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Parametric study of direct filling system of medium-head navigation locks

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ABSTRACT

As part of the research focusing on the safety of vessels during the lockage in navigation locks, two different 1D numerical modeling approaches were tested. These approaches are used to determine the force effects on vessels during the direct filling process of the navigation lock. These numerical models were verified using data measured on a physical model. Using the selected 1D model, a parametric study focusing on the impact of the basic parameters of the navigation lock including the lifting velocity of the gates on the maximum hawser forces was performed. The research has shown that with a suitable design of the upper gate, the direct filling system may also be used for medium-head navigation locks with a normal lift of up to 5 m.

KEYWORDS

navigation lock, hawser force, filling system, numerical model, physical model, parametric study

1. INTRODUCTION

Determining the effects of flowing water, which create hawser forces is the basic criterion for assessing the appropriate method of leveling for the navigation lock. The safe and smooth lockage of a vessel in the lock chamber depends mainly on the speed and filling method. The Filling/Emptying (F/E) time of navigation locks must be reduced to minimize transit time, but excessive inflow/outflow generates surges and excessive hawser forces, resulting in increased risk of accidents in the lock chamber [1]. Due to hawser forces generated by the flowing water during the lockage, vessels inside the lock may move uncontrollably and collide with gates, side walls or with other vessels. The risk is particularly high for small, recreational ships and the lock equipment – impact by large ships. This could damage the vessel or the gate, which are the most sensitive structures in the chamber. For this reason, it is necessary to reduce hawser forces acting in horizontal direction on ships in lockage. Navigational safety is an important criterion in the navigation lock as well as near the water structures [2].

In mooring applications, the system is generally under-damped, and the displacement of the moored vessel oscillates with an exponential decay in amplitude [3]. A distinction is made between hawser forces acting in longitudinal and transverse direction. The components of these forces are created based on the F/E system of the lock chamber (short culverts or direct filling). The magnitude of the hawser forces is also influenced by the size and position of vessels in the lock chamber [4]. The emptying process generally creates significantly weaker forces acting on the vessels than during filling, because energy dissipation occurs outside the lock chamber. For this reason, the article only focuses on the lock filling process.

According to [4], five different components of the longitudinal force F_{long} act on the vessel in the lock chamber during direct filling process. These are: a component caused by translatory waves in the lock chamber F_{transl}, a component caused by the momentum decrease in longitudinal direction of the chamber $F_{impulse}$, a component caused by the impact of the

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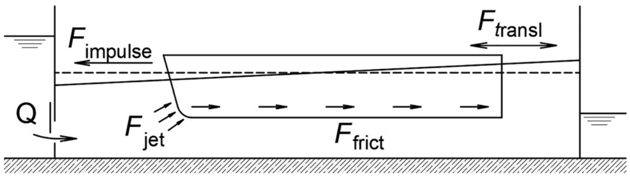

Fig. 1. Longitudinal force components occurring during direct filling of the lock: *Q* is the inflow into the chamber, broken line is the surface of still water in the chamber, solid line is the water surface during leveling in the chamber

Table 1. Threshold for longitudinal force

VESSEL Class	Hawser force criteria (‰ of total ship displacement) In filling	At emptying or filling with floating bollards
CEMT III	1.50	2.00
CEMT IV	1.10	1.50
CEMT Va	0.85	1.15
CEMT Vb	0.75	0.75
Small ships	3.00	3.00

filling jet against the bow of the ship F_{jet}, a component caused by the friction force F_{frict} and the component caused by the density differences in the lock chamber F_{dens}. The F_{dens} component only occurs if salt and fresh water are mixed during filling. This force is not present in inland locks and it is not addressed in this paper. Longitudinal force components existing in inland locks are shown in Fig. 1.

Vrijburcht [5] states that during direct filling of the chamber, translatory waves are caused by the flow rate and bounce from the vessel and the gate creating water level differences. The concentrated filling jet and the decrease in momentum along the length of the chamber lowers the water level in front of the bow of the vessel, which contributes to the water level difference in the longitudinal direction of the chamber and creates a longitudinal force on the vessel. In the absence of the differences in water density, the translatory waves, the momentum decrease and the friction force represent the main components of the longitudinal force acting on the vessels. The effect of the filling jet on the vessel is usually negligible, provided that the vessel is moored at a sufficient distance from the area of the concentrated flow and the blockage area of the cross-section of the lock chamber represented by the vessel is not too high. If these assumptions are met, the resulting longitudinal force equals to:

$$F_{long} = F_{transl} + F_{impulse} + F_{frict} + F_{jet}. \quad (1)$$

The assessment of the longitudinal force, at the design stage, acting on the vessel in the chamber is usually done by numerical modeling [6] or by using physical models [7] and [8]. The components of the individual forces may only be measured in limited ways or they may be derived from numerical models. For this reason, the water level slope, which has the most significant impact on hydrodynamic load, is most often used to quantify these forces. The resulting longitudinal force on the vessel may be calculated using the following formula:

$$F_{transl} = W \cdot S = W \cdot \frac{(H_{bow} - H_{stern})}{l_s}, \quad (2)$$

where, F_{transl} is a component caused by translatory waves [N]; W is the displacement weight of the ship [N]; S is the water level slope between the bow and stern [-]; H_{bow} and H_{stern} are the water levels at the bow and the stern of the ship [m] and l_s is the length of the ship [m].

For inland navigation vessels, the longitudinal force limits are set by international and national regulations, or as recommended in [9–11]. The longitudinal force acting on ships is often defined by the relative value of the longitudinal water level slope in formula (2), as recommended by the Permanent International Association of Navigation Congresses (PIANC) [4, 5], see Table 1.

Appropriate handling when opening the filling gates (nonlinear opening of the filling gates compared to linear opening) can reduce the maximum longitudinal force and shorten the filling time. According to the research [1], up to 30% shorter filling times are achieved using nonlinear opening. Studies [12] and [13] describe in detail the optimization of nonlinear opening.

2. METHODS

The aim of numerical modeling is to describe the behavior of a real physical phenomenon while using a model and the similarity between the real and the abstract system. However, the obtained description of the phenomenon is an accurate approximation of the actual state, which is so complex that it cannot be expressed analytically. In order to numerically approximate the solution, discretization methods are used, which replace the system of differential equations with algebraic ones which are solved by numerical models.

Further, 1D numerical models used in engineering practice are described and verified. Availability is their advantage, as most of them are open source. Another advantage is small demand on hardware. Therefore, they are also suitable for optimization analysis of the design of direct F/E of locks.

Verelst [6] compares numerical models using software VUL_SLUIS, LOCKFILL, LOCKSIM and DELFT3D. However, these models are only calibrated for heads of up to 3 m [6, 14].

In the research two 1D numerical approaches were tested, namely superposition of waves and 1D Saint Venant for a head of up to 5 m.

2.1. Superposition of waves

Using the method of superposition of waves, it is possible to determine the longitudinal forces on the ship caused by all components of these forces using the 1D calculation. The method allows the calculation of various F/E systems in the heads of the lock, e.g., openings in the lock gates, lifting gates or short culverts in the lock head walls [14]. The superposition of waves is used to calculate individual components of longitudinal force (waves) according to the immediate flowrate changes during leveling. Translatory waves travel to and fro in the lock chamber with a complete reflection against the lock gates and a partial reflection against the bow and stern of the ship. The magnitude of the wave reflections at the bow and stern of the ship depends on the blockage by the ship. The water level differences in the lock chamber and the component of the longitudinal force created by the translatory waves are derived simultaneously using one-dimensional continuity and momentum equations similar to paragraph 2.2. The complete derivation of the longitudinal force components can be found in [15]. In the method of superposition of waves it is possible to use the option of parameterization of a filling jet, which propagates behind the gates [6].

2.2. 1D Saint Venant formula

A simple 1D model based on the approximation of Saint Venant's equations was used to simulate the longitudinal slopes in the lock chamber. The approach is based on the assumption of a dominant flow rate and water level slopes along the longitudinal direction of the lock chamber and on the approximation of depth and velocity by using mean values for the individual cross sections. The relationship between the flow rate Q [$m^3 \cdot s^{-1}$] and the cross-section area A [m^2] is given by the continuity Eq. (3) and by the momentum Eq. (4):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q\,, \qquad (3)$$

$$\frac{\partial Q}{\partial t} + \beta \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} = gA\left(s_0 - s_e - s_f\right)\,, \qquad (4)$$

where q [$m^2 \cdot s^{-1}$] is lateral flow rate (zero in our case); β [-] is the Boussinesq coefficient; h [m] is the water depth; s_0 [-] is the slope of the bottom (zero in our case); s_e [-] is the local loss due to widening/narrowing of the cross section and s_f [-] is the friction loss. Cross area $A = b_k \cdot h$, where b_k [m] is the width of the lock chamber.

In the research, the inflow into the chamber is realized by a narrow slit at the bottom immediately behind the filling opening at the upper gate, while the assumption of the mean profile velocity using 1D schematization is inaccurate. Therefore, a modification using the Boussinesq coefficient, which is a momentum-correction factor for the non-uniform velocity profile, is used. The Boussinesq coefficient is defined as:

$$\beta = \frac{\int_0^A u^2 dA}{\overline{u}^2 \cdot A} = \frac{\sum_{i=1}^{n} u_i^2 \cdot A_i}{\overline{u}^2 \cdot A}\,, \qquad (5)$$

where u_i [$m \cdot s^{-1}$] is local velocity in the A_i [m^2] section, $\overline{u}$ [m^2] is the mean profile velocity for total area A [m^2]. In case of a profile with filling jet can consider only two sections: section of jet area A_{jet} [m^2] with velocity u_{jet} [$m \cdot s^{-1}$] and the rest area A_0 [m^2] with negligible velocity $u_0 \cong 0$, where $A = A_{jet} + A_0$. Then the Boussinesq coefficient can be expressed from Eq. (5) as $\beta = A/A_{\mathrm{jet}}$. The increased value β then decreases the water level behind the leveling openings around the filling stream – similarly as in reality.

A simplified approach was used to simulate the draft of ships in the lock chamber, where the transverse area is reduced by the area of the submerged (wet) hull of the ship A_s [m^2]: $A = b_k.h - A_s$. This modification of the area A is made in the cross-sections where the vessel is located. The implementation of the model was prepared using HEC-RAS software.

3. VERIFICATION

The United States Army Corps of Engineers (USACE), conducted measurements of hawser forces during F/E in the lock for more than 60 models using a geometric similarity scale of 1:25 ($l_r = 25$) and performed these measurements in 10 real locks. Experiments performed on physical lock models have shown very good agreement with the actual 'in-situ' measurements [16]. In order to verify 1D numerical model, a physical model of Vb class lock chamber was constructed, which was used to optimize the planned Děčín lock on the Elbe River. The lock is 24 m wide, 200 m long and the cross-section profile of the chamber is rectangular. The primary F/E system in this lock utilizes a sidewall port system. During the experiment with the sidewall port system was tested, including direct filling through the opening under the upper radial gate of the lock (Fig. 2a), which is designed as a backup. A direct filling system is usually designed for chambers with head up to 3 m [6, 11 and 14]. While maintaining a sufficient distance of the ship from the upper gate and while appropriately handling the gate opening, the proposed direct filling system may also be used for head exceeding 3 m. The design of the radial gate in the upper head offers many operational advantages, including the option of direct filling of the lock in case of failure of the primary F/E system, transfer of antifreeze flow through the lock, transfer of flood flow and transfer of ice floes. It is necessary to deal with sediment transport of the river bed to eliminate the risk of clogging the lock [17].

The physical model of the lock chamber was built under the assumption that dominant gravitational forces will apply according to Froud's law of mechanical similarity between reality and the model. The ratio of the Froud number of the prototype (index p) and the physical model (index m) is $F_r = F_p/F_m = 1$. Based on the validity of Froud's law of mechanical similarity, the condition $Re_r = 1$ cannot be met at the same time, but it is necessary to ensure simulated flows so that fully turbulent flow conditions on the prototype and on the model exist and that the roughness is not dependent on the Reynold's number [18]. This was achieved by a suitable choice of the scale of geometric similarity $l_r = 20$, where it is possible to achieve $Re_m > 10^5$ on the model for the

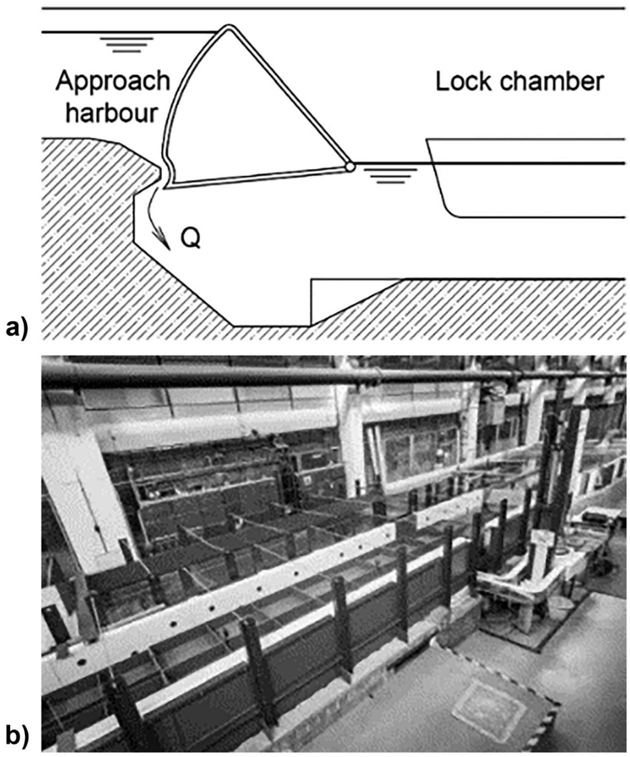

Fig. 2. a) Scheme of a radial gate in the upper head of the lock chamber modified for direct filling system; b) a view of the physical model

decisive majority of the filling time of the lock chamber. To measure a slope of the water surface in the chamber, pressure probes with a sampling frequency of 1 Hz were installed on the bottom of the chamber. A view of the physical model of the Děčín lock is shown in Fig. 2b. The basic parameters of the tested chamber are given in Table 2.

1D numerical models were constructed using software LOCKFILL (Superposition of waves) and HEC-RAS (1D Saint Venant) for direct filling of the lock through the gate opening under the radial gate. The ratio between the width of the filling gate opening and the width of the chamber b/b_k = 1. The lifting rate of the gate opening under the gate was

Table 2. Basic parameters of the lock chamber prototype

Geometry	Parameter	Value-unit
Initial water level of the approach harbor	h_v	10.47 m
Initial water level in the lock chamber	h_k	4.91–8.78 m
Level lock chamber bottom	z_k	0 m
Length of the lock chamber	l_k	200 m
Width of the lock chamber	b_k	24 m
Surface area of the gate openings	A_h	7.2 m^2
Width of gate openings	b_h	24 m
Ship length	l_s	135 m
Ship breadth	b_s	2 × 10.45 m
Ship draft	t_s	1.40–2.20 m
Distance from bow to lock gate	x_s	5 m
Vertical angle of bow	α	60°
Horizontal angle of bow	γ	90°

chosen in the range v = 0.001–0.010 m s^{-1}. Numerical models were set for a head of H = 5.56 m. Figure 3 shows the course of the water level and filling inflow for gate opening variant v = 0.0050 m·s^{-1} for individual model approaches.

Figure 3 clearly shows that there are minimal differences between the modeled (broken and dashed-and-dot lines) and the measured (solid line) values of the flow rate (0–60 m^3.s^{-1}) and the water levels time series h_l (0.00–5.56 m). The graph also shows the total filling time for the individual approaches. The maximum deviation of the peak flow rate is up to 2.5%. Next, the relative longitudinal force S (expressed as water level slope between the bow and stern in Eq. (2) acting on ships is compared (see Fig. 4).

If gate opening occurs at lift rate of v = 0.0050 m·s^{-1}, there is a very good match throughout the filling time.

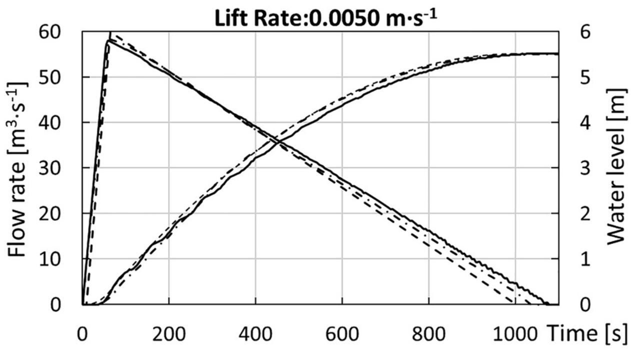

Fig. 3. Course of the flow rate and water level in time: solid line, Physical model, broken line, 1D Superposition of waves, dash-and-dot line, 1D Saint Venant

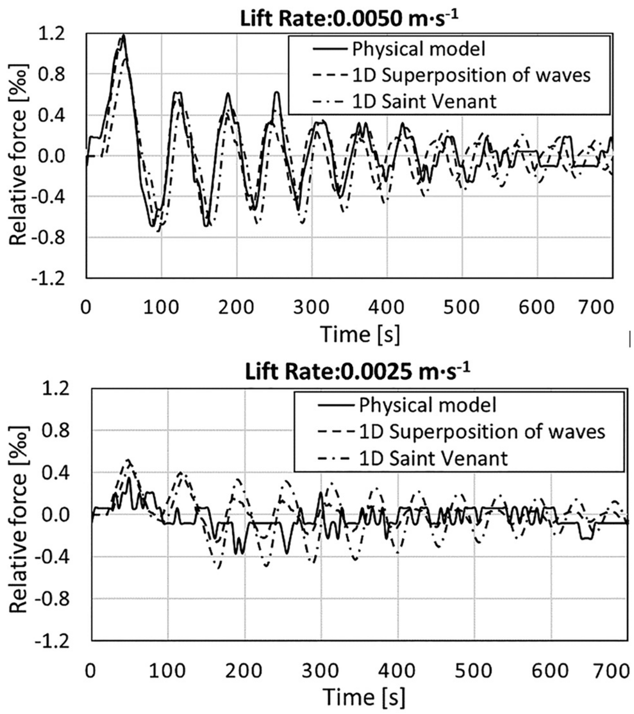

Fig. 4. Graph showing the course of the relative longitudinal force for individual variants

Compared to the 1D Saint Venant approach, the method of superposition of waves achieves a better agreement of the maximum water level slope between bow and stern of the ship. Both mathematical approaches show a longer wave period in the order of single percentage units, which causes a change in the frequency of the harmonic oscillation waveform, which is evident since the time of filling, approximately $T = 500$ s. The other test using slow gate opening $v = 0.0025$ m s^{-1} does not show such clear match or agreement between both mathematical approaches and the physical model. This is due to the limited ability to monitor the water level (1 mm accuracy) which corresponds to the relative longitudinal force sensing accuracy of 0.15‰.

Furthermore, Fast Fourier Transform (FFT) was used to perform frequency analysis, which quantifies periodic properties of the relative longitudinal force oscillation according to individual approaches. Figure 5 shows an excellent match of the main frequency of force load for gate opening speed $v = 0.0050$ m s^{-1}. The maximum signal intensity $A(f)$ is approximately at $f = 0.016$ Hz for all approaches, which corresponds with a relative longitudinal force period of approximately 62 s, which is also apparent from Fig. 4. When testing gate opening with lift rate $v = 0.0025$ m$\cdot$s^{-1}, the main frequency is not visible at all for the physical model. This fact may be attributed to the measuring limits on the physical model.

4. PARAMETRIC STUDY

Based on the verification, the method of wave superposition was chosen for the parametric study, which achieved better agreement with the physical model. The study was

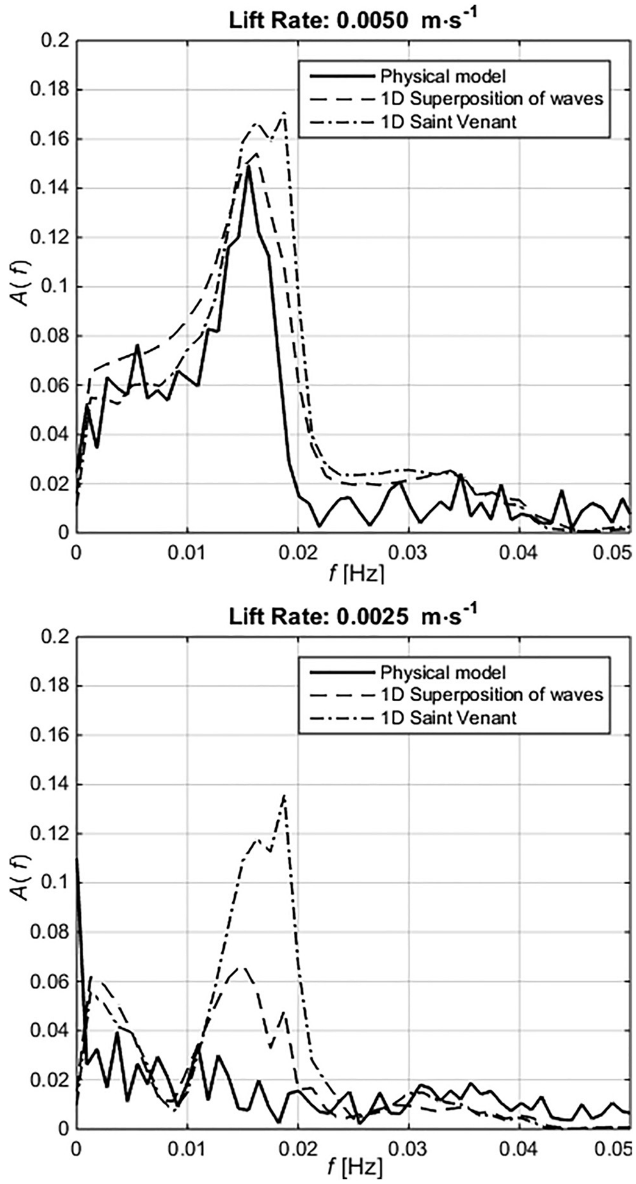

Fig. 5. Frequency analysis

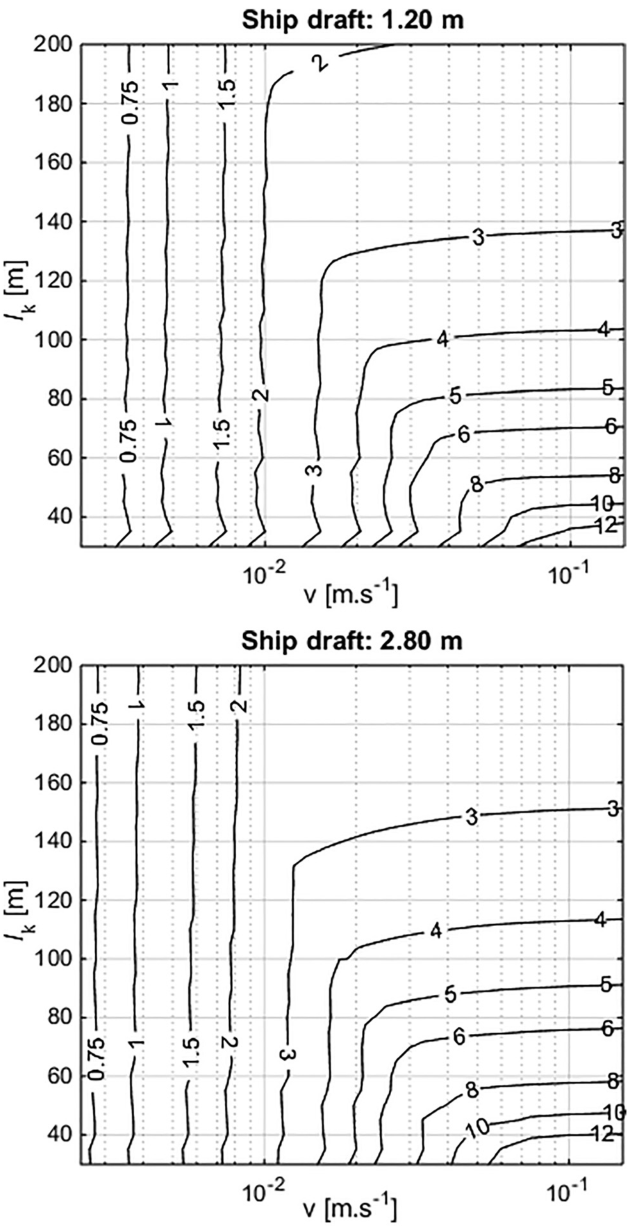

Fig. 6. Isoline S_{max} for ship draft t_s = 1.20 and 2.80 m

performed in the Matlab environment, which was used to initiate the calculation of wave superposition in batches and simulated in LOCKFILL. Basic parameters used in the study: draft of the ship t_s, the length of the lock chamber l_k and the lift rate v. A total of six ships with draft from 1.20 to 2.80 m were selected. These drafts were selected based on the classification provided by the European Conference of Ministers of Transport (Conférence Européenne des Ministres des Transports – CEMT). The length of the lock chamber ranged from 30 to 200 m by 5 m increments, so a total of 35 lengths combinations were used, which represent a large range of waterways – from regional waterways (in the Czech Republic) to class VIb according to CEMT. During the parametric study, the length of the ship was always considered 10 m shorter than the length of the lock chamber ($x_s = 5$ m). The lift rate was set from 0.0025 to 0.1500 m s^{-1}. According to individual parameters, 10,710 combinations of calculations were compiled. The evaluation parameter is the maximum relative longitudinal force $S_{\max}$ recorded during the leveling. Figure 6 shows the dependence of $S_{\max}$ on the basic parameters of the lock. The graph shows that the length of the lock chamber l_k does not affect the maximum magnitude of the relative longitudinal force for low lift rate $v < 0.0100$ m s^{-1}.

The graph also shows the effect of the ship draft on the maximum relative longitudinal force $S_{\max}$. It follows that the lower ship draft allows faster filling time maintaining the same longitudinal forces. The responsible design of the lock should include a parametric study to analyze the sensitivity of all variables that affect longitudinal forces and thus filling time. The parametric study can be used to optimize the hydraulic design as well as the operation of locks.

5. CONCLUSIONS

This paper compares the suitability of two different approaches using 1D numerical modeling for different variants of navigation locks utilizing direct filling system. Wave superposition and 1D Saint Venant methods were used, which allowed us to simulate the direct filling process of the lock chambers. The superposition of wave model was selected for the parametric study focusing on the basic parameters of the lock.

The research came to the following main conclusions:

– If the energy dissipation system used during the filling in the navigation lock is suitably designed and the ship is positioned inside the chamber at a sufficient distance from the gate used for the filling, then only the longitudinal force components caused by translatory waves F_{transl} and the components caused by the decrease of momentum along the longitudinal direction $F_{impulse}$ may be used to determine the maximum longitudinal force on the ship. These force components may be determined by using water level slope between bow and stern of the ship;
– Based on the verification of 1D numerical approach and based on the results obtained from the physical model, the tested 1D mathematical model may be used with sufficient reliability to design direct filling systems for lock chambers;
– The direct filling system of navigation lock can be used for head up to 5 m (medium-head navigation lock) for providing that a suitable gate design and an energy dissipation system was applied;
– The parametric study made it possible to quantify the influence and sensitivity of individual parameters of the lock chamber, and the ship, on the resulting longitudinal forces;

It should be noted that the lock filling process is a complex procedure that may be simulated using 1D numerical model but only under certain and simplified conditions, which are applicable to the preliminary design phase. In the case of a detailed design of a specific lock, it is strongly recommended to use a physical model to verify its hydraulic properties. When combined with physical models, 1D numerical model is useful tool for optimizing lock and filling systems.

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