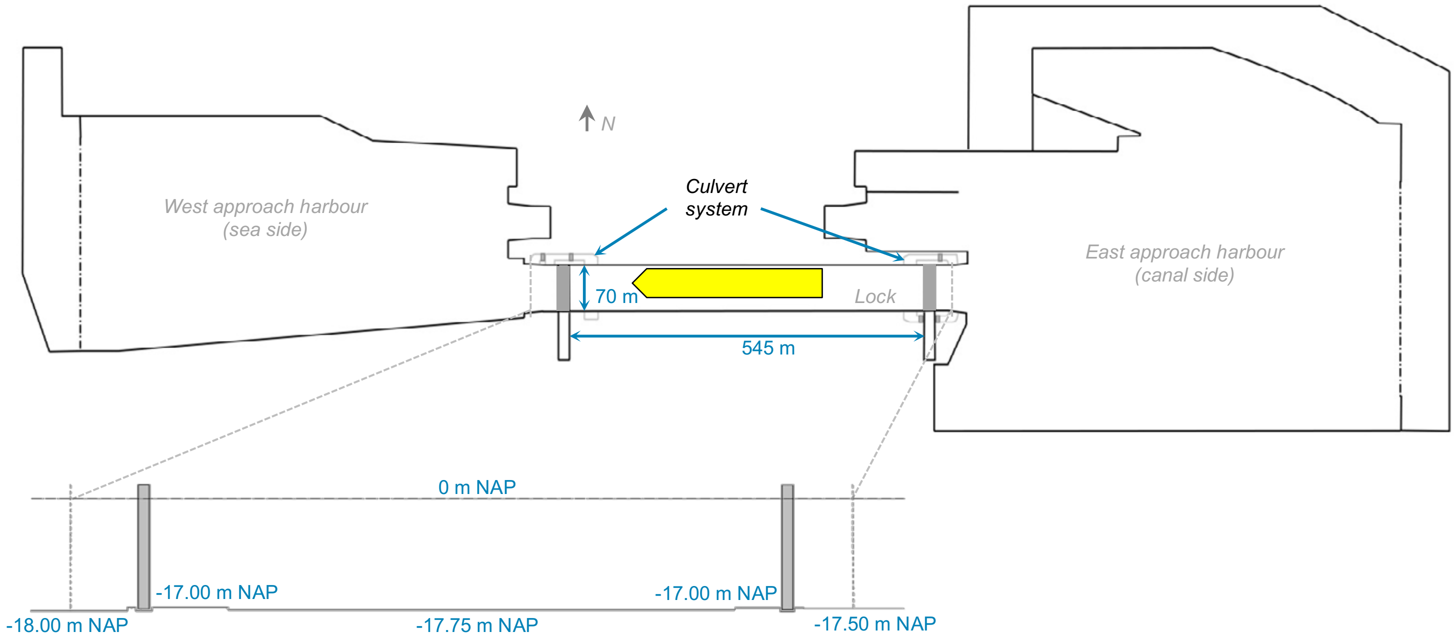
All the relevant physical flow phenomena are automatically included in the scale model. More than 200 tests were performed for both lock heads by varying levelling scenarios, water level conditions, valve lifting programmes, and the position of the ship in the lock. In total, more than 200 parameters have been measured simultaneously over time, including:

- Water levels
- Conductivity
- Temperature
- Position of valves and gates
- Forces on the ship
- Discharge
- Pressure
- Flow velocity

In addition, blue dye was added to the salt water and a system of eight cameras was used to provide visualization of the interaction of fresh and salt water.

The type of vessel also influences the hydraulic forces acting on it. In this project two types of design vessel were considered: a bulk carrier and a container ship. The main particulars of the vessels are presented in the table below. The maximum allowable draft of the vessels that has been used in the tests is 14.05 m in fresh water, due to canal restrictions upstream of the new lock.

Vessel characteristics	Bulk carrier “Breesaap”	Container ship “Wijkermeer”
Length overall L_{oa} (m)	330	366
Length between perpendiculars L_{pp} (m)	320.75	349.00
Breadth (m)	52	52
Design draft (m)	19.00	14.50
Max. allowable draft (m) (ρ=1000 kg/m^3)	14.05	14.05
Weight (N)	1.870×10^9	1.663×10^9



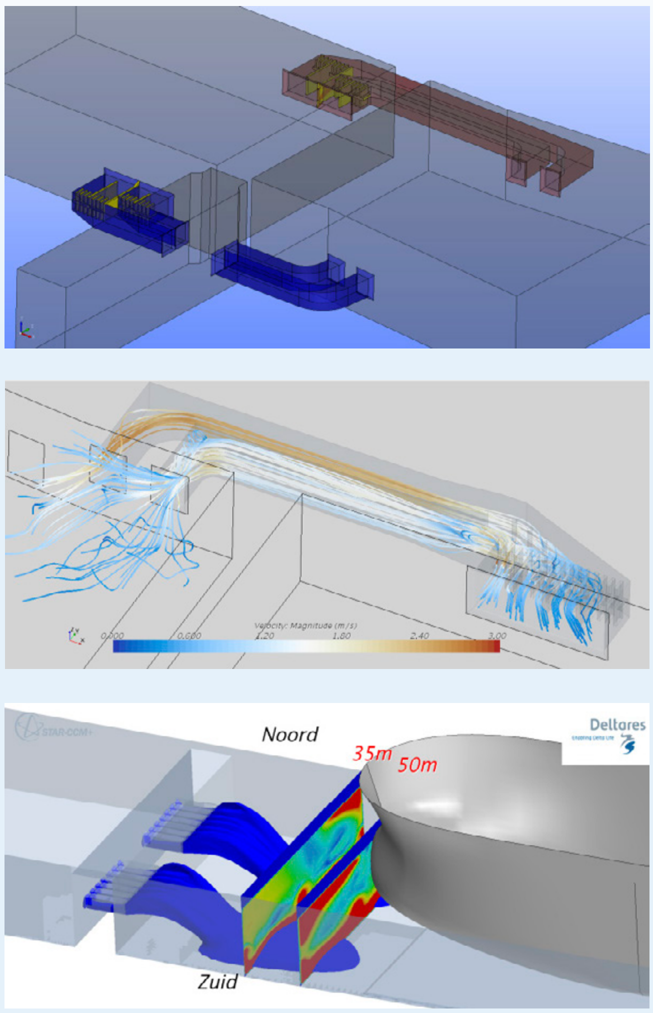
Layout of the scale model.

Hydraulic design of the levelling system

Deltares acted as a specialist consultant for the hydraulic design of the two reference levelling systems that were considered in the tender for the new sea lock of IJmuiden. The total cross-sectional area of the openings in the gates and the culverts has been determined by using the one-dimensional flow-force model LOCKFILL, which also includes the effect of the jets on the vessel's bow and the force component due to the internal density waves (stratified flow).

Given the dimensions of the levelling systems, a number of alternatives for the layout of the culvert system have been considered. The hydraulic design, i.e. 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 and O'Mahoney, 2014). To make it possible to study a large number of variants, all calculations were carried out for situations with a constant flow and without a free water surface. The models consisted of the levelling system and parts of the lock approach and the chamber. Attention has been given to the flow conditions in the culverts or the gate openings, the detachment points of the flow and the distribution of the incoming flow over the cross section of the chamber. The loss coefficients of all specific parts of the systems have been determined. 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 results illustrate that CFD can be used in an early stage of lock design to make assessments of a design's viability. Furthermore, optimizations of the levelling system can be judged both qualitatively and quantitatively.



From top to bottom: Three-dimensional CFD model of the culverts at the inner head, flow pattern through the northern culvert of the inner head, and velocity contours of filling through the gate openings at the outer head, with the presence of a ship.

Forces on the vessel

The hydraulic design of the levelling system has a significant impact on the forces acting on the vessel during lock operations. The forces generated during filling and emptying processes can be attributed to the combined effect of translatory waves, momentum variation, skin friction, filling jet, and density currents. For safety and/or comfort reasons it is required that these forces stay within acceptable limits. In this project, the maximum allowable forces acting on the vessel during levelling are 0.20 ‰ in the longitudinal direction and 0.12 ‰ in the transversal direction, defined as a permillage of the ship's weight. These limits are represented as red horizontal lines in the adjacent figure presenting force measurements.

In the scale model, the ship was attached to two independent support frames that allowed placement of the vessel at any location within the lock chamber. Each frame is equipped with a force sensor to measure forces in both longitudinal and transversal direction, allowing the determination of surge and sway forces and yaw moment. The vessel was free to move in the other degrees of freedom (heave, pitch and roll).

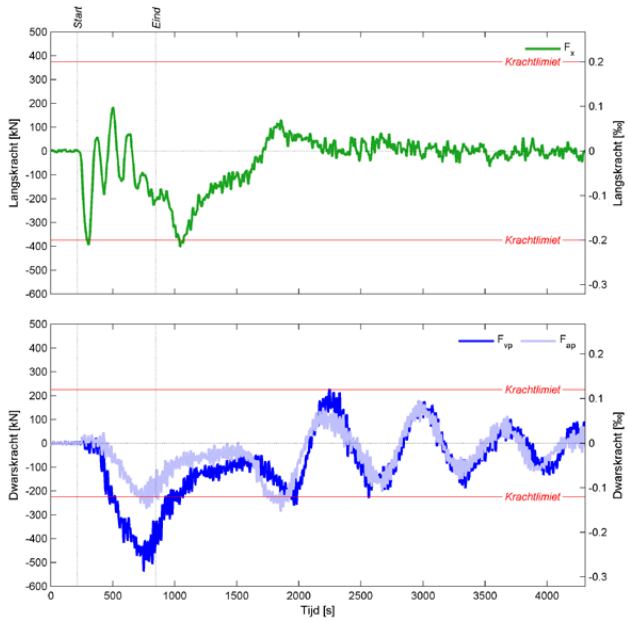
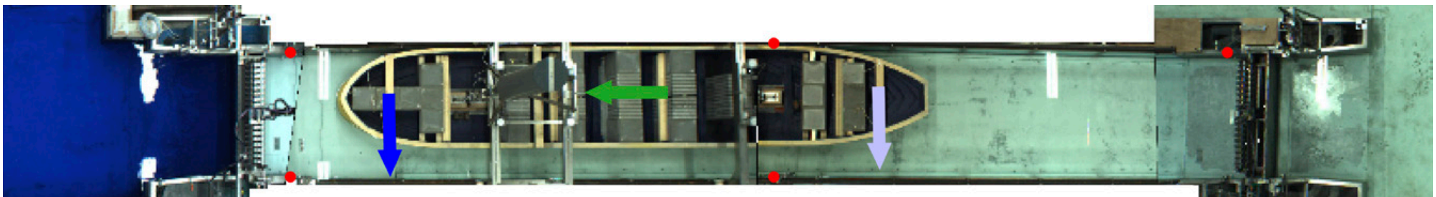
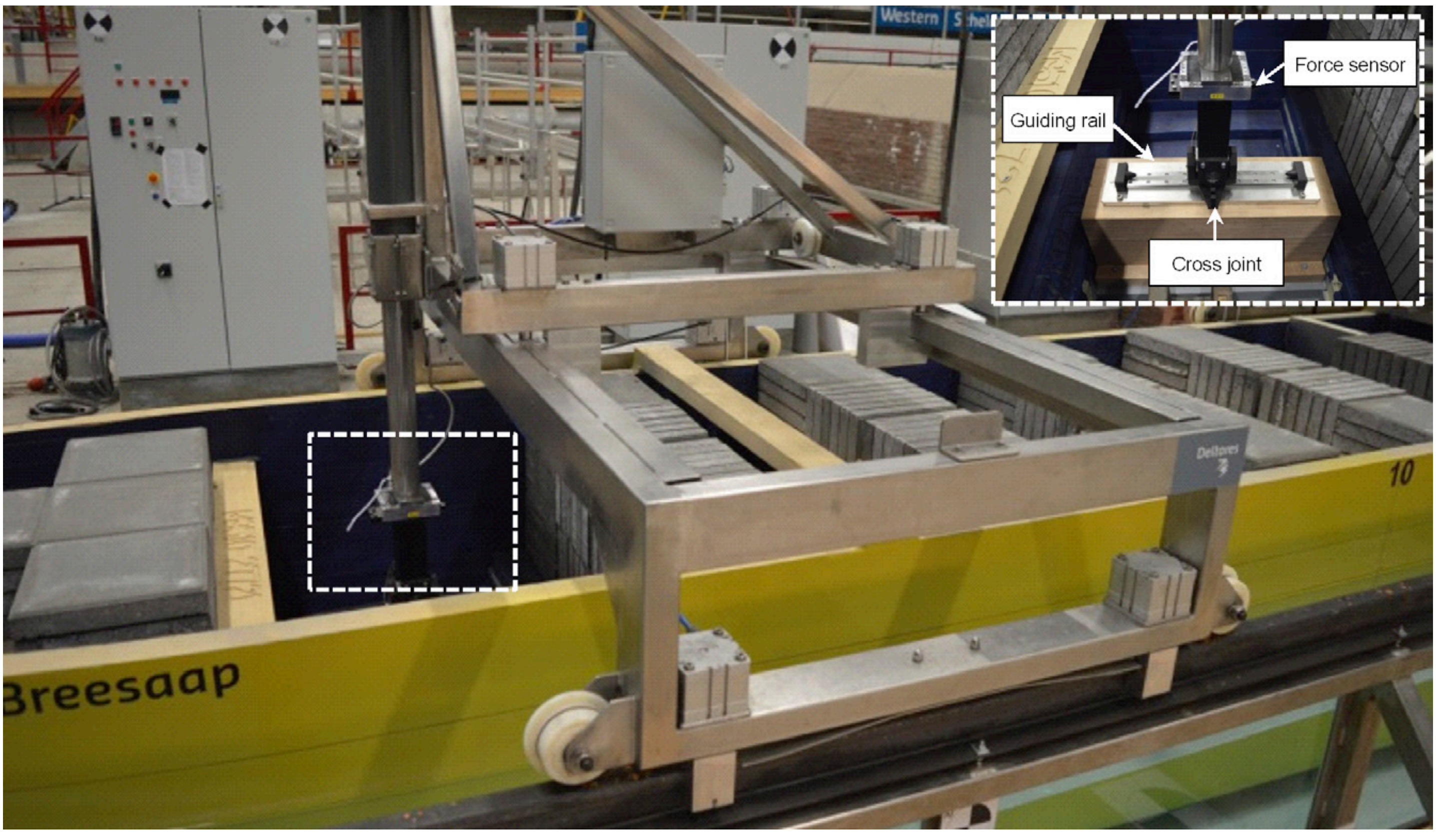


Illustration of measured forces on the vessel moored near the inner head when filling from the canal. Top: Longitudinal forces, bottom: transversal forces forward (dark blue) and aft (light blue).



Top view of the vessel moored near the outer head. The arrows indicate the positive direction of the forces acting on the vessel; the red dots indicate the locations where density profiles have been measured.



Close up of the model ship, support frame and force sensors.

Density effects

In sea locks usually a density difference is present between the water in the sea (denser) and the water in the canal (fresher). During levelling and after opening the lock gate, the two water bodies with different densities will interact with each other. The effect of gravity acting on the density difference results in the generation of density currents that propagate in the lock chamber. When filling a fresh water lock from the sea side, a salt water current propagates along the bottom of the lock, beneath the fresh water. At the same time, a fresh water current propagates in the opposite direction over the denser water. This phenomenon is highly relevant for the safety of lock operations since hydrodynamic loads generated by density differences can induce high forces on the ship.

The presence of a density current during levelling and after opening the lock gate is evident in the force measurements, in both longitudinal and transversal force components. The lock exchange that takes place when the gate opens leads to peaks in both force components, which can largely exceed the force limits.

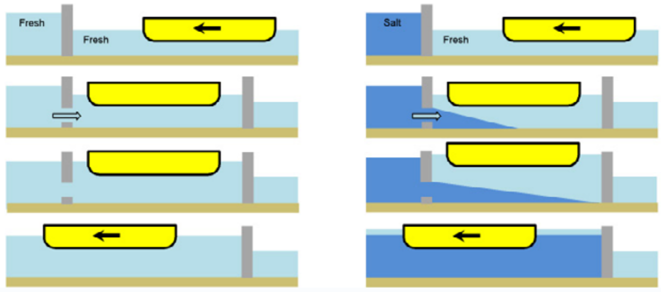
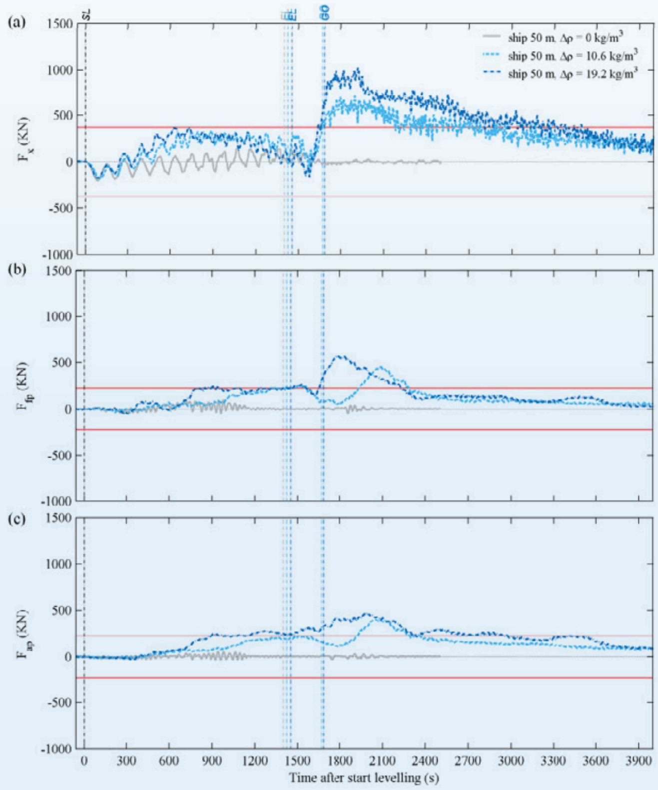
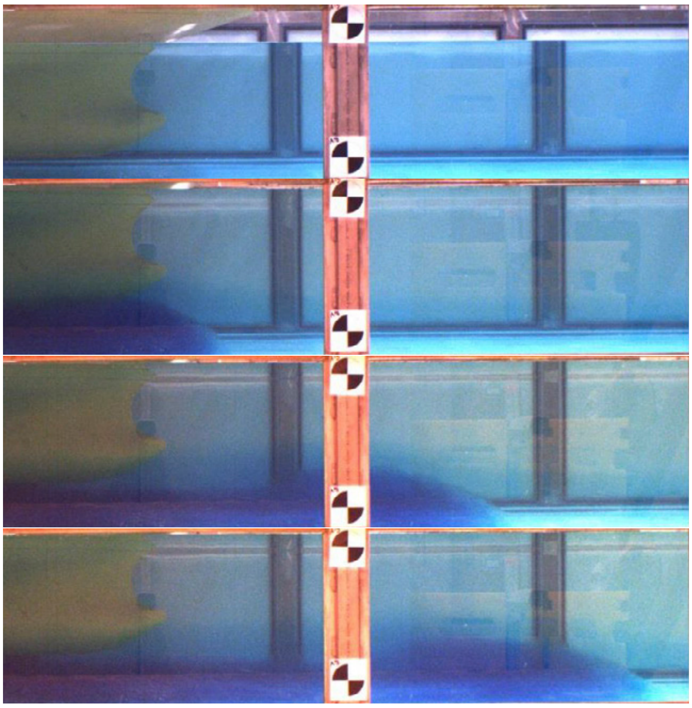


Illustration of the levelling process with and without a density difference.

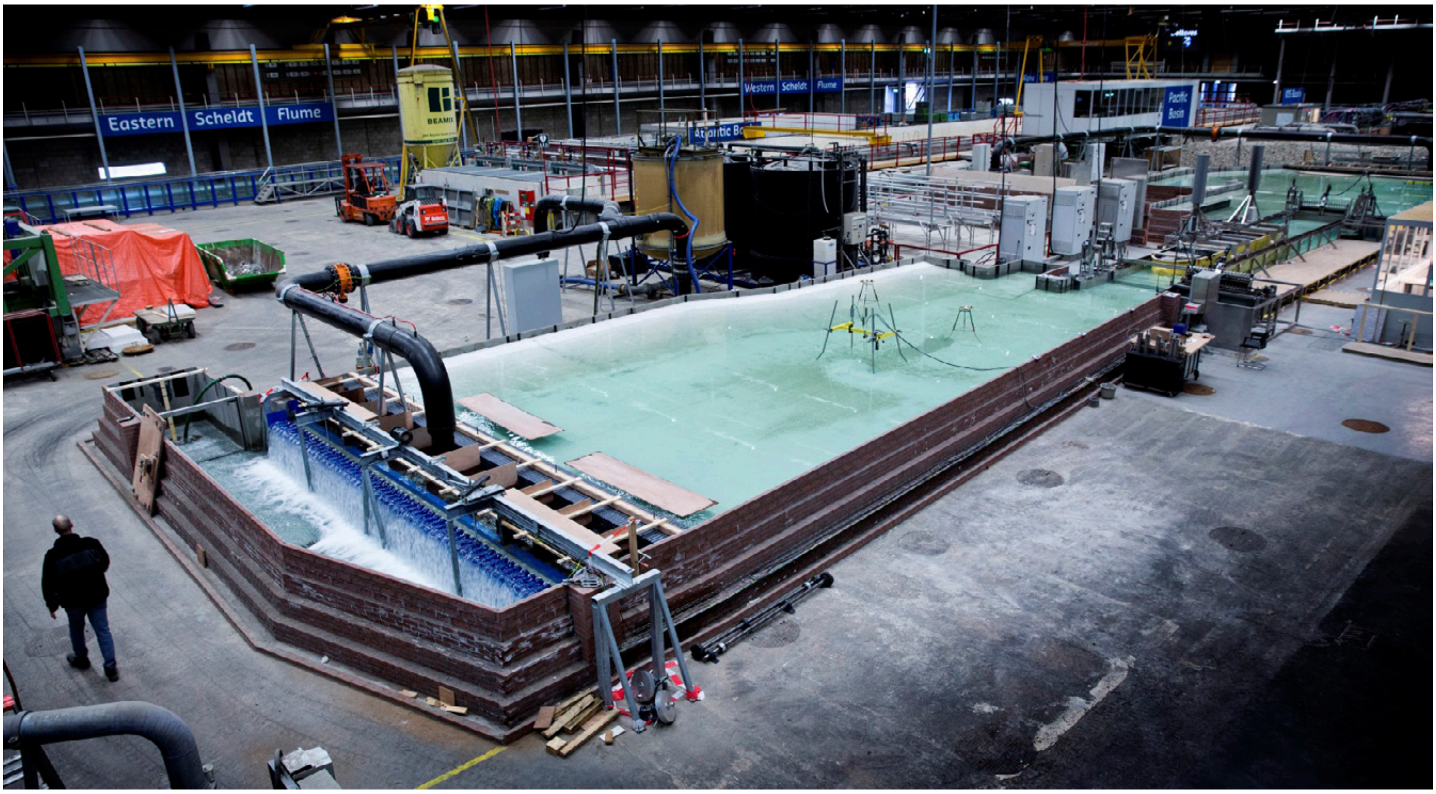


Force measurements for tests filling from the sea, with and without a density difference: a) longitudinal force, b) transversal force at the bow, c) transversal force at the stern. The first vertical line (SL) denotes the start of levelling, the next set of vertical lines (EL) denotes the end of levelling and the last set (GO) the moment the gate is fully open.



Density current propagating in the lock passing the stern of the vessel.

Density current propagating into the lock chamber after opening the gate.



Results of the study

The scale model study, in combination with the performed numerical work, provided unique insight to the hydraulic functioning of the reference design of the new sea lock of IJmuiden and showed the importance of a correct evaluation of hydrodynamic forces acting on the vessel. The results showed that the presence of a density difference induces high forces on the vessel during levelling and even higher forces when opening the lock gate due to the lock exchange phenomenon. A smaller density difference results in lower forces on the vessel; however not in a direct proportional way. The spatial distribution of the density current around the ship plays an important role, for which mixing of fresh and salt water, ship blockage and the velocity of the density current are important parameters to take into account. Some of these parameters are not known a-priori and are not straightforward to determine without a physical scale model.

In general, during levelling and after opening of the lock gate, in the presence of a density difference, the vessel is pushed towards the saltier side of the lock and away from the lock chamber wall. This has a direct effect on the tension in the mooring lines. The maximum allowable forces that the mooring lines can resist, in combination with allowable vessel movements, the capacity of the winches and the capability of the crew to handle the mooring lines, determine the limits for safely operating the lock during levelling.

The extensive scale model study led to a valuable dataset that has been used for validation of several numerical models in order to create a well validated computational toolbox to be used in the further design of locks. The information provided by this study was fundamental to the client in the process of defining contractual requirements for the tender to build the new sea lock of IJmuiden.

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