ON HAWSER FORCE CRITERIA FOR NAVIGATION LOCK DESIGN: CASE STUDY OF MARITIME LOCKS IN PORT OF ANTWERP

by

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ABSTRACT

The first part of this paper offers a general reflection upon the issue of mooring line forces and ship behaviour during filling/emptying of (maritime) navigation locks. The philosophy behind the so-called hawser force criterion and the classical approach to deal with it in design studies, is described first. Secondly, some innovations in the definition, verification and validation of the design criteria are highlighted. In the second part of this paper, a case study is presented focusing on two maritime locks in the Port of Antwerp (Belgium): the Zandvliet lock (L x W = 500m x 57m) and the Berendrecht lock (L x W = 500m x 68m). To illustrate and comment upon the hawser force issues, results of scale modelling, in situ measurements and numerical modelling are discussed, in comparison to published hawser force criteria.

1. INTRODUCTION

The hydraulic design of a lock filling/emptying system aims at (among other issues) minimization of the filling/emptying time, constrained by the so-called hawser force criterion. The latter criterion is meant to guarantee a certain degree of safety (and comfort) to a moored vessel and to the lock infrastructure during lock filling/emptying.

In section 2 of this paper, the philosophy behind the hawser force criterion and the classical approach to deal with it in design studies, is described first. Secondly, some innovations in the definition, verification and validation of the design criteria are highlighted. This section is to a great extent based on DE MULDER, T. (2009).

In section 3, a case study is presented which focuses on the Zandvliet lock and the Berendrecht lock in the Port of Antwerp (Belgium). In order to illustrate and comment upon the hawser force criterion issues, scale model results, in situ measurements and results of numerical modelling efforts are discussed, in comparison to published hawser force criteria.

Conclusions are presented in section 4.

2. HAWSER FORCE CRITERION

2.1 Philosophy

The hawser force criterion attempts to quantify the necessary limitation of ‘turbulence’ (in the wide sense) generated by the lock filling/emptying, in order to limit the displacement of the vessel and the associated forces in the vessel-positioning system (e.g. mooring lines). Note that the water flow, the lock (chamber and filling/emptying system), the vessel and its positioning system mutually interact, see Figure 1.

2.2 Criterion

The appreciation of safety and comfort during a lock filling/emptying operation contains both objective elements (e.g. forces on the vessel, forces in the mooring lines, slope of the water surface, slope of

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the vessel, displacement of the vessel) and subjective elements (e.g. feeling of the captain, pilot, lockmaster).

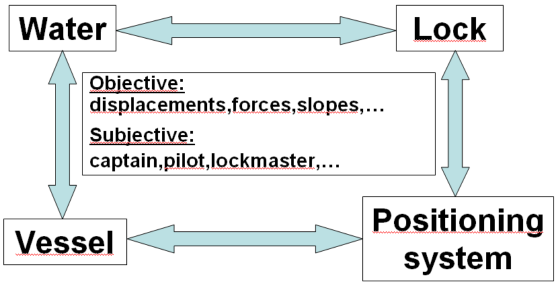


Figure 1 : Constituting elements of a hawser force criterion

The hawser force criterion sets an upper bound (i.e. a threshold value) to an objective element. I.e. the definition of the criterion. To assess whether a given filling/emptying system meets the defined criterion, a verification tool should be available. In order to assess whether the adopted definition and its associated verification tool lead to both safe and comfortable as well as economic lockages, validation efforts should be carried out.

2.3 Classical approach

The 'classical' approach consists of a hawser force criterion being defined in terms of the hydrodynamic force on the vessel. This force should not exceed a given threshold value, expressed in absolute terms or in relative terms (as a fraction of the vessel's displacement weight).

A scale model is used as a verification tool. To avoid a complicated measurement set-up, no attempt is (usually) made to represent the real vessel-positioning system (consisting of e.g. mooring lines, winches, bollards) in the scale model. See also paragraph 3.2 of the case study.

Note that the selected definition and verification tool of the classical approach on purpose aim at methodological simplicity.

Validation is mainly restricted to gathering (in an often unsystematic way and often triggered by incidents) feedback from the authorized personnel, once the lock is operational.

2.4 Innovations

Several innovations can be distinguished in 'modern' design studies, see PIANC (2009). Some of these will be briefly presented in this section. The overview is inevitably biased by the specific working experience of the authors and does not aim at completeness.

2.4.1 Definition of threshold values according to vessel-positioning system characteristics

Originally, the threshold value for the hydrodynamic force of a vessel used to be specified as a (often country-specific) constant (depending somewhat on the vessel size). Later on, it was attempted to define the threshold value as a function of the characteristics of the vessel-positioning system.

Focusing on inland navigation, PARTENSCKY, H.-W. (1986) and VRIJBURCHT, A. (1994) developed a methodology to account for the mooring line characteristics. Dynamic effects are accounted for by considering the ship and its mooring lines as an (idealized) mass-spring system, for which the relation between a given external force F and the (maximum) reaction force R in the spring is known (by means of a so called dynamic magnification factor which represents the ratio R/F). Application of this methodology resulted in differentiated threshold values by RIJKSWATERSTAAT-BOUWDIENST (2000) for filling operations of inland navigation locks with fixed vs. floating bollards.

The above-mentioned methodology was also explored by DE MULDER, T. in CPP (2007a) during the conceptual design studies for the Third set of Panama locks (e.g. for the 12,000 TEU container design vessel). For large ocean-going vessels, however, another particular methodology was developed earlier by VRIJER, A. (1974) and VRIJER, A. (1977), accounting for mooring line and winch characteristics. The latter methodology resulted in a set of threshold values (for the hydrodynamic forces and moments), depending on line type, pre-tension in the cables and vessel size. See also paragraph 3.3 of the case study.

2.4.2 In situ measurements for validation purposes

Thanks to evolutions in measuring and data-acquisition equipment, in situ measurements of water surface slopes are feasible (albeit sometimes with a limited accuracy, especially in the transversal direction of the lock chamber). Water surface slopes are representative for the hydrostatic component of the hydrodynamic force on the vessel (see e.g. KALKWIJK (1973)), which is often (but not always !) the dominant force component. Even measurements of the ship motion itself have become feasible nowadays (both during lock filling/emptying as well as during sailing in/out of the lock).

Direct measurement of mooring line forces would be most interesting for gaining insight but is less practical to set-up (without perturbing the lock operations).

Based on several measurements of water surface slopes by Flanders Hydraulic Research (in several maritime and inland navigation locks, with different types of filling/emptying systems) it turns out that hawser force threshold values published in ‘modern’ literature seem to be rather conservative, i.e. the measurements show that in reality the moored vessels are often subjected to larger hydrostatic forces (slopes) than could be expected from the published threshold values, while no major complaints about the degree of safety and comfort in the associated locks are known. See also paragraph 3.3 of the case study.

2.4.3 Application of numerical models as verification tools

Thanks to the enormous increase of computational power, numerical models of different types (and physical/numerical complexity) have become available to predict hydrostatic and/or hydrodynamic forces on a ship’s hull, hence as a verification tool for the hawser force criterion.

On one end of the numerical model spectrum, there are 1D or 2D models solving the shallow water equations (SWE) for the water flow in a lock in the presence of a (schematized) ship’s hull. On the other end of the spectrum, there are 3D Computational Fluid Dynamics (CFD) codes solving the Reynolds-Averaged Navier-Stokes (RANS) or Euler equations in the filling/emptying system and in the lock chamber around a (realistic) ship’s hull. The latter models can optionally even account for Fluid-Structure-Interaction (FSI). See also paragraph 3.5 of the case study. It is good to know that most (if not all) CFD codes were originally developed for internal flow, hence applications which involve free surface flow still might cause some extra challenges.

Whereas the SWE based models are computationally cheap and within reach of all consulting engineers, the RANS or Euler based models still require huge computational resources which are not readily available. Moreover, they require highly skilled operators. The consequence is that - especially during conceptual design studies (but actually also during further design) - the number of filling/emptying scenario’s and layouts that can be studied with the CFD tools is limited. Yet, CFD codes are certainly helpful in detailed design of parts of the filling/emptying system.

In general terms, it can be stated that SWE based numerical models are capable of comparing different filling/emptying conditions or filling/emptying systems in relative terms based upon predictions of the longitudinal component of the slope or force (although the parametrization of the effect of direct filling jets is still a challenge), but the performance is still questionable in the transversal direction.

Summarizing, numerical modelling is a valuable tool in the (conceptual) design studies of a new lock. Yet, a scale model to finalize the design is still to be advocated nowadays (unless the new lock is sufficiently akin to an existing lock for which validation data are available).

2.4.4 Numerical simulation of mooring line forces and ship behaviour

Inspired by the study of wind wave effects on a ship moored at an (off shore or port) terminal, there is a trend towards numerical modelling of the complete system, i.e. the water flow, the mooring line forces and the motion of the ship moored in a lock.

Yet, it should not be overlooked that navigation locks are characterized by shallow and confined flow effects, which are still less well known (resulting in a wide range of e.g. estimated added mass and hydrodynamic damping coefficients).

A dynamic modelling of the complete system should ideally be carried out in a fully coupled way (i.e. with one integrated computer model). Alternatively, a chain of one-way-coupled independent models can be used (e.g. one model for predicting the time history of the water flow, which is used as input for a model which predicts the time history of the ship's motion and the mooring line forces). The latter methodology has been applied by VANTORRE, M. (Maritime Technology Division, Ghent University) and DE MULDER, T. (Flanders Hydraulics Research) during the conceptual design for the new Panama Canal locks, see e.g. CPP (2007a) and CPP (2008).

Notice that the aforementioned methodologies result in time histories of the mooring line forces and the ship motion, which allows to directly assess the degree of safety during a lockage (by comparison to the mooring line strength characteristics and to the available space in the lock chamber).

In any case, the above-mentioned modelling efforts require the specification of many input parameters, some of which are only roughly known during the (conceptual) design studies. Yet, it turns out that the resulting ship motion is sometimes very sensitive to the particular choice of some parameters and to the assumed mooring line (and winch) handling strategy.

3. CASE STUDY: ZANDVLIET AND BERENDRECHT LOCKS

3.1 Description of locks

The Zandvliet and Berendrecht locks are twin locks situated in Antwerp (Belgium) at the right bank of the tidal river Scheldt. These locks are two of the maritime accesses to the (non-tidal) docks of the Port of Antwerp, see Figure 2.

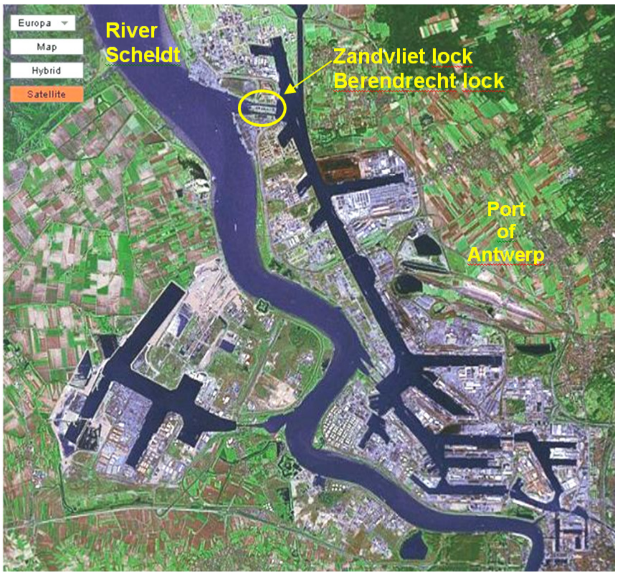


Figure 2 : Location of Zandvliet and Berendrecht locks in Port of Antwerp

The Zandvliet and Berendrecht locks are operational since 1967 resp. 1989. Both locks are equipped with two pairs of rolling gates, see Figure 3. See also Figure 4 for gate numbering (n° 1 to 4).

The length of the lock chamber (between the outer gates n° 1 and 4) is 500 m in both cases. The width of the Berendrecht lock chamber (68m), however, is larger than the one of the Zandvliet lock (57 m).

The sill of both locks is at a level of -13.58 m T.A.W. (where T.A.W. denotes the vertical reference plane in use in Belgium, which is situated around low water).

At the river side, the water level varies with the tide (MLW=+0.09 m T.A.W. and MHW=+5.15 m T.A.W.). At the dock side, the normal water level is at +4.17 m T.A.W. The maximum head value during lock operation is in the order of 5 to 6m.

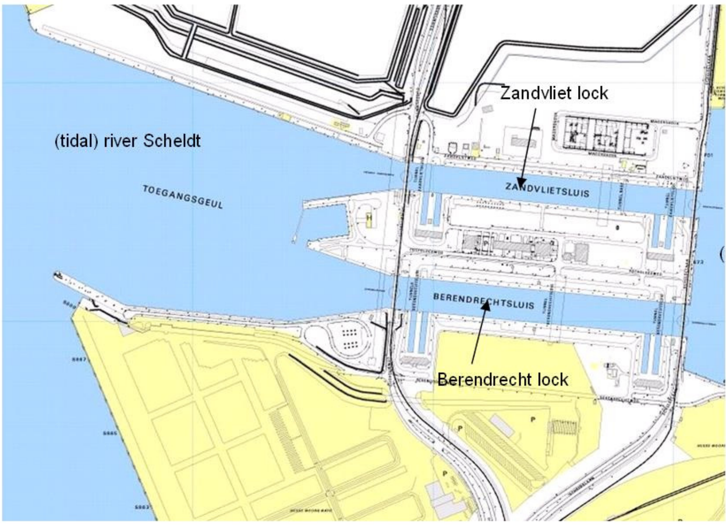


Figure 3 : Plan view of Zandvliet and Berendrecht locks

The filling-emptying system of both locks consists of short culverts in the lock heads, bypassing the gates, see Figure 4. The so-called lower lock head is at the river side, whereas the upper lock head is at the dock side.

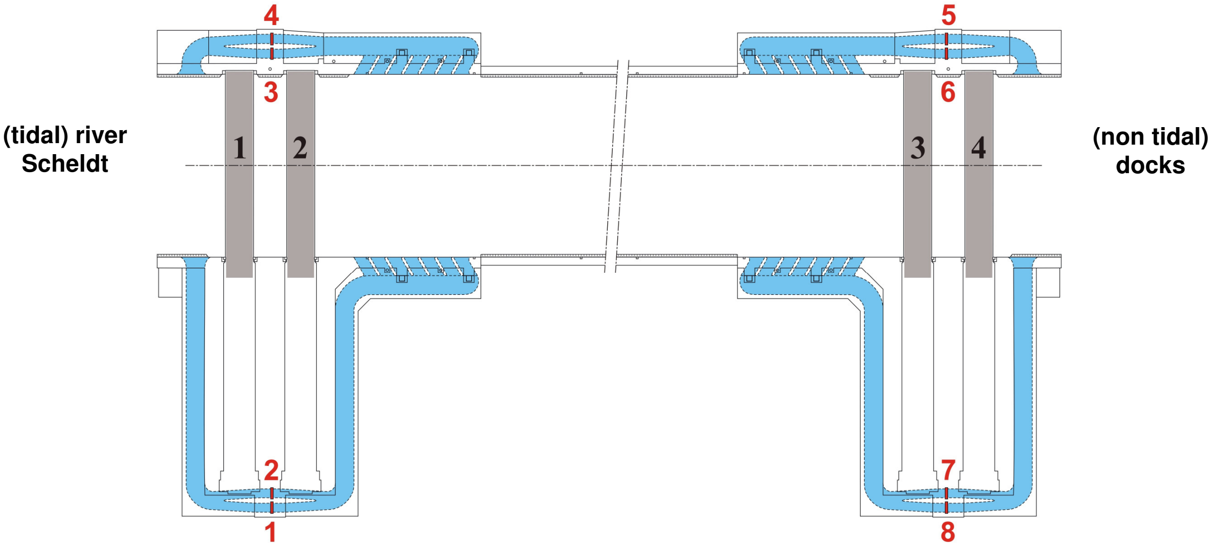


Figure 4 : Plan view of filling-emptying systems in lower lock head (left) and upper lock head (right)

Note that the southern culverts are longer than the northern ones, since the southern ones have to bypass the gate recesses.

In each culvert, 2 vertical lift valves are present. See Figure 4 for numbering of valves. The valve opening time is in the order of 3 min. resp. 5 min. for the Zandvliet lock resp. Berendrecht lock, see Table 1.

Lock	Zandvliet		Berendrecht	
Lock head	Lower	Upper	Lower	Upper
Valve opening time [mm:ss]	3:05	3:33	5:18	5:13

Table 1 : Valve opening times

The cross-section of the culverts is larger for Berendrecht (H x W = 7m x 7m) than for Zandvliet (H x W = 6m x 6.5m).

Some more constructional details can be found in PIANC (1986).

3.2 Scale modelling

During the design of the Zandvliet lock, a scale model study at scale 1:25 was carried out by Flanders Hydraulics Research, see SMETS, E. & STERLING, A. (1961) and Figure 5. For the more recent Berendrecht lock, no specific scale modelling efforts were made.

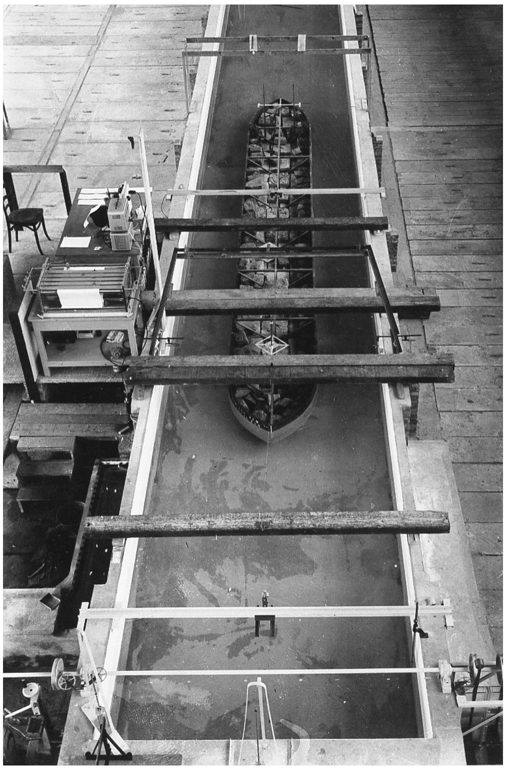


Figure 5 : Scale model of Zandvliet lock (1:25)

Only lock filling operations were investigated, since the hawser forces in case of emptying are (commonly) expected to be less important, since energy dissipation takes place outside the lock chamber.

Only the longitudinal component of the hydrodynamic force on a ship was measured during lock filling, since the transversal component was believed to be very small.

In the scale model lock chamber, the gate recesses were not accounted for. Yet, the culverts were modelled correctly, i.e. the differences between south and north culvert because of the gate recesses were accounted for.

Several filling tests were carried out, with different model ships (see Table 2), ship positions, initial heads and valve opening times.

Ship's size [ton]	Length [m]	Beam [m]	Draft [m]
100,000	273.75	41.00	14.50
60,000	243.75	32.88	12.88
30,000	188.00	25.75	10.38
20,000	200.00	23.75	6.50

Table 2 : Some ship's used in scale model study of Zandvliet lock

Note in Table 2 that the largest ship considered in the scale model study - i.e. the ship with a displacement of 100,000 ton - has a length of about half the lock chamber length between the outer gates (i.e. the gates n° 1 and 4).

A sample of measured longitudinal forces on the 20,000 ton resp. 100,000 ton ships, is presented in Table 3 resp. Table 4. Only the maximum value of the time-varying force during a filling operation is tabulated. The maximum forces are expressed as a fraction of the ship's displacement weight, in promille. In SMETS, E. & STERLING, A. (1961), no estimate of the force measurement accuracy is presented.

Test n°	Displacement ship [ton]	Distance bow from upper gate [m]	Level Scheldt [m T.A.W.]	Level dock [m T.A.W.]	Initial head [m]	UKC at begin filling [%]	Valve opening time [mm:ss]	Max. long. force [‰]
1	20,000	87.25	-0.83	+4.17	5	96	04:51	0.49
2	20,000	87.25	-0.83	+4.17	5	96	07:13	0.47
3	20,000	87.25	-0.83	+4.17	5	96	10:17	0.42
4	20,000	87.25	-0.83	+4.17	5	96	12:58	0.38
5	20,000	87.25	-0.83	+4.17	5	96	14:07	0.36
6	20,000	87.25	-0.83	+4.17	5	96	17:16	0.27

Table 3 : Measured forces on 20,000 ton ship in scale model study of Zandvliet lock

Test n°	Displacement ship [ton]	Distance bow from upper gate [m]	Level Scheldt [m T.A.W.]	Level dock [m T.A.W.]	Initial head [m]	UKC at begin filling [%]	Valve opening time [mm:ss]	Max. long. force [‰]
7	100,000	91.25	+2.17	+4.17	2	9	05:07	0.45
8	100,000	91.25	+2.17	+4.17	2	9	07:20	0.32
9	100,000	91.25	+2.17	+4.17	2	9	09:28	0.26
10	100,000	91.25	+2.17	+4.17	2	9	12:00	0.21
11	100,000	91.25	+2.17	+4.17	2	9	14:14	0.19
12	100,000	91.25	+2.17	+4.17	2	9	16:21	0.16

Table 4 : Measured forces on 100,000 ton ship in scale model study of Zandvliet lock

From Table 3 and Table 4 it is clear that - for a given ship, ship position and initial head - the maximum longitudinal force on the ship increases if the valve opening time decreases. Note that in both tables the smallest valve opening time is in the order of 5 minutes, which is significantly larger than the value of about 3 minutes which is nowadays valid for the prototype Zandvliet lock (see Table 1). This implies that in the propotype situation, the force could be significantly larger than the highest force values appearing in Table 3 (i.e. 0.49‰ for the 20,000 ton ship) and Table 4 (i.e. 0.45‰ for the 100,000 ton ship).

In the scale model study of SMETS, E. & STERLING, A. (1961), some effort was made to investigate (approximately) the influence of the "mooring line elasticity" onto the measured hydrodynamic forces (by introducing springs with different spring constants in the measurement set-up). It turned out that the maximum longitudinal force varies with the amount of longitudinal displacement that the model ship is allowed for. As a consequence, a range of maximum longitudinal forces is tabulated for the test cases presented in Table 5.

Note that for some test cases in Table 5, the range of maximum longitudinal forces is large.

Test n°	Displacement ship [ton]	Distance bow from upper gate [m]	Level Scheldt [m T.A.W.]	Level dock [m T.A.W.]	Initial head [m]	UKC at begin filling [%]	Valve opening time [mm:ss]	Max. long. force [‰]
13	100,000	91.25	+2.17	+4.17	2	9	09:40	0.21-0.24
14	60,000	41.25	+0.17	+4.17	4	7	09:40	0.32-0.40
15	60,000	87.00	+0.17	+4.17	4	7	09:40	0.31-0.36
16	60,000	87.00	+2.17	+4.17	2	23	09:40	0.16-0.21
17	30,000	107.50	-0.83	+4.17	5	24	09:40	0.26-0.36
18	30,000	38.00	+0.17	+4.17	4	33	09:40	0.29-0.33
19	30,000	222.25	-0.83	+4.17	5	24	09:40	0.18-0.30
20	30,000	222.25	+0.17	+4.17	4	33	09:40	0.14-0.25

Table 5 : Measured forces in scale model study of Zandvliet lock (modified measurement set-up, incl. springs)

The influence of the initial head on the maximum longitudinal forces has not been investigated in depth in the scale model study. Yet, from a comparison of testcases n° 15 and 16 in Table 5, it follows that – for a given ship, ship position and valve opening time – the maximum longitudinal force increases with the initial head. Also a comparison of testcases n° 19 and 20 in Table 5 – but preferably in the graphs presented in SMETS, E. & STERLING, A. (1961) – leads to the same conclusion.

Analogously, no extensive investigation of the influence of the ship position onto the maximum longitudinal forces has been carried out in the scale model study. However, a comparison of testcases n° 14 and 15, as well as test cases n° 18 and 20 in Table 5 – but preferably in the graphs presented in SMETS, E. & STERLING, A. (1961) – leads to the (preliminary) conclusion that – for a given ship, initial head and valve opening time – the maximum longitudinal force increases with the distance of the bow to the upper gate (i.e. the gate in the upper lock head through which the lock chamber is filled).

3.3 Hawser force criteria

Based on SMETS, E. & STERLING, A. (1961), it seems that during the design of the Zandvliet lock in the nineteen-sixties, no clear-cut hawser force criterion was specified. Only occasionally reference was made to the maximum values of about 1 ‰ for the longitudinal force on a ship, which were at the time common for designs of (inland navigation) locks in Belgium and neighbouring countries, see PIANC (1986). As a consequence, no comments are found in the scale model reports that the measured forces were considered (too) high for certain filling conditions.

As mentioned in section 2.4.1, later on attempts were made in literature to define hawser force criteria which take account of vessel size and vessel-positioning system characteristics.

In maritime locks like the Zandvliet lock, ships are typically moored along the lock chamber wall with four lines: one head line, one stern line, one for spring and one aft spring. This configuration has been studied by VRIJER, A. (1974 and 1977), see Figure 6. Based upon a rational (but somewhat schematized) methodology (taking into account realistic mooring line and winch characteristics) hawser force criteria were proposed for different sizes of ocean-going vessels, different rope types and different degrees of pre-tension in the ropes, see Table 6. Note that the criteria are expressed as maximum (longitudinal and transversal) hydrodynamic forces (and hydrodynamic moments) on a moored vessel that should not be exceeded.

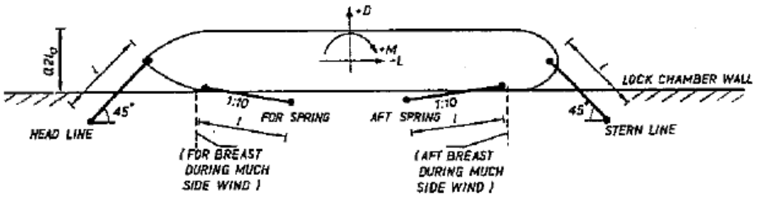
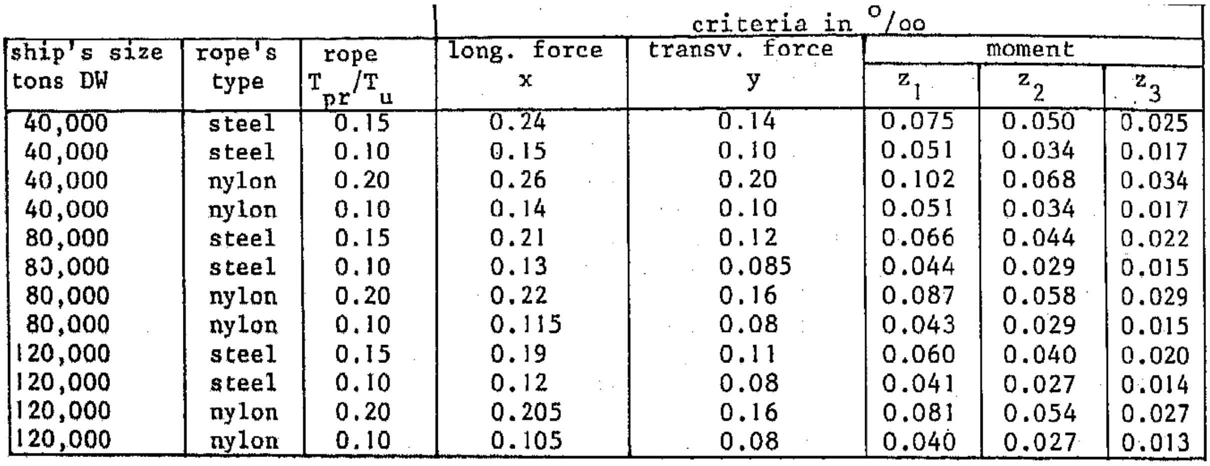


Figure 6 : Mooring line configuration considered in VRIJER, A. (1977)



ship's size tons DW	rope's type	rope T_{pr}/T_u	criteria in $^o/_{oo}$ long. force x	transv. force y	moment z_1	z_2	z_3
40,000	steel	0.15	0.24	0.14	0.075	0.050	0.025
40,000	steel	0.10	0.15	0.10	0.051	0.034	0.017
40,000	nylon	0.20	0.26	0.20	0.102	0.068	0.034
40,000	nylon	0.10	0.14	0.10	0.051	0.034	0.017
80,000	steel	0.15	0.21	0.12	0.066	0.044	0.022
80,000	steel	0.10	0.13	0.085	0.044	0.029	0.015
80,000	nylon	0.20	0.22	0.16	0.087	0.058	0.029
80,000	nylon	0.10	0.115	0.08	0.043	0.029	0.015
120,000	steel	0.15	0.19	0.11	0.060	0.040	0.020
120,000	steel	0.10	0.12	0.08	0.041	0.027	0.014
120,000	nylon	0.20	0.205	0.16	0.081	0.054	0.027
120,000	nylon	0.10	0.105	0.08	0.040	0.027	0.013

Table 6 : Hawser force criteria proposed in VRIJER, A. (1977)

According to Table 6, the longitudinal force on e.g. a 100,000 ton ship should not exceed (depending on the rope type and degree of pre-tension) 0.11 to 0.22 ‰. These criteria can be compared to the measured values in the scale model study of Zandvliet lock (see Table 4) where a range of 0.16 to 0.45‰ was found for the 100,000 ton ship, depending on the valve opening time, which varied in a range of about 16 to 5 minutes. In principle, such a comparison should take the measurement accuracy of the scale model data into account, but the latter has not been presented in SMETS, E. & STERLING, A. (1961). Nevertheless, it seems clear that the scale model results do not meet the criteria, unless an extremely high valve opening time is used. This observation suggests that the published criteria are rather conservative.

Since no transversal force components were measured in the Zandvliet scale model study, no comparison can be made to the criteria for the transversal force (nor for the moments) presented in Table 6.

When comparing measured values in scale model studies to the abovementioned criteria of VRIJER, A. (1977), one should keep in mind that the vessel position and the vessel positioning system are not identical in both cases. In a scale model, the model ship is centred in the transversal direction of the lock chamber and is (without realistic mooring lines and winches) attached to a measurement set-up (with force sensors) which keeps the vessel more or less fixed in the horizontal plane (but allows a vertical displacement when filling or emptying the lock chamber).

3.4 In situ measurements

Water surface slopes – which are representative for the hydrostatic forces on ships moored in the lock chamber, see KALKWIJK (1973) – have been determined, based upon several measurement campaigns (2007-2008) in both the prototype Zandvliet and Berendrecht locks.

In each measurement campaign, a number of (synchronously logging) water level sensors were mounted in ladder recesses (see Figure 7) distributed along both lock chamber walls (see Figure 8).

Figure 7 : Water level sensor (left) mounted in ladder recess of lock chamber wall (right)

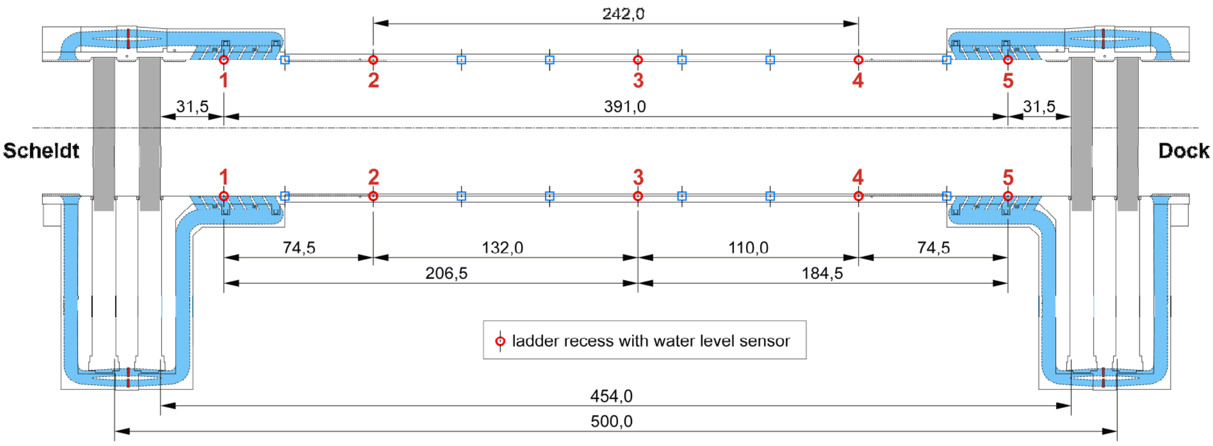


Figure 8 : Position of water level sensors (red numbers) along both lock chamber walls

From the observed (instantaneous) water level differences among two sensors, it is straightforward to calculate the corresponding (instantaneous) water surface slopes. The smaller the distance between the sensors, however, the less accurate the corresponding water surface slope can be determined. By means of the sensors in the outer ladder recesses (i.e. the sensors indicated by red nrs. 1 and 5 in Figure 8, which are spaced 391m apart), a reasonably accurate (i.e. up to about ±25%) estimate of the so-called end-to-end slope can be obtained. Both an end-to-end slope along the northern lock wall as well as along the southern lock wall can be defined. Note that the end-to-end slope is in principle more relevant (as a measure for the longitudinal component of the hydrostatic force) for tall ships (i.e. ships having a length which is a non-negligible fraction of the lock chamber length).

Some examples of measured data during lock filling or emptying of Zandvliet and Berendrecht locks are shown in Figure 9, Figure 10 and Figure 11. Note that the lock chamber length (i.e. the rolling gates that were used) and the number of culvert valves in operation (due to maintenance) are not identical for all tests during the measurement campaigns. This complicates the analysis of the results.

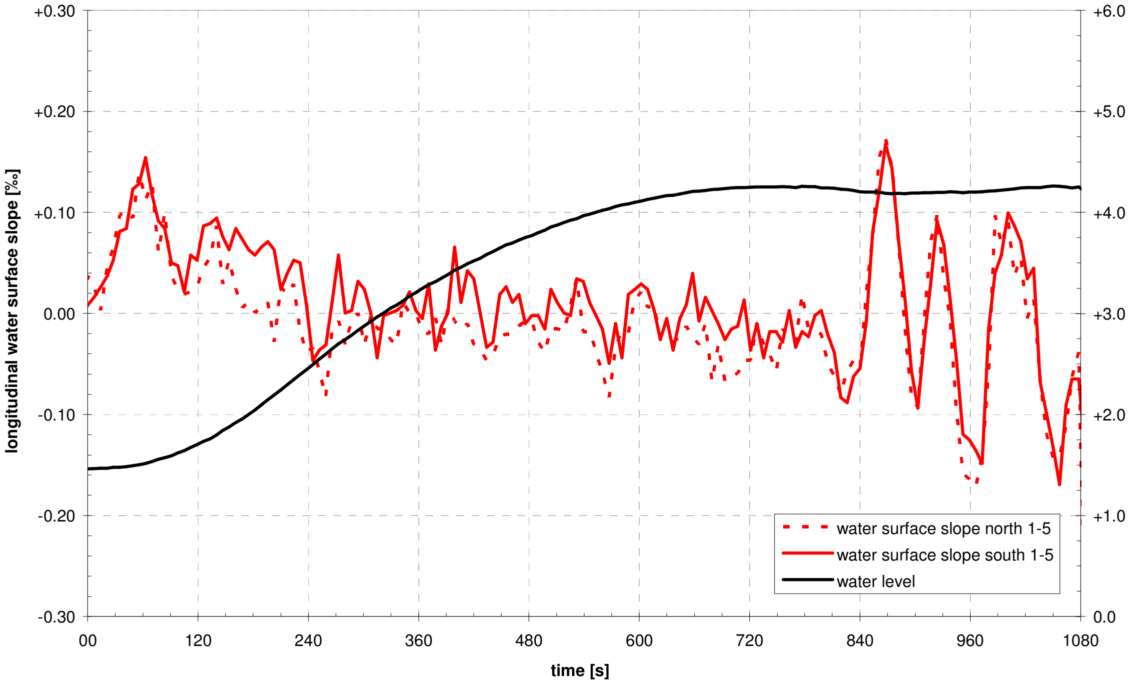


Figure 9 : Example of measured water level and end-to-end slopes in Zandvliet lock (filling through upper lock head of lock chamber between gates n° 2 and 3 ; one valve out of order ; initial head ≈ 2.7m ; peak value end-to-end slope ≈ +0.15 ‰)

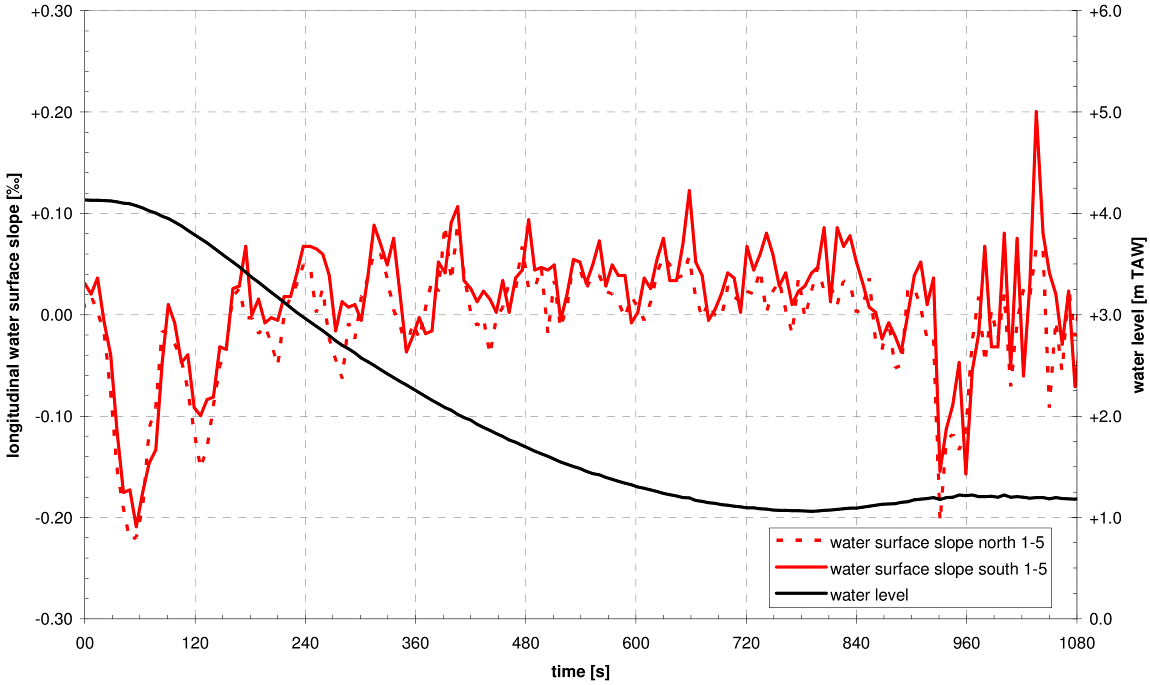


Figure 10 : Example of measured water level and end-to-end slopes in Zandvliet lock (emptying through lower lock head of lock chamber between gates n° 2 and 4 ; one valve out of order ; initial head ≈ 3.0m ; peak value end-to-end slope ≈ -0.22 ‰)

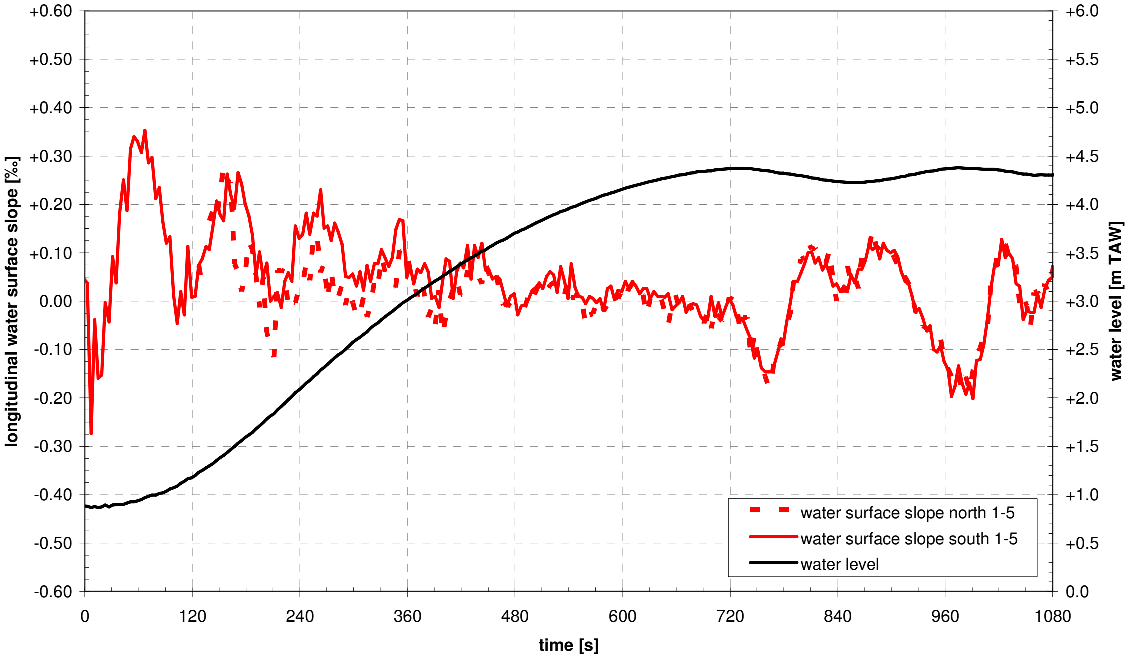


Figure 11 : Example of measured water level and water surface slopes in Berendrecht lock (filling through upper lock head of lock chamber between gates n° 1 and 4 ; all valves in operation ; initial head ≈ 3.4m ; peak value end-to-end slope ≈ +0.35 ‰)

Note in the examples above that the peak value of the end-to-end slope during lock filling/emptying appears in the early phase of the filling/emptying operation, but that after equalization of the lock chamber (i.e. during the overtravel phase), the same order of magnitude of end-to-end slopes have been measured (and in some other examples the slope was even significantly higher than the slopes during lock filling/emptying). It is not clear to which extent the latter observations are due to flow induced by ships or by manipulation of culvert valves and rolling gates.

In Figure 12 resp. Figure 13, the peak value of the end-to-end slope in Zandvliet lock resp. Berendrecht lock is presented as a function of the initial head. The data correspond to lock filling operations through the upper lock head, during different measurement campaigns.

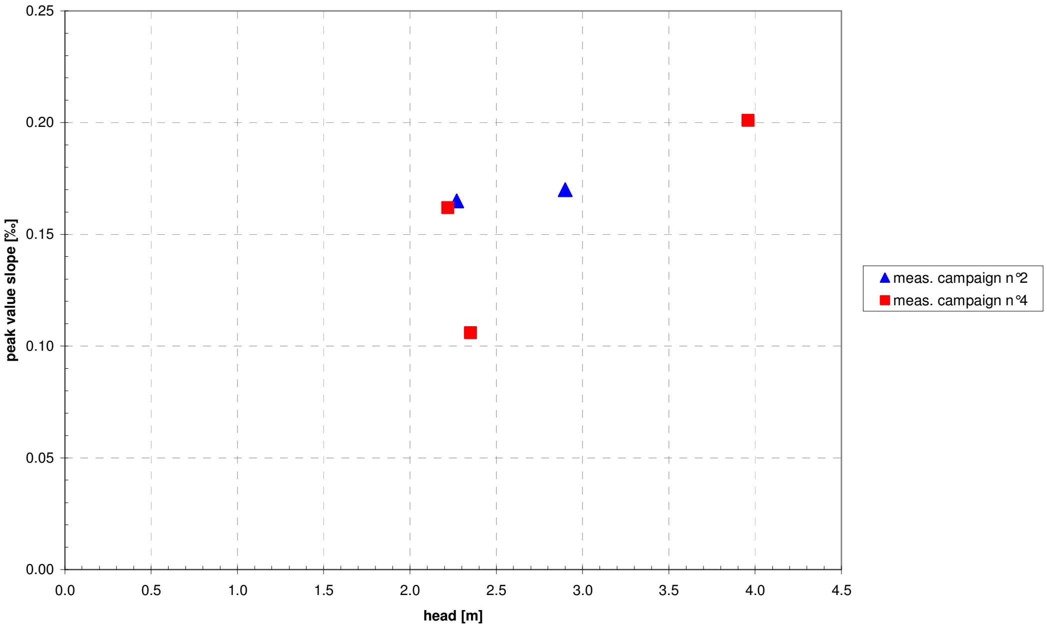


Figure 12 : Peak values of end-to-end slope vs. initial head in Zandvliet lock (filling through upper lock head of lock chamber between gates n° 2 and 4 ; one valve out of order)

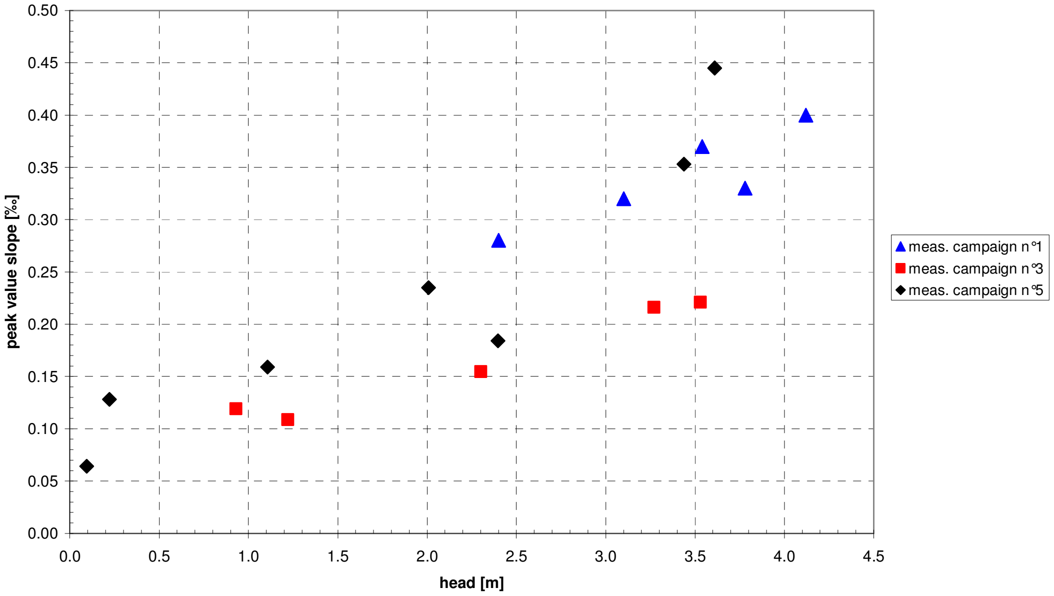


Figure 13 : Peak values of end-to-end slope vs. initial head in Berendrecht lock (filling through upper lock head of lock chamber between gates n° 1 and 4 ; one valve out of order in measurement campaigns n° 1 and 3)

Figure 12 and Figure 13 show that the peak value of the end-to-end slope increases with increasing initial head.

The highest peak value for the end-to-end slope which appears in Figure 12 is about 0.20‰. In other types of lock filling/emptying operations during the measurement campaigns in Zandvliet lock, even a value of about 0.30‰ has been found.

Analogously for the Berendrecht lock, the highest value for the end-to-end slope appearing in Figure 13 is about 0.45‰. This value turns out to be the maximum value during lock filling/emptying operations in all measurement campaigns in Berendrecht lock.

The aforementioned maximum values of the in situ measured end-to-end slopes during lock filling/emptying (i.e. 0.30‰ for Zandvliet lock and 0.45‰ for Berendrecht lock), which are representative for the hydrostatic force on a vessel, should in principle not be compared to the published criteria for the hydrodynamic force on a vessel (i.e. 0.11 to 0.26‰, depending on ship size, rope type and degree of pre-tension in the ropes, see Table 6), since the nature of the forces (hydrostatic vs. hydrodynamic) is not identical. Nevertheless, since the hydrostatic force is (according to literature) often the dominant component of the hydrodynamic force during lock filling/emptying, a comparison makes some sense. Even if the measurement accuracy of the in situ measured end-to-end slopes (i.e. about ± 25%) is accounted for, such a straightforward comparison leads to the conclusion that the hydrostatic force on a vessel during lock filling/emptying can be in practice (much) higher than allowed for by the threshold values for the hydrodynamic force. (A similar conclusion can be preliminary drawn when considering the situation after equalization of the lock chamber, but here some more analysis of the data is needed.) The foregoing conclusion suggests that the criteria published in 'modern' literature are rather conservative, allthemore since no complaints about the degree of safety or comfort during lockage in the Zandvliet and Berendrecht locks are known to the port authorities.

During the measurement campaigns, the Zandvliet and Berendrecht locks were in operation. This means that each filling or emptying operation for which water surface slopes were measured, is characterised by a different number, size and position of ships moored in the lock chamber. Some attempt was made to analyse the influence of these parameters onto the end-to-end slopes. So far, however, not enough data are available to draw unambiguous conclusions.

Note that in the different measurement campaigns in the Zandvliet and Berendrecht locks discussed above, the respective valve opening times (see Table 1) remained constant. Hence, the influence of the valve opening time onto the measured end-to-end slopes cannot be investigated.

So far, the in situ measurement campaigns have focused on water surface slopes. In the course of 2010, it is the intention of Flanders Hydraulics Research to extend these measurements by simultaneously measuring the motion (6 degrees of freedom) of a moored ship during lock filling/emptying. It is hoped that this will lead to an improved measurement accuracy and to more insight into the hawser force issue.

3.5 Numerical modelling

With numerical models based on the shallow water equations (SWE), the (translatory wave) flow and the corresponding water surface slopes in the lock chamber (incl. gate recesses) can be simulated during lock filling or emptying. The presence of moored vessels in the lock chamber can be accounted for by imposing an artificial pressure field, such that the 'trough' in the free surface has approximately the same dimensions as the ship's hull.

Both 1D models [like e.g. LOCKSIM developed by SCHOHL, G.A.(1998 and 2005)] and 2D models [like e.g. DELFT3D developed by Delft Hydraulics] can be used.

In case of DELFT3D (contrary to LOCKSIM), the flow in the culverts is not solved for during the simulations. Hence, pre-calculated (with 1D software like e.g. LOCKSIM, WANDA3 or FLOWMASTER) time series of discharge through the culverts have to be specified as input boundary conditions in the DELFT3D model.

Note that with a 2D model, both an end-to-end-slope along the northern and the southern lock walls can be estimated, whereas a 1D model only can predict one (transversally averaged) end-to-end slope.

An example of a filling operation of the Zandvliet lock is given in Figure 14. Both the 1D (LOCKSIM ; average slope) and 2D (DELFT3D ; north and south slope) numerical results are shown, in comparison to the measured end-to-end water surface slopes along both the northern and the southern lock chamber walls.

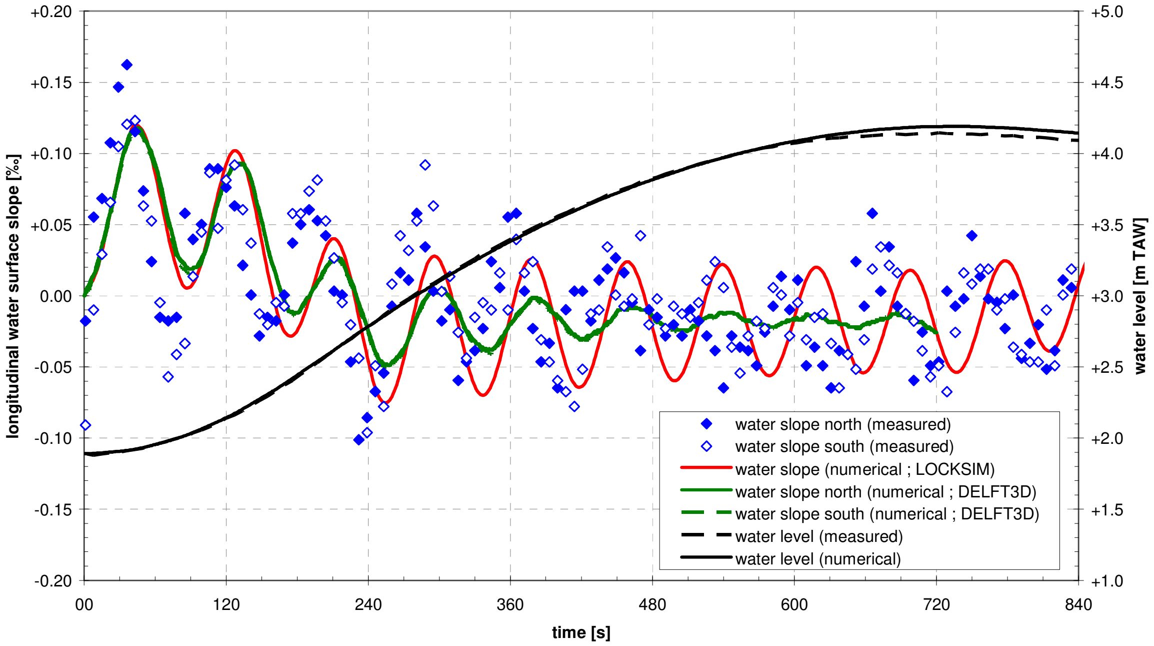


Figure 14 : Comparison of numerical model results and in situ measurements (filling through upper lock head of Zandvliet lock between gates n° 2 and 4; one valve out of order ; initial head ≈ 2.3m)

Note that the 1D and 2D numerical results do not deviate much in the prediction of the first few oscillations of the slope, but the damping of the subsequent oscillations is significantly different. This conclusion holds also for other types of lock filling/emptying operations in both the Zandvliet and Berendrecht locks. The differences in damping behaviour of the 1D and 2D models is due to differences in the numerical schemes (hence, different amounts of timestep-dependent numerical damping) and differences in the available physical damping mechanisms present in both models.

The differences between 1D and 2D model results as to the maximum value of the end-to-end slope during lock filling or emptying operations are relatively small, see Table 7. The same conclusion can be drawn as to the maximum value of the water surface slope between bow and stern of moored ships, see also Table 7.

Lock	F/E	initial head [m]	end-to-end slopes			slope between bow-stern of ship		
			LOCKSIM [‰]	DELFT3D north [‰]	DELFT3D south [‰]	largest ship in lock chamber	LOCKSIM [‰]	DELFT3D [‰]
Zandvliet	F	2.71	+0.192	-	-	MSC Delhi	+0.223	-
		2.22	+0.120	+0.118	+0.116	Stolt Shearwate	+0.141	+0.164
	E	2.99	-0.215	-0.205	-0.206	Multi Trader	-0.253	-0.289
Berendrecht	F	3.78	+0.158	+0.152	+0.153	Iran Mahallati	+0.183	+0.170
		3.27	+0.152	+0.154	+0.148	Maria Knutsen	+0.179	+0.172
	E	4.24	-0.149	-0.134	-0.134	Olesia	-0.166	-0.183
		3.18	-0.179	-0.166	-0.170	Msc Togo	-0.217	-0.228

Table 7 : Comparison of predicted maximum water surface slopes with 1D and 2D numerical models for filling (F) or emptying (E) of Zandvliet and Berendrecht locks

Note also in Figure 14 and Table 7 that the differences between the 2D model predictions of the northern and southern end-to-end slope maxima are very small.

From Figure 14, it follows that the numerically predicted time series of end-to-end slope agrees qualitatively well with the in situ measured time series. Nevertheless, there are quantitative differences both in amplitude and phase of the slope oscillations.

Table 8 offers a comparison between in situ measured and numerically predicted maximum values of the end-to-end slope in several filling or emptying operations in both Zandvliet and Berendrecht lock.

lock	F/E	initial head [m]	measured slope [‰] (average north/south)	numerical slope [‰] (LOCKSIM)	deviation [%] = $\frac{\lvert num.\rvert - \lvert meas.\rvert}{\lvert meas.\rvert}$
Zandvliet	F	2.71	+0.147	+0.192	+31
		2.22	+0.143	+0.120	-16
	E	2.99	-0.215	-0.215	0
Berendrecht	F	4.01	+0.560	+0.202	-64
		3.44	+0.353	+0.222	-37
		2.22	+0.127	+0.139	+9
	E	4.11	-0.168	-0.144	-14
		1.38	-0.127	-0.116	-9
		1.19	-0.164	-0.150	-9
		0.85	-0.105	-0.081	-23

Table 8 : Comparison of in situ measured and numerically predicted maximum end-to-end slopes for filling (F) or emptying (E) of Zandvliet and Berendrecht locks

Note in Table 8 that for some lock filling operations the numerically predicted peak value of the end-to-end slope can deviate more than 25% from the measured value, i.e. more than the estimated accuracy of the in situ measurements (see section 3.3).

All the foregoing observations put into evidence that the (1D and 2D) numerical models based on the SWE, are not really suited to quantify water surface slopes (i.e. hydrostatic forces) in absolute values. Yet, it is commonly agreed that those models are capable of comparing different filling/emptying conditions or filling/emptying systems in relative terms.

In Figure 15, the maximum water surface slope during lock filling as predicted by the 1D LOCKSIM model is presented as a function of the initial head. The slope denotes the so-called end-to-end slope defined by numerical ‘sensors’ located in the positions nr. 1 and 5 of Figure 8. Figure 15 contains results of both the Zandvliet lock and the Berendrecht lock. Both results of an empty lock chamber (i.e. no ships) as well as results in which a ship (i.e. the MSC Colombia with length x beam x draft = 294m x 32.2m x 9.9m) is present in the lock chamber are shown in the graph.

Note that for all cases in Figure 15, the maximum water surface slope increases with the initial head. This correlation was also found in the scale model results and in the in situ measurements of slopes.

Note that the predicted slopes in Figure 15 are smaller for the Berendrecht lock than for the Zandvliet lock (which has a smaller width and valve opening time than the Berendrecht lock). This observation cannot be confirmed by means of scale model results, since no scale model was set-up for the Berendrecht lock. Neither is it possible by means of the collected in situ measured slopes, since not enough Zandvliet lock data are available which allow a fair comparison with Berendrecht lock data (i.e. identical use of gates and identical number of valves in operation, identical number/size/position of ships).

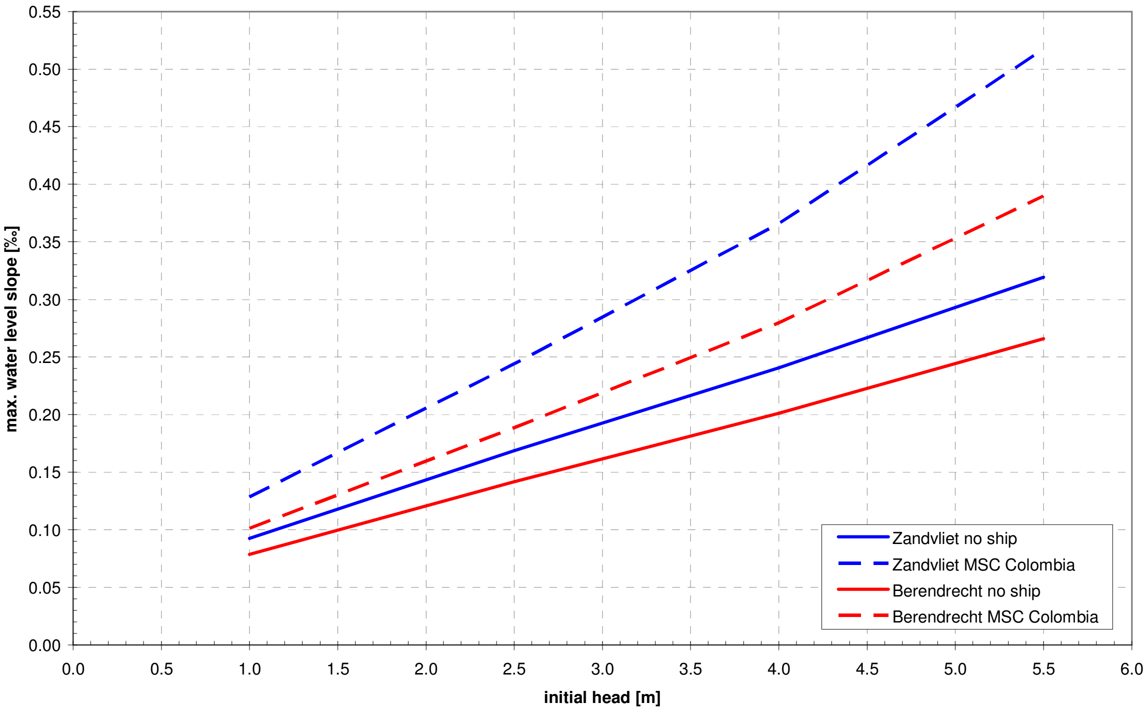


Figure 15 : Maximum end-to-end slope predicted with 1D model as a function of the initial head in Zandvliet and Berendrecht locks (filling through upper lock head of lock chambers between gates n° 1 and 4 ; all valves in operation)

Note that the numerically predicted maximum water surface slopes in Figure 15 are higher in presence of a ship than in case of an empty lock chamber. This correlation cannot be confirmed by means of the scale model results, since no water surface slopes were reported in SMETS, E. & STERLING, A. (1961). Neither is it possible so far to draw such a conclusion from the collected in situ measured slopes.

Similar numerical simulations as in Figure 15 (not presented in this paper) have shown that the predicted maximum water surface slopes increase with decreasing valve opening time. This correlation can be confirmed by means of the scale model results. The influence of the valve opening time onto the in situ measured end-to-end slopes, however, cannot be investigated because the valve opening time was kept constant throughout all measurement campaigns.

From the foregoing paragraphs, it is clear that certain correlations which are present in the 1D (or 2D) numerical model results for the longitudinal slopes (or hydrostatic forces), are confirmed by the scale model results and/or the in situ measurements. This contributes to the confidence that the 1D or 2D numerical models are capable of comparing different filling/emptying operations or filling/emptying systems in relative terms. Nevertheless, some caution is justified as long as not all correlations in the numerical model results have been confirmed in situ measurements and/or scale model results.

The latter remark is even more valid with respect to the prediction of transversal slopes (or hydrostatic forces) by means of 2D numerical models, since so far neither scale model results nor (sufficiently accurate) in situ measurements are available for validation purposes.

The question arises whether more complex numerical models, like 3D CFD codes based on the RANS or Euler equations, have a superior quality for the prediction of (longitudinal and transversal) slopes and forces, as compared to (1D or 2D) numerical models based on the SWE.

During the conceptual design of the third set of locks for the Panama Canal, the Consorcio Pos-Panamax has applied such codes (e.g. the so called Fluent and Ananas codes) to the benchmark case of the Zandvliet lock, see CPP (2007b). The computational effort of those 3D codes, however, is huge in comparison to the (1D or 2D) SWE codes. This inevitably constrains the number of test runs and the associated analysis efforts that are feasible in a (conceptual) design process.

In some 3D test runs the filling discharges through the culverts were predicted in the 3D simulation, whereas in others the filling discharges were predicted off line by 1D codes and were imposed as boundary conditions to the 3D model. In some 3D runs the hull of the ship was schematized to a prismatic volume, but in other simulations more realistic hull shapes were investigated. In some 3D test runs, Fluid-Structure-Interaction (FSI) was accounted for, albeit restricted to 1 degree of freedom of the ship (heave). Some of the aforementioned 3D runs were simulated with the Fluent code (RANS equations, no FSI), whereas others with the Ananas code (Euler equations, with or without FSI).

From the efforts that were carried out by CPP, one can draw some (preliminary and partial) conclusions.

In an example inspired by (but not fully identical to) a test from the FHR scale model study (1961), the maximum longitudinal (hydrostatic) force on a prismatic hull (box) - i.e. the maximum water surface slope between bow and stern - that is predicted by a 3D CFD code (without FSI) deviates less than 5% from the results of the 1D and 2D shallow water codes. This maximum slope appears to be the first peak in the oscillating time series of the slope.

For the subsequent peaks, however, the 3D CFD and 2D SWE results gradually deviate both in amplitude and phase. The 3D results are less damped and the frequency of the oscillations increases more in time throughout the lock filling operation.

Running a 3D RANS code and a 3D Euler code leads to quasi the same time series of slopes/forces.

The results of a 3D Euler code (without FSI) for a prismatic hull shape only show small deviations from the ones corresponding to a more realistic hull (having the same displacement weight).

When running the 3D Euler code with a more realistic hull, the forces with FSI are larger than (and contain a higher-frequency component than) the ones without FSI. The maximum force values with and without FSI have a relative deviation of about 25%.

It is obvious that there is room for additional research in order to verify the aforementioned preliminary conclusions. Moreover, it would be interesting to investigate more in depth the capabilities of 3D CFD codes for predicting hydrodynamic forces in the transversal direction, both for a vessel located centrally in the lock chamber as well as for a vessel moored close to a lock wall.

4. CONCLUSIONS

Hawser force criteria are meant to guarantee a sufficient degree of safety and comfort during lock filling/emptying operations of a lock that is being designed. Some subjective elements (i.e. feelings of the captain, pilot, lockmaster) in the appreciation of safety and comfort are hard to quantify. Therefore, one is obliged to rely upon a quantification of the ‘objective’ elements (e.g. forces, water surface slopes, displacements) in order to meet the goal of safe and comfortable, but preferably also economic designs. This will always remain a challenge.

Traditionally, hawser force criteria are defined in terms of the hydrodynamic force on a vessel. The associated threshold values published in ‘modern’ literature seem to be rather conservative, as was demonstrated in the case study of Zandvliet and Berendrecht locks (and in some other lock studies the authors were involved in).

In principle, 3D CFD codes are nowadays available as verification tool for such criteria, in addition to the classical scale model. Yet, both types of verification tools are time-consuming and require large resources and specialized operators, hence their use in conceptual design is rather limited.

Both 1D and 2D numerical codes based on the shallow water equations (SWE), however, do not suffer from the aforementioned drawbacks and are within reach of all consulting engineers. By nature, these codes cannot predict the full hydrodynamic force on a vessel, but are restricted to the hydrostatic component, which is determined by water surface slopes. This is often the dominant component. As a consequence, it would be beneficial if alternative hawser force criteria were defined in terms of water surface slopes. This ‘paradigm shift’ is strongly advocated, but should go along with intensive validation efforts based on scale modelling and in situ measurements of water surface slopes. For both types of validation tools, due attention should be paid to measurement accuracy. In addition, it is recommended to correct for the historical bias towards the longitudinal direction and give due attention to transversal slopes and forces.

Besides water surface slopes and forces, also ship behaviour (displacements) could be explored as a means to define alternative hawser force criteria. In situ measurements are nowadays possible and will hopefully lead to more insight. Also numerical modelling of the ship behaviour is feasible nowadays. Yet, the ‘classical’ methodological simplicity of not having to model the vessel-positioning system (e.g. mooring lines, winches), is lost in this approach. As a consequence, a large number of input parameters have to be specified. Some of them require further research (e.g. the ones related to the confined water conditions of a large ship in a lock chamber). Moreover, the time evolution of the ship displacements seems to be very sensitive to certain parameter settings.

No matter which constitutive variable is used to formulate hawser force criteria, and no matter which tool is used to verify whether a given threshold value is not exceeded, it is clear that absolute truth is not within reach. Yet, it is commonly agreed that it is possible to compare different filling/emptying systems or filling/emptying operations in relative terms. As illustrated with the case study in this paper, this assertion can to a large extent be corroborated by an intercomparison of results of scale modelling, numerical modelling and in situ measurements, but additional validation efforts are still needed.

To summarize, one can state that the hawser force issue is a complex and still not resolved problem. Notwithstanding all impetus to initiate extra research, common sense and pragmatism should not be overlooked. In many prototype situations, a (slight) deterioration of the lock filling/emptying time (e.g. by increasing the valve opening time) is acceptable (in view of the total time needed for a lock passage), and might be adequate to relieve to a great extent eventual hawser force problems.

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