Scale model research and field measurements for two new large sea locks in the Netherlands

by

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ABSTRACT

In the Netherlands two new large sea locks are currently being built: the new lock of IJmuiden, providing access to the port of Amsterdam and the new lock of Terneuzen, providing access to the port of Ghent. Both navigation locks will be part of existing lock complexes that form a barrier between fresh and salt water. During levelling and when the gate is opened significant forces will develop on the vessels in the lock chamber due to density currents. This paper describes part of the physical scale model research and field measurements that have been carried out during the design process of these locks, focusing on the forces on moored vessels that develop during the lock-exchange. The results of these studies have been used to determine requirements for lock operations for the future largest locks in the Netherlands, at IJmuiden and Terneuzen.

1 INTRODUCTION

Both new locks of IJmuiden and Terneuzen will be much larger than the existing locks to be able to receive larger vessels in the future. As, together with the dimensions of the new lock chambers also the size of the vessels travelling though the new locks will increase, it is expected that hydrodynamic forces on the vessels will increase in the future. Since the strength of the mooring lines does not increase proportionally to the mass of a vessel with larger dimensions, the occurrence of hydrodynamic forces is more critical for these larger vessels. The mooring line loads and vessel motions resulting from hydrodynamic forces during levelling and the lock-exchange are therefore a decisive factor in the design and operation of the new locks.

To have a good understanding of the hydraulics of the new locks, extensive studies have been performed during the design process of the levelling system of these locks using both numerical and physical models. A general overview of the design process of these two new sea locks in the Netherlands is presented by Kortlever *et al.*, 2018 and the role of numerical models in the design of the levelling system of the new lock of Terneuzen is addressed by Mahoney *et al.*, 2018.

Since both the new lock of IJmuiden and Terneuzen are sea locks, a density difference over the lock is present and for both locks the density current leads to dominant forces on the moored vessel during levelling and the lock-exchange. For the lock of IJmuiden and Terneuzen two different types of levelling systems are used: openings in the lock gate for IJmuiden and a longitudinal filling system with bottom grids for Terneuzen. The development of hydraulic forces during levelling will therefore be different for both locks. However when the gate is opened, the processes will be similar for both locks. When the gate opens, water with different densities on both sides of the gate will exchange due to pressure differences, whereby the denser (saltier) water will flow underneath the less dense (fresher) water and the fresher water will flow over the saltier water. This process is called a lock-exchange and it is only to a limited extent influenced by the design of the levelling system of a lock. This process is described in detail by Vrijburcht, 1991 and is illustrated in Figure 1. An overview of the effects of density differences during levelling for the new lock of IJmuiden is provided by Nogueira *et al.,* 2018. The research described in this paper, shows that the forces on the vessels in the lock chamber, as a result of the density currents when opening of the gate, will often exceed the forces during levelling.

This paper focuses on the lock-exchange process in the new locks of IJmuiden and Terneuzen and the hydrodynamic forces related to this phenomenon on the vessels moored in the lock. Design options to influence the large-scale process of gravity driven currents are limited and the occurring

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forces are therefore hard to influence. In practice the forces on the ships are therefore handled with operational measures, instead of by extensive design modifications to the lock itself. The objective of the research presented here was to provide engineers and pilots with information on the magnitudes an evolution of forces that can be expected in the new locks, so that they can better prepare on how the future operation of mooring and unmooring vessels and sailing out of the lock will change in these larger locks.

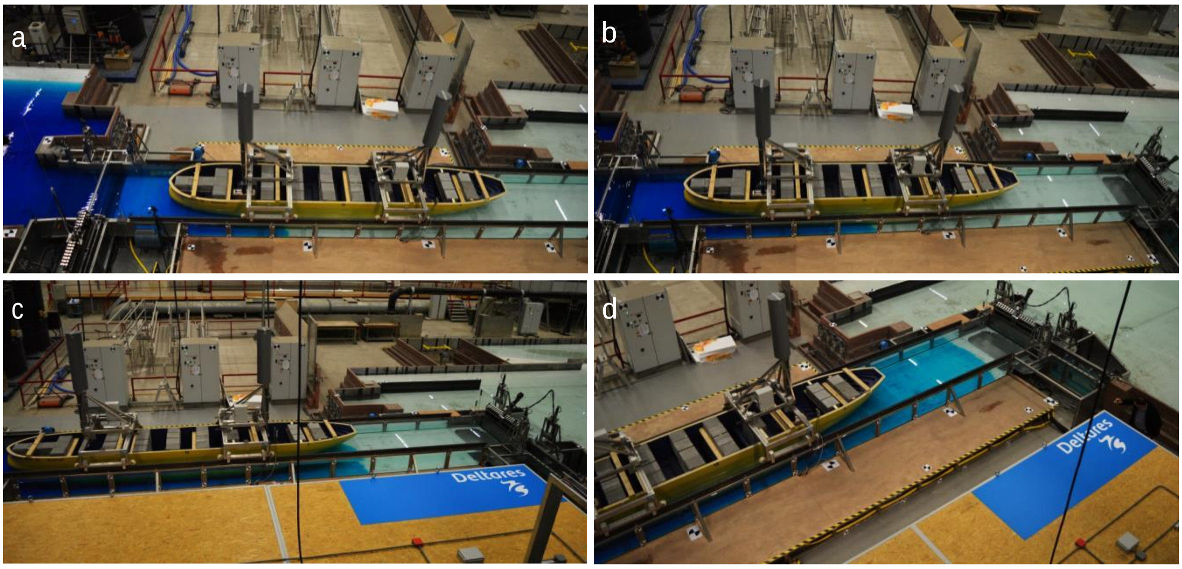

Figure 1: A lock exchange process, in which salt water (colored blue) enters a fresh lock chamber after the gate is opened. The pictures are taken sequentially in time from (a) to (d).

For the design of the levelling system of both locks, a design vessel was defined with maximum allowable dimensions for which the locks would still be able to achieve acceptable levelling times. For the study on lock-exchange effects however, described in the present paper, also smaller vessels have been considered. From an operational point of view these smaller vessels will be more relevant than the largest vessel that can pass the lock, since they will visit the new locks more frequently and these vessels will be the first vessels that the pilots will have to guide safely through the new locks.

The study described in this paper consists of three parts:

- Physical scale model study on the design vessel for both IJmuiden and Terneuzen
- Physical scale model study on a smaller vessel in the new lock of IJmuiden
- Field measurements in the North Lock of IJmuiden

By combining the results of the three abovementioned measurement series, a clear view was obtained on what operational requirements need to be met during the lock-exchange in the new locks of IJmuiden and Terneuzen.

2 MAIN PARTICULARS OF THE NEW LOCKS

2.1 New lock of IJmuiden

The new lock of IJmuiden will have a length of 545 m and a width of 70 m. The floor level of the lock chamber is located at NAP-17.75 m (NAP = Amsterdam Ordnance Datum) and for daily operation water depths typically vary around 18 m, with head differences typically around 1 to 1.5 m. The maximum operational water levels at the sea side can range from NAP-1.65 m to NAP+4.00 m, under extreme design conditions. The water level of the canal will remain relatively constant at a level of NAP-0.40 m. The new lock of IJmuiden is aimed to be in operation in 2020.

The new lock is significantly larger than the currently operational North Lock (Noordersluis in Dutch), which will be replaced by the new lock of IJmuiden. The North Lock is presently the largest lock of the IJmuiden lock complex with main dimensions of 400 m x 50 m x 15 m (length x width x depth). The North Lock is comparable in size to the new lock in Terneuzen and can therefore serve as a reference for that lock.

2.2 New Lock of Terneuzen

The new lock of Terneuzen is equipped with four gates and will have a minimum length of 402 m and a maximum length of 452 m, and a width of 55 m. The floor level of the lock chamber is located at NAP-16.80 m and operational water levels at the sea side range from NAP-2.69 m to NAP+4.60 m. In the current design of the lock, a sill is present at the inner head with its top at the level of NAP-14.12 m to reduce salt intrusion into the canal. In the future this sill may be heighted, if needed. The presence of a sill at the inner head will reduce forces that develop during the lock-exchange at that head. If the sill is heightened in the future, the lock-exchange forces may be reduced even further. What makes the situation in Terneuzen different from the new lock of IJmuiden is that the canal has a higher water level than in IJmuiden. The water level of the canal is located at a constant level of NAP+2.13 m. As a result of this, higher head differences, will occur on a more frequent basis than in IJmuiden, with daily head differences up to 4 m. The lock is aimed to be in operation in 2022.

3 FORCE CRITERIA

When designing the levelling system of a lock, criteria are determined for the maximum allowable forces on the vessels moored in the lock. These criteria are typically based on the maximum forces that can be handled by the minimum strength of the mooring lines required for that type of vessel, under the assumption that all hydrodynamic forces are absorbed by the mooring lines and that horizontal vessel motions need to be restricted. Usually a safety margin is included in these criteria; for example, the mooring line loads are not allowed to exceed 50% of the minimum breaking load (MBL) of the mooring lines. These maximum allowable force criteria are often expressed as a permillage of the weight (displacement) of a vessel. The larger the displacement of a vessel is, the smaller is the value of the maximum allowable force permillage, since the required strength of the mooring lines does not increase proportionally to the weight of the vessel.

Hydrodynamic forces during levelling have different origins and have typically a fast-varying character, e.g. as a result of translatory waves. Also when the gate opens such fast-varying translatory waves may develop as a result of a small residual water level difference over the gate at the end of levelling. During the subsequent lock-exchange process however, the character of the hydrodynamic force changes more gradually due to the relatively large scale and slow nature of density currents, and the force due to density currents is always directed to the side of the vessel where the water is saltier. In addition, also the way of handling the vessel after the gate has been opened is different from the way during levelling. During levelling all horizontal vessel motions need to be restricted and the vertical displacement of the vessel is compensated for by careful control of the winches. After the gate has been opened however, the vessel needs to be unmoored and to a certain extent controlled vessel motions can be allowed as the vessel prepares to sail out of the lock. In addition, once the gate is open and the mooring lines are disconnected it is also possible to use the main propeller and possibly tugboats to control the motions of the vessel. Due to the different character of the operations during levelling and the lock-exchange, the mooring criteria as defined for levelling do formally not apply to the lock-exchange.

The mooring criteria as defined for levelling will however be mentioned as a reference in this paper, although they are formally not applicable to the process studied here. However, by comparing the forces that develop during the lock-exchange to the force criteria for levelling, insight is provided whether the hydrodynamic forces can be absorbed theoretically by the mooring lines alone, or that additional measures might be required. The force criteria and occurring hydraulic loads will not only be expressed as a permillage of the vessels weight in this paper, but also as absolute values in metric tons. This makes it easier to compare different vessels (or the same vessel with different draughts) to each other and it allows for a straightforward comparison to typical mooring line strengths and tugboat capacities, which are typically expressed in metric tons.

The force criteria for levelling of the new locks at IJmuiden and Terneuzen are defined as a maximum longitudinal force and maximum transversal forces acting at the location of the fore and aft perpendicular of the vessel. The combination of the three forces (longitudinal, transversal fore pp., and transversal aft pp.) determines the maximum allowable surge force, sway force and yawing moment. The mooring criteria for the different vessels (see Section 4 for the main particulars of the vessels) considered in this study are given in Table 1.

Table 1: Force criteria for the different considered vessels in metric tons (and as permillage of the actual weight of the vessel). $F_{crit,\ long}$ = maximum allowable longitudinal force, $F_{crit,\ trans}$= maximum allowable transversal force at the fore and aft perpendicular.

Name	Type	Draught [m]	$F_{crit,\ long}$ [ton] ([‰])	$F_{crit,\ trans}$ [ton] ([‰])
Breesaap	Design vessel IJmuiden	14.05	38 (0.20 ‰)	23 (0.12 ‰)
The Flying Dutchman	Small vessel IJmuiden, loaded	14.00	24 (0.21 ‰)	16 (0.14 ‰)
The Flying Dutchman	Design vessel Terneuzen	12.50	24 (0.24 ‰)	16 (0.16 ‰)
The Flying Dutchman	Small vessel IJmuiden, ballast	9.00	24 (0.35 ‰)	16 (0.24 ‰)

4 PHYSICAL SCALE MODEL

To simulate the complete levelling cycle of both new locks at IJmuiden and Terneuzen a physical scale model facility has been built at Deltares at scale 1:40. The overall objective of the scale model research was to determine the levelling times that can be achieved for the considered levelling systems and to study the lock-exchange that occurs when the gate is opened. To that end, the physical scale model has been equipped with movable gates that open automatically after levelling.

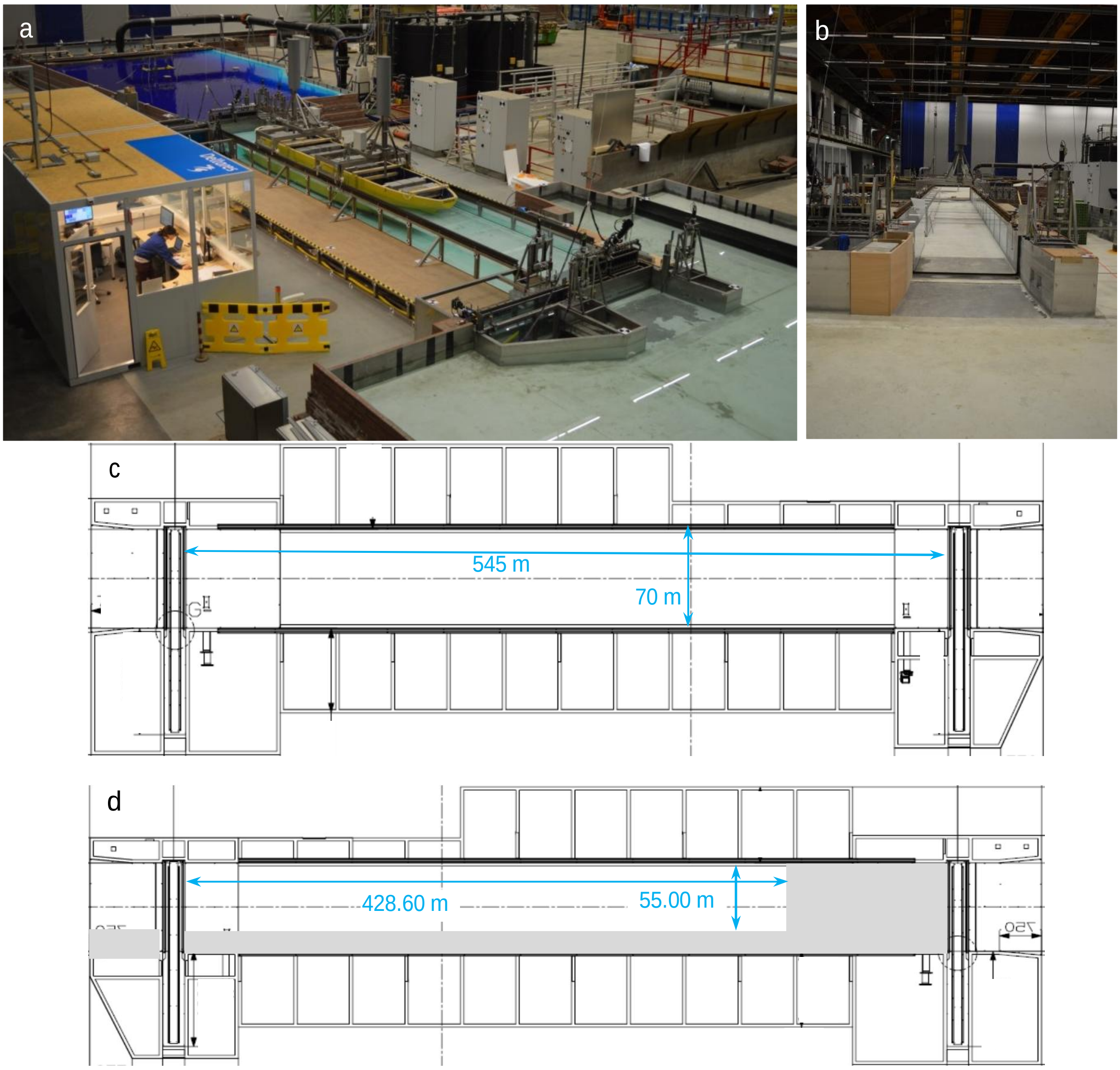

Figure 2: Overview of the scale model facility of IJmuiden (a) and modified lock chamber for the lock of Terneuzen (b). The main dimensions of the lock are given in (c) for the IJmuiden tests and in (d) for the Terneuzen tests.

In the scale model, the lock chamber, the lock heads, the levelling system and also parts of the approach harbours are represented. In Figure 2 an impression of the scale model facility is given. A predetermined density difference over the lock is maintained by adjusting the water density of the approach harbours between tests. The approach harbours have been equipped with movable weirs to set the water levels in the approach harbours to the desired level. Vertical density profiles have been determined at several locations in the scale model by measuring conductivity and temperature. Furthermore, water levels, flow velocities, positions of valves and gates, and forces on the vessel have been measured. In total more than 200 measurement channels have been logged simultaneously.

Originally, the physical scale model has been built for the hydraulic study of the new lock of IJmuiden. To be able to also test realistic situations for the new lock of Terneuzen, the available scale model has been modified to match the dimensions of the new lock of Terneuzen, including the sill at the inner head.

4.1 Scale model measurements for IJmuiden

In the hydraulic scale model studies for the new lock of IJmuiden two vessels have been considered, the design vessel *Breesaap* and a smaller vessel *The Flying Dutchman*, at two draughts. Both vessels are bulk carriers and the main particulars are given in Table 2. Also a container vessel was studied in the design process of the new lock, but for conciseness this vessel will not be considered in this paper. The *Breesaap* represents the largest vessel that can pass the new lock under normal levelling conditions. The *Flying Dutchman* is representative for an Aframax class of vessels that now visits the port of Amsterdam on a regular basis and is one of the larger vessels that currently passes through the North Lock. Figure 3 shows both vessels in the physical scale model of the new lock of IJmuiden.

Table 2 : Main particulars of the considered vessels for the new lock of IJmuiden

Name	*Breesaap*	*The Flying Dutchman*
Type	bulk carrier	bulk carrier
Length over all (Loa)	330 m	257 m
Length between perp. (Lpp)	320.75 m	252 m
Beam	52 m	40 m
Draught, loaded	14.05 m*	14 m
Draught, ballast	-	9 m
Displacement, loaded	$1.91{\cdot}10^8$ kg	$1.12{*}10^8$ kg
Displacement, ballast	-	$6.68{*}10^7$ kg

* This is maximum allowable draught in the lock. When coming from the seaside, the vessel will be lightered from its maximum draught of 18 m to this draught before entering the lock.

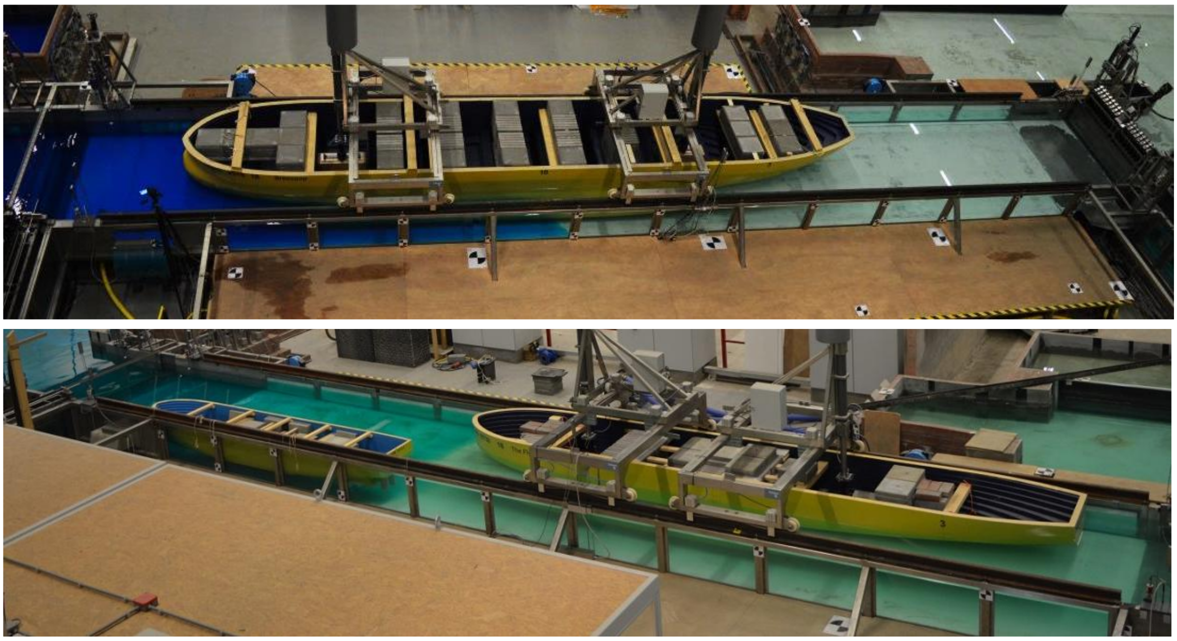

Figure 3: The vessels used in the scale model study of the new lock of IJmuiden during a lock-exchange, with Breesaap (above) and The Flying Dutchman (below, on the right). In the lower panel also a smaller vessel has been moored in the lock to investigate the effect of multiple vessels in the lock chamber at the same time.

The hydraulic studies that were performed for the design of the levelling system for the new lock of IJmuiden were extensive. In total more than 250 tests were performed in the physical scale model. In approximately one third of these tests the gate was opened after levelling and a lock-exchange occurred. The variations that were studied considering the hydrodynamic forces during lock-exchange included: opening the gate after filling and emptying conditions, for inner and outer lock head, with different initial water level differences, different positions of the vessel in the lock chamber, different initial density differences, variations of density distribution in the lock-chamber (homogeneous or stratified), variations in the gate program and the effect of multiple vessels in the lock chamber simultaneously. For conciseness not all variations which have been studied will be discussed in this paper. Only the main conclusions will be discussed, highlighting the most important characteristics of the lock-exchange process.

4.2 Scale model measurements for Terneuzen

The bulk carrier *The Flying Dutchman*, considered a smaller vessel for the new lock of IJmuiden, is defined as design vessel for the new lock of Terneuzen (see Table 3). The draught that was considered in the tests is 12.5 m, being the maximum draught at which the vessel may enter the lock independent of the tide.

Table 3: Main particulars of the considered vessel for the new lock of Terneuzen

Name	*The Flying Dutchman*
Type	bulk carrier
Length over all (Loa)	257 m
Length between perp. (Lpp)	252 m
Beam	40 m
Draught	12.50 m*
Displacement	$9.84*10^7$ kg

* This is the maximum draught in the lock considered in the tests. The vessel has a maximum draught of 16.3 m.

The hydraulic study for the new lock of Terneuzen consisted of more than 50 tests, including a wide range of hydraulic conditions. The performed test program included seven tests in which the gate was opened after levelling, also for different hydraulic conditions. The initial head difference at the beginning of levelling was varied, since for filling conditions the density difference over the gate at the end of levelling (when the gate is opened) is determined by the amount of water that is introduced into the lock chamber during levelling. For emptying conditions, the density difference over the gate is hardly influenced by the levelling process. In addition to the tests in which the gate was opened after levelling, several "pure" lock-exchange test haven been performed without levelling prior to opening of the gate. These tests can be considered as representative for emptying tests. In these pure lock-exchange tests several different gate programs have been tested, to investigate the influence of the gate opening program on the hydrodynamic forces on the moored vessel.

In the tests presented in this paper, mainly conditions at the inner head are considered. In an earlier performed measurement campaign also some preliminary results for the lock-exchange at the outer head were obtained. The setup of these tests will not be described in detail here, but in those tests a vessel that was slightly wider than the design vessel was considered then and not the full range of water levels could be studied. Although the results of these preliminary tests are not fully representative for the actual situation of the new lock of Terneuzen, the findings from this preliminary study will be incorporated in the discussion of the results, as they are thought to be illustrative for the dominant physical processes for the lock-exchange at the outer head.

5 FIELD MEASUREMENT CAMPAIGN

Following the physical scale model work, a field measurement campaign was conducted in which forces on vessels in the North Lock of IJmuiden were measured during the lock-exchange. This measurement campaign was conducted by the Pilot Association Amsterdam-IJmond (Schotman, 2017). The main reason for performing these measurements was to serve as a reference for the forces that were found in the scale model tests. This would help the pilots to determine a relation between the physical scale model results, under well-known controlled conditions, and the current day-to-day practice of the pilots, in which conditions are not always well defined.

The forces that occur in reality during a lock-exchange are usually not known. Pilots are aware of density forces due to the lock-exchange, but mooring line forces are not monitored. The crew on deck adjusts the tension in mooring lines based on experience and their perception, such as the peeps and squeaks of the winches. The pilot oversees the response of the vessel and will give appropriate orders to the crew members controlling the winches. Although, the process is normally well under control and ships are handled merely based on extensive experience, it is on beforehand not always known how large lock-exchange forces will be and incidents with relatively large vessel motions or breaking lines still happen occasionally.

Before the start of the measurements it was for example not clear, whether or not the forces that currently occur during the lock-exchange in the North Lock exceed the formal levelling force criteria regularly. Since for the new locks it was expected that this would be the case, the field measurements helped the pilots to assess whether this exceedance would lead to operational problems, or that under normal operations also forces higher than the force criteria for levelling could be handled safely. Another aspect was that knowing the magnitudes of forces that currently occur under normal conditions, would place the higher forces that will occur in more extreme conditions in the new, larger locks in perspective.

Figure 4: Left panel: View through a fairlead on a tugboat that measures the longitudinal force; right panel: Aframax tanker 'Densa Crocodile' in the North Lock during the measurement campaign.

The forces during the lock-exchange in the North Lock are measured using a tugboat. The vessel was connected to the tugboat by a line from the aft, via the center lead. Figure 4 gives an impression of a measurement. In all tests the vessel was positioned at approximately 80 m from the gate of the outer head. The tests started the first moment the gate started to move. All lines to the bollards on the chamber wall were disconnected as quickly as possible and in all tests this was the case before the gate was fully open. At the moment that the pilot observed that the vessel started to move forward as a result of the density current, using an accurate pilot positioning system, the tugboat was ordered to pull backwards to compensate the movement. The movement of the vessel was monitored carefully and by adjusting the power of the tugboat, the vessel was kept in position for a large part of the lock-exchange process. The forces in the mooring lines were monitored on the on-board equipment of the tugboat or derived from the tugboat capacity diagram. Although the measurement method is quite crude, it was a quick and accessible approach that provided reliable first order of magnitude results. Repetitions tests confirmed the reliability of this method, by giving similar forces under similar conditions with similar vessels.

In the measurement campaign only situations for the outer lock head were considered, meaning that the (outgoing) vessel sails from the canal towards the sea. For this situation, the longitudinal force is larger than the transversal forces and thought to be the most important from operational viewpoint.

Therefore only the longitudinal force is measured. Although transversal forces can be significant as well, measuring these would lead to a more complex measurement set-up which was unfortunately not possible within this project. Four types of vessels are considered in the tests, summarized in Table 4.

Table 4: Considered vessel types in the field measurements

Type	Dimensions *(approx.)* L x B [m]	Loading condition	Draught *(approx.)* T [m]
Aframax	250 x 44,0	Loaded	14
		Ballast	9
Panamax	225 x 32,2	Loaded	14
Handysize	183 x 32,2	Loaded	12
Handysize-wide	183 x 40,0	Loaded	10

The test campaign was conducted in the period of April – October of 2017 and a total of eight tests have been performed. All tests have been performed under similar conditions, with weather conditions that were as mild as possible to avoid external influences, such as wind effects. The water levels of the outer approach harbour were around mean lockage level during the tests, ranging between NAP-0.66 m and NAP+0.67 m.

One of the largest unknowns during the tests was the density distribution in the lock and in the approach harbour at the moment that the gate opens. The density difference over the gate, driving the lock-exchange, depends among others on the fresh water discharge from the neighboring flushing sluice, meteorological conditions, and previous lockages and may vary between tests. The tests have therefore been conducted during a relatively dry period of the spring and summer. In the wetter periods of that summer, in which more variation of the density on the canal side of the lock may be expected, no tests were carried out. Since no density measurements were available, a realistic estimate of the density difference had to be made to be able to interpret the results. Based on available historic measurements, it has been assumed that in all test a density difference of 12 kg/m^3 was present between the outer approach harbour and the lock chamber.

To verify the assumption that the density difference would not vary too much between the tests, a repetition tests was included in the test program and it confirmed indeed only a small variation in the measured longitudinal force. Furthermore, it was expected that due to possible strong easterly winds the density difference over the lock would increase, due to upwelling effects in the outer approach harbour. By also conducting an additional test immediately after a period with strong easterly winds, it was confirmed that for this condition the longitudinal force increased significantly, up to 45 %, during the lock-exchange (results of this verification test are not presented in this paper for conciseness).

6 MEASUREMENT RESULTS

6.1 IJmuiden (physical scale model)

For the new lock of IJmuiden two vessels have been considered: the design vessel (*Breesaap*) and a smaller Aframax class bulk carrier (*The Flying Dutchman*), see Table 2 for the vessel characteristics. The results will be discussed for these two vessels separately.

<u>Design vessel (Breesaap):</u>
Figure 5 shows and example of measured water levels and forces on the vessel in time. It illustrates how forces develop during a typical lock-exchange for the design vessel in the new lock of IJmuiden.

For conditions in which the lock is filled through the outer head, the forces during levelling exist mainly of a combination of translatory waves and a slower varying density force. When the gate is opened, a sharp increase in the longitudinal force is observed due to the density current that creates a water level gradient over the length of the ship. The longitudinal force is directed towards the outer approach harbour (always in the direction towards the saltier water), pushing the vessel out of the lock. The maximum longitudinal force is reached shortly after the gate has been fully opened and only decreases slowly over the next 45 minutes. Also the transversal forces are significant, pulling the vessel off the lock wall. It takes a little longer for the transversal forces than for the longitudinal force to reach their maximum value.

For the inner head, the development of the forces is different from the outer head. For the filling condition that is shown, quite large translatory waves can be observed in the longitudinal force during levelling. Also already a strong buildup of transversal force is present during levelling, due to the incoming fresh water through the lock head. When the gate opens, the transversal force on the bow increases especially, pulling the bow off the lock wall. The magnitude of the longitudinal force also increases, but remains smaller than the magnitude of the transversal forces. The longitudinal force is now directed into the lock chamber (towards the saltier water), pushing the vessel backwards towards the closed gate.

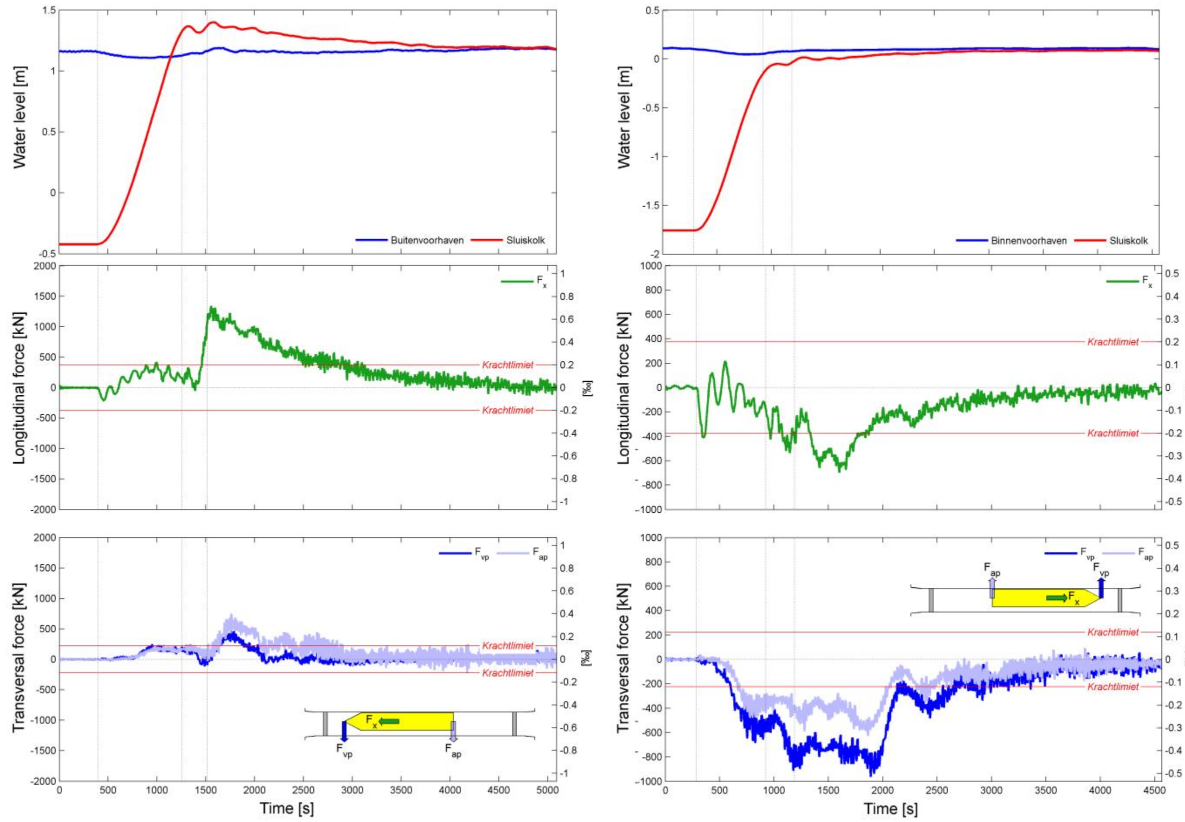

Figure 5: Typical results for the development of the hydrodynamic forces during levelling and the lock-exchange. Left panels: opening the gate after filling through the outer head, right panels: opening the gate after filling through the inner head. Top panels: water levels in the lock chamber (red) and approach harbour (blue). Middle panels: longitudinal force (green). Bottom panels: transversal force bow (dark blue) and transversal force aft (light blue). The gray vertical lines indicate in chronological order: Start of levelling, End of levelling (gate starts to move), and Gate is fully opened. The horizontal red lines indicate the force criteria for levelling (Note the difference in vertical scales for the left and right panels).

The results presented in Figure 5 illustrate the main challenges considering the lock exchange process. For outgoing ships at the outer head, the longitudinal force is the largest and the most relevant. Since this force is directed towards the open gate, the risk of a collision with the gate is small and the density driven current actually helps the vessel to leave the lock. The main challenge is to release all the mooring lines in time, before the vessel gains to much speed and cannot be stopped. When mooring lines cannot be released in time, there will be a chance on line breakage. Also, when two vessels are moored in the lock chamber simultaneously, the second vessel will have to wait until the first vessel has sailed out of the lock, before it can release its mooring lines. During that period, the mooring lines have to be able to withstand the hydrodynamic forces due to the lock-exchange.

For ingoing ships at the inner head, the transversal force on the bow has the largest magnitude and is the most relevant from operational point of view. Pilots need to take sufficient precautions that the bow is not pulled off the wall by the density forces, with the risk that the vessel will hit the opposite wall or another adjacent vessel (e.g. a tugboat). The longitudinal force is also significant, but not as large and might be easier to control, since it takes some time before it reaches its maximum value. At that moment in time the mooring lines may already be released and the main propeller can be used to compensate the longitudinal force. However, one should be aware that in case of engine failure this is actually a critical situation, since the vessel will be pushed backwards, towards the closed gate, which has a water retaining function in this setting.

Considering the complete data set that has been obtained from all the conducted measurements, the range of maximum values of forces due to the lock-exchange for the design vessel of the new lock of IJmuiden is given in Table 5. These results mainly include tests which a relatively large density difference, to obtain maximum design values, but also a number of tests with a relatively low density difference (i.e. 10 kg/m^3). The highest values in Table 5 can therefore be interpreted as upper limits and the lower values as realistic common situations.

Table 5: Range of magnitudes of the maximum forces measured during lock-exchange for all tested conditions for the design vessel of the new lock of IJmuiden.

Outer head	
$F_{long, max}$	58 – 136 ton
$F_{trans, max, bow}$	32 – 79 ton
$F_{trans, max, aft}$	36 – 76 ton
Inner head	
$F_{long, max}$	34 – 75 ton
$F_{trans, max, bow}$	40 – 98 ton
$F_{trans, max, aft}$	24 – 64 ton

The main conclusion drawn from this overview is that forces as a result of the lock-exchange will be large. Also under relatively mild conditions forces will well exceed the formal levelling criteria (longitudinal: 38 ton and transversal: 23 ton). It was furthermore concluded that the largest forces during the lock-exchange do not always occur under extreme water level conditions. On the contrary, when water level heads are small, the density differences at the end of levelling are often the most extreme, since not much water is sluiced into the lock chamber during levelling. This means that the most severe lock-exchanges will occur at water levels that happen on a daily basis.

Furthermore, it is important to consider that the maximum force alone is not showing the complete picture. Also the moment in time at which this force occurs is important. It is therefore essential to also consider the development of the forces during lock exchange in relation to the operation in practice. The density current propagates relatively slowly and when the gate is opened the vessel will remain fully moored for only a short period.

Smaller vessel (The Flying Dutchman)

To investigate how the forces during the lock-exchange would change as a function of vessel size, also a smaller ship, *The Flying Dutchman* (see Table 2), was considered in the physical scale model. This type of vessel was of particular interest for the Pilots, since it is comparable to (relatively large) vessels that currently visit the IJmuiden North Lock.

For this vessel “pure” lock-exchange tests have been carried out, without prior levelling. Both lock-exchanges at the outer and the inner lock head have been tested. The water levels of the approach harbours corresponded to mean conditions, with NAP + 0 m for the outer approach harbour and NAP – 0.40 m for the inner approach harbour. The initial density difference over the active gate was around 16 kg/m^3. Two loading conditions of the vessel have been considered (loaded and in ballast), to investigate the influence of the draught of the vessel on the resulting forces. Table 6 shows the results of a selection of the performed tests.

When comparing the hydrodynamic forces that are measured on *The Flying Dutchman* and the *Breesaap* under similar hydrodynamic conditions, it was found that the forces on the smaller vessel are smaller than on the design vessel. The forces are still quite large however and exceed the formal criteria as defined for levelling (24 ton in longitudinal direction and 16 ton in transversal direction, see Section 3) also for this smaller vessel. Similar to the design vessel, the longitudinal forces are largest at the outer head and the transversal forces on the bow are largest at the inner head. For the outer head, it is shown that the forces due to the lock-exchange in loaded condition are larger than in ballast condition, which can be expected based on the larger blockage of the vessel, which is defined as the wet cross-sectional area of the vessel A_{vessel} divided by the wet cross-sectional area of the lock A_{lock}. For the lock-exchange at the inner head, this is not the case, since the maximum longitudinal force is largest in ballasted condition. The difference between transversal forces on the bow, which are the most relevant for this condition, is small for the two loading conditions.

Table 6: Maximum lock exchange forces on *the Flying Dutchman* in the new lock of IJmuiden

Test	Draught [m]	Initial density difference [kg/m^3]	Lock head	$Fl_{ong,max}$ [ton] ([‰])	$F_{trans, max, bow}$ [ton] ([‰])	$F_{trans, max, aft}$ [ton] ([‰])
IJM1	14	16,5	Outer	69 (0.61)	28 (0.25)	49 (0.43)
IJM2	9	16,5		46 (0.68)	15 (0.23)	16 (0.24)
IJM3	14	16,2	Inner	29 (0.26)	49 (0.43)	36 (0.32)
IJM4	9	16,4		36 (0.54)	45 (0.68)	16 (0.24)

The results for both lock heads show that the lock-exchange behaves fundamentally different for both lock heads. This is related to the fact that after opening the gate the interface between fresh and salt water has a different vertical position. At the outer head, a salt water wedge enters the fresh lock-chamber over the bottom, while at the inner head a fresh water wedge enters the saltier lock chamber in the top of the water column. This is illustrated in Figure 6 and was already described by Vrijburcht, 1991.

Figure 6: Schematised exchange process in a lock with initially fresh water (left) and initially salt water (right). Adapted from Vrijburcht (1991).

6.2 Terneuzen (physical scale model)

In the tests for the new lock of Terneuzen presented here, a different levelling system (openings in the lock gate) was considered than that will be actually built (longitudinal filling system with bottom grids). During the design process of the lock, design considerations changed as a result of the physical scale model study (see also Kortlever *et al*. 2018). The overall performance of the final levelling system will be verified in a new physical scale model study in the near future. The different levelling systems will lead to a different density distribution in the lock chamber at the end of levelling and this may thus lead to (small) differences during the lock-exchange. It is expected that the main conclusions presented here will still hold for the new levelling system that is now being designed. Note also that only lock-exchanges after filling the lock are affected by the changes in the design and not lock-exchanges after emptying.

For the new lock of Terneuzen mainly lock-exchanges at the inner head have been considered. Also some “pure” lock-exchange tests (without levelling) at the outer head have been performed, although this was a rather small dataset during a preliminary phase of the test campaign. The maximum forces during the lock-exchange are summarized in Table 7. The density difference in all tests was approximately 16 kg/m^3. Similar to the other datasets that are considered in this paper, the forces during the lock exchange are large and exceed the current criteria defined for levelling.

Table 7: Range of magnitudes of the maximum forces measured during lock-exchange for all tested conditions for the design vessel of the new lock of Terneuzen.

Outer head	
$F_{long, max}$	53 – 77 ton
$F_{trans, max, bow}$	28 – 32 ton
$F_{trans, max, aft}$	28 – 35 ton
Inner head	
$F_{long, max}$	28 – 49 ton
$F_{trans, max, bow}$	14 – 42 ton
$F_{trans, max, aft}$	6 – 27 ton

In the preliminary test campaign, during which the lock-exchange at the outer head has been studied, the maximum water level at the outer head could not be achieved due to height limitation of the model basin at that time. The maximum water level that then was considered was NAP + 1.23 m, while in the later test campaign, after adjustments to the test setup, water levels in the outer approach harbour up to NAP + 4.60 m have been considered. Since from all performed measurements it is concluded that lock-exchange forces generally increase with larger water depths, it is therefore expected that in reality forces at the outer head may even exceed the upper values mentioned Table 7.

6.3 IJmuiden North Lock (field measurements)

The results of the field measurement campaign can be used to relate the forces that are measured in the physical scale model for the new locks to the daily practice in the North Lock. The results of the field measurement campaign in the North Lock are presented in Table 8. The measured maximum longitudinal force $F_{long,max}$ ranges from 25 ton to 47 ton for lock-exchanges at the outer head. When the measured forces are expressed as a permillage of the displacement of the vessel, it ranges from 0.30 ‰ (Tectus) to 0.59 ‰ (Stena Premium). During the lock-exchange, the longitudinal forces exceed in the majority of the tests the typical force criteria for levelling, which are defined for the North Lock as 0.25 ‰ and 0.30 ‰ for 45,000 dwt and 90,000 dwt vessels respectively (Delft Hydraulics, 1983).

Table 8: Test conditions and results of the field measurement campaign in the North Lock.

Test no	Name vessel	Type	Loading condition	Wind direction and force	Length [m]	Beam [m]	Draught (aft) [m]	Draught (bow) [m]	Displacement [ton]	$Fl_{long,max}$ [ton]	$F_{long, max}$/Displ. [‰]
NO1	Stellata	Aframax	Loaded	NNW 2	238	42	13.9	13.9	117,573	43	0.37
NO2	Densa Crocodile	Aframax	Loaded	W 4/5	244	44	13.7	13.7	109,160	47	0.43
NO3	Dong-a-thetis	Aframax	Ballast	NNW 3	250	44	8.8	5.8	56,476	25	0.44
NO4	Tectus	Panamax	Loaded	WZW 3	228	32.2	14.1	14.1	84,300	25	0.30
NO5	Nave Atropos	Panamax	Loaded	NNW 1	225	32.2	12.8	12.8	77,083	30	0.39
NO6	Alpine Mary	Handysize	Loaded	ESE 2	183	32.2	11.7	11.7	51,212	25	0.49
NO7	Torm Carina	Handysize	Loaded	N 1	183	32.2	11.8	11.8	53,119	25	0.47
NO8	Stena premium	Handisize – wide	Loaded	W 2	183	40	10.4	10.4	58,965	35	0.59

Since the performed tests were not conducted under extreme conditions, it shows that in practice density induced forces during the lock-exchange will often be larger than during levelling. Furthermore it is shown that, since no large problems are encountered during daily operation, pilots are well capable of controlling the vessel under conditions in which current force criteria are exceeded. When the results for the different vessel types are considered, the following observations are made:

Aframax: The dimensions of the vessels in test NO1 and NO2 are similar and the measured value of $F_{long,\ max}$ is of the same order of magnitude for both tests, around 45 ton. This confirms reasonable repeatability given the large number of uncertainties related to the test setup. In test NO3 an Aframax tanker is considered in ballast condition and the longitudinal force decreases to 25 ton at this smaller draught.

Panamax: The Panamax size vessels are shorter and less wide than the Aframax size tankers. The measured forces for this vessel class are also significantly lower than for the Aframax class: 25 – 30 ton.

Handysize: Compared to the Panamax-type vessels, the length of the Handysize class vessel is much smaller, the draught is only slightly smaller and the beam is similar. The measured forces are similar to those found for the Panamax size vessels: 25 ton. Based on these results it is concluded that the length of a vessel is not a dominant factor for the longitudinal force during a lock-exchange.

Handysize-wide: The vessel that is considered in this class has same overall dimensions as in the Handysize class, but is significantly wider. The larger beam results in an increase of 10 ton for the maximum longitudinal force: 35 ton.

Based on comparisons of the measurement results for the different vessel classes, the most important factors related to the main dimensions of the vessels governing the magnitude of longitudinal forces during a lock-exchange can be identified: the draught of the vessel is important (Aframax loaded vs ballast conditions), the beam of the vessel is important (Handysize vs Handysize-wide) and length is of less importance (Panamax vs Handysize). These results confirm that the blockage of the wet cross-section is a dominant factor that determines the forces due to density driven currents. The relation between the measured forces and the blockage is illustrated in Figure 7, showing the results presented in Table 8 graphically.

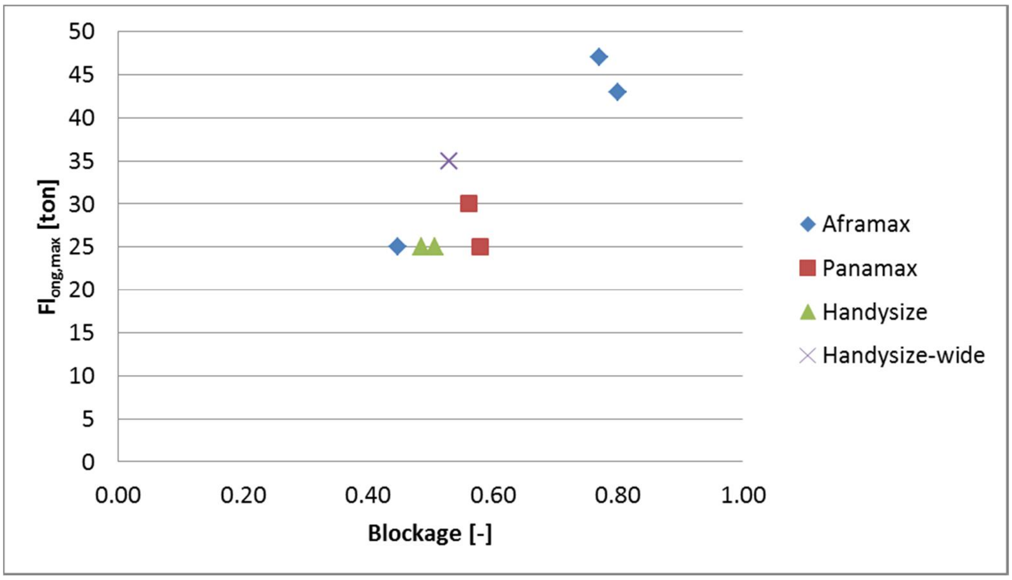

Figure 7: The measured maximum longitudinal force as function of blockage (A_{vessel}/A_{lock}).

Because in the scale model tests of the new locks of IJmuiden and Terneuzen a vessel (*The Flying Dutchman*) is considered that is comparable in size to an Aframax tanker, the results of tests NO1, NO2, and NO3 will be used to find a relation between the physical scale model measurements and the field measurements. This comparison provides insight in how much lock-exchange forces may change for these types of vessel in a larger lock.

7 COMPARISON OF DATASETS

When comparing the different datasets, the main challenge is that the tested conditions vary between the dataset. Not all tests have been conducted with the same density difference for example and often multiple parameters are varied at the same time, which makes inter- or extrapolation between the tests not straightforward. To allow for a fair comparison between the different locks, it is necessary to identify the dominant factors influencing the forces during a lock-exchange. This is possible using all measurement data, because the data sets are quite extensive and consider many hydraulic variations. Below the most important factors are identified that influence the water level slopes over the vessel during the lock-exchange.

- Density difference: a larger density difference over the gate at the moment that the gate opens will result in a stronger lock-exchange and higher forces on the vessel. The density difference will be influenced by the preceding levelling process, by meteorological circumstances, and to a certain extent also by previous lockages.
- Blockage: a larger blockage will generally result in a larger density difference over the length of the vessel, which leads to higher forces.
- Relative under keel clearance: the relative under keel clearance is defined as water depth divided by draught of the vessel. The more a vessel is positioned in the upper part of the water column, the larger the forces will be. Furthermore, a larger water depth will lead to a stronger lock-exchange and to larger forces.

- Transversal asymmetry: the magnitude of transversal forces will increase when the difference in density distribution on both sides of the vessel increases. This will be the case when transversal asymmetry, which is often related to the beam of the vessel, increases. When there is no asymmetry - e.g. a vessel is moored in the centerline of the lock- no transversal forces due to density differences will occur.

Most of these aspects are closely interrelated and they are sometimes counteracting each other. For example, a larger water depth will often go hand in hand with lower blockage ratios. As the one will generally lead to an increase and the other to a decrease of lock-exchange forces, it is often hard to predict on beforehand in what situation the largest forces will occur. By selecting individual tests from different datasets, in which only one parameter was varied these general trends could be identified. This is illustrated in Figure 8, in which tests are compared with the same density difference and blockage. The relative under keel clearance, dependent on water depth and draught, varied between the tests, showing larger forces for the tests in which the vessel was more located in the upper part of the water column (corresponding with a larger value of the relative under keel clearance). Note that the transversal asymmetry also varies between the tests (i.e. vessels with a different beam in the tests in North Lock and different lock widths for the tests with *The Flying Dutchman*), but this mainly influences the transversal forces and not the maximum longitudinal forces.

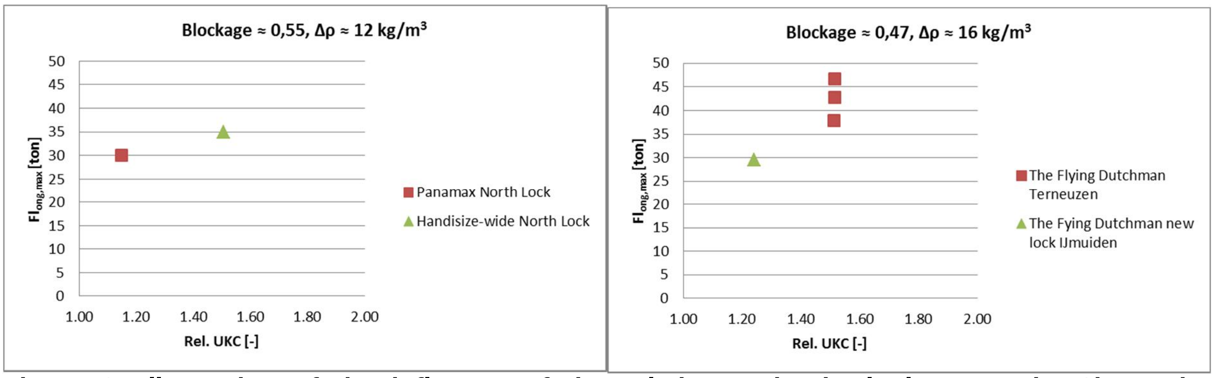

Figure 8: Illustration of the influence of the relative under keel clearance (UKC) on the maximum longitudinal force for test with similar density difference and blockage. Left panel: outer head tests in the North Lock of IJmuiden for two different vessels (field measurements). Right panel: inner head tests for two different locks with *The Flying Dutchman* (scale model measurements).

Taking into account the dependencies mentioned above, the datasets described above are compared and the main findings are summarized below:

In the North Lock, the measured longitudinal forces during the lock-exchange at the outer head exceed the formal force criteria for levelling for Aframax-size vessels by approximately a factor of two. For a similar size vessel in the new lock of IJmuiden the measured forces in the physical scale model were even higher. But it should be considered that in the physical scale measurements a homogeneous density difference of 16.5 kg/m^3 was present and the in the field measurements in the North Lock the density difference is estimated at 12 kg/m^3. When the results are corrected for this difference, it is likely that the longitudinal forces at the outer head will increase only lightly, by approximately 0 % - 20 %, in the new lock of IJmuiden under similar circumstances. The main reason for the relatively small force increase is that the blockage in the new lock is a factor 2 smaller than in the North Lock for the same ship, although the lock itself is much deeper. For the transversal forces at the outer head not enough information is available to make a good comparison between the North Lock and the new lock of IJmuiden.

When comparing the new lock of IJmuiden to the North Lock for inner head lock-exchanges, the two most important factors are also the larger water depth in the new lock and the smaller relative blockage due to the larger lock dimensions. From the results presented in Table 6 follows that, by comparing test IJM3 and IJM4 with different draughts, the influence of blockage is not as pronounced for the inner head as for the outer head. It is therefore assessed that the longitudinal forces in the new lock of IJmuiden will remain comparable to the North Lock for similar size vessels. The transversal forces will increase however, as a result of the increase in asymmetry due to the larger lock width.

For the design vessel of the new lock of IJmuiden, the lock-exchange forces will be larger than for the smaller Aframax-size vessels. The maximum forces will not increase exactly proportional to the displacement of the vessels (displacements differ by almost a factor 2), but the increase in forces will be a little smaller. It is expected that under similar conditions the lock-exchange forces on the design vessel will be one and a half times larger than on an Aframax-size vessel.

In the new lock of Terneuzen, larger longitudinal forces than in the new lock of IJmuiden can be expected for similar vessels. This is mainly due to the fact that the water depth in lock chamber is typically larger in Terneuzen than in IJmuiden, due to the higher level of the canal. As a result of the larger water depth, the lock exchange will be stronger. Transversal forces are comparable between the new lock of Terneuzen and IJmuiden, although the asymmetry will be larger in the new lock of IJmuiden.

The insights described above are summarized in Table 9. The situations for which it was not possible yet to give a good estimate of typical magnitudes of lock-exchange forces are indicated with a question mark.

Table 9: Relative comparison of the maximum forces during lock-exchange between the currently operational North Lock and the new locks of IJmuiden and Terneuzen.

Situation		Outer head		Inner Head	
		$F_{long,\,max}$	$F_{trans,\,max}$	$F_{long,\,max}$	$F_{trans,\,max}$
A	Aframax-size vessel in the North Lock	1	1	1	1
B	Aframax-size vessel in the new lock of IJmuiden	~1.1 x A	?	~A	> A
C	Design vessel in the new lock of IJmuiden	~1.5 x B	~1.5 x B	~1.5 x B	~1.5 x B
D	Design vessel in the new lock of Terneuzen	> B	~ B	> B	~ B

8 SUMMARY

The presented physical scale model studies and field measurements yielded new insights into the dominant factors that are important in lock-exchange processes of sea locks. The results of these studies have been used to determine requirements for lock operations for the future largest locks in the Netherlands, at IJmuiden and Terneuzen. The hydrodynamic forces that develop during a lock exchange process are influenced by many factors and it is therefore difficult to predict on beforehand in what situation the largest forces will occur.

It has been shown that hydrodynamic forces on a vessel during a lock-exchange will often exceed the forces during levelling. These larger forces can typically be coped with by operational measures, because the operation of unmooring and sailing out of the lock is different than line handling during the levelling process itself. However, in the design of new sea locks, one should be aware of the potentially large forces due to density currents when the gate opens and these lock-exchange effects should be studied as an integral part of the design of the lock.

After the results of the field measurement campaign and physical scale model results have been compared, it was concluded that in the future situation larger forces on vessels may be expected than currently experienced in the existing large sea locks. The results of the presented studies will help pilots to prepare on how to handle the larger vessels in the future largest locks in IJmuiden and in Terneuzen.

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