Evaluation of hydraulic and nautical performance of Sea lock IJmuiden after two years of operation

van der Hout, A. J.; Schotman, A. D.; Kempenaar, R.; Kortlever, W. C.D.

Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 35th PIANC World Congres 2024

Citation (APA)
van der Hout, A. J., Schotman, A. D., Kempenaar, R., & Kortlever, W. C. D. (2024). Evaluation of hydraulic and nautical performance of Sea lock IJmuiden after two years of operation. In J. S. Schoonees (Ed.), *Proceedings of the 35th PIANC World Congres 2024* (pp. 1411-1417). PIANC.

35th PIANC World Congress, 29 April – 3 May 2024, Cape Town, South Africa
Paper Title: Evaluation of hydraulic and nautical performance of Sea lock IJmuiden after two years of operation
Authors Names: AJ van der Hout, AD Schotman, R Kempenaar & WCD Kortlever

Evaluation of hydraulic and nautical performance of Sea lock IJmuiden after two years of operation

AJ van der Hout[1,2], AD Schotman[3], R Kempenaar[3] & WCD Kortlever[4]
1 Deltares, The Netherlands; Arne.vanderHout@deltares.nl
2 Delft University of Technology, The Netherlands
3 Pilot Association Amsterdam-IJmond, The Netherlands
4 Rijkswaterstaat GPO, Ministry of Infrastructure and Water Management, The Netherlands

Abstract: On the 26th of January 2022 the new Sea Lock IJmuiden in the Netherlands was officially opened. Before the lock was put in use, two in-situ measurement campaigns have been carried out to verify the performance of the lock and after one year of operation a third measurement campaign was performed. The present paper provides an overview of these three monitoring campaigns conducted in the first two years of operation. The measurements verified that the lock performed within predetermined requirements and outcomes of the measurements were used to derive safe procedures for vessel handling during lockage. The findings were in good agreement with expectations from physical scale model research and numerical simulations performed earlier in the design process of the lock. For Sea lock IJmuiden, density currents play a major role in the lock operation. Better understanding of these processes led to a safer lock operation. A fundamental aspect for the success and usefulness of these measurement campaigns was the cooperation between all parties involved in the locking process.

Keywords: Navigation lock, Density currents, Mooring line forces, Levelling, Lock exchange

Introduction

On the 26th of January 2022 the new Sea Lock IJmuiden in the Netherlands was officially opened. Sea lock IJmuiden is one of the largest navigational locks in the world, with a lock chamber length of 545 m, a width of 70 m and a water depth of 18 m. The new sea lock is part of the IJmuiden locking complex which consists of 5 navigation locks and one discharge sluice (Figure 1). The new lock provides large sea-going vessels access to the Port of Amsterdam, now and in the future, and on the long term the lock is intended to replace the North Lock, which has been in service for almost 100 years.

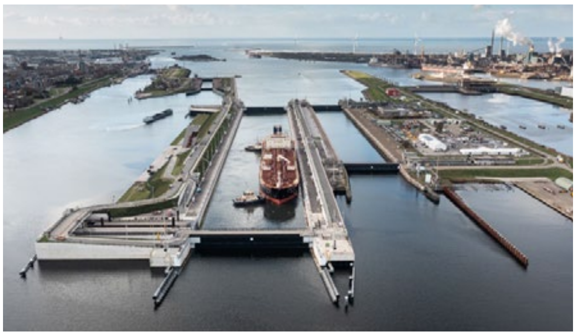

Figure 1 IJmuiden lock complex, with Sea lock IJmuiden in the middle and the North lock on the right side. Looking from the North Sea Canal towards the North Sea (Source: Rijkswaterstaat).

During the design of the lock, extensive hydraulic studies have been carried out for the design of the levelling system and to optimize locking operations, ensuring a safe and efficient levelling process. The hydraulic studies consisted of a combination of numerical model studies [1] and several physical scale model test campaigns [2], [3], [4], [5], and [6], and a field measurement campaigns [7] and [8]. Density currents during levelling formed a key-element in the design of the levelling system. Besides the levelling process, the subsequent lock-exchange proved to be the dominant physical process leading to large hydraulic forces on the vessels in the lock.

Before the lock was put in use, two in-situ measurement campaigns have been carried out to verify the performance of the lock. After little over a full year of operation, a third four-week monitoring campaign has been conducted. The three measurement campaigns had each a different objective:

- Campaign 1: Verification of the performance levelling system;
- Campaign 2: Establishing nautical procedures;
- Campaign 3: Optimizing nautical procedures, focussing on multiple ships in the lock chamber.

The present paper provides an overview of these three monitoring campaigns conducted in the first two years of lock operation. Below, the setup of each measurement campaign is provided, and their main outcomes are described. The paper provides an overview of the lessons learned, considering practical experiences obtained during operation and reflects on how the actual operation of the lock compares to assumptions made during the design.

Used measurement equipment

Density and water level

As density currents in the lock chamber play a crucial role in the operation of Sea lock IJmuiden, much attention was paid to measure density distribution in all three measurement campaigns. Density currents do not only largely influence the levelling process but also induce large forces on (moored) vessels in the lock and are thereby a dominant aspect for nautical operations. For the interpretation of the locking operation, it was therefore fundamental to know the density distribution in the lock chamber and approach harbours during levelling and entering and leaving of the lock. Next to density measurements, also the water level was monitored to measure leveling times and discharge curves and establish discharge coefficients of the levelling system.

Water levels and density were measured using up to 25 CTD sensors, measuring conductivity, temperature, and pressure. The instruments used were CTD-Divers of vanEssen Instruments ([9], Figure 2), type DI271 with a pressure range of 10 m and type DI272 with a pressure range of 50 m. The divers with a larger pressure range were applied at larger depth and the sensors with a smaller pressure range near the surface. Since accuracy of the latter sensor types have a larger accuracy (±0.5 cm), these pressure readings were used to determine the water level elevation.

Figure 2 CTD diver used during the measurement campaigns (Source: vanEssen Instruments).

The measured conductivity and temperature are converted to density using the UNESO-1981 (Sea water) formula [10]. Conductivity σ [mS/cm] and temperature T [°C] are converted to salinity S [-] (expressed in PSU, *Practical Salinity Unit*) following:

$$r_t = 0.6766097 + 2.00564 * 10^{-2}T + 1.104259 * 10^{-4}T^2 \ldots -6.9698 * 10^{-7}T^3 + 1.0031 * 10^{-9}T^4$$

$$\sigma(35,t) = r_t * \sigma(35,15), with\ \sigma(35,15) = 42.910$$

$$R_t = \sigma(S,t)/\sigma(35,t)$$

$$S = 0{,}0080 - 0{,}1692R_t^{1/2} + 25{,}3851R_t + 14{,}0941R_t^{3/2} - 7{,}0261R_t^2 + 2{,}7081R_t^{5/2} + \Delta S$$

$$\Delta S = \frac{(T-15)}{1+0{,}0162(T-15)}(0{,}0005 - 0.0056R_t^{1/2} - 0.0066R_t \ldots -0{,}0375R_t^{3/2} + 0{,}0636R_t^2 - 0{,}0144R_t^{5/2})$$

And then salinity S [-] to density ρ [kg/m^3]:

$$\rho_0 = 999{,}842594 + 6{,}793952 * 10^{-2}T - 9{,}095290 * 10^{-3}T^2 + \ldots 1{,}001685 * 10^{-4}T^3 - 1{,}120083 * 10^{-6}T^4 + 6{,}536332 * 10^{-9}T^5$$

$$A = 8{,}24493 * 10^{-1} - 4{,}0899 * 10^{-3}T + 7{,}6438 * 10^{-5}T^2 - \ldots 8{,}2467 * 10^{-7}T^3 + 5{,}3875 * 10^{-9}T^4$$

$$B = -5{,}72466 * 10^{-3} + 1{,}0227 * 10^{-4}T - 1{,}6546 * 10^{-6}T^2$$

$$C = 4{,}8314 * 10^{-4}$$

$$\rho = \rho_0 + AS + BS^{3/2} + CS^2$$

Based on pressure and the density of the water, the height of the water column above the sensor can be computed, and since the vertical position of the sensors was known, the surface elevation could be determined.

Mooring forces

In measurement campaign 2, also forces in the mooring lines of vessels moored in the lock chamber were measured by four load cells (EMHA – Techno Fysica). Two types of load cells were used for this, with a capacity of 55 ton and 85 ton. The load cells could be read out in real-time via a wireless connection, using a sample frequency of 1 Hz. The accuracy of the load cells was 1% of the full measurement range.

Figure 3 Mooring force measurement setup.

Figure 3 shows the test setup used to measure mooring line forces. A load cell was connected to a bollard by a sling. When a vessel approached the linesmen connected the mooring lines to the other end of the load cell using a soft sling. In case double mooring lines were used, both lines were connected to one load cell. The test setup was designed to be flexible, meaning that the load cells could be placed on all bollards in the lock, depending on the selected mooring position of the vessel.

Lock operation
During all test campaigns the operation of the lock itself was also monitored. The parameters that were logged and used for analysis included the position of the gates and the position of the levelling valves. In measurement campaign 2 and 3 also the position of the vessels was monitored and experiences by the pilots were collected.

Measurement campaign 1 – Levelling system verification tests

Objective
Before the lock was put in service, a series of acceptance tests were carried out. One of these acceptance tests was the verification of the performance of the levelling system. The tests were carried out in June 2021, and were commissioned by the contractor that build the lock, OpenIJ. The objective of the test campaign was twofold:

- To measure levelling times and compute discharge coefficients of the leveling system, and verify that discharge curves matched design requirements;
- To verify the working of the permanent measurement system installed for the operation of the lock.

During the design of the lock extensive hydraulic studies have been performed using a physical scale model and numerical models. The levelling system was designed to meet certain levelling times for different head differences [3]. For small head differences, relatively straightforward valve lifting programs could be used with a constant lifting speed. However, for larger head differences more complex lifting programs had to be applied to limit the hydrodynamic forces on moored vessels, mainly due to density currents in the lock chamber. The present verification tests assessed whether measured discharge curves met design requirements, which was a contractual responsibility of the contractor (OpenIJ). If the measured discharge curves would be similar the ones established in the physical scale model research, desired leveling times would be met and hydrodynamic forces on moored vessel during leveling would stay within acceptable (safe) limits. All tests were therefore carried out without vessels being present in the lock.

The tests have been performed during spring tide to have a head difference that was as large as possible. In test campaign 1, a total of eight levelling tests were performed, both filling and emptying the lock chamber. The first four levelling tests were conducted with constant valve lifting speed to accurately determine the properties of the leveling system, i.e., discharge coefficients. In the last four tests, real (more complex) lifting programs were applied, corresponding to the head difference that was present at that time. The measured water levels were compared to design criteria using the numerical model LOCKFILL [11], which was calibrated earlier on physical scale model results.

Measurement setup
The measurements were aimed to accurately measure the levelling process. For this, especially the water level in the lock chamber needed to be monitored precisely. At 6 locations in the lock chamber the water level was measured using a CTD-divers installed at a level approximately 1.5 m below mean sea level. At two of those locations, close to the lock gates, an array of 5 CTD-divers was used to measure the vertical density distribution. Next to that, in each approach harbor and array of 5 CTD-divers was placed to measure the density distribution and water level there, see Figure 4. In the arrays, the 5 CTD-divers were equally distributed over the entire water depth with a mutual distance of approximately 4 m.

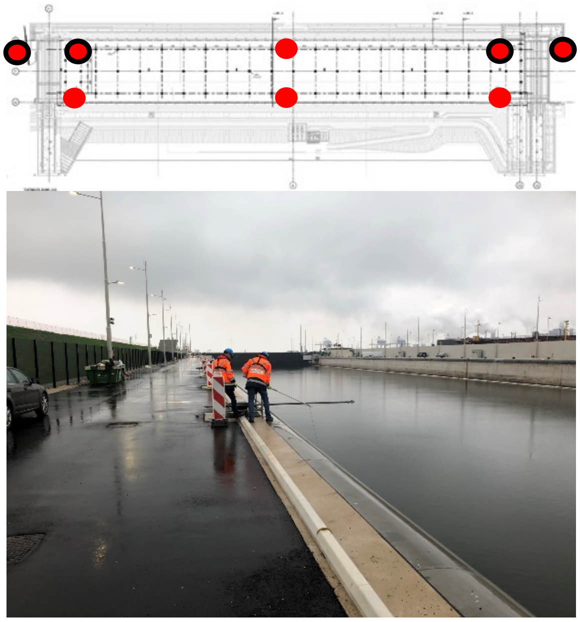

Figure 4 Top: measurement locations in test Campaign 1. Red dots indicate a single CTD-diver, red dots with a black line indicate and array of 5 CTD-divers. Bottom: collecting the CTD-divers after a measurement to process the results.

To be able to measure water level slopes in the lock chamber and free surface effects, like translatory waves, a sample frequency of 1 Hz was applied.

Main outcomes
Figure 5 shows a typical measurement result for a test with a constant valve lifting speed. The left

panel shows the measured water levels in lock chamber (red line), outer approach harbour (blue line), and inner approach harbour (black line). The right panel shows the corresponding change in water level in time, i.e., discharge curve. The presented test is a filling test on the seaside without a density difference present over the active gate.

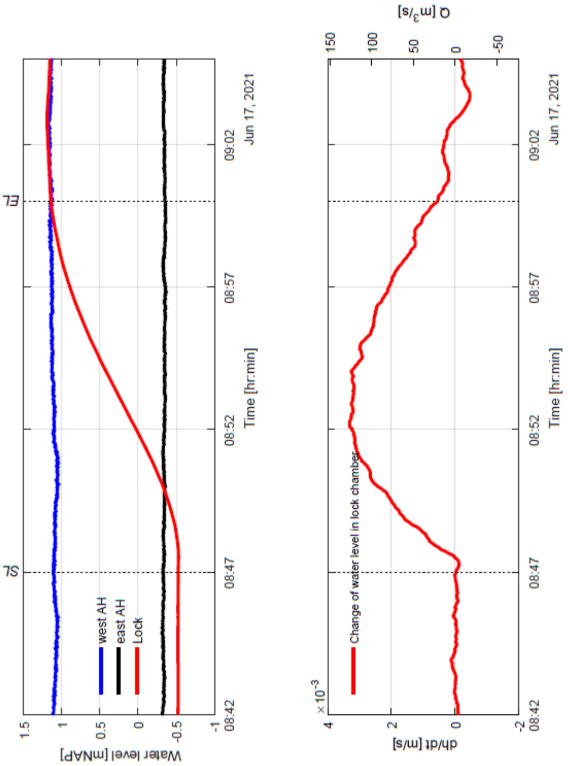

Figure 5 (rotated 90 degrees for readability). Left panel: measured water levels in approach harbours and lock chamber (red line). SL and EL indicate start and end leveling respectively. Right panel: corresponding discharge curve (change in water level in time).

The main conclusions from the test results were:

- The measured discharge coefficients corresponded well to designed values. At small valve openings, measured discharges were a little higher than expected and at large valve openings discharges were slightly smaller. Differences were small enough to keep the lifting programs as established prior in the physical scale model research.
- The permanent measurement system for lock operation and the levelling system itself performed within requirements.
- An attention point showed to be the measurement of water level difference over the active gate. Before the gate is allowed to be opened, the water level difference over that gate (actually, a pressure difference measured at the height of the valve opening) needs to be below a certain threshold value. When instantaneous values are used, (short) free surface effects may lead to oscillations around this threshold value, causing gate operation to stop. Some smoothing (averaging) of measured values is therefore needed. This may however elongate levelling times. When defining contractual requirements for leveling times in the design phase, this aspect was not sufficiently addressed.

After successful completion of the verification of the performance of the leveling system, the lock was accepted by Rijkswaterstaat and focus then turned to the nautical operation of the lock, described in next Section.

Measurement campaign 2 – Nautical test weeks

Objective

Prior to the opening of the lock, nautical test weeks were organized. The objective of these tests was to let users (pilots, lock operators, linesmen, tugboat drivers, etc..) get familiar with the lock and to establish clear nautical procedures to ensure safe locking operations.

As part of these nautical test weeks, density distribution and mooring forces were measured for a period little over 4 weeks. The test programme was designed in close cooperation between Deltares, the pilots, Rijkswaterstaat, Port of Amsterdam and other involved parties. Based on hydraulic design studies. it was expected that large mooring forces would occur due to density currents, especially during the lock exchange phase (see, [2] to [8]). Therefore, much attention was paid to the procedures of line handling during this phase and to ship behaviour when sailing in or out of the lock chamber.

Measurement setup

The mooring line forces were measured using 4 the load cells described before. The density distribution in the lock chamber was measured by 5 arrays of 5 CTD-divers equally spread over the full depth of the lock. Figure 6 shows the location of the CTD-diver arrays. Since the main interest was now on relatively slow processes (density currents) and not on the levelling process itself, a sample rate of 10 s was applied. Next to these semi-permanent density measurements, also manual density profile measurements were conducted in approach harbours on regular basis. These measurements provided additional information on the density difference over the lock complex.

The sensor arrays were placed strategically to provide insight in density variation over the length and width of a vessel. For inbound vessels, sailing from sea towards the canal, large transversal forces were expected and two arrays on opposite sides of the lock chamber were placed to provide insight in transversal density differences. For outbound vessels, sailing from canal to sea, large longitudinal forces were expected, and arrays were placed to provide most insight in longitudinal density differences.

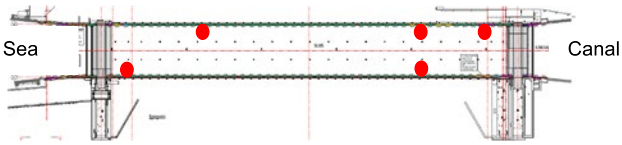

Figure 6 Measurement locations in test Campaign 2. Red dots indicate array of 5 CTD-divers.

During the present measurement campaign four types of tests were carried out:

- Floating tests
  After releasing the mooring lines, the vessel floated out of the lock chamber without propulsion, driven by the density current of the lock exchange. Vessel motion was monitored, and tugboats were kept standby for safety. These tests gave insight in where vessels would tend to go and how much time pilots would have to respond adequately.
- Manoeuvring tests
  Normal entry and exit manoeuvres were executed. Experiences of pilots were collected, and manoeuvring strategies were evaluated.
- Mooring force tests
  The vessel is kept in place by mooring lines during levelling and a large part of the lock exchange to measure mooring forces.
- Sway-away tests
  An alternative method of releasing the mooring lines is investigated, resulting in controlled vessel motions, while reducing mooring line forces.

Main outcomes
A more elaborate description of the outcomes is provided in [12]. Here, only the highlights are discussed.

A typical result of a mooring force test is shown in Figure 7. A clear relation between density differences and mooring line forces was observed. The order of magnitude of forces was in line with expected values, based on previous physical scale model research. In the presented test result in Figure 7, the combined force in two bow hawsers reached up to 68 tons, thereby exceeding the maximum break holding capacity of the winch.

The density and force measurements showed that the forces resulting from the lock exchange are significant and can exceed the break holding capacity of the winches shortly after opening the lock gate, potentially leading to uncontrolled ship movements. It has also been observed that winch brakes slip more in practice than they should theoretically. For inbound vessels, density currents mainly push the bow of the vessel away from the quay wall, thereby creating large forces in the bow hawser. For outbound vessels, the largest forces are directed in longitudinal direction, pushing the vessel out of the lock chamber towards sea.

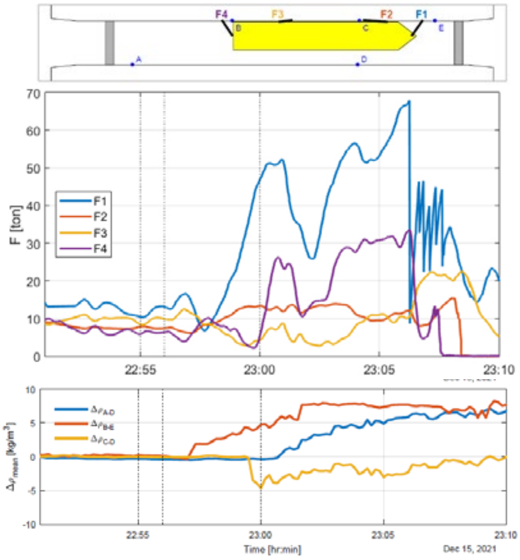

Figure 7 Measured forces (middle panel) and corresponding mean density differences between the different CTD-arrays (bottom panel), for a ingoing Capesize vessel with a mooring configuration shown in the top panel.

For incoming ships, releasing the fore spring and aft mooring line before the door is fully open appears to be a good tactic, so-called shearing, to reduce mooring line forces in the mooring lines to an acceptable level. The ship must have sufficient space in the lock chamber to be able to move away from the lock wall in a controlled manner. For outgoing ships, the same tactic is less effective.

When approaching the lock, opening the lock gate must be properly timed. Opening the lock gate too late may lead to strong density currents which may adversely affect ship manoeuvring while entering. Opening the gate too early may lead to unnecessary salt intrusion in the freshwater system. A safe and workable compromise must be chosen, considering nautical interests and wishes to reduce salt intrusion as much as possible.

The results of the measurement campaign have been discussed extensively with the different stakeholders. Based on the findings from the Nautical Test Period, nautical procedures for the IJmuiden Sea lock have been established.

Measurement campaign 3 – Optimizing nautical procedures

Objective

Since the Sea Lock IJmuiden came in to use in 2022, the number of lockages has been minimized as much as possible to reduce salt intrusion into the freshwater system. Due to the relatively large volume of the lock chamber, it contributes much more to the salt load into the Noth Sea Canal than the other locks in the IJmuiden complex. The IJmuiden Sea Lock will only be fully operational in 2025 when additional mitigating measures against salt intrusion further upstream in the canal have been finalized.

As measurement campaign 2 showed that large mooring line forces could during the lock exchange, which could be managed well with careful line handling and vessel operation, little knowledge was available how multiple vessels in the lock chamber would interact with each other. Due to the limited use of the lock, and since measurement campaign 2 was conducted under well controlled circumstances, more knowledge was needed to assess whether the nautical procedures could be optimized under regular operation. The main questions that remained after measurement campaign 2 were:

- What size of ships can be moored safely next to each other (inbound vessels)
- How does the density distribution in the lock chamber affect manoeuvring behaviour of ships sailing out of the lock (outbound vessel)

In February and March 2023, the North lock (the second largest large navigation lock in the IJmuiden complex) was temporarily out of service for maintenance. During (part of) this period, density measurements were performed in Sea Lock IJmuiden and vessel behaviour was monitored. The aim of these measurements was to answer the abovementioned questions, by providing a good understanding of density currents under normal lock operation. Special attention was paid to the interaction of multiple ships in the lock chamber.

Measurement setup

Similar to the previous measurement campaigns, several arrays of CTD-divers were placed in the lock chamber and approach harbours to measure the density distribution. Each array consisted of 5 CTD sensors spread out equally over the depth of the lock. The location of the 4 arrays is presented in Figure 8, amounting to a total of 20 semi-permanent density measurements for a period of 29 days. Since the density difference over the lock gate when it opens is an important parameter for the strength of the lock exchange, and thereby the hydrodynamic forces on the vessel, arrays of CTD divers ware placed on both sides of each lock gate.

Next to the semi-permanent density measurements, manual density profile measurements were conducted on a regular basis, by lowering a separate CTD sensor into the water, to obtain higher resolution data on the exact shape of density profile over the vertical.

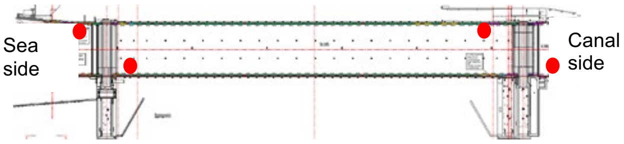

Figure 8 Measurement locations in test Campaign 3. Red dots indicate array of 5 CTD-divers.

The pilots monitored vessel behaviour during lock operation and experiences were collected for each vessel that transited the lock during the measurement period.

Main outcomes

The data collected provides a good understanding of what conditions occur during daily continuous use of the lock. Figure 9 shows an example of vertical density profiles measured. Figure 10 shows a typical example of how mean density changes in lock chamber and approach harbour over one day.

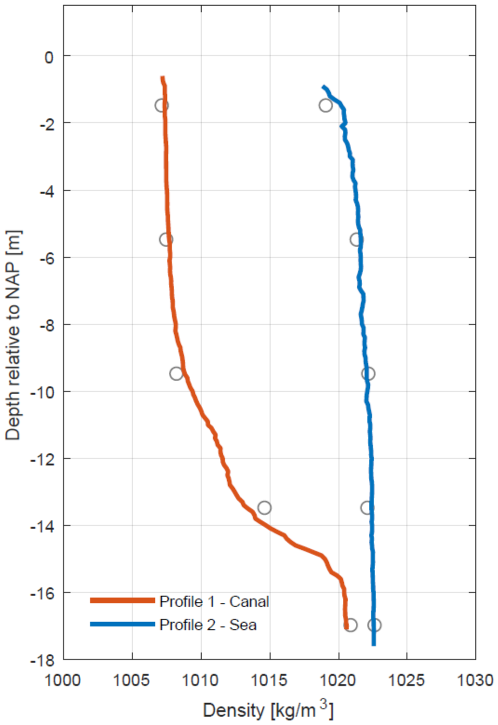

Figure 9 Density profiles in both approach harbours. Comparison between semi-permanent density measurements (grey circles) and manual profile measurements (solid lines).

The pilots used the measurement data to better explain the manoeuvring behaviour of ships during lock passages. These interpretations are presented in [12] separately. Based on the results of the measurement campaign, nautical guidelines for the use of the lock have been optimized, with now providing clearer guidance on which size of vessels can be moored next to each other and under what conditions. The measurements created more awareness and understanding of how density currents influence ship behaviour in Sea Lock IJmuiden.

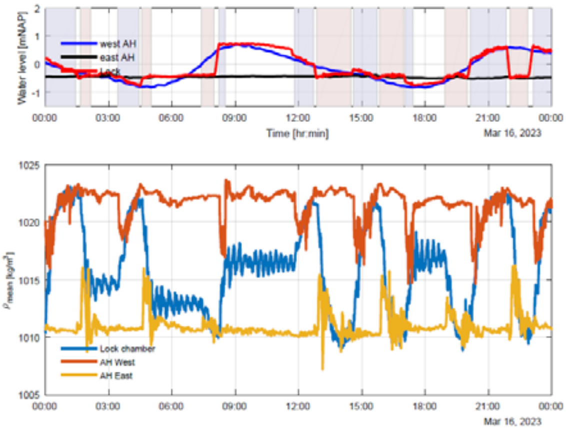

Figure 10 Top panel: variation of water level in the lock chamber (red line), inner approach harbour (black line) and outer approach harbour (blue line). The shaded rectangular areas show the moments the gates were opened (purple = outer gate, pink = inner gate). Bottom panel: mean densities in the lock chamber (blue line), outer approach harbour (orange line), and inner approach harbour (yellow line).

Conclusions

After completion of the Sea Lock IJmuiden three in-situ measurement campaigns were performed. These measurements verified that the lock performed within predetermined requirements and outcomes of the measurements were used to derive safe procedures for vessel handling during lockage. The findings were in good agreement with expectations from physical scale model research and numerical simulations performed earlier in the design process of the lock. The measurement results provided users of the lock - pilots, lock operators, linesmen, tug masters - important knowledge on dominant processes during levelling and lock-exchange. For Sea Lock IJmuiden, density currents play a major role in the lock operation. Better understanding of these processes led to a safer lock operation. A fundamental aspect for the success and usefulness of these measurement campaigns was the cooperation between all parties involved in the lockage process.

References

[1] O'Mahoney, T. S. D., and A. De Loor (2015), Computational fluid dynamics simulations of the effects of density differences during the filling process in a sea lock. In Proc., 7th PIANC SMART Rivers Conf. Brussels, Belgium: PIANC.

[2] Nogueira, I. S., T. O'Mahoney, A. van der Hout, and W. Kortlever. (2017), Effect of density differences on the forces acting on a vessel during locking operations. In Proc., 37th IAHR World Congress, 3710–3719. Madrid, Spain: International Association for Hydro-Environment Engineering and Research (IAHR).

[3] Kortlever, W. C. D., A. J. Van der Hout, T. S. D. O'Mahoney, A. de Loor, and T. Wijdenes (2018), Levelling the new sea locks in the Netherlands: Including the density difference." In Proc., Book of Abstracts, 34th PIANC World Congress, 127–144. Brussels, Belgium: PIANC.

[4] van der Hout, A.J., Nogueira, H.I.S., Kortlever, W.C.D., Schotman, A.D. (2018), Scale model research and field measurements for two new large sea locks in the Netherlands, 34th PIANC world congress, Panama 2018.

[5] Nogueira, H. I. S., P. Van der Ven, T. O'Mahoney, A. De Loor, A. J. Van der Hout, and W. Kortlever (2018), Effect of density differences on the forces acting on a moored vessel while operating navigation locks, J. Hydraul. Eng. 144 (6): 04018021. https://doi.org/10.1061/(ASCE) HY.1943-7900.0001445.

[6] Helena I. S. Nogueira, Arne van der Hout, Tom S. D. O'Mahoney, and Wim C. D. Kortlever (2024), The Impact of Density Differences on the Hydraulic Design of Leveling Systems: The Case of New Large Sea Locks in IJmuiden and Terneuzen, J. Waterway, Port, Coastal, Ocean Eng., 2024, 150(1): 05023002

[7] Schotman, A.D. (2017), Kolkuitwisseling in de Nieuwe Zeesluis een gevaar of niet? *Een onderzoek naar de krachten op zeeschepen als gevolg van de uitwisselingsstroming* (in Dutch), Thesis Master in Maritime Piloting Stodel, 22-12-2017

[8] van der Hout, A.J., Schotman, A.D., Hoff, T., Van der Veen, J.W., Quax, A. (2022), Innovative mooring in locks using ShoreTension: density and mooring force measurements in the North Lock IJmuiden, PIANC Smart Rivers 2022, October 18-21, Nanjing, China

[9] Van Essen (2023). Product manual. https://www.vanessen.com/products/data-loggers/ctd-diver/

[10] UNESCO (1981), The practical salinity scale 1978 and the international equation of state of seawater 1980. Tenth report of the Joint Panel on Oceanographic Tables and Standards (1981), (JPOTS), Sidney, B.C., Canada. UNESCO technical papers in marine science, No. 36.

[11] De Loor, A., O. Weiler, and W. Kortlever. (2013), Lockfill: A mathematical model for calculating forces on a ship while levelling through the lock head, PIANC SMART Rivers Conf. Brussels, Belgium, PIANC.

[12] A.D. Schotman, R Kempenaar, A.J. van der Hout and P. Valk (2024). How to take in service safely the biggest sea lock in the world? - A practical point of view on the nautical aspects from the Amsterdam Pilots, 35th PIANC World Congress, 29 April – 3 May 2024, Cape Town, South Africa.