Paper 55 - Computational Fluid Dynamics simulations of the effects of density differences during the filling process in a sea lock

O’MAHONEY T. S. D., DE LOOR A.
Deltares, Hydraulic Engineering, Delft, The Netherlands

Email (1st author): tom.omahoney@deltares.nl

ABSTRACT: This paper reports results from the application of Computational Fluid Dynamic (CFD) simulations of a leveling process in a sea lock using a fully 3D finite volume code (Star-CCM+). The model incorporates a free surface in the lock, saltwater density effects by means of a transport equation for salt, a turbulence model validated for negatively buoyant jet flows and a fixed ship. Mesh deformation with overset meshing is used for the moving door valves. The leveling system incorporates door openings with breaking bars. The lift head of the leveling process has a maximum of approximately 4.5m.

1 INTRODUCTION

The entrance from the North Sea to the Port of Amsterdam is at IJmuiden where a lock complex of 3 locks, the North Lock, the Middle Lock and the South Lock. A proposed new sea lock of 70m wide, 545m long and approximately 17m deep is being researched by means of a scale model at Deltares (see Figure 1 for the proposed location). As part of this research modern 3D numerical techniques have been used to simulate the flow during leveling and during the lock exchange process after the opening the lock gates. In this paper the simulations investigating the leveling process will be presented.

The engineering challenge of designing a leveling process at a lock stems from the trade-off between a fast leveling process and a safe one. In order to reduce the lockage times for ships the leveling should be as quick as possible. However, during the leveling process the forces on the ships, moored to bollards at the side of the lock, can be large. The different forces which can be present are as follows: forces due to translating waves, momentum decrease, friction, from the filling jet, but also due to differences in density along the length of the ship (Vrijburcht, 1991). In the 1D program LOCKFILL, developed by Deltares, these forces are calculated separately based on a schematization of the filling/emptying flow and the forces superimposed to predict a total force during the leveling process. CFD can be used to determine the parameters used in the LOCKFILL schematization (de Loor *et al*, 2013). The schematization involves a simplification, especially for the forces due to the filling jet and the density difference, which requires calibration to experimental results and is therefore not always generally applicable for a wide range of leveling systems. The application of a generic model would be a useful tool in lock leveling system design.

Figure 1: View of the proposed location of the New Sea Lock in IJmuiden (new lock superimposed in yellow)

At a sea lock, where the density difference between salt water and fresh water is large, the forces as a result of the density current in the lock can be the most important force during leveling. Owing to the buoyancy effects on the salt water jets as they enter the lock chamber the flow field can also be vastly different than the case without density differences. Including the effects of density difference in the 3D numerical simulations gives insight into this phenomenon.

The use of 3D CFD to predict forces on the ship during leveling has previously been investigated (Thorenz and Anke, 2013). In those simulations the CFD predicted longitudinal forces 50% higher than in the scale model experiments. The setup of the simulations with a vessel that rose with the water level is also very computationally expensive. As such, the prediction of forces on the ship with CFD is not yet practicable for a design project. However, qualitative and quantitative assessments of the flow pattern, without an attempt to predict forces on the ship, can be helpful in comparing different leveling systems, interpreting scale models results or assessing the relative importance of different physical phenomena, as is done in this paper for density differences.

In this paper 3D CFD simulations of the new sea lock at IJmuiden are performed. Firstly the resistance and discharge coefficients of the leveling system are calculated by means of a permanency test with a constant flow. For a given discharge, the drop in water level characterizes the total resistance of the system when the door valves are fully open. Good agreement is seen with the experimental measurements showing that CFD can be used to characterize resistances in this way. These CFD simulations are relatively short in duration.

Secondly a leveling process without a ship is simulated. The leveling system is steered by means of moving valves in the door which are simulated in the CFD model by means of an overset mesh algorithm in Star-CCM+. The discharge curve is a result of the CFD simulations. Comparison measurements of velocities in the lock chamber from the scale model tests are not available. Finally a leveling process with a ship present and a density difference is simulated.

The results show that CFD can be used in an early stage of lock design to make assessments of a design's viability but that a fully functioning virtual prototype of a lock in CFD needs more validation data of the complex flow fields in the lock chamber. Only limited results from the scale model of the lock are available for publication at this time.

2 SETUP OF THE CFD MODEL

2.1 *Geometry*

The geometry of the model is based on the scale model for the new sea lock at IJmuiden in the Netherlands. The CFD model is therefore at the same scale as the scale model, although some tests have been performed at prototype scale. The scale model is built with two leveling systems; one of gate openings and one with culverts. The systems are different at the western and eastern heads of the lock. The gate openings have breaking bars at the lock chamber side of the door at the western head, with the door valves at the sea side of the door. The door is identical at the eastern head meaning that the breaking bars are at the canal side of the door.

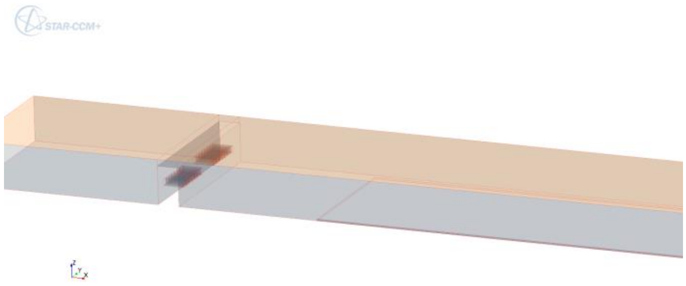

Figure 2: Geometry with gate openings, the approach harbor is on the left and the lock chamber is on the right

The door openings are placed relatively high in the door to reduce the residual lift head owing to density differences at the end of leveling. 14 gate openings are used in two sets of 7 symmetrically placed with respect to the lock's longitudinal centre axis.

The culverts have a much more complicated geometry. The restrictions in available space at the lock complex in IJmuiden necessitated that the culverts had to be fitted into a small space. At the eastern head leveling is achieved through the door recess; a comparable system is currently in operation at the North Lock in IJmuiden. At the western head one culvert runs underneath the lock chamber to exit opposite the other culvert. The current system at the North Lock with the culverts running around the outside of the gate recesses is not applicable because of the lack of space. Each culvert distributes the flow across a wide area using a grid of beams.

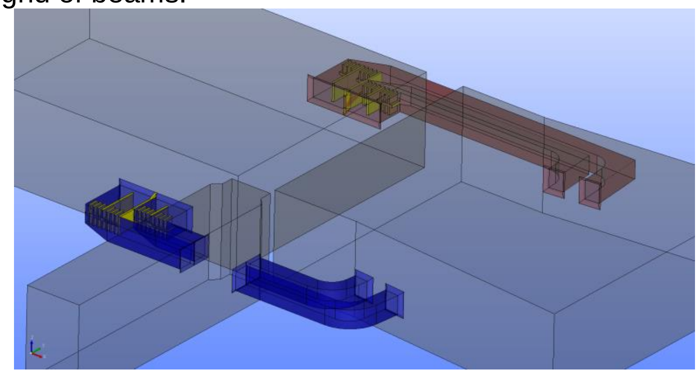

Figure 3: Geometry with culverts eastern lock head

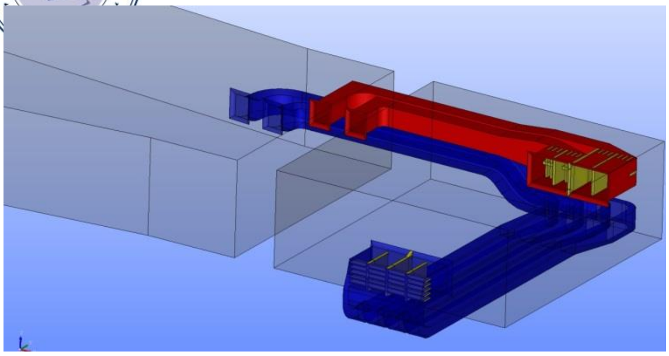

Figure 4: Geometry with culverts western lock head

2.2 *Mesh*

Meshes have been made with the Star-CCM+ Trimmer algorithm which uses a split-hexahedral algorithm to generate meshes that are aligned with the free surface and flow direction, in this case, whilst still resolving a complex surface in the geometry.

For the simulations of the leveling process, a moving door valve is added to the geometry by means of an overset mesh. The door valve does not have the detailed geometry of the valve in the scale model but rather a simplified geometry of a square plate with small thickness. The overset mesh is unstable for complex geometries when using the split hexahedral trimmer meshing algorithm. Using this method the valve could not be fully closed or fully opened at respectively, the beginning and end of the lifting programme. The newest version of the software claims to solve this issue but it has yet to be tested on this model.

2.3 *Numerical properties*

The numerical setup of the simulations uses an implicit time marching scheme which does not require a Courant Friedrich Levy (CFL) number of 1 for stability. Instead the time-step is determined by the stability of the free surface. In this application the free surface does not change rapidly and a timestep of 0.05 seconds is enough in all cases. This gives a CFL number of between 20 and 40. The order of the time discretization is first order. All other gradients, including the volume fraction for the VoF model, are discretized using second order schemes.

2.4 *Physical models*

All models are run with an Unsteady RANS formulation of the Navier-Stokes equations with a realizable k-ε turbulence model.

The simulations are run as a two-phase Volume-of-Fluid (VOF) model with air and water as the two phases. The free surface is captured with some mesh refinement but not sufficient to resolve waves on the surface. The cells are also stretched along the surface, with an aspect ratio of no more than 10.

For simulations with a density difference an additional scalar quantity, salt concentration, is added to the model. This adds an additional scalar transport equation to the model. The turbulent Schmidt number, a measure of the additional advection of the scalar quantity owing to turbulent eddies but modeled as an additional diffusion directly correlated to the eddy viscosity, is set to 0.9. The density of the water phase in this instance is dependent on the local concentration of this quantity, ranging from 1020 to 1000 kg/m3. An additional body force term is added to the momentum equations to represent the buoyancy force. Also density gradient terms are added throughout the Navier-Stokes equations but these terms are negligible because the density difference is limited to 2%.

2.5 *Boundary and inital conditions*

All walls in the domain are set as smooth no-slip walls. The assumption of smooth walls is appropriate for the scale model where the materials, stainless steel or Perspex are very smooth. For simulations at prototype scale a roughness should be assumed.

For the simulations of the discharge coefficient water level boundaries with hydrostatic pressure boundaries are set upstream and downstream. For simulations of a leveling process only the upstream boundary is set such, the downstream boundary being the end wall of the lock chamber. These boundary conditions do not force a specified mass flow; rather the mass flow is a result of the computation of pressure differences across the lock door. They also allow a dynamic pressure/velocity profile to develop at the inlet and outlet boundary rather than imposing a uniform flow here; this reduces the required computation domain.

The top boundary is set as an air boundary at atmospheric pressure.

All simulations are started at rest with negligible turbulence and water levels according to the appropriate water levels from the corresponding scale model test. In the case of the simulations of discharge coefficients the approximate end water level is set as an initial condition.

2 DETERMINING THE DISCHARGE COEFFICIENTS OF THE LEVELLING SYSTEM

2.6 *Introduction*

The discharge coefficients of the leveling system are a key parameter in a model for the determination of the discharge curves. Given the discharge coefficients at different valve position a simple hydraulic calculation can be performed to generate the expected discharge curve and leveling time for a given lifting programme of the valves. An a priori method of calculating the discharge coefficients of a levelling system without performing scale model tests is very desirable. For more information on the definition of the discharge coefficient and the validation of CFD for the calculation of such coefficients see van de Ven and O'Mahoney (2015).

2.7 *Gate openings*

For the tests with the gate openings, two configurations were tested, with and without the breaking bars. Only the discharge coefficients were determined for the configuration without breaking bars. Subsequently the choice was made to include the breaking bars in all the leveling tests.

The gate openings are 2.2m wide and 3m high in prototype scale. The channels through the door have a rectangular cross-section. At the opening on the western side of the door the corners are rounded off with a fillet of 30cm (see Figure 1).

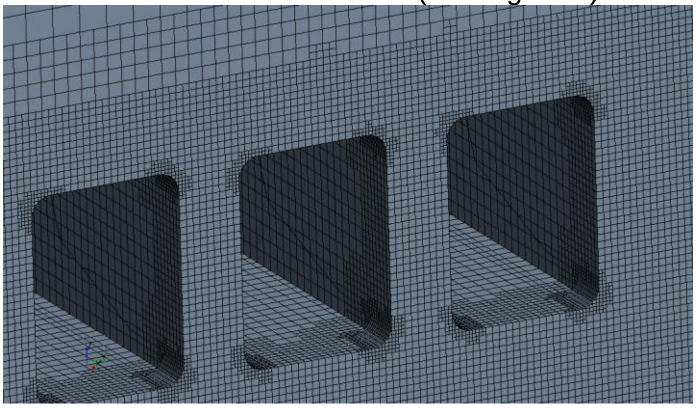

Figure 5: View of the surface mesh of the gate openings without breaking bars

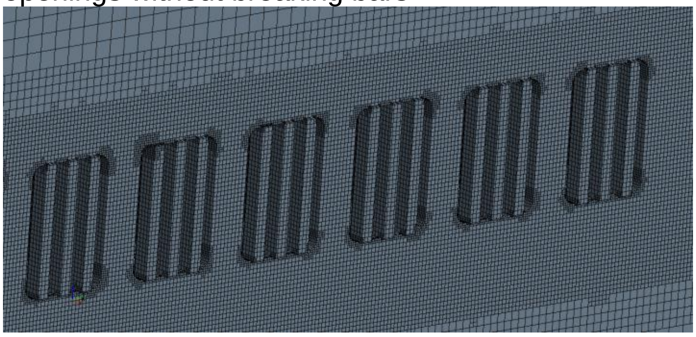

Figure 6: View of the surface mesh of the openings with breaking bars

When the breaking bars are present they are located on the lock chamber side of the door athe western lock head and on the approach harbor side of the door for the eastern lock head. Three vertical breaking bars, each of 30cm width, are evenly distributed across the opening (see Figure 2).

The simulations without the breaking bars show a jet which is more unstable than when the breaking bars are present. The venturi effect in the, caused by the separation at the entrance, is stronger when the extra resistance of the breaking bars is present. The high velocities of the flow in the door remain farther downstream when the breaking bars are not present, even though the blockage of the breaking bars creates locally high velocities between the bars.

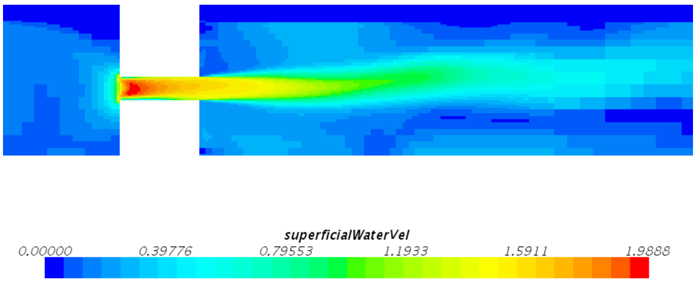

Figure 7: Contour plot of water velocity magnitude of the door valves without breaking bars

For the fully open door valve and an homogeneous density in approach harbor and lock chamber the jet remains horizontal in the lock chamber. Fluid in entrained from below and above the jet, causing recirculation along the bed and the free surface, flowing towards the door.

The discharge coefficients have been calculated for the gate openings at both prototype scale and model scale. The Values are slightly larger at prototype scale because the relatively little resistance in that case leads to relatively fewer losses owing to friction. Clearly less effect is small but not negligible.

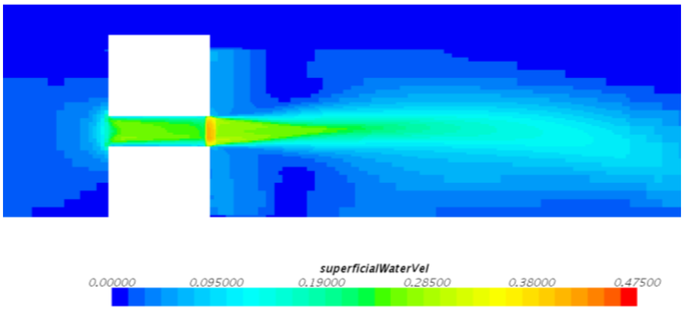

Figure 8: Contour plot of water velocity magnitude of the door valves with breaking bars

Table 1: Comparison of discharge coefficients for the gate openings

Case	CFD prototype	CFD model	Measurement
With breaking bars	0.52	0.50	0.49
Without breaking bars	0.84	0.82	0.76

The agreement of the CFD values with the measurements is good. The best agreement is seen when comparing the simulations at model scale, because the friction is more comparable. The openings with breaking bars show better agreement than without breaking bars. This is ascribed to the dominance in the determination of the discharge by the open surface area, which is very accurately recreated in the CFD. In the case without breaking bars the smaller geometric differences and small roughness elements (steel plates on the door not sitting perfectly flush with the openings) have a proportionally larger effect on the results and are not included in the CFD model.

2.3 *Culverts*

For the tests with the culverts separate tests were conducted for the eastern lock head and the western lock head. In all test the mouth of each culvert is similar, with a resistance screen of vertical beams in the wall, support structures splitting the exit into four chambers and fillets of between 1m and 1.5m at the chamber wall. The southern culvert mouth at the western lock head is somewhat different because of the asymmetry at that head. On the southern side the culvert runs underneath the lock chamber floor and makes a 180° turn in the vertical. Because of this the resistance screen as horizontal beams. An example of the mouth is given in Figure 5.

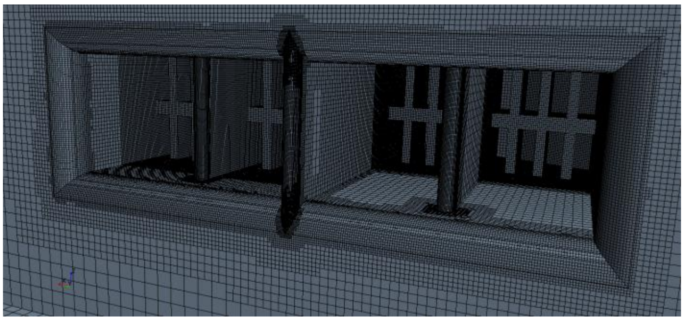

Figure 9: View of the surface mesh of the mouth of the culvert

The flow during a steady-state test is not necessarily symmetric as the resistances on the north and south sides are not equal if the valves are fully open. In a leveling process this can be corrected by asymmetrically opening the valves.

For the culverts at the eastern lock head the flow on the southern side goes through the gate recess, producing extra losses by fully open valves. Here the difference in discharge between north and south is relatively small and the flow in the lock chamber is largely symmetric. The steady-state nature of the flow conditions gives a situation different from a leveling process. Here the flow has developed fully such that the initial inertia of the jets in the lock chamber which starts at rest is gone. The jets are turned to the downstream boundary.

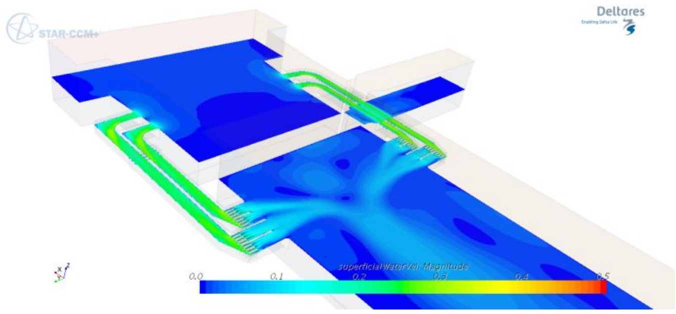

Figure 10: Contour plot of the water velocity magnitude for the culverts at the eastern lock head.

For the western lock head the flow is much more asymmetric with a higher discharge through the northern culverts. After the jets co-impinge at the centre of the lock chamber the flow is forced towards the southern wall.

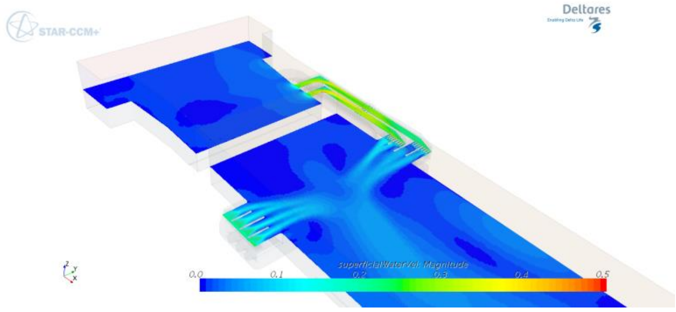

Figure 11: Contour plot of the water velocity magnitude for the culverts at the western lock head.

Table 2: Comparison of loss coefficients for the culverts

Case	CFD model	Measurement
Eastern lock head	2.82	2.85
Western lock head	2.42	2.47

The agreement of the measured loss coefficients with the calculated values is excellent. The loss is dominated by the restriction of the open area through the resistance screen in the lock walls and this is very accurately modeled in the 3D CAD geometry of the CFD model.

3 FLOW FIELD SIMULATIONS DURING THE LEVELLING PROCESS – FILLING AT THE WESTERN LOCK HEAD

3.1 *Levelling without ship or density differences*

Levelling tests have been simulated with moving door valves for the gate openings with breaking bars. In the first instance simulations were made for a homogeneous density distribution between harbor and lock, that is to say with freshwater. All simulations were made at model scale to enable 1:1 comparison with the measurements. All conditions in the text are converted to prototype scale but all figures are in the original model scale. The initial lift head for this run is 1.56m with a water depth in the lock initially 17.1m. The valves are lifted with a speed of 5mm/s. The valve is placed approximately 1m inside the western side of gate.

In Figure 12 a vertical cross section is shown of velocity magnitude contours at a moment when the valve is half open. At this point the flow rate is approximately at its maximum. The flow under the valve shows a venture effect from the narrowing owing to the separation at the valve tip and at the entrance to the duct. The jet that is formed stays attached to the bottom of the duct before it feels the resistance of the breaking bars (the vertical cross section is taken at a point between the breaking bars). The jet can entrain fluid from the area above but not from below. Owing to the resistance of the breaking the jet expands but only the area above it is available and it is given a trajectory in the vertical. This trajectory is continued into the lock chamber where the jet of water reaches the free surface.

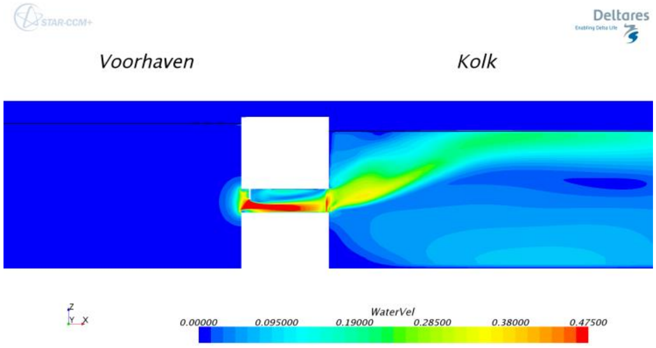

Figure 12: Vertical cross-section: water velocity magnitude with the door valve half open; leveling without density differences

In Figure 13 the leveling process is shown from a 3D view with an isosurface of velocity and vertical cross-sections at 35m and 50m from the door. These are the positions where the ship could come to lie. The isosurface of velocity shows the region where the velocity is 1m/s or more in prototype scale. The view is taken at the moment of the maximum extent of this high velocity region. The isosurface does not cross the 50m line and therefore it can be concluded that during the leveling process here the velocity is never higher than 1m/s at this cross section. That the high velocity region reaches the free surface is also clearly shown by the orange area. As the leveling process comes to an end the discharge decreases and the high velocity region within the isosurface decreases in size.

3.2 *Levelling without ship with density differences*

A leveling process through the door openings including density differences has been performed. For this case a saltwater approach harbor and freshwater lock chamber has been simulated. The valves are lifted with the same speed but the discharge curve is different, owing to the different pressure profile in the harbor is the initial pressure drop over the openings less than in the homogeneous case. However, the maximum discharges and the shape of the discharge curve are very similar. It is also known that the forces on the ship owing to the density flow can be very high.

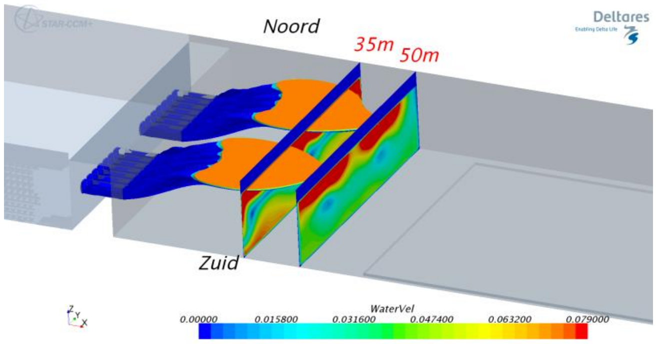

Figure 13: Isosurface of velocity, coloured by water level; plus, vertical cross-sections of water velocity magnitude contours at the stop lines. Door valve is half open; leveling without density differences

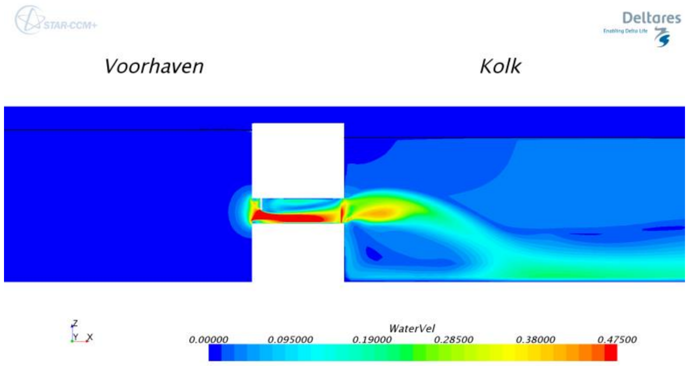

Figure 14: Vertical cross-section: water velocity magnitude with the door valve half open; leveling with density differences

Even though the discharge curves are similar between the case with and without density differences the flow pattern is very different (compare Figure 12 with Figure 14). The same mechanism at work in the homogeneous case gives the filling jet a vertical trajectory in the gate duct but the density differences in this case force the trajectory to bend downwards under buoyancy in the lock chamber. The saltwater entering the lock eventually flows along the bottom of the chamber (see Figure 15). The velocities are much higher in this case with the isosurface of velocity at 1m/s reaching beyond the 50m line, albeit with these high velocities only being achieved along the lock floor.

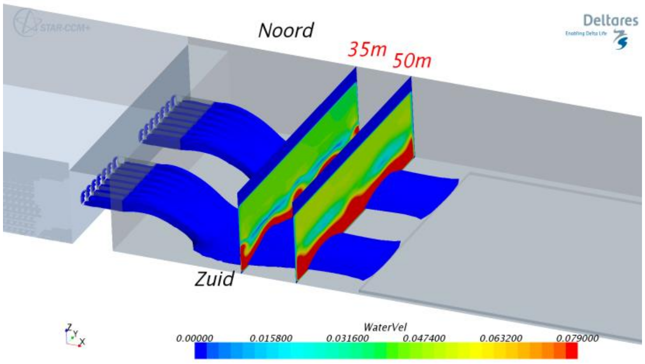

Figure 15: Isosurface of velocity, coloured by water level; plus, vertical cross-sections of water velocity magnitude contours at the stop lines. Door valve is half open; leveling with density differences

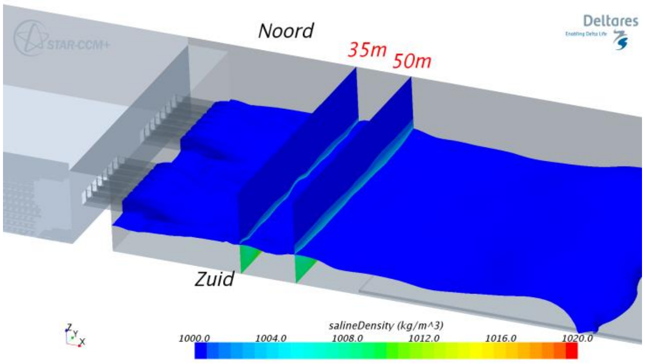

Figure 16: Isosurface of salt concentration; plus, vertical cross-sections of water density contours at the stop lines. Door valve is half open; leveling with density differences

Figure 16 shows the shape of the density current as it flows through the lock. The layer of dense fluid stays along the bottom and travels in a quasi 2D manner. The front head is very similar to the shape of a density current in a typical lock exchange flow (Benjamin, 1968, Shin *et al* 2004). In fact, the front travels with a nearly constant speed, just like in the lock exchange flow. The density of the water in the salt wedge is however not the same as the density in the approach harbor. Instead the saltwater entering the lock is mixed with the fresh water in the lock. As the front develops the fresh water is continually entrained, causing a recirculation of freshwater along the free surface in the direction of the lock gate. The density of the salt wedge depends on the amount of mixing and entrainment. In this simulation the density is 1008kg/m^3. The amount of mixing is also very important for the eventual forces which the ship experiences. This value can also be used to estimate the important parameter, the entrainment coefficient, in the schematization of the density flow in the 1D program LOCKFIL.

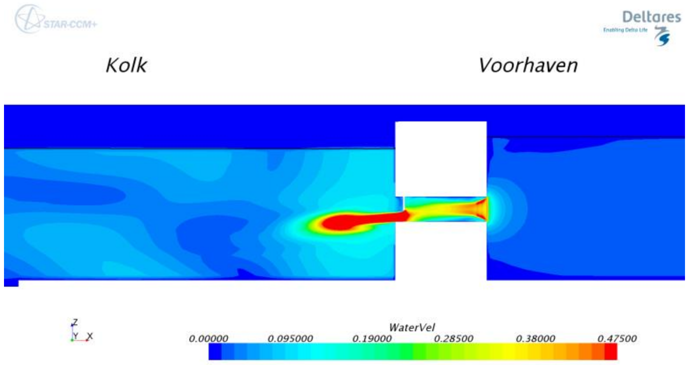

Figure 17: Vertical cross-section: water velocity magnitude with the door valve half open; leveling without density differences

4 FLOW FIELD SIMULATIONS DURING THE LEVELLING PROCESS – FILLING AT THE EASTERN LOCK HEAD

4.1 *Levelling without ship or density differences*

A levelling process at the eastern lock head has been simulated without density differences. In this scenario the initial lift head is 1.89m with a water depth of 17.4m. The water levels differ only slightly from the case at the western lock head but the gate is in the opposite orientation, with breaking bars at the harbor side and the door valves 1m from the lock chamber side of the door. This gives a very different flow pattern in the lock chamber. Similarly, although this is not simulated in this work, in the presence of density differences the lock chamber would be filled initially with salt water and the filling from the approach harbor would be with freshwater meaning that the filling jet would rise under buoyancy to the free surface.

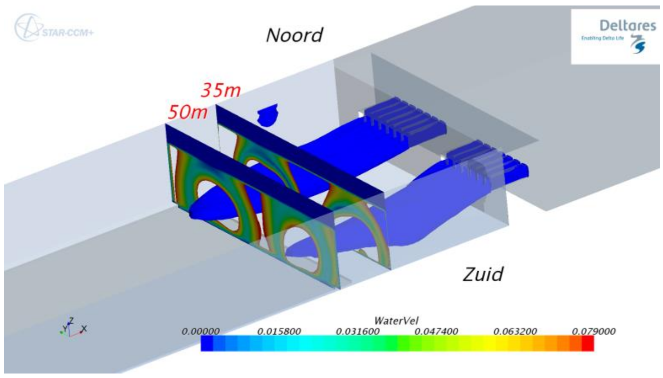

Figure 18: Isosurface of velocity, coloured by water level; plus, vertical cross-sections of water velocity magnitude contours at the stop lines. Door

valve is half open; leveling without density differences

In Figure 17 the vertical cross-section on the velocity contours is shown at the moment that the dorr valve is only half open. This moment is also approximately the moment of maximum discharge. With the gate oriented in this way the filling jet enters the lock chamber with only half the height of the gate openings and the velocities in the lock chamber are much higher. The jet is also largely horizontal as it has not been redirected by the breaking bars.

In Figure 18 the extent of the high velocity zone within the isosurface of velocity is clearly much larger than in the filling case at the western lock head. The two combined jets from the 2 sets of 7 openings reach beyond the 50m line, where a ship could be positioned. In the presence of density differences the fresh water flow would be forced into the small gap between the ship and the lock chamber wall at the side of the lock. If the ship is to be placed eccentrically in the lock (not in the middle) then this could cause large transverse forces.

5 FLOW FIELD SIMULATIONS DURING THE LEVELLING PROCESS – FILLING WITH FRESHWATER

5.1 *Levelling with fixed ship and density differences*

A leveling process at the western lock head with a fixed ship has been simulated. Attempts to simulate a ship which rises with the rising water level have been unsuccessful owing to numerical instability and inaccuracy of the mesh deforming algorithm. In a fixed position the ship begins the leveling process with the correct draft but as the water level rises the ship does not rises, the keel clearance stays the same. The forces on the ship are therefore not representative of the forces during leveling and they are not presented here. Instead only the effect on the flow pattern at the beginning of leveling is studied.

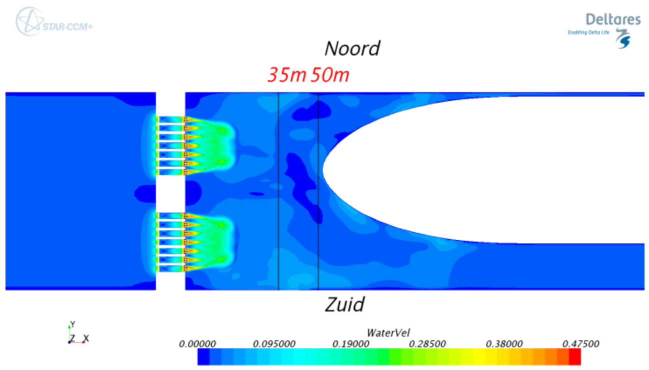

Figure 19: Horizontal cross-section: water velocity magnitude with the door valve half open; leveling with density differences

In Figure 19 a top view of a horizontal cross-section at the midpoint of the openings is shown. The ship is placed eccentrically in the lock chamber with 1.5m clearance at the northern side. The flow around the ship is subsequently asymmetric. The CFD results capture a faster moving salt water wedge in the broader gap next to the ship than in the narrower gap. This agrees with observations in this and other scale models.

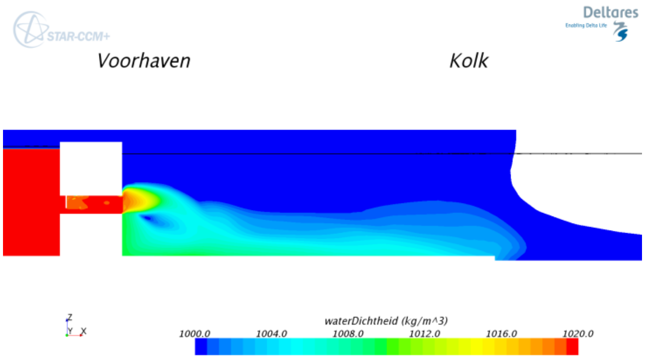

Figure 20: Vertical cross-section: water density with the door valve half open; leveling with density differences, before reflection against bow

Figures 20 and 21 are vertical cross-sections showing contours of density at different times in the leveling process. The first figure shows the salt wedge before it has reached the bow of the ship. IN the second figure the salt wedge has reached the ship and partially reflected back towards the gate. The density in the salt water wedge that runs along the ship is greater than in the case without the ship. This implies that less fresh water is entrained in the flow in the region in front of the bow. This can be explained by the presence of the ship which reduces the available volume of freshwater which can be entrained but also causes some of the salt wedge to be reflected which again raises the density of the water in the layer above the salt water flow. The entrained water is subsequently of a higher density. The different amount of entrainment and mixing of the salt water and freshwater has a big effect on the forces on the ship.

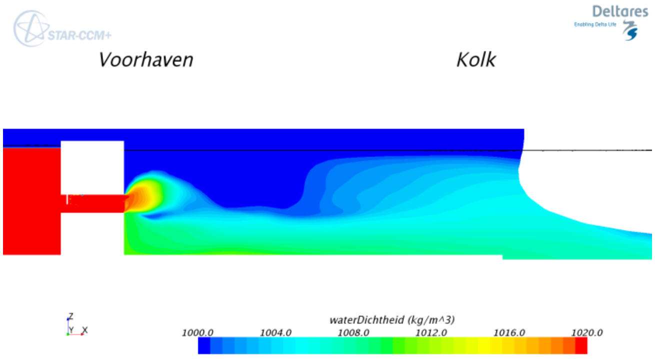

Figure 21: Vertical cross-section: water density with the door valve half open; leveling with density differences, after reflection against bow

The flow around the ship is very asymmetric. In Figure 22 the isosurface of velocity is gain shown. This seams largely symmetric and at this stage in the leveling process is unaffected by the presence of the ship. However, at the vertical cross-sections, particularly visible at 35m, the flow near the free surface is much faster at the northern side of the lock. There the velocities contours are strongly coloured red. The freshwater which is forced into movement by the salt water entering the lock has travelled along the narrow side of the ship and is therefore travelling much faster than at the southern side. This can cause high transverse forces on the ship.

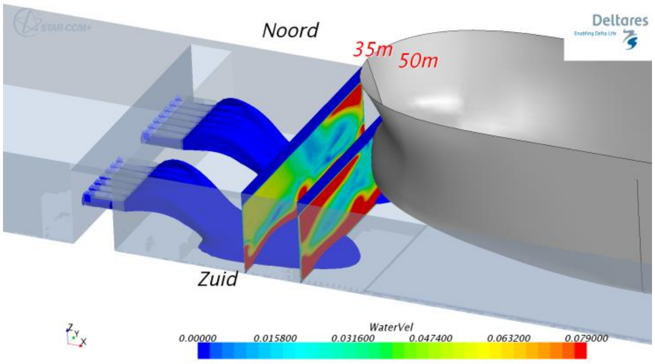

Figure 22: Isosurface of velocity, coloured by water level; plus, vertical cross-sections of water velocity magnitude contours at the stop lines. Door valve is half open; leveling without density differences

Transverse forces can also be caused by the different density profiles on the northern and southern sides of the ship. In Figure 23 in can be seen that a different density field is developing as the salt wedge reflects off the bow of the ship at the northern side. The contours at 35m are very different from the at the north and south.

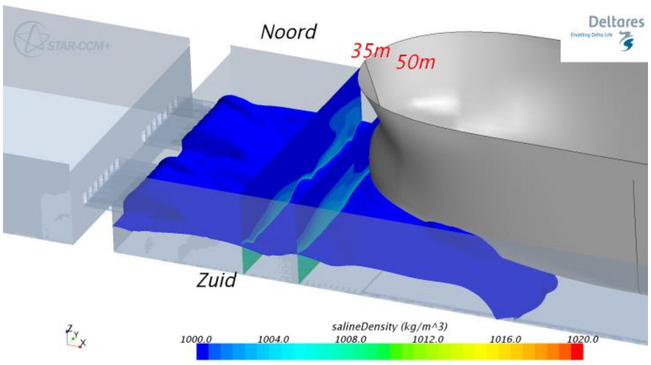

Figure 23: Isosurface of salt concentration; plus, vertical cross-sections of water density contours at the stop lines. Door valve is half open; leveling with density differences

6 CONCLUSION

CFD simulations have been performed for a lock at a salt water / fresh water interface. The hydraulic characteristics of the leveling system can be well predicted by the CFD by means of steady state calculations with a free surface. In this work the discharge and loss coefficients of the gate openings and culverts have been calculated with CFD and the agreement with experiments is excellent. The biggest deviation is in the case with the gate openings without breaking bars where most probably the small geometrical details of the scale model, which are not included in the CFD 3D CAD, are the cause of the discrepancies.

Using CFD for a transient leveling process is more problematic. The moving valves are here simulated by means of an overset mesh method in Star CMM+, where the mesh of the CFD domain is updated at every timestep to account for the movement of the valves. The flow field in the lock during leveling can be captured and qualitative assessments of its behavior made. In the absence of density differences the flow is pushed upwards by the breaking bars towards the free surface. When density differences are included the salt water entering the lock falls under buoyancy effects and counteracts the effect of the breaking bars pushing the flow upwards. The flow field is consequently very different. CFD can also give an estimate of the amount of mixing between salt and fresh water and therefore the density in the saltwater front as it flows along the chamber bottom.

When the breaking bars are not at the lock side of the gate the filling jets are much stronger with a much larger high velocity region in the lock chamber, extending beyond the probable location of the ship. This can also be used to assess the likelihood of transverse forces on the ship.

Simulations with the ship in the lock chamber have also been attempted. If the ship is allowed to rise with the sea level by means of the overset mesh algorithm the results become too inaccurate and they are not presented in this paper. If the ship is given a fixed keel clearance then the flow field can be assessed at the beginning of leveling only as during leveling the draft of the ship is no longer correct. The reflection of the salt water front against the bow of the ship can be seen and the strong asymmetric flow field than this creates when the ship is positioned eccentrically can also be identified. The forces on the ship as calculated by the CFD are not accurate.

ACKNOWLEDGEMENTS

The authors wish to thank Wim Kortlever at the Dutch Ministry of Public Works (Rijkswaterstaat, RWS) for their permission to publish this work which is part of the research into the New Sea Lock at IJmuiden funded by RWS.

REFERENCES

Vrijburcht, A., 1991. Forces on Ships in a Navigation Lock induced by Stratified Flows, *PhD Thesis*, Delft University of Technology

de Loor, A., Weiler, O., Kortlever, W., 2013, LOCKFILL: A mathematical model for calculating forces on a ship while levelling through the lock head, *Proceedings of the PIANC SMART Rivers Conference 2013*, Paper 93

Thorenz, C., Ankel, J., 2013, Evaluation of ship forces for a through-the-gate filling system, *Proceedings of the PIANC SMART Rivers Conference 2013*, Paper 45

van de Ven, P., O'Mahoney, T. S D., 2015, Comparison of scale model measurements and 3D CFD simulations of loss coefficients and flow patterns for lock levelling systems, *Proceedings of the PIANC SMART Rivers Conference 2015*, Paper 105

Star-CCM+, Available from http://www.cd-adapco.com/products/star-ccm-plus

Benjamin, T., J., 1968, Gravity currents and related phenomenon, *Journal of Fluid Mechanics,* **31**(02) p 209-248

Shin, J. O., Dalziel, S. B., Linden, P. F., 2004, Gravity currents produced by lock exchange, *Journal of Fluid Mechanics*, **521**, p1-34