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Comparison of Software for Computation of Longitudinal Forces on a Ship in a Lock Chamber During Levelling with Openings in the Lock Gate

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Abstract: *To assess the longitudinal force on a ship in a lock chamber in a design phase, mostly numerical modelling is carried out. This paper compares the longitudinal forces on a ship in the lock chamber computed with the programs VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D. Therefore, 16 cases of levelling a lock chamber are selected, differing in lock type, ship type, type of levelling operation, the type of openings in the lock gate and the valve type. These cases are simulated with the four considered programs. The variation in time of the computed discharge through the openings in the lock gate, the computed water level in the lock chamber, and levelling times are only briefly discussed, while the computed longitudinal forces on the ship in the lock chamber are discussed in detail. When the lock is emptied or when the filling of the lock is dominated by translatory waves, the four different programs compute comparable forces on the ship in the lock chamber. For filling a lock when multiple force components are relevant, higher forces are computed with VUL_SLUIS and LOCKFILL, being comparable to each other, than those computed with LOCKSIM and DELFT3D, also being comparable to each other. The frequency analysis of the predicted time series of longitudinal forces shows that the spectrum corresponding to VUL_SLUIS, LOCKFILL and LOCKSIM is characterized by the presence of the same peak frequency components.*

Keywords: *Navigation lock, filling and emptying system, numerical modelling.*

1. Introduction

For most inland navigation locks in the Flemish region of Belgium, the lift height is limited to 2-3 m. Therefore, lock filling and emptying usually takes place through openings in the lock gate sealed by (vertical lift or butterfly) valves. These levelling systems are characterized by a main water motion along the longitudinal axis of the lock chamber. Consequently, longitudinal hydrodynamic forces on the ship are dominantly present. Therefore, this paper deals only with through the gate levelling systems and with the computation of the longitudinal hydrodynamic force on the ship in the lock chamber but does not consider the computation of transversal forces nor moments on the ship in the lock chamber. Moreover, with the exception of DELFT3D (which adopts a 2DH formulation), the programs considered are based on a 1D-formulation, hence only the longitudinal force can be predicted. Therefore, whenever the force on a ship is mentioned in the remainder of this paper, it refers to the longitudinal hydrodynamic force on the ship in the lock chamber.

The longitudinal hydrodynamic force is induced by the pressures and shear stresses exerted by the water flow along the hull of the ship. At a given point of the hull, the pressure is not necessarily identical to the hydrostatic pressure induced by the local water level (which varies along the ship and in time during the levelling). Indeed, in some locations important dynamic pressures might be present (e.g. due to the direct effect of the filling jets onto a ship with bow and keel in the vicinity of the openings in the filling gate). Nevertheless, the resultant force of the hydrostatic part of the pressures, which is induced by instantaneous water level differences between bow and stern of the ship, often turns out to be an important force component. The latter observation implies the importance of predicting well the time-varying water levels at bow and stern. Other force components need to be discerned and modelled, however.

Beem et al., 2000 e.g., distinguish five different components (Figure 1) of the longitudinal force (F_{long}) on a ship in a lock chamber. These five different components consist of a hydrostatic component due to translatory waves in the lock chamber (F_{transl}), a component due to the momentum decrease between bow and stern of the ship ($F_{impulse}$), a component due to the impact of the filling jet against the bow of the ship (F_{jet}), a component due to friction of the flow against the ship and the lock chamber walls (F_{frict}) and a component due to density differences in the lock chamber (F_{dens}).

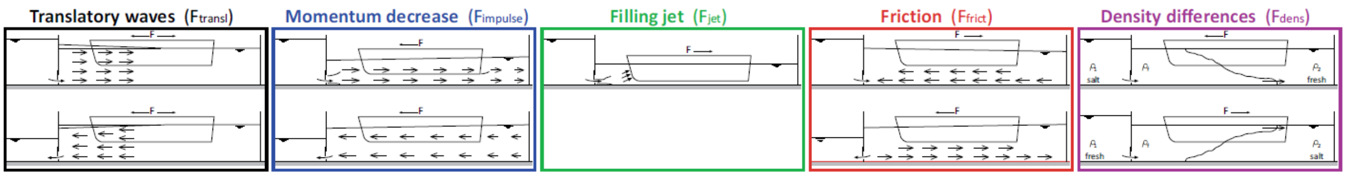

Figure 1. Components of longitudinal hydrodynamic force on a ship in a lock chamber during filling (above) and emptying (below) (Beem et al. 2000).

In turn, the component due to momentum decrease between bow and stern of the ship ($F_{impulse}$) can be decomposed into two terms: a first one is the momentum decrease due to the decreasing discharge with increasing distance from the leveling openings ($F_{impulse,Q}$), while the second one is the momentum decrease due to dissipation of the filling jets in the lock chamber ($F_{impulse,jet}$). Consequently, the force on a ship can be written from these different components using Eq. (1):

$$F_{long} = F_{transl} + F_{impulse,Q} + F_{impulse,jet} + F_{jet} + F_{frict} \; (+F_{dens}) \qquad (1)$$

It should be noted that in Eq. (1) the force component due to density differences is mentioned for the sake of completeness but is put between brackets since density effects will play no role in the considered simulations. Moreover, prediction of F_{dens} would not even be possible with VUL_SLUIS, LOCKSIM and the available version of LOCKFILL. Note that when emptying a lock chamber, the force components related to the filling jet (i.e. $F_{impulse,jet}$ and F_{jet}) are not present.

To assess the force on the ship nowadays mostly numerical modelling is carried out using software that computes (some or all of) the above-mentioned force components. At Flanders Hydraulics Research, the programs VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D are available to compute the force on a ship in the lock chamber when levelling the lock through openings in the lock gate. The research described in this paper encompasses a comparison of these four different programs for 16 cases of levelling a lock chamber through openings in the lock gates.

The outline of the paper is as follows: A description of the four different programs and their major input is given in Section 2. Section 3 describes the lock levelling cases selected for the comparison. For the selected cases, the forces on the ship in the lock chamber computed with the different programs are compared in Section 4. Section 5 summarizes the conclusions of this paper.

2. Software and Input

For carrying out the simulations, the programs VUL_SLUIS 01.54.00 (Verelst et al. 2017), LOCKFILL 5.03.00 (Deltares 2016), LOCKSIM windows version 1.21 (Schohl G.A. 1998) and DELFT3D-FLOW version 5.00.00.1287 (Deltares 2014) are considered.

VUL_SLUIS and LOCKFILL describe in a schematized way the levelling process of a lock chamber with openings in the lock gate. The discharge into or out of the lock chamber is computed using instantaneous water level differences between the mean water level in the lock chamber and the approach harbour using the surface area and discharge coefficients of the openings in the lock gate. The water level variations in the lock chamber and the component of the force due to translation waves are modelled by means of a 1D formulation consisting of a superposition of waves that are generated at a given time step, subsequently propagating in the lock chamber and reflecting (fully) at the lock gates or (partially) at bow and stern of the ship. The other force components are derived using a momentum balance between the bow and stern of the ship. In addition, use is made of a parameterization of the filling jet spreading downstream of the filling openings. The program LOCKFILL was originally developed by Deltares and commissioned by Rijkswaterstaat-Bouwdienst of the Dutch government. Since 2015, LOCKFILL is made freely available to third parties through the website of Deltares. The program VUL_SLUIS is a MATLAB program developed, for internal use, by Flanders Hydraulics Research and is largely based on the literature with relation to LOCKFILL.

LOCKSIM is the numerical modelling software developed by Dr. G.A. Schohl at the Tennessee Valley Authority's Engineering Laboratory for simulating one-dimensional transient filling and emptying flows in navigation locks. In LOCKSIM, the levelling system is represented by a hydraulic network of closed conduits (with friction and local head losses) and the lock chamber by open channel components. The discharge through the openings in the lock gate is modeled as a local head loss between the approach channel and the water level near the lock gate used for levelling. The water level movement in the lock chamber is computed by solving the 1D Saint-Venant equations for the open channel components by means of Preissmann's four-point implicit scheme ('box scheme'). In LOCKSIM, a ship in the lock chamber can be taken into account by reducing the wet section (with beam x draft) and increasing the wetted perimeter (with beam + 2 x draft, unless this sum exceeds the top width) of the open channel components where the ship is situated.

The Delft3D-FLOW module within the Delft3D software suite is developed by Deltares to carry out multidimensional hydrodynamic simulations, solving the Navier-Stokes equations under the shallow water and the Boussinesq assumptions. To simulate the flow in a lock chamber, the Delft3D-FLOW program (further referred to as DELFT3D) is run in 2DH mode, implying that the 2D Saint-Venant equations are solved for the depth-averaged flow. The equations are solved by means of an Alternating Direction Implicit (ADI) timestepping method over a rectangular grid in the lock chamber. The ADI-method splits one time step into two stages, consisting of half a time step. In both stages, all the terms of the model equations are solved in a consistent way with at least second order accuracy in space. It is possible to model a ship in the lock chamber as a floating structure. This requires the application of a local surface pressure field, the horizontal dimensions of which are equal to the length and the width of the ship and the pressure value of which is chosen such as to induce a 'trough' in the water surface equal to the draft of the ship. Because in this paper only longitudinal forces on the ship are compared, the external pressure field is applied centrically between the lock chamber walls. The surface pressure field modifies the pressure gradient term in the momentum equations. In addition, an artificial compressibility coefficient is introduced in the continuity equation, increasing the wave speed below the floating structure. Friction of the ship onto the water flow cannot be accounted for. It should be noted that within DELFT3D it is not possible to compute the discharge entering the lock chamber from the instantaneous water level differences between lock chamber and approach harbor using the section and the discharge coefficient of the openings in the lock gate. Therefore, the discharges through the openings in the lock gate computed with VUL_SLUIS are in DELFT3D used as input for the discharge locations at the upstream end of the lock chamber. As a sensitivity analysis, also simulations are carried out with DELFT3D using the discharges computed with LOCKSIM as an input.

From the water level variation in the lock chamber computed with LOCKSIM and DELFT3D, the longitudinal component of the hydrodynamic force on the ship is computed using Eq. (2) (InCom Working Group 106 2009):

$$F_{long} = W \times S = W \times \left(\frac{H_{bow} - H_{stern}}{L}\right) \quad (2)$$

where, F_{long} is the longitudinal component of the hydrodynamic force [N], W is the displacement weight of the ship [N], S is the water level slope between bow and stern [-], H_{bow} and H_{stern} are the water level at the bow and the stern of the ship [m] and L is the length of the ship [m]. The force computed based upon Eq. (2) accounts for the hydrostatic force on the ship due to translatory waves in the lock chamber. Because the 1D Saint-Venant equations in LOCKSIM, respectively, the 2D Saint-Venant equations in DELFT3D also implicitly take a momentum decrease along the hull of the ship into account (and LOCKSIM even accounts for friction along the ship's hull), the aforementioned force components are also (to a large extent) accounted for. In contrast to LOCKFILL and VUL_SLUIS, however, Eq. (2) does not account for the force component due to the impact of the filling jet and the part of the momentum decrease due to the dissipation of the filling jets. Adding the latter components in a post-processing step, e.g. based on the model formulations adopted in VUL_SLUIS and LOCKFILL, it is possible but was not considered in this paper.

Within LOCKFILL, LOCKSIM and DELFT3D, it is tried to perform a simulation with the same input parameters as in VUL_SLUIS. It should be noted that the time step in VUL_SLUIS or LOCKFILL is rather arbitrarily defined and does not have to fulfill a Courant stability criterion. Within LOCKSIM, the same time step is applied as in VUL_SLUIS and LOCKFILL. The distance between the reaches to define the open channel components in the lock-chamber in LOCKSIM is considered to fulfill the Courant-criterion, being equal or just greater than one. For the DELFT3D-simulations, a slightly different strategy is followed to define the cell size of the numerical model grid and the time step. The cell size of the numerical model grid is selected in such a way that between the lock wall and the side of the ship a sufficient number of cells, i.e. a minimum of three, are present. For practical reasons, a rectangular grid is constructed with the cell size along the axis of the lock chamber equal to the cell size perpendicular to the axis of the lock chamber. Following this reasoning, for all cases, with exception of Case09 and Case16, a cell size of 0.25 m in both directions is considered. Because of Case09, respectively, Case16 consider locks with a length of 473 m, respectively, 427 m and a width of 57 m, respectively, 55 m, a cell size of 0.25 m would result into a large amount of cells and consequently into a large computational time and large output files. Therefore, a cell size of 0.50 m in both directions is considered for both these cases. The time step for the simulations with DELFT3D then follows from the condition that the Courant-number is equal to 1.0.

For an easy generation of the input files within a certain program the same time step and grid size is used for all 16 cases considered. To define the time step or the grid size within LOCKSIM and DELFT3D, the Courant-number is calculated using the highest water depth in the lock chamber. Consequently, within these programs it is possible that deviations from the optimal Courant-number (i.e. 1.0) are present, taking into account the varying water level in the lock chamber and the initial water depth being not equal for all the 16 selected cases. As a consequence, the numerical discretization errors might be higher than in the optimal case. Table 1 provides an overview of the selected time step and grid size for the four considered programs.

Table 1. Selected time step and grid size for the different programs; n.a. = not applicable.

Software	Time step	Grid size
VUL_SLUIS	0.2 s	n.a.
LOCKFILL	0.2 s	n.a.
LOCKSIM	0.2 s	1.0 m
DELFT3D	0.006 s	0.25 m / 0.50 m for Case09 and Case16

In DELFT3D the horizontal eddy viscosity ν_{hor} is an input parameter. As a rule of thumb, Eq. (3) is used to estimate the horizontal eddy viscosity for all cases:

$$\nu_{hor} = 0.1\ U\ \Delta x \tag{3}$$

where ν_{hor} is the horizontal eddy viscosity [m²/s], U is the flow velocity [m/s] and Δx is the cell size in longitudinal direction [m]. This results in a horizontal eddy viscosity between 0.0020 m²/s and 0.0156 m²/s. If the minimum value of 0.0020 m²/s is used in a simulation with DELFT3D, spurious oscillations in the time series of the force on the ship show up, disappearing when increasing the horizontal eddy viscosity to a rather arbitrary value of 0.05 m²/s.

3. Selected Lock Leveling Cases

For the comparison in this paper, 16 cases of levelling a lock chamber through openings in the lock gate are selected. These cases consist on the one hand of cases that were used for the definition and validation of the program VUL_SLUIS (Verelst et al. 2017). On the other hand, Case09 and Case10 are locks in the Flemish region of Belgium where in-situ measurements of the water level variation were performed and other cases were selected from recent design projects (Case11 until Case15) in the Flemish region of Belgium.

Error! Reference source not found. provides a graphical characterization of the selected lock leveling cases in lock type (sea lock or inland navigation lock), ship type (sea-going ship, inland navigation ship or recreational ship), type of operation (filling or emptying), the type of openings in the lock gate (rectangular or circular) and the valve type (lifting valves or butterfly valves). Table 2 provides for each case an overview of some characteristic dimensions, i.e. the lock length, the lock width, the ship length, ship width, ship draft, the distance between the bow of the ship and the lock gate, and the blockage ratio of the ship in the lock chamber.

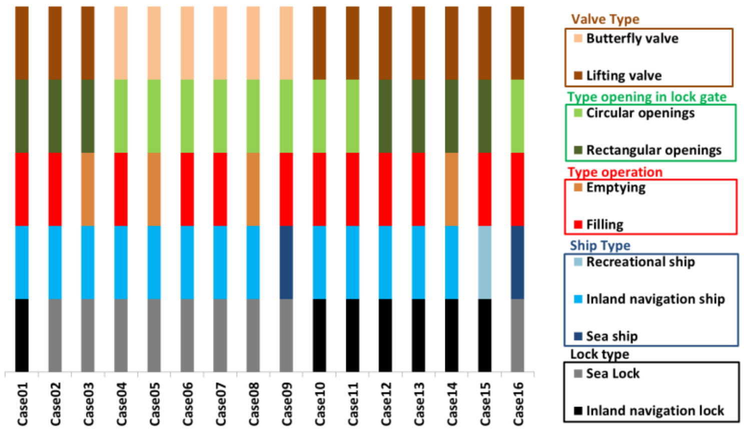

Figure 2. Characterisation of selected lock levelling cases.

Table 2. Overview of characteristic dimensions of the selected lock levelling cases.

	Lock length	Lock width	Ship length	Ship width	Ship draft	Distance ship lock gate	Blockage ratio
	m	m	m	m	m	m	%
Case01	200.0	16.0	110.0	11.40	2.80	7.5	54
Case02	182.5	22.0	135.5	16.84	3.20	10.0	46
Case03	182.5	22.0	135.5	16.84	3.20	10.0	23
Case04	200.0	16.0	110.0	11.40	2.80	7.5	54
Case05	200.0	16.0	110.0	11.40	2.80	7.5	30
Case06	182.5	22.0	135.5	16.84	3.20	10.0	46
Case07	182.5	22.0	135.5	16.84	3.20	10.0	46
Case08	182.5	22.0	135.5	16.84	3.20	10.0	23
Case09	473.0	57.0	82.0	11.50	4.29	55.0	5
Case10	256.6	25.0	99.0	9.57	2.70	7.5	20
Case11	258.1	12.5	185.0	11.40	3.50	7.0	68
Case12	259.0	16.0	185.0	11.40	3.50	5.1	59
Case13	130.0	10.5	105.0	9.50	3.00	5.0	64
Case14	130.0	10.5	105.0	9.50	3.00	5.0	41
Case15	130.0	10.5	12.0	3.40	1.40	5.0	11
Case16	427.0	55.0	265.0	40.00	12.50	50.0	63

4. Comparison of Computed Forces on the Ship in a Lock Chamber

Concerning the variation in time of the discharge through the openings in the lock gate and the variation in time of the water level in the lock chamber, negligible differences are computed between VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D. With exception of Case09, for all cases a relative difference in levelling time between LOCKFILL and VUL_SLUIS and between DELFT3D and VUL_SLUIS of maximum 0.6 % (in absolute value) is computed and a value varying between -1.4 % and -4.8 % for the relative difference between LOCKSIM and VUL_SLUIS is also computed. For Case09, a relative difference in levelling time of 3.0 % is computed between LOCKFILL and VUL_SLUIS and 1.9 % between LOCKSIM and VUL_SLUIS. The levelling times computed with LOCKFILL, respectively LOCKSIM, are slightly longer, respectively shorter, than those computed with VUL_SLUIS. These differences in levelling time and in variation in time of water level and discharge between VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D are negligible. Therefore, this section only compares the forces on the ship in the lock chamber computed with the four different programs.

In section 4.1, the comparison of the forces is carried out for cases concerning emptying a lock or filling a lock dominated by translation waves, while in section 4.2 the other cases of filling a lock chamber when multiple force components are relevant are considered. Within these sections both a graphical comparison as a statistical comparison of the variation in time of the force computed with the different programs is carried out. For the statistical comparison, the BIAS and root-mean-square-error (RMSE) are computed. Section 4.3 compares for some cases the power density spectrum, as the result of a fast-Fourier transform of the time series with the forces computed with the different software programs.

It should be noted from Table 1 that the time step in VUL_SLUIS, LOCKFILL and LOCKSIM is 0.2 s, while the time step in DELFT3D is 0.006 s. The output of the simulations with DELFT3D, however, is saved with a time step of 3 s. For the computation of the BIAS, RMSE and the power density spectrum, the time series of forces computed with DELFT3D is interpolated to a time series with the same time step as those computed with VUL_SLUIS, LOCKFILL and LOCKSIM. The computation of BIAS and RMSE considers also the simulations carried out with VUL_SLUIS as a reference, not implying that VUL_SLUIS generates the most accurate results. The accuracy of a program should follow from an elaborate validation exercise, which is not in the scope of this paper. Some earlier reported indications of accuracy, even though based on a limited number of cases and on other types of lock levelling systems than considered in this paper, indicate relative differences of tens of percentages between extreme values of measured (in prototype or physical model) and computed end-to-end water level slopes in the lock chamber or computed forces on the ship (De Mulder et al. 2010; Waterloopkundig Laboratorium 1994; Vrijburcht 1991; Menendez et al. 2014; Menendez and Badano 2011).

4.1. Cases Concerning Emptying a Lock or Filling a Lock Dominated by Translation Waves

When emptying a lock chamber (Case03, Case05, Case08 and Case14), only the component due to translation waves (F_{transl}), the component due to momentum difference because of the decreasing discharge ($F_{impulse,Q}$), and the component due to friction (F_{frict}) are present. Besides the emptying of a lock chamber, this section also discusses the cases for lock filling where translation waves are dominant, i.e. Case09 and Case10. From **Error! Reference source not found.** follows that the distance between the small sea ship and the lock gate for Case09 is relatively large, i.e. 55 m and that for Case10 the blockage ratio of the inland navigation ship in the lock chamber is rather low (20 %). Consequently, for these two cases the component of the force due to the impact of the filling jet ($F_{impulse,jet}$ and F_{jet}) is not relevant or even absent.

As an example, Figure 3 presents for Case03, Case08, Case09 and Case10 the variation in time of the force on the ship computed with VUL_SLUIS, LOCKFILL, LOCKSIM and Delft3D. It should be noted that the force with units ‰ in this figure is expressed relative to the displacement weight of the ship. With DELFT3D, simulations are carried out with the discharge through the openings in the lock gate from LOCKSIM as an input (indicated with the red dashed lines in Figure 3) instead of the discharge from VUL_SLUIS as input. As mentioned in section 2, in VUL_SLUIS computes the discharge through the openings in the lock gate using the instantaneous water level difference between the mean water level in the lock and in the approach harbour, while in LOCKSIM the instantaneous water level difference is considered between the water level in the lock chamber near the lock gate used for levelling and the water level in the approach harbour.

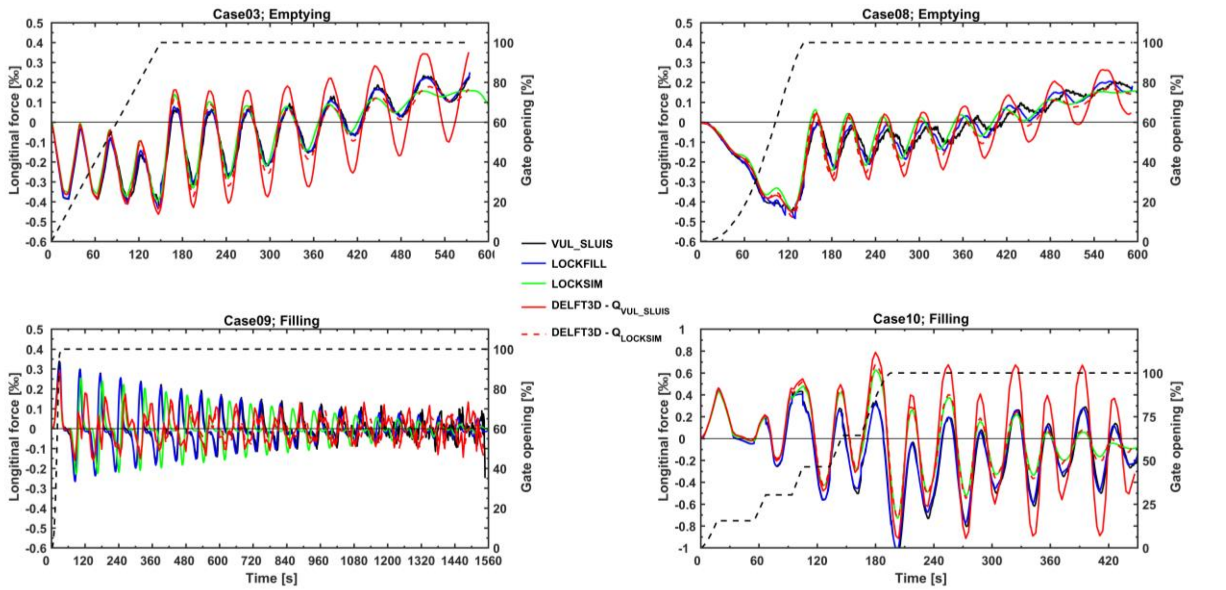

Figure 3. Variation in time of computed force on the ship in the lock chamber.

For all cases, from Figure 3 follows that the forces computed with VUL_SLUIS and LOCKFILL are approximately the same and that with LOCKSIM comparable forces are computed as with the latter programs. When using the discharges from VUL_SLUIS as input in DELFT3D, the computed forces differ somewhat from the forces computed with the other programs. During the phase that the openings in the lock gate are fully opened, with DELFT3D a lower damping of the force is computed than with the other programs. However, when using the discharge from LOCKSIM as input in DELFT3D the damping of the computed force on the ship is higher, especially towards the end of levelling, and the resulting forces on the ship in the lock chamber are approximately the same as those computed with LOCKSIM.

The same conclusions follow from Figure 4, comparing for Case03, Case05, Case08, Case09, Case10 and Case14 the BIAS and RMSE between the time series of forces computed with LOCKFILL, LOCKSIM and DELFT3D and the time series of forces computed with VUL_SLUIS. Both BIAS and RMSE are presented relative to the (in absolute value) extreme value of the force. Between the time series of forces computed with VUL_SLUIS and LOCKFILL a maximum bias of 3 % and a maximum RMSE of 11 % is computed. Higher values until 11 %, respectively, 30 % of the extreme value of the force are computed for the BIAS, respectively, the RMSE between the time series of forces computed with VUL_SLUIS and LOCKSIM and the time series of forces computed with VUL_SLUIS and DELFT3D. The higher values of 30 % for the RMSE between the forces computed with VUL_SLUIS and LOCKSIM and between VUL_SLUIS and DELFT3D for Case09 can be explained by the phase shift between the forces computed with LOCKSIM, DELFT3D and VUL_SLUIS. This phase shift is explained by the method of implementation of the gate recess in the different programs.

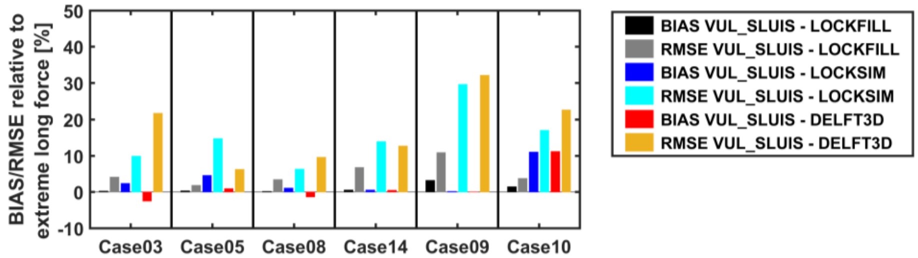

Figure 4. BIAS and RMSE relative to extreme value of longitudinal force (in %) between time series of forces computed with VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D.

4.2. Cases Concerning Filling a Lock with Multiple Force Components Relevant

This section discusses all other cases of filling the lock chamber, i.e. Case01, Case02, Case04, Case06, Case07, Case11, Case12, Case13, Case15 and Case16, when multiple force components are relevant and for most cases the component of the force due to momentum decrease is dominantly present. As an example, Figure 5 presents for Case02, Case06, Case13 and Case15 the variation in time of the force on the ship computed with VUL_SLUIS, LOCKFILL, LOCKSIM and Delft3D. It should be noted that as in section 4.1 the force on the ship with units ‰ in this figure is expressed relative to the displacement weight of the ship. For Case02 and Case06 the force on the ship computed with LOCKFILL shows near the end of the filling an oscillating behavior, due to the time step of 0.2 s that considered for the simulations. When changing the time step in LOCKFILL from 0.2 s to 1.0 s, these oscillations disappear, showing what is visualized by the light blue dotted lines in the upper left and upper right panels of Figure 5. Analogue as in section 4.1, the simulations with DELFT3D are carried out both using the discharge through the openings in the lock gate from VUL_SLUIS as input (full red line Figure 5) and using the discharges from LOCKSIM as input (dashed red line in Figure 5).

At first, from Figure 5 follows that the first peak of the forces computed with all programs is almost the same. The amplitude and period of this first peak is dominated by the component of the force due to translation waves, which is mainly influenced by the discharge that is entering the lock chamber. At the beginning of levelling of the lock chamber the other components of the force on the ship are small compared to the component due to translatory waves.

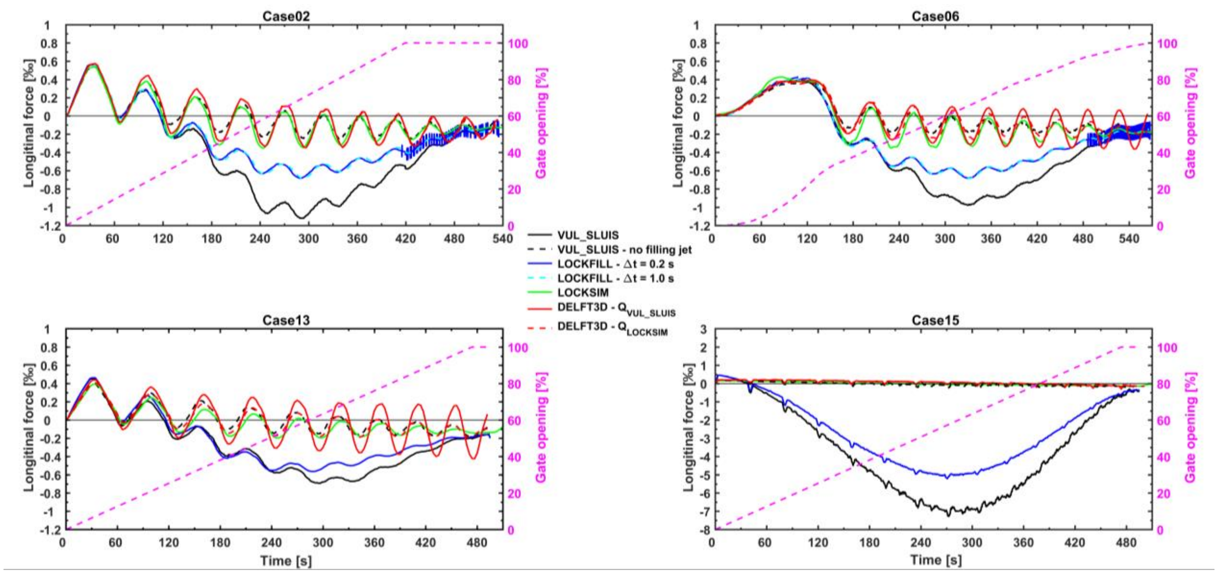

Figure 5. Variation in time of computed longitudinal force on ship.

Secondly from Figure 5 follows that DELFT3D and LOCKSIM compute for all cases comparable forces on the ship, being considerably lower than the forces computed with VUL_SLUIS and LOCKFILL. The latter two programs compute more or less comparable forces, but the forces computed with VUL_SLUIS being somewhat higher than the forces computed with LOCKFILL. The differences in the computed forces between VUL_SLUIS and LOCKFILL consider the computation method of the discharge in the filling jet and the momentum in the filling jet (Verelst et al. 2017). The discharge and the momentum in the filling jet influence mainly the component of the force due to momentum decrease because of the dissipation of the filling jet and the component due the impact of the filling jet against the bow of the ship. The higher differences in the computed forces on the ship between LOCKFILL/VUL_SLUIS on the one hand and LOCKSIM/Delft3D on the other hand can be explained by the fact that the latter two programs, as mentioned in section 2, do not take into account the influence of the concentrated filling jet. For Case15, the case with a recreational ship in the lock chamber as well as LOCKFILL as VUL_SLUIS compute high forces (up to -4 ‰ with LOCKFILL and – 7 ‰ with VUL_SLUIS) being a consequence of the high component of the force due to momentum decrease. It should be noted that at this moment both LOCKFILL and VUL_SLUIS are not validated for recreational ships in a lock chamber.

To illustrate the influence of the concentrated filling jet on the computed force of the ship in the lock chamber, for all 16 considered cases a simulation is carried out with a special version of VUL_SLUIS, where the influence of the concentrated filling jet is not taken into account when computing the force on the ship in the lock chamber. For these simulations, the force on the ship is computed using Eq. (4):

$$F_{long,no\ jet} = F_{transl} + F_{impulse,Q} + F_{frict} \tag{4}$$

where $F_{long,\ no\ jet}$ is the longitudinal force on the ship without taking into account the influence of the filling jet [N], F_{transl} is the component due to translatory waves, $F_{impulse,\ Q}$ is the component due to momentum decrease because of the decreasing discharge, and F_{frict} is the component due to friction. The force on the ship computed with VUL_SLUIS without taking into account the influence of the concentrated filling jet ($F_{long,no\ jet}$) is also visualized in Figure 5 using the dashed black lines. Besides the absence of the influence of the concentrated filling jet for these simulations, also the coefficient for the damping of translation waves in VUL_SLUIS is reduced from 0.40 to 0.05, leading to an increase of the amplitude of the forces and to a better agreement with the amplitude of the forces computed with DELFT3D and LOCKSIM.

The dashed black lines in Figure 5 show that the forces computed with VUL_SLUIS without taking into account the influence of the concentrated filling jet are now comparable to the forces computed with LOCKSIM and DELFT3D. For Case02 and Case06, the amplitude of the force computed with VUL_SLUIS is somewhat lower than the amplitude of the force computed with LOCKSIM, on his turn being lower than the amplitude of the force computed with DELFT3D using the discharge from VUL_SLUIS as input. For Case15, the case with the recreational ship in the lock chamber with VUL_SLUIS and LOCKSIM now the same forces on the ship are computed. Using the discharge through the openings in the lock gate from LOCKSIM instead of the discharge from VUL_SLUIS as input in DELFT3D does not result for Case02 into any difference between the computed forces but results for Case06 and Case13 however into a damping of the forces on the ship being higher than the damping of the forces using the discharges from VUL_SLUIS as input. The latter forces computed with DELFT3D using the discharges of VUL_SLUIS as input are approximately the same as those computed with LOCKSIM.

Figure 6 compares for all cases of filling of a lock when multiple force components are present, the BIAS and RMSE between the times series of the forces computed with VUL_SLUIS and those computed with LOCKFILL, LOCKSIM and DELFT3D. The BIAS and RMSE are, as in section 4.1, presented relative to the extreme value of the computed force. The BIAS and the RMSE between the forces computed with VUL_SLUIS and the forces computed with LOCKSIM and DELFT3D are computed both for the situation with and the situation without taking into account the influence of the concentrated filling jet. When taking into account the influence of the concentrated filling jet, between the forces computed with VUL_SLUIS and LOCKFILL a maximum value of the BIAS, respectively, RMSE is computed equal to 19 %, respectively, which is 23 % of the extreme value of the computed force. Between the time series of forces computed with VUL_SLUIS and LOCKSIM and the forces computed with VUL_SLUIS and DELFT3D, higher values of the BIAS (until 50 %) and RMSE (until 60 %) are computed. Compared to the cases concerning emptying a lock or filling a lock dominated by translation waves, the maximum values of BIAS and RMSE are considerably higher for the cases of filling a lock chamber when multiple force components are present. When the influence of the concentrated filling jet is neglected, considerably lower values of the BIAS (until 6 %) are computed between the time series of forces computed with VUL_SLUIS and LOCKSIM and the time series of forces computed with VUL_SLUIS and DELFT3D than when taking into account the influence of the filling jet. Also, the computed RMSE is lower, being 19 %, respectively, 30 % between the time series of forces computed with VUL_SLUIS and LOCKSIM, respectively, the forces computed with VUL_SLUIS and DELFT3D.

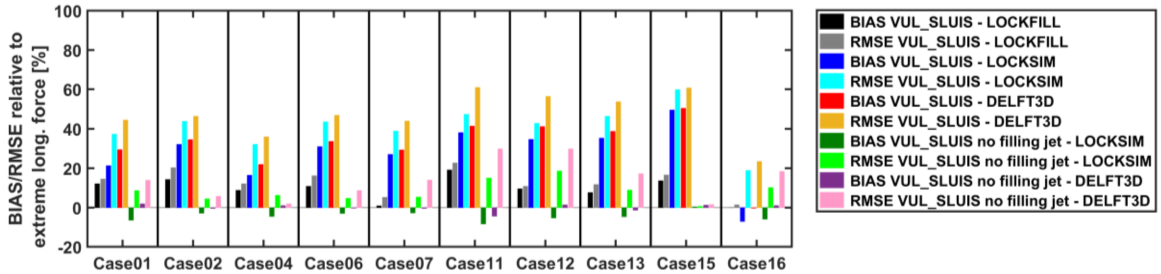

Figure 6. BIAS/RMSE relative to extreme longitudinal force (in %) between forces computed with VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D.

4.3. Comparison of Power Density Spectrum

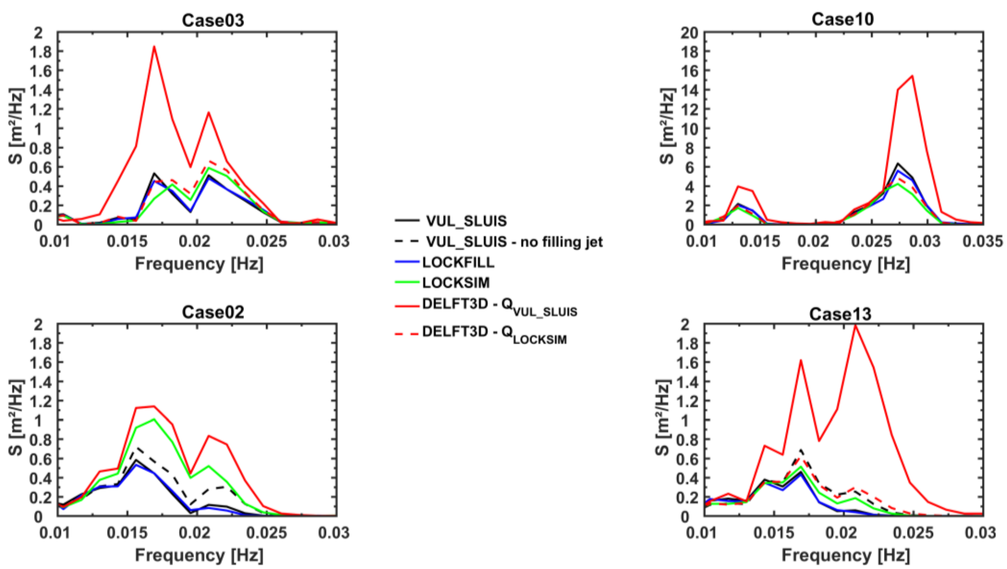

Figure **7** presents as an example for Case03 (emptying a lock), Case10 (filling a lock with only translation waves present), Case02 and Case13 (filling a lock with multiple force components present) the power density spectrum of the forces computed with VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D. The power density spectrum of the forces compute with DELFT3D is for all cases visualized as well as using the discharge through the openings in the lock gate from VUL_SLUIS as input as using the discharge from LOCKSIM as input. For Case02 and Case11 also the power density spectrum of the forces computed with VUL_SLUIS without taking into account the influence of the filling jet is visualized.

For the graphical visualization of the computed power density spectrum, the limits of the frequency axis are assessed based on the period of harmonic oscillation in a lock chamber (Deltares 2016), computed with Eq. (5).

$$T = \frac{2(l_k - l_s)}{\sqrt{g\,h_k}} - \frac{2 l_s}{\sqrt{g\frac{b_k h_k - b_s d_s}{b_k}}} \qquad (5)$$

where T is the period of harmonic oscillation [s], l_k and b_k are the length and width of the lock chamber [m], l_s, b_s and d_s are, respectively, the length, width and draft [m] of the ship in the lock chamber, g is the gravitational acceleration [m/s²] and h_k is the water depth in the lock chamber [m]. Using this equation and the data of Table 2, results for Case02 and Case03 into an harmonic oscillation period of 64.0 s (= 0.016 Hz) for the minimum water depth of 5.33 m and a period of 39.2 s (= 0.025 Hz) for the maximum water depth of 10.73 m are calculated. For Case10, respectively, Case13 an harmonic oscillation period of 67.8 s (= 0.015 Hz), respectively, 62.2 s (= 0.016 Hz), is computed for the minimum water depth of 5.17 m, respectively, 4.23 m and a period of 75.3 s (= 0.013 Hz), respectively, 40.2 s (= 0.025 Hz) for the maximum water depth of 6.28 m, respectively, 6.61 m.

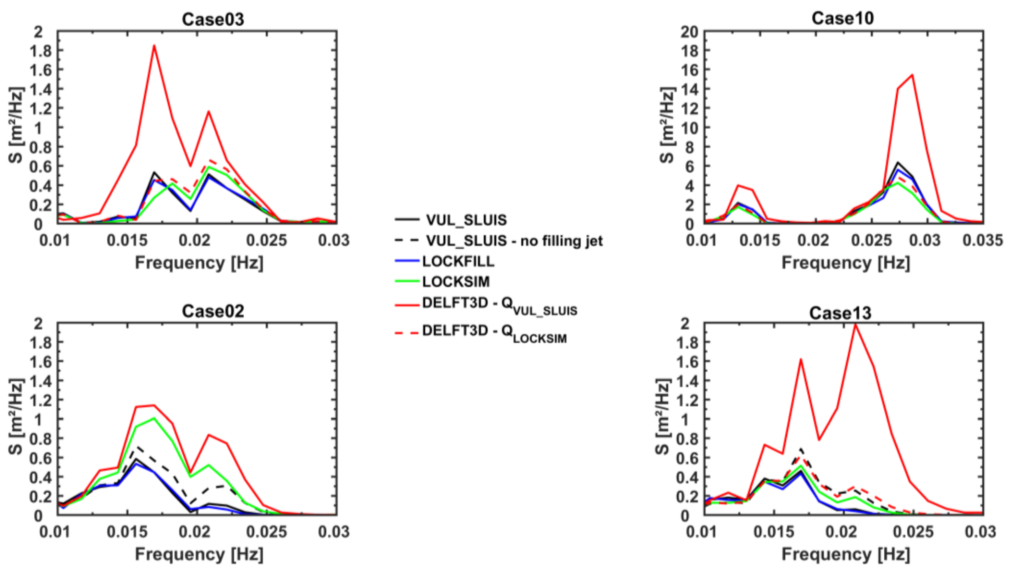

Figure **7** shows that the time series of the forces computed with VUL_SLUIS (with influence of the filling jet) and LOCKFILL are characterized by the presence of the same frequency components. For Case03 and Case10, the time series of the forces computed with LOCKSIM are characterized by the same frequency components as those computed with VUL_SLUIS and LOCKFILL, while for Case02 and Case13 the time series of the force computed with LOCKSIM is characterized by the presence of slightly higher frequency components then those computed with VUL_SLUIS (with influence of filling jet) and LOCKFILL. When neglecting the influence of the concentrated filling jet in VUL_SLUIS and changing the coefficient for the damping of translation waves for Case02 and Case13, the force computed with VUL_SLUIS is characterized by slightly higher frequency components, hence by a slightly lower period compared to the original simulation with VUL_SLUIS.

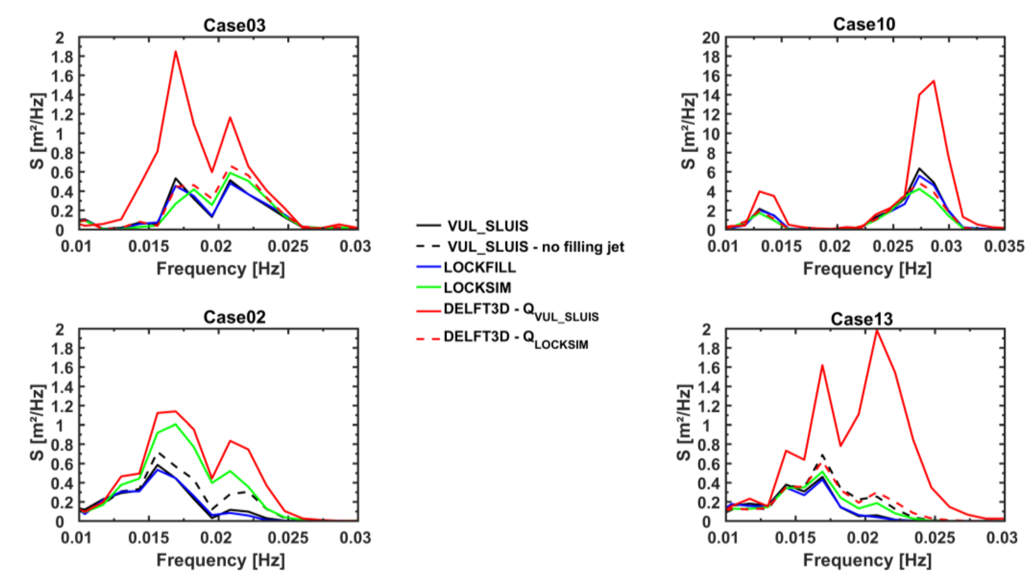

Figure 7. Power density spectrum for Case03 (emptying), Case10 (filling only translation waves), Case02 and Case13 (filling multiple force components present).

The time series of the forces computed with DELFT3D using the discharge through the openings in the lock gate from VUL_SLUIS as input is characterized by slightly lower frequency components when emptying the lock chamber (Case03) and slightly higher frequency components when filling the lock chamber (Case02, Case10 and Case13), than the time series of the forces computed with the other programs. This was also noticed in the previous paragraphs, where DELFT3D using the discharge from VUL_SLUIS as input computes near the end of levelling forces with a slightly increasing period when emptying the lock chamber (Case03) and a decreasing period when filling the lock chamber (Case02 and Case10). However, when considering the discharge through the openings in the lock gate from LOCKSIM as input in DELFT3D, the power density spectrum of the forces shows for Case03, Case10 and Case11 the presence of the same frequency components as in the other programs. For Case02, this computation results in almost no difference in the frequency components of the computed forces, because of the negligible differences between the discharges computed with VUL_SLUIS and LOCKSIM. This concludes that the damping and to a lesser extent the period of the forces computed with DELFT3D is influenced by the computed discharges through the openings in the lock gate used as input for the simulation.

5. Conclusions

To assess the longitudinal force on the ship in a lock chamber during lock levelling through openings in the gate, mostly numerical modelling is carried out nowadays. This paper compared the results of the programs VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D for 16 selected cases of levelling systems with openings in the lock gate, differing in lock type, ship type, type of operation, the type of openings in the lock gate and the valve type. Concerning the levelling time and the variation of the water level in the lock chamber, negligible differences between the different programs are computed.

The comparison of the forces computed with the different programs firstly conclude that for emptying a lock and for filling when the force component due to translatory waves is dominantly present, all four programs compute comparable longitudinal forces. Secondly, for filling cases where all components of the forces are relevant, and certainly when the component of the momentum decrease is dominant, the influence of the concentrated filling jet is not negligible. In these cases, LOCKFILL and VUL_SLUIS take into account the influence of the filling jet in the computation of the force on a ship in a lock chamber, whereas LOCKSIM and DELFT3D do not. This results in considerably higher forces computed with VUL_SLUIS and LOCKFILL, being comparable to each other, than those computed with LOCKSIM and DELFT3D, also being comparable to each other. When in VUL_SLUIS the influence of the concentrated filling jet is not taken into account, forces are computed which are comparable to those computed with LOCKSIM and DELFT3D. Adding the influence of a concentrated filling jet in a post-processing step to the latter two programs, e.g. based on the model formulations adopted in VUL_SLUIS and LOCKFILL, is possible but was not considered in this paper.

The damping and to a lesser extent the period of the forces computed with DELFT3D depend noticeably on the discharges through the openings in the lock gate used as an input. When these discharges are computed with a software using the mean water level in the lock chamber (e.g. VUL_SLUIS and LOCKFILL), with DELFT3D forces computed and characterized by a lower damping and slightly higher, respectively, lower periods, when emptying, respectively, filling a lock than with the other programs and when the discharges as input are computed with a software using the water level next to the lock gate used for levelling (e.g. LOCKSIM). In the latter situation, comparable forces are computed as with the other programs.

For design purposes, where mostly the extreme value of the computed forces is compared with a criterion, the influence of the concentrated filling jet during filling of a lock influences noticeably the negative extremum, while the positive extremum remains the same. The different damping behavior of the forces computed with DELFT3D depending on the discharges used as input does not influence the first peak of the computed forces, being generally the positive extremum when filling a lock and the negative extremum when emptying a lock but influences noticeably the negative extremum when filling a lock and the positive extremum when emptying a lock.

For the intercomparison of the considered programs in this paper, the simulations carried out with VUL_SLUIS are considered as a reference, not implying that the simulations with VUL_SLUIS yield the most accurate results. To assess the accuracy of the computed forces, predicted with whatever software, further validation with measurements is recommended.

6. Acknowledgements

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