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FIELD INVESTIGATIONS AND NUMERICAL CALCULATIONS CONCERNING MODERN VESSELS ENTERING AND EXITING LÜNEBURG SHIP LIFT

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ABSTRACT

Within the framework of improving the navigational conditions in the north-east canal system of Germany and considering the forecast increase in traffic on the Elbe Lateral Canal (ESK) between the Elbe River and the west-east canal system, the Federal Waterways Engineering and Research Institute (BAW) carried out investigations concerning large modern inland navigation vessels entering and exiting the ship lift at Lüneburg. The ship lift is a bottleneck for such ships because the water depth in its trough is restricted to approximately 3.4 m for reasons of structural stability. Thus the question arose as to the conditions under which the lockage of large vessels with a beam width of 11.4 m and 2.8 m draught could be permitted. The main questions to be answered were:

- At which ship speed could the wave height inside the trough, generated during entry, be restricted to such an extent that the water would not exceed the freeboard and the maximum permissible load of the drive system of the ship lift would not be exceeded?
- At which maximum impact velocity might a ship hit the gate protective barrier in the final phase of entry?
- At which ship speed could the ship touch the bottom of the trough during exit?

On the basis of a comprehensive literature survey concerning previous model and field tests on the subject as well as calculations with an unsteady one-dimensional model of water motion and ship behaviour, the permissible incoming speed was estimated first. Full-scale field tests were then carried out, especially to explore the “human factor” in possible ship speeds, with the main result that even high ship speeds, resulting in waves of about 1 m in height, caused no significant navigational problems. On the other hand, even at high ship speeds, the average time a ship takes to enter the lift could not be reduced to a predetermined value because the ship-generated waves slow down the ship in the trough. Thus the hydraulic conditions, wave height and squat, define the permissible ship speeds.

1. INTRODUCTION

The behaviour of vessels entering and leaving locks and ship lifts, as well as the associated hydrodynamic problems, are without doubt subjects of special interest in the field of waterway engineering. In the past, the problem attracted the attention of waterway engineers whenever existing locks no longer satisfied the requirements of ships with increasingly large hulls. Model and field investigations were subsequently carried out to determine the possibilities and limits of shipping traffic and the operation of the existing structures. The aim of these investigations was the quantitative determination of the following parameters:

1. Ship squat when a vessel enters and leaves a lock
2. Time taken to enter and exit and the associated speeds
3. Changes in the water level in the chamber
4. Return current velocities
5. Ship resistance

A study of Lüneburg ship lift on the Elbe Lateral Canal (ESK) conducted by the Federal Waterways Engineering and Research Institute (BAW) forms the background to this paper. The study sought to determine which conditions would enable larger vessels than those currently using the canal to enter and exit the ship lift safely. The first stage of the investigation consisted of evaluating the findings of previous navigational tests at locks and ship lifts with the aid of scale models and field tests (BAW, 2004a), taking into account papers by the following research establishments:

- VWS, FAS and BAW (Amtsberg, 1936; Kiehnel, 1936; FAS, 1964 and 1966; Felkel and Steinweller, 1977; BAW, 1973, 1989 and 2004a)
- VBD (Versuchsanstalt für Binnenschiffbau, the Test Centre for Inland Navigation Vessels in Duisburg, recently renamed the Development Centre for Ship Technology and Transport Systems (DST)) (VBD, 1981, 1993 and 2003a; Bross, 1994)
- Franzius-Institut, Technical University of Hanover (Franzius-Institut, 1969)
- Rijkswaterstaat (Kooman, 1973)

- British Transport Docks Board (BTDB, 1980 and Cooper et al.,1978)
- Russian institutes MIVT, LIVT, VNIIG and SO RAN (e.g. Kiriakov, 1972; Kiriakov et al., 1975; Romanov and Yanenko , 1974 and 1975; Atavin, 1977; Yanenko, 1994; Pochabov, 1997 and Klementiev, 2002)
- U.S. Army Corps of Engineers (Maynord, 1987) and Naval Surface Warfare Center (Fisher et al., 1978)

The analysis of the available literature focused on the results obtained for the first three parameters enumerated above. The results for return current velocities were not analysed as the investigations concerned had dealt with relatively old locks with an inadequately protected bottom, in which there was a risk of the bottom being eroded by excessive flow velocities. The results of the investigations into ship resistance were, for the most part, not analysed as this aspect is no longer relevant and the investigations had dealt mainly with how to determine the engine power required by vessels entering and exiting locks.

The analysis of earlier investigations concerning the assessment of the hydrodynamic conditions that occur when vessels enter and exit locks and ship lifts, which were mostly conducted with scale models, showed that it is very difficult to transfer physical model tests with a sufficient degree of accuracy owing to the difficulties in simulating the complex processes occurring during those operations. This applies in particular to the simulation of the motion of vessels running into a lock or ship lift and is the reason why field investigations were considered necessary and planned. Their aim was to obtain reliable results for the known boundary conditions for large vessels entering and exiting Lüneburg ship lift as well as to confirm and generalize the results of earlier model and field investigations so that forecasts for variable boundary conditions can be made.

In addition to the difficulties involved in simulating exactly what happens when a vessel enters a lock by means of a scale model, the limits of assessing the highly unsteady conditions theoretically by means of simple analytical methods and by applying a steady-state approach became evident during the preliminary investigations. The differential equations describing the physical event of a vessel entering or leaving a lock, the equations for the motion of the water (Saint-Venant equations) and the associated equations for the motion of the vessel cannot be resolved theoretically for general cases on an analytical basis. Approximate solutions to specific problems can only be achieved with simplifying assumptions. Thus a mathematical simulation with a numerical model is required to describe the complex operation. In this case, it was possible to apply an existing one-dimensional numerical method developed by the Development Centre for Ship Technology and Transport Systems, DST, (Chen et al., 2001) in the investigations carried out by the Federal Waterways Engineering and Research Institute. The results of the field investigation at Lüneburg ship lift were also invaluable when the model was calibrated by the DST and when verifying the results of the simulation.

2. RESULTS OF FIELD INVESTIGATIONS AT LÜNEBURG SHIP LIFT

2.1 TEST PROGRAMME

The tests were conducted in the eastern trough of the twin ship lift. They were carried out mainly in order to resolve the technical, nautical and hydraulic questions. When planning and conducting the tests, the different conditions for ascent and descent at the ship lift also had to be taken into account. In practice, the depth of water in the trough nowadays is 3.34 m at the downstream level and 3.42 m at the upstream level, with the nominal depth, h, being 3.38 m. In addition, the motion of the vessel and the water level were expected to be affected by the canal bridge extending the 107.8 m long trough on the upstream side, the base of that structure being 0.5 m lower than the trough. The test programme therefore included vessels entering and exiting the ship lift on the upstream and downstream sides.

A total of 14 sailing tests were conducted with the MS "Loetschental", with an even draught, d, of 2.80 m, over two days. The vessel entered the ship lift 5 times at the upstream level (IN-UL) and 3 times at the downstream level (IN-DL) and exited the ship lift 4 times at the downstream level (OUT-DL) and twice at the upstream level (OUT-UL). The governing test parameter for the running-in tests was the speed with which the vessel approached the ship lift. This approach velocity was varied in order to cover the range of speeds that usually occur in practice. The range of approach speeds, U_0, was 2.0 km/h $\leq U_0 \leq$ 8.0 km/h. The exit speed was limited by the blockage ratio, i.e. the critical ship speed. The boundary conditions and the designations of the sailing tests are given in Tables 1 and 2.

to the sailing tests, surge tests were planned and conducted upstream of the ship lift to measure the fluctuations in the water level. The purpose of the measurements was to determine how the discharge of the residual water when emptying the water saving lock Uelzen I affects the fluctuations in the upstream water level at the ship lift as these need to be taken into account in the assumed loads.

In addition to the sailing tests, surge tests were planned and conducted upstream of the ship lift to measure the fluctuations in the water level. The purpose of the measurements was to determine how the discharge of the residual water when emptying the water saving lock Uelzen I affects the fluctuations in the upstream water level at the ship lift as these need to be taken into account in the assumed loads.

	Entry from upstream					Entry from downstream		
Designation of the test	IN-UL-1	IN-UL-2	IN-UL-3	IN-UL-4	IM-UL-5	IN-DL-1	IN-DL-2	IN-DL-3
Approach speed [km/h]	2.0	3.1	3.7	5.8	8.0	2.8	3.8	5.5

Table 1 – Boundary conditions and designation of sailing tests in which the vessel entered the ship lift

	Exit to downstream				Exit to upstream	
Designation of the test	OUT-DL-1	OUT-DL-2	OUT-DL-3	OUT-DL-4	OUT-UL-1	OUT-UL-3
Mean exit velocity in the trough [km/h]	0.86	0.94	0.87	0.89	0.77	0.82

Table 2 – Boundary conditions and designation of sailing tests in which the vessel exited the ship lift

2.2 PERFORMANCE OF THE NAVIGATIONAL TESTS AND OBSERVED RESULTS

The analysis of the tests is principally based on measurements of the water levels and on tacheometer readings. The changes in the water level were measured by a number of pressure sensors installed in the trough and the approaches to the ship lift. This provided detailed information about the wave movements in the chamber – which result from the rise in the water level in the chamber due to the “piston effect” caused by a vessel entering the chamber and the drop in water level occurring when a vessel leaves the chamber – and the formation of standing waves with the frequency typical of the "half-open" oscillation system. The maximum rise in the water level was also recorded by video observation of gauges and with the aid of wave sensors at the closed end of the trough. The highest rise in the water level – approx. 1.0 m – was measured at the fastest chosen approach speed of 8 km/h.

The above mentioned surge tests was about 20 cm. Depending on the moment at which the upper gate of the ship trough at Lüneburg is opened – just before or just after the approach of the surge – the water level in the trough can rise or fall during the period of time in which the upper gate is open. This fact had to be taken into account in the assumed loads.

Based on the tacheometer measurements at the bow and stern of the ship, it was possible to record the relevant motion of the vessel as it entered and left the ship lift. The evaluation of the tests included the determination of the following parameters: ship speed, trim angle, midship sinkage, squat at bow and stern of the vessel. These parameters are shown in Figures 1 and 2 for vessels entering and exiting the ship lift respectively.

2.3 ANALYSIS OF TEST RESULTS

Some of the most important results obtained by evaluating the tests are discussed below. They relate to the following:

- maximum rise in the water level in the trough when a vessel enters the lift,
- maximum impact velocity at the gate protective barrier,
- maximum squat when a vessel exits the lift.

With regard to the determination of the magnitude of the rise in the water level that occurs when a vessel enters the trough, a comparison of the maximum values recorded in Lüneburg and a formula taken from the well-known investigations conducted by Kooman (1973), derived from measurements of a scale model, showed that the rises in the water level were far too high with Kooman’s formula for the low blockage ratio investigated, especially for high depth-based Froude numbers defined by $Fr_{h0} = U_0 / \sqrt{g\,h}$, where U_0 represents the approach velocity of the ship to the lock chamber or the ship lift. In order to find a suitable method of forecasting the maximum rise in water level, the field investigations conducted at the Lüneburg ship lift (BAW, 2005) were first analysed, taking account of previous test results obtained by the BAW at Friedrichsfeld Lock (BAW, 2004a) and Kooman's field measurements.

A new method of calculating the maximum rise in the water level at a lock or trough gate when a vessel enters from the downstream side was then determined by means of a regression analysis. It provides a better representation of the actual conditions, resulting the following relationship:

$$\frac{\Delta h_{max}}{h} = 1.64\left(\frac{b}{B}\right)^{0.75}\left(\frac{d}{h}\right)^{1.46} C_B^{\;0.45}\; Fr_{h0}^{\;1.46}. \qquad (2.1)$$

Accordingly, the relative rise in the water level, $\Delta h_{max} / h$, can be represented as a function of the governing parameters, which are the ratio of the beam width of the ship to the width of the trough, b/B, the ratio of draught to water depth, d/h, the block coefficient of the ship, C_B (displaced volume, divided by the product of $l\,b\,d$, l=ship legth), and the Froude number, Fr_{h0}.

Conversely, it is possible to use equation (2.1) to calculate the permissible approach speed so that the freeboard, defined by the relief openings in the trough gates, will not be overtopped. It is then analysed for the special boundary conditions in Lüneburg as trough water depths, beam widths and draughts, which are assumed to be variable.

Consequently, assuming that the depth of water in the trough is 3.35 m, the maximum permitted approach speed was calculated to be 5.2 km/h. This would ensure that the raised water level is lower than the minimum freeboard in the trough, which can be reduced by a surge height of 0.2 m as shown above, taking the largest of the vessels investigated, which had a beam of 11.65 m and a draught of 2.80 m. Increasing the depth to 3.50 m would result in a reduction in the permitted approach speed of the design ship by 1 km/h to 4.2 km/h. The reason for this reduction is the fact that the freeboard is reduced by 0.15 m.

The excess trough supporting forces, i.e. the forces in the drive spindles of the trough, result directly from the load due to the rise in the water level in the trough. At Lüneburg ship lift they must not exceed 1350 kN. In order to calculate the maximum trough holding force, the distribution of changes in water level during the 8 "running-in" tests were analysed to correlate the corresponding peak values of the excess forces to Δh_{max}. From this it was possible to estimate the maximum approach speed required to comply with the limit for the trough holding force under the variable boundary conditions at Lüneburg, resulting in 3.4 km/h for the largest ship considered at a trough water depth of 3.35 m. The permitted approach speed increases only slightly - to 3.5 km/h - when the trough water depth is raised to 3.50 m.

Another speed-related problem of ships entering locks and ship lifts concerns the issue of how to design the impact protection barrier to take account of variable boundary conditions (ship size, depth of water in the trough). This requires the estimation of the maximum impact velocity at the gate protective barrier. From available former model and field results at locks, only ship entries from the downstream side and where the depth of the water above the sill at the lower lock gates more or less corresponded to the depth of water in the chamber were taken into consideration

The tests at Lüneburg ship lift, conducted with a wide range of approach speeds between 2.0 km/h and 8.0 km/h, produced the remarkable result that the speed of the ship inside the trough, after a brief, but pronounced deceleration phase and disregarding wave-induced fluctuations during the further process of entry, is almost independent of the approach speed. Further results demonstrated that the speed of the ship in the trough is evidently determined essentially by the blockage ratio. An example of the correlation, which was confirmed by a number of other studies, is shown in Figure 3. It is based on the aforementioned investigations conducted by Kooman (1973) on push-tow units entering a lock. The entry of a push-tow unit at a steady speed is shown in a path-time diagram for various blockage ratios which were realized in the model by varying the depth of water in the lock chamber. It can be seen very clearly that, after a phase of uneven deceleration, the ship enters the lock at a more or less steady speed, which is limited by the blockage ratio and is referred to as the "final speed", U_f, in the following.

In accordance with Figure 3, the path-time law can be used as the governing equation for the quantitative description of the motion of the ship for the uniform translation, with

$$x = x_0 + U_f\, t \qquad (2.2)$$

where x is the distance, in metres, between the bow of the ship and the gate after the ship passes the gate, t is the time after the ship has passed the gate and x_0 is the distance covered in the first deceleration phase of the entry into the lock, in metres.

The empirical determination of the dependence of the parameter x_0 for the description of the unsteady motion of the ship in the first phase of entering the lock showed that there is a significant dependence on the ship dimensions and may be roughly parameterized by the ship length, l. A good approximation for the parameter x_0 was obtained with the linear correlation:

$$x_0 = 0.44\,(l - l_0) \tag{2.3}$$

The quantity l_0 is an empirical constant and was determined as 57 m, which limits the applicability of the equation to smaller ships.

A correlation with the critical ship speed, U_{cr}, according to the one-dimensional canal theory was sought in order to identify an analytical equation for determining the final speed, U_f, not only for reasons relating to dimension theory but also to find out more about the phenomenon itself. The critical ship speed was determined according to Schijf (PIANC, 1987) as follows:

$$\frac{U_{cr}}{\sqrt{g\,h}} = \left(\frac{2}{3}\right)^{3/2} \left(1 - \frac{1}{n} + \frac{U_{cr}{}^2}{g\,h}\right)^{3/2} . \tag{2.4}$$

The investigation of the functional dependence between the critical ship speed, U_{cr}, and the final speed, U_f, of a ship entering a lock resulted in the equation:

$$\frac{U_f}{\sqrt{g\,h}} = 0.30 \left(\frac{U_{cr}}{\sqrt{g\,h}}\right)^{0.71} . \tag{2.5}$$

This relationship for the final speed formed the basis for estimating the speed of the vessel when it hit the impact protection barrier and consequently for the design of the impact protection, taking account of the fluctuations in speed due to the translatory waves occurring as the ship enters a lock.

The time a vessel takes to enter the trough of a ship lift or a lock chamber, t_e, can be calculated as a function of the incoming path, x_e, by means of equation (15) and by substituting the equations (16) and (18) as follows:

$$t_e = \alpha \,\frac{x_e - x_0}{U_f} . \tag{2.6}$$

A correction factor α is added to take account of stopping the vessel at the end of the entry process. A good correlation with the entry times measured in the site investigations was obtained with the above empirical equation in which α was taken as 1.17.

In spite of the different hydrodynamic conditions that exist when a ship enters and exits a ship lift or lock, there are a number of parallels between entry and exit. Thus the lock exit can also be divided into characteristic phases, in addition to which there is a physically determined final speed which is expressed directly by the critical ship speed obtained by equation (2.4). A comparison of ships entering and exiting Lüneburg ship lift and other locks showed that the measured entry and exit times differed only slightly. The exit times can therefore be estimated roughly by means of the above equations.

The last phenomenon to be analysed is the squat of the ship. The latest findings on this subject show that the risk of a vessel touching bottom is greater when it leaves a lock than when entering it. A number of methods of calculating the midship sinkage and the local squat at bow or stern in locks and canals are available in the literature. However, existing approximations for estimating the squat result in considerable differences in the calculated squat, especially if they are applied to the extremely narrow cross section in a lock or a ship lift. Therefore they are generally valid only within strictly defined limits.

In the search for a reliable method of forecasting squat in the variable boundary conditions in locks, it was possible to go back to scale model investigations of the ship lifts at Niederfinow and Rothensee conducted by the former FAS agency in Berlin (FAS, 1964) and to systematic investigations conducted on model locks (FAS,1966). A regression analysis resulted in the relationship:

$$\frac{\Delta d_{max}}{h} = 2.03\,(n-1)^{-1.15}\; C_B^{-0.31}\; Fr_h{}^{1.63} \tag{2.7}$$

It demonstrates that the maximum relative stern squat, Δd_{max}, of a vessel leaving the lift is determined by the blockage ratio, $1/n$ (n = cross section of the trough, divided by product $b\ d$), the block coefficient, C_B, and the depth-based Froude number, Fr_h, defined as $Fr_h = U / \sqrt{g\,h}$, with the exit velocity, U, as the numerator. The data used to

derive the squat formulae comprised the following ranges of parameters:
$1.17 \le n \le 3.26,\ 0.018 \le Fr_h \le 3.26$, *and* $0.83 \le C_B \le 0.96$

In order to verify the new equation for the squat of vessels leaving a lock, the results of the calculations were compared with the squat measurements conducted by the BAW at Lüneburg ship lift (BAW, 2005), the results of previous field investigations conducted by the BAW at Marbach lock on the River Neckar (BAW, 1990) and other empirical methods of determining the squat of vessels exiting a lock or sailing along a canal. It was shown that the new empirical method reflects the results of the measurements very well. The squat equation was then applied to the conditions at Lüneburg for the most onerous design assumptions. These were:

1. The ship exits at the critical ship speed.
2. The entire passage of a vessel through the lock is affected by the dynamic drawdown of the upstream water level.

The dynamic underkeel clearances determined on the basis of these assumptions demonstrate that, given a trough water depth of 3.35 m and a ship draught of 2.8 m, it is not possible to maintain the desired dynamic underkeel clearance of 0.20 m for any of the ships in the study and that, even the one ship with the smallest beam considered, touches the bottom under the assumed conditions. Increasing the depth of the water in the trough by as little as 15 cm results in a clear improvement in the situation. The recommendation to increase the depth of water in the trough of the ship lift to 3.50 m is based on these results.

3. NUMERICAL INVESTIGATIONS

There are a number of publications in the literature that deal with numerical investigations of a ship entering or leaving a lock, including those by Vrijburcht (1986 and 1991), Atavin et al. (1998) and Chen et al. (2001). The method of Chen was used here and is briefly described as follows.

Two coordinate systems are used: an earth-bound system $Oxyz$ and a system $\hat{O}\hat{x}\hat{y}\hat{z}$ moving horizontally with the ship. They are interrelated by:

$$x = \hat{x} + \xi(t) - l/2, \quad y = \hat{y}, \quad z = \hat{z}, \quad t = \hat{t}, \qquad (3.1)$$

where l is the ship length and $\xi(t)$ is the distance covered in the lock (from the lock gate to the ship bow). The sinkage of the ship's centre of gravity, G, is denoted by $s(t)$, the trim by $\theta(t)$ (stern up positive).

Therefore its dynamic local cross-sectional area, S_d, under the undisturbed water level, $z = 0$, can be derived from its static value, S_0, as follows:

$$S_d(\hat{x},t) = S_0(\hat{x}) + b(\hat{x})[s(t) + (\hat{x} - \hat{x}_G)\theta(t)]. \qquad (3.2)$$

Only the strictly symmetrical case is considered here, i.e. in which a symmetrical ship enters a symmetrical lock along its centreline, see figure 4.

Moreover, the problem is simplified so that it is one-dimensional, i.e. the free surface is $z = \zeta(x,t)$, the mean fluid velocity in x-direction is $u(x,t)$, and the dynamic local canal cross-sectional area filled with water is

$$A(x,t) = A_0(x) - S_d(\hat{x},t) + [B(x) - b(\hat{x})]\zeta(x,t). \qquad (3.3)$$

The flow is therefore modelled by the following mass-conservation and momentum equations:

$$\frac{\partial A}{\partial t} + \frac{\partial (uA)}{\partial x} = 0, \qquad (3.4)$$

$$\frac{\partial u}{\partial t} + \alpha_1 \frac{U}{A} u - \alpha_2 \frac{\partial^2 u}{\partial x^2} + u \frac{\partial u}{\partial x} + g \frac{\partial \zeta}{\partial x} = 0. \qquad (3.5)$$

The empirical α_1-term in Eq. (3.5) describes a mean local friction on the canal side-walls and the surface of the ship's hull (Prandtl-Tietjens, 1931); it has a dominant effect, but its value is determined by trial and error in the numerical calculation. The α_2-term represents a small viscous wave damping and may be neglected. Since by virtue of symmetry only three degrees of freedom (surge, heave and pitch) are involved, the relevant hydrodynamic forces and moment acting on the ship are evaluated as

$$F_x = \rho g \int_{-l/2}^{l/2} \left\{ \zeta \frac{d}{d\hat{x}} \left[S_0(\hat{x}) + b(\hat{x})(s + \theta(\hat{x} - \hat{x}_G)) \right] + \frac{\zeta^2}{2} \frac{db}{d\hat{x}} \right\} d\hat{x} \qquad (3.6)$$

$$F_z = \rho g \int_{-l/2}^{l/2} \left[\zeta + s + \theta(\hat{x} - \hat{x}_G)\right] b(\hat{x})\, d\hat{x} \tag{3.7}$$

$$M_{\hat{y}G} = -\rho g \int_{-l/2}^{l/2} \left[\zeta + s + \theta(\hat{x} - \hat{x}_G)\right] b(\hat{x})(\hat{x} - \hat{x}_G)\, d\hat{x}. \tag{3.8}$$

The corresponding equations of motion are:

$$m\frac{dU}{dt} = F_x + F_d, \quad m\frac{dW}{dt} = F_z, \quad J_{\hat{y}\hat{y}G}\frac{d^2\theta}{dt^2} = M_{\hat{y}G}, \tag{3.9}$$

where

$$U = d\xi / dt, \quad W = -ds / dt, \tag{3.10}$$

and F_d is the excess of net effective propeller thrust over the hull frictional resistance, expressed as:

$$F_d = T - R_f \tag{3.11}$$

In the calculation either the thrust, T, or the speed of revolution of the propeller is assumed to remain constant. In the former, the thrust may be evaluated throughout at its equilibrium value before the ship reaches the gate. In the latter, the quasi-steady propeller curve of K_T over J can be used to compute the instantaneous thrust. The frictional resistance, R_f, is updated continuously using the ITTC 1957 formula with an empirical velocity-increase correction similar to Emerson's (1959).

Introducing static water-plane integrals

$$A_w = \int_{-l/2}^{l/2} b(\hat{x})d\hat{x}, \quad M_w = \int_{-l/2}^{l/2} (\hat{x} - \hat{x}_G) b(\hat{x})d\hat{x}, \quad I_w = \int_{-l/2}^{l/2} (\hat{x} - \hat{x}_G)^2 b(\hat{x})d\hat{x}, \tag{3.12}$$

and dynamic auxiliary integrals

$$I_{sink}(t) = \int_{-l/2}^{l/2} \zeta(x,t) b(\hat{x})d\hat{x}, \qquad I_{trim}(t) = \int_{-l/2}^{l/2} (\hat{x} - \hat{x}_G)\zeta(x,t) b(\hat{x})d\hat{x}, \tag{3.13}$$

the last two equations in Eq. (3.12) can be rendered in a compact form:

$$m\left(\frac{d^2s}{dt^2} + \alpha_s \frac{ds}{dt}\right) + \rho g\left(A_w s + M_w\theta + I_{sink}\right) = 0 \tag{3.14}$$

$$J\left(\frac{d^2\theta}{dt^2} + \alpha_t \frac{d\theta}{dt}\right) + \rho g\left(I_w\theta + M_w s + I_{trim}\right) = 0 \tag{3.15}$$

with $J = J_{\hat{y}\hat{y}G}$ for simplicity, and α_s and α_t as empirical damping coefficients for sinkage and trim respectively.

The numerical investigations were performed by VBD/DST (VBD, 2004 and DST, 2005) including the following steps:

- Modification of the Finite-Difference-Method by Chen (VBD, 2004),
- Calibration of the modelling based on the test case MS "Loetschental",
- Verification of the numerical model
- Parametric change of the ship's beam

The corresponding calculations for Lüneburg ship lift performed by Stuntz (DST, 2005) were in accordance with previous numerical investigations and it was shown that the principal hydrodynamic effects of a ship entering or leaving locks could be well predicted using the one-dimensional unsteady method. It was also shown that the results were basically in good agreement with the full-scale investigation at Lüneburg ship lift and also with the empirical methods based on previous model and full-scale investigations. Figure 5 shows the horizontal motion in respect of the position of the ship for different incoming ship speeds. Figure 6 shows the horizontal motion for a fixed incoming ship speed with the total ship beam being varied. The influence of the blockage effect with increasing beam can be clearly seen in this case.

Concluding that, in most cases, the numerical prediction showed the main effects of the ship's motion on entering or leaving the lock, the method could be improved as follows:

- Formulation of more sophisticated frictional terms for ship and channel

- Inclusion of the trim moment of the propeller action
- Consideration of influences due to the change in the geometry of the boundary and on the propeller thrust

4. ADDITIONS AND CONCLUSIONS

The analysis of available data on the hydrodynamic processes that occur when ships enter and exit locks and ship lifts, with the aim of resolving the problems at Lüneburg ship lift, showed clearly that it is difficult to arrive at sufficiently precise quantitative forecasts with the existing simple empirical and semi-empirical methods. This is due to the inherent problem of taking account of the complex transient situation of a ship entering a lock or ship lift, including all the accompanying interactions. Such forecasts also exhibit large uncertainties. Based on the detailed analysis of the earlier empirical and semi-empirical methods and the results of the field and numerical model investigations for Lüneburg ship lift, the current findings regarding maximum squat, the maximum rise in water level, the time taken to enter or leave a lock and the speed on entering and leaving can be summarized as follows in a generalizing way:

1) Existing work on problems concerning ships entering and exiting locks shows that the physical conditions during those operations vary and therefore need to be investigated separately. Such investigations generally focus on the assessment of the safety of vessels against touching bottom. Due to the sharp drawdown in the water level behind the ship owing to the “piston effect” and the effect of propulsion in the restricted cross-section of the lock, the degree of ship squat is generally greater when a ship leaves a lock than when it enters it and must therefore be regarded as the more serious case.
2) Within the range of the approach and exit speeds that are common in practice, the maximum squat occurs at the stern of the ship at the low blockage ratios to be found in locks. The propeller thrust has a considerable effect on the magnitude of the squat, not only when a vessel enters a lock but also when it exits it. Even temporary increases in the propeller speed lead to an increase in the squat when a ship enters and exits a lock.
3) As only low exit speeds are possible at low blockage ratios and, moreover, as the maximum squat frequently occurs when the ship accelerates quickly prior to exiting a lock, the risk that a vessel may touch the bottom of a lock with an extremely low blockage ratio cannot be dealt with by specifying permitted exit speeds. Instead, the required blockage ratios and ratios of draught to water depth must be provided for the most onerous load condition.
4) An analysis of the squat occurring when a ship exits a lock in a steady-state case shows that a rise in the critical speed increases the maximum possible squat that can occur in a lock at a given ratio of draught to water depth and a decreasing ratio of trough width to beam widt. This also means that widening a lock without increasing the depth of the water in the chamber will even exacerbate the risk that a ship could touch bottom.
5) Neither the size and geometry of the outer harbour and the lock approach nor the length of the lock have any objectively verifiable effect on the investigated hydrodynamic parameters that are of relevance to ships entering and exiting locks. The influence of the shape of a vessel can be covered by a single parameter, i.e. the block coefficient. In hydraulic terms, the influence of the shape of the bow is only secondary. However, the incoming speed can be subjectively influenced by the shape of the bow and the design of the lock approach.
6) Investigations at locks carried out in the past did not reveal any marked differences between the maximum squat of push tow units and that of single vessels. This is due to the fact that push tow units are composed of several units that move relative to each other in a vertical direction so that they are not subject to higher degrees of trim when in motion.
7) At locks with a system of culverts, the squat is considerably reduced when the discharge gates are open. At locks where the depth of water above the sill or in the chamber is low, the culvert gate should therefore be opened if there is a risk that an incoming or outgoing vessel could touch the bottom or the sill.
8) One particular feature of the evaluation of the problems relating to squat is the cross-section of the transitional section between the outer harbour and the lock. The passage of the ship causes a higher degree of trim to occur in this area which may not only result in a local maximum squat, but also in an absolute maximum squat when the ship enters the lock. Experience shows that it is not possible to eliminate this problem in a way that is relevant to practice by designing the transition so that it is gradual. Theoretical investigations of this phenomenon, which has not yet been sufficiently studied, demonstrate that what is known as the “supersquat” (after Huval, 1980) increases in the transitional cross-section if the latter is deepened, but not widened, even though the increase in the underkeel clearance is greater than the increase in the supersquat.

9) The path of a vessel becomes increasingly irregular as the blockage ratio decreases and the incoming speeds increase owing to the translatory waves that occur as the vessel enters the lock. The average vessel speed inside the trough approaches the critical speed which is governed essentially by the blockage ratio. This effect means that the time a vessel takes to enter a lock is not significantly reduced by increasing its approach speed if the blockage ratio is low. For economic reasons, it is possible to state an optimum approach speed for entry into the lock at which, if complied with, the risks arising from faulty manoeuvres on a very irregular entry path due to excessively high approach speeds, the possible risk of damaging the impact protection owing to excessively high impact velocities and exceeding the freeboard in ship lifts can be limited.
10) In spite of the fact that the hydrodynamic conditions differ on entry and exit, there are parallels with regard to the sailing speeds and sailing times. Both can be described qualitatively by characteristic phases and in both cases there is a quasi-steady sailing speed in the restricted cross-section which is limited by the critical speed. The conclusion drawn from a comparison of the recorded entry and exit times was that the times taken to enter and exit a lock are very similar and can be estimated from existing empirical results for the time taken to sail into a lock.

5. SUMMARY

Based on the detailed analysis of previous sailing tests with ships entering and exiting a lock and the results of the field investigations conducted at Lüneburg ship lift, new empirical relationships have been developed to determine the maximum rise in water level when a vessel enters a lock, the squat when a vessel leaves a lock and the time a vessel takes to enter a lock. They are stated in a report on this subject (BAW 2004b). Based on these methods, calculations are being performed for Lüneburg ship lift to forecast the permitted approach speed that must be complied with to avoid activation of the relief openings and the trough holding device due to the rise in the water level when a vessel enters a lock, to determine the required working capacity of the impact protection system and to ensure the underkeel clearance required to prevent a vessel touching bottom. In addition, principles for the calculation of the performance of the lift are being drawn up. The large-scale tests thus formed the basis for resolving the questions raised by the Waterways and Shipping Office (WSA) in Uelzen concerning the operation of the ship lift as well as the safety and ease of navigation at the lift. Furthermore, they formed the basis for the calibration, verification and continuing development of a numerical calculation method to enable conclusions to be drawn for locks and ship lifts with other boundary conditions in future.

REFERENCES

1. Amtsberg, H., "Modellversuche über das Einschleppen von Kanalkähnen in den Trog eines Schiffshebewerkes", Mitteilungen der Preußischen Versuchsanstalt für Wasserbau und Schiffbau Berlin, Heft 24, 1936, pp. 84-111
2. Atavin, A.A., Vasiliev, O.V., Stepanova, P.V. Tarasevich, V.V. and Yanenko, A.P.,. "The Computation of lockage and Navigation of Vessels on the System of Ship-Canals", Proceedings of the 3rd International Conference on Hydro-Science and engineering (ICHE), Technical University Cottbus, 31.8. – 3.9.1998
3. Atavin, A.A, "Fluctuations in the water level that occur when a vessel exits the chamber of a ship lock" (in Russian), Dinamika sloschnoj sredy, Novosibirsk, Vol. 30, 1977, pp.35-52
4. BAW, "Bericht über die Schiffahrtsversuche Marbach 1989", Bundesanstalt für Wasserbau, Bericht L-231.2/23 Karlsruhe, July, 1990
5. BAW, "Modellversuche über das Einfahren eines Schubverbandes in eine 12 m breite Schleuse", Bundesanstalt für Wasserbau, Auszug aus dem 1. Versuchsbericht BAW-W 357, Annex.1, Karlsruhe, February, 1973
6. BAW, "Naturuntersuchungen Schleuse Friedrichsfeld. Teil I: Einfahr- und Liegebedingungen an der Schleusengruppe", Gutachten-Nr. 3.03.10042.00, Karlsruhe, February, 2004a
7. BAW, "Untersuchungen zu den Ein- und Ausfahrbedingungen in das Schiffshebewerk Lüneburg", Bundesanstalt für Wasserbau, Gutachten-Nr. 3.04.10044.00, Karlsruhe, February, 2004b
8. BAW, "Untersuchungen zu den Ein- und Ausfahrbedingungen in das Schiffshebewerk Lüneburg. Naturuntersuchungen und Prognoserechnungen", Bundesanstalt für Wasserbau, Gutachten-Nr. 3.04.10044.00, Karlsruhe, September, 2005
9. British Transport Docks Board, "The locking of ships with high blockage factors : a report to the National Ports Council", British Transport Docks Board, Research Station, London : National Ports Council, 1980
10. Broß, H., "Einfluss der Bugformen von Binnenfahrzeugen auf das Einfahrverhalten in Schleusen", Binnenschifffahrt - ZfB, Nr. 13, 1994, pp. 33-36
11. Chen, X-N., Zöllner, J. and Sharma, S.D., "Ship entry into a lock", STG Summer Conference, Gdansk, 2001

12. Cooper, D. H., Morris, M.G.H. und Radley, K.J., "Some aspects of a study of ships with high blockage factors", 7th International Harbour Congress, Antwerp, 22-26 May 1978, Volume 1, Section 1.2, pp. 2.01/1-2.01/13
13. FAS, "Trogeinfahrten der Schiffshebewerke Niederfinow und Rothensee", Bericht 126,1; Forschungsanstalt für Schiffahrt, Wasser- und Grundbau, Berlin, 1964
14. FAS, "Strömungsverhältnisse in Kanälen und Schleusenvorhäfen (Abschlußbericht zum Forschungsthema), Teil II: Fahrdynamische Verhältnisse an Schleuseneinfahrten", Bericht 381,1, Forschungsanstalt für Schiffahrt, Wasser- und Grundbau, Berlin, 1966
15. Felkel, K., Steinweller, H., "Naturversuche und Modellmessungen über das Einfahren eines Schubverbandes in eine 12 m breite Schleuse und über das Ausfahren", Zeitschrift für Binnenschifffahrt und Wasserstraßen, Vol. 104, No. 6, 1977, pp. 294-300
16. Fisher, S., Jenkins, D. and Day, W, "Results of model experiments to define resistance and sinkage of a large ship transiting a lock of the panama canal", David W. Taylor Naval Ship Research and Development Center, Ship Performance Department Report DTNSRDC/SPD-0881-01, December, 1978
17. Franzius- Institut, "Modellversuche für die Seeschleuse Finkenwerder", Franzius-Institut für Wasserbau und Küsteningenieurwesen, Bericht, Hanover, June, 1969
18. Huval, C.J. “Lock approach canal surge and tow squat at lock and dam 17 Arkansas River project. Mathematical model investigation”, U. S. Army Engineer Waterways Experiment Station, Hydraulics Laboratory, Technical Report HL-80-17, September, 1980
19. Kiehnel, H., "Über Widerstände und Fahrzeiten beim Einschleppen von Schiffen in Schleusen", Mitteilungen der Preußischen Versuchsanstalt für Wasserbau und Schiffbau Berlin, Heft 24, 1936, pp. 4-81
20. Kiriakov, S.S, "Current theory on the calculation of the hydrodynamic sinkage of ships when entering locks" (in Russian), Trudy Leningradskogo Instituta vodnogo Transporta, Vol. 132, 1972
21. Kiriakov, S.S., Timoschina, V. and Beliakova, T., "Permitted speed of ships in locks" (in Russian), Recnoj Transport, No. 8, 1975, pp.44-45
22. Klementiev, A.N, "Major theoretical theses and material from field studies of ships entering a lock (taking the Gorodetski Lock as an example)", Volga State Water Transport Academy, Nizhni Novgorod, 2002
23. Kooman, C, "Navigation locks for push tows", Rijkswaterstaat communications no. 16, The Hague, 1973
24. Kooman, C., "The development and application of design rules for canals and locks suitable for push-tow units and traditional craft", Proceedings of Symposium Aspects of navigability of constraint waterways, including harbour entrances, volume 3, paper 19, Delft, the Netherlands, April 24-27, 1978
25. Pochabov, P.V. and Kiriakov, S.S., “Differentovanie sudno pri dviženie(provodke) vkamere sudoprpusknogo sooruženie”, Puvyženie nadežnosti mechaničeskogo oborudovanija sudochdnych girotechnike, Moskovskij Institut Vodnogo Transporta, Moskva, 1991
26. Pochabov, P.V., “Povyšenie ěffektivnosti ěkspluatacii vodnych putej i transportnogo flota. Kanaly, šljusy, sudopod”emniki, dissertacija doktora techničeskich nauk, Moskva-Krasnojarsk, December, 1997
27. Pochabov, P.V., “Gidrodinamičeskoe vzaumodejstvie mežsudochodnymi sooryženijami”, Avtoreferat dissertacii doktora techničeskich nauk, Sankt-Petersburg, 2003
28. Maynord, S.T., "Effect of lock sill and chamber depth on transient time of shallow draft navigation", USACE , Engineer Research and Development Center, Technical Report ERDC/CHL TR-00-13, August, 2000
29. Maynord, S.T., "Safe navigation speeds and clearance at lower sill, temporary lock 52, Ohio River", Corps of Engineers, Waterways Experiment Station, Hydraulics Laboratory, Technical Report HL-87-3, April, 1987
30. Millward, A., "A Preliminary Design Method for the Prediction of Squat in Shallow Water",' Marine Technology, 27(1):10-19, January, 1990
31. Norrbin. N.H., "The Effects of Flow Confinement and Asymmetry on a Ship in a Fairway Passage",' Workshop on Ship Squat in Restricted Waters, Panel H-10 (Ship Controllability), Hydrodynamics Committee, SNAME, July 1996, pp. 87-93
32. Permanent International Navigation Congress, “Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways”, PIANC, Supplement to bulletin no. 57, 1987
33. Romanov, E.M. and Yanenko, A.P., "Laboratory equipment for determining the hydraulic phenomena that occur when ships with high deadweight capacities enter chambers of ship locks" (in Russian), Izvestija vyssich ucebnych zavedenij, Series: Stroitel’stvo i architektura, Novosibirsk, 1974, no. 9, pp. 108-110

34. Romanov, E.M.; Yanenko, A.P., "Several results of the experimental determination of the conditions occurring when ships with high deadweight capacities enter chambers of ship locks" (in Russian), Izvestija vyssich ucebnych zavedenij, Series: Stroitel’stvo i architektura, Novosibirsk, 1975, no. 10, pp. 101-104
35. Stuntz, N. "Numerische Nachrechnung der Naturuntersuchungen zu den Ein- und Ausfahrten am Schiffshebewerk Lüneburg", Entwicklungszentrum für Schiffstechnik und Transportsysteme e.V.(DST), Duisburg, Bericht 1782, August, 2005
36. VBD, "Modellversuche über das Ein- und Ausfahrverhalten eines Schubverbandes in Main-Schleusen", Versuchsanstalt für Binnenschiffbau e.V., Duisburg, Bericht Nr. 988, March, 1981
37. VBD, "Einfluß der Bugformen von Binnenfahrzeugen auf das Einfahrverhalten in Schleusen", Versuchsanstalt für Binnenschiffbau e.V., Duisburg, Bericht Nr. 1338, February, 1993
38. VBD, "Numerische, experimentelle und technisch-wirtschaftliche Untersuchungen zur Entwurfsoptimierung und Wettbewerbssteigerung von Binnenschiffen" Teilprojekt: "Erhöhung der zulässigen Breite von Binnenschiffen beim Befahren kanalisierter Binnenwasserstraßen", Versuchsanstalt für Binnenschiffbau e.V., Duisburg, Bericht 1642, May, 2003a
39. VBD, "Numerische Simulation der Schiffsbewegungen bei der Ein- und Ausfahrt in das Schiffshebewerk Lüneburg", Versuchsanstalt für Binnenschiffbau e.V., Duisburg, Bericht 1703, September, 2003b
40. VBD, "Modifizierung eines Computerprogramms zur Simulation der Schiffsdynamik bei Schleusenein- und -ausfahrt (Schiff_Lock)", Versuchsanstalt für Binnenschiffbau e.V., Duisburg, Bericht 1711, August, 2004
41. Vrijburcht, A., "Calculations of wave height and ship speed when entering a lock", 2nd Internat. Conf. on Navigation Locks, Wroclaw, Poland, 1986, May 20-22, 18 pp., also: Delft Hydraulics Publication 391, 1986
42. Vrijburcht, A. "Vertical motions of ships sailing into or out of locks and the related water motions", XXIV IAHR Congress, Madrid, Spain, Sept. 9-13, 1991, 8 pp., also: Delft Hydraulics, publication no. 461, Nov., 1991
43. Yanenko ,A.P. and V.V. Tarasevich, "Determination of the optimum cross-sectional dimensions of the chambers of ship locks" (in Russian), Izvestija vyssich ucebnych zavedenij, Series: Stroitel’stvo i architektura, Novosibirsk, 1994, no. 7/8, pp. 124-129
44. Yanenko, A.P., "Improving the performance of ship locks and determination of lock dimensions" (in Russian), Novosibirsk State Water Transport Academy, Author's Presentation on Dissertation B, Novosibirsk, 1994

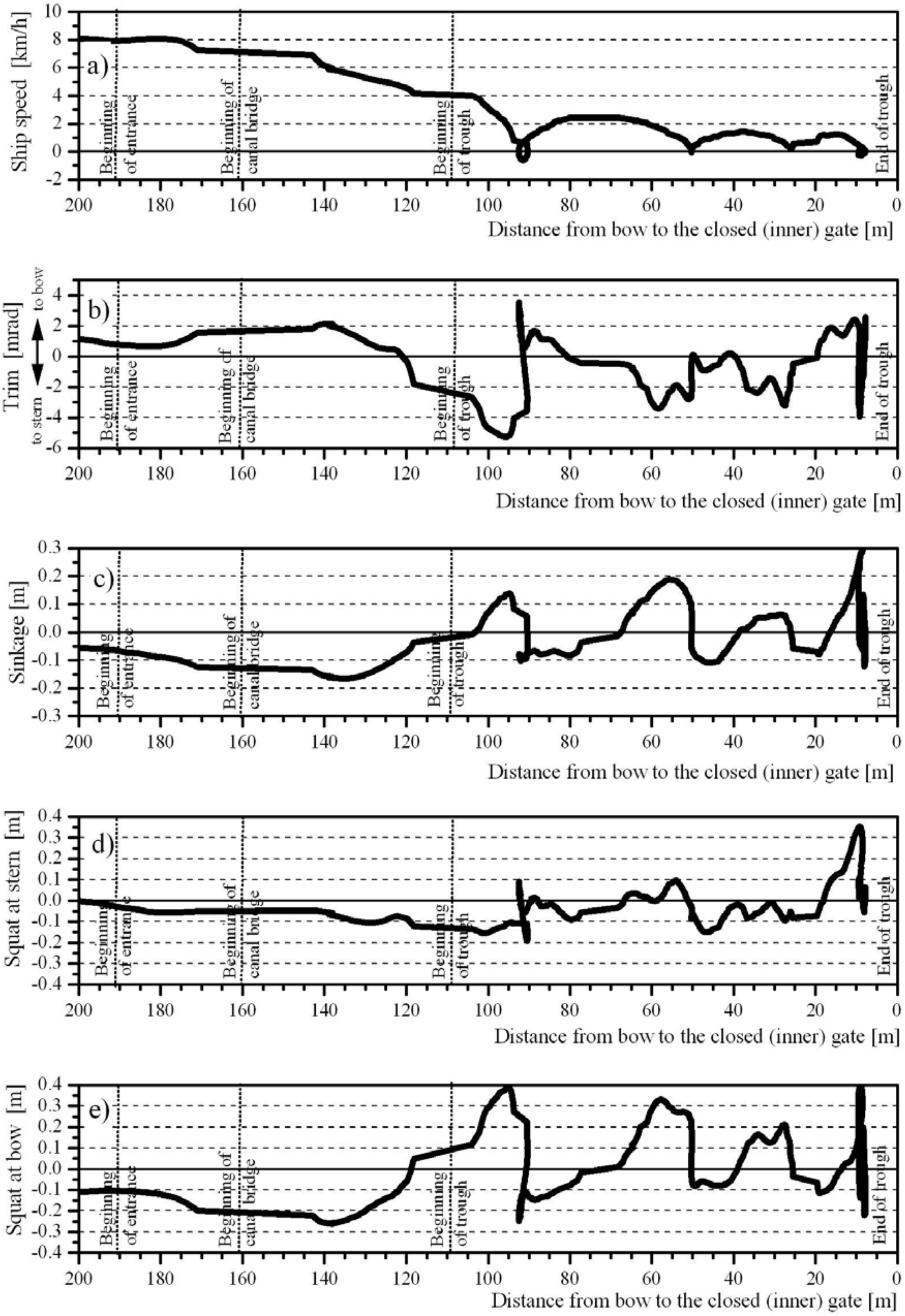

Figure 1 – "Running-in test" no. 5 with MS "Loetschental" entering on the downstream side (IN-DL-5)
a) Ship speed, b) Trim, c) Squat,
d) Sinkage at stern, e) Sinkage at bow
as a function of the distance between the bow and the closed inner gate of the trough

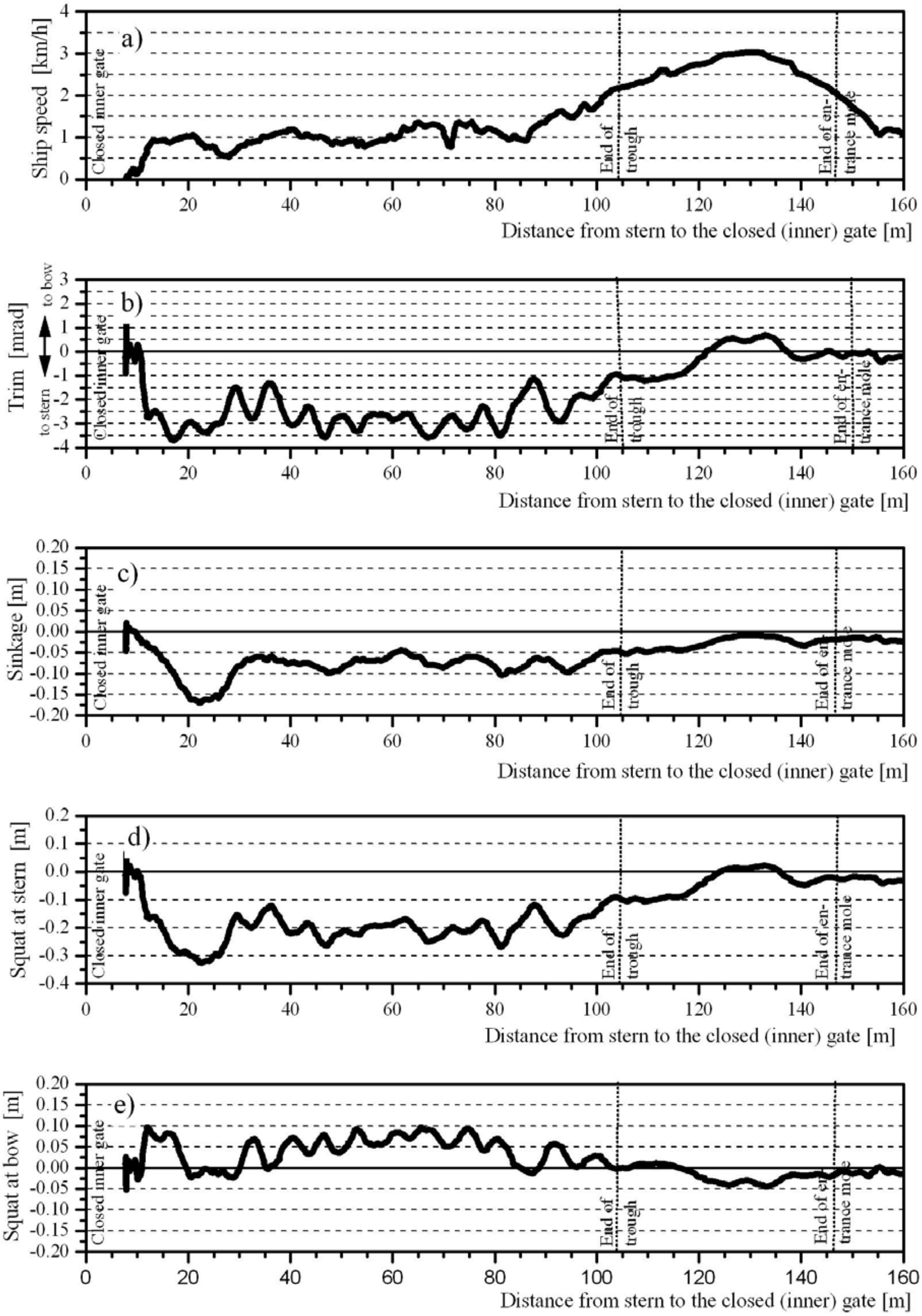

Figure 2 – "Running-out test" no. 2 with MS "Loetschental" exiting on the downstream side (OUT-DL-2)
a) Incoming speed, b) trim, c) hydrodynamic squat,
d) sinkage at stern, e) sinkage at bow
as a function of the distance between the bow and the inner edge of the southern side of the trough

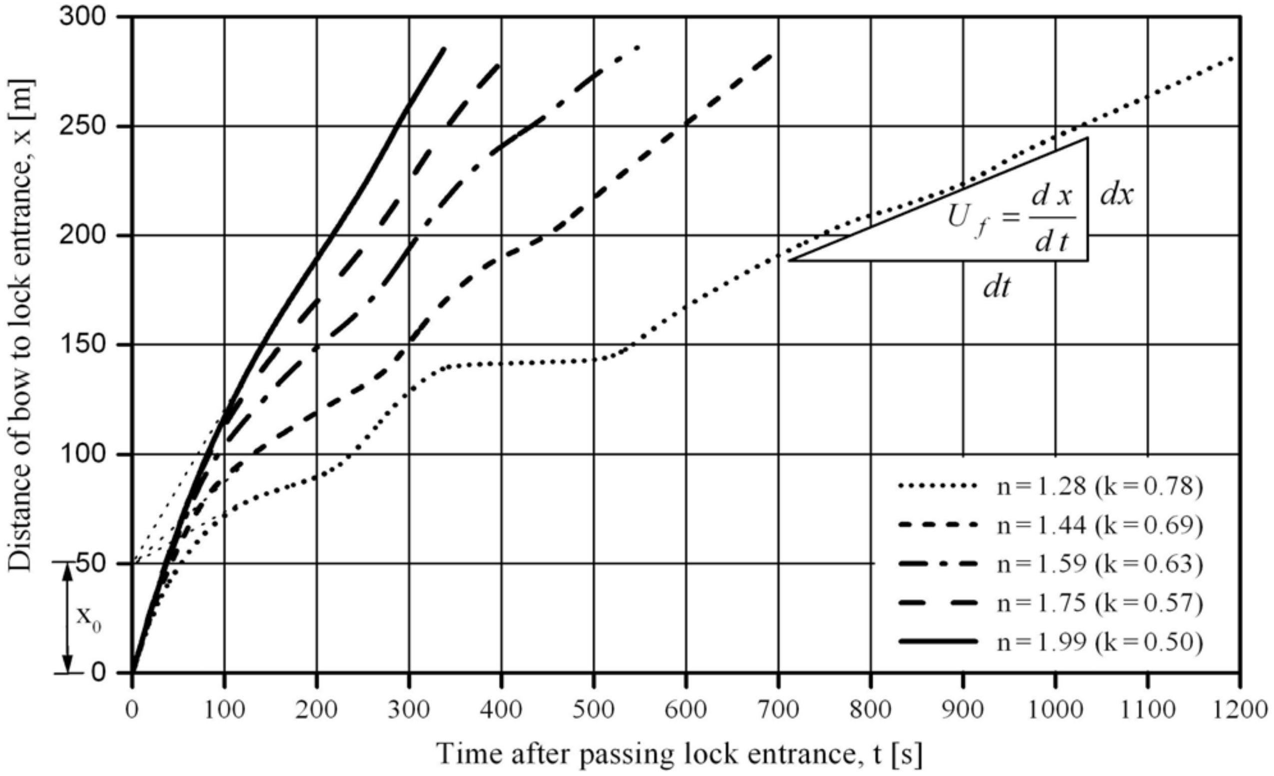

Figure 3 – Path-time diagram of the sailing speed of a push tow in a lock during entry at various blockage factors (after Kooman, 1973)

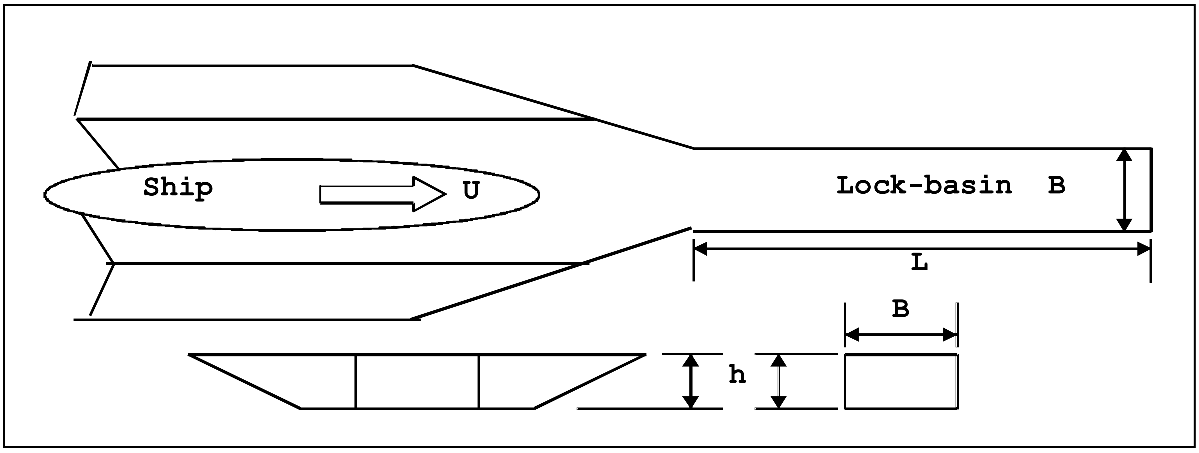

Figure 4 – Schematic diagram of the problem of ship entry into a lock.

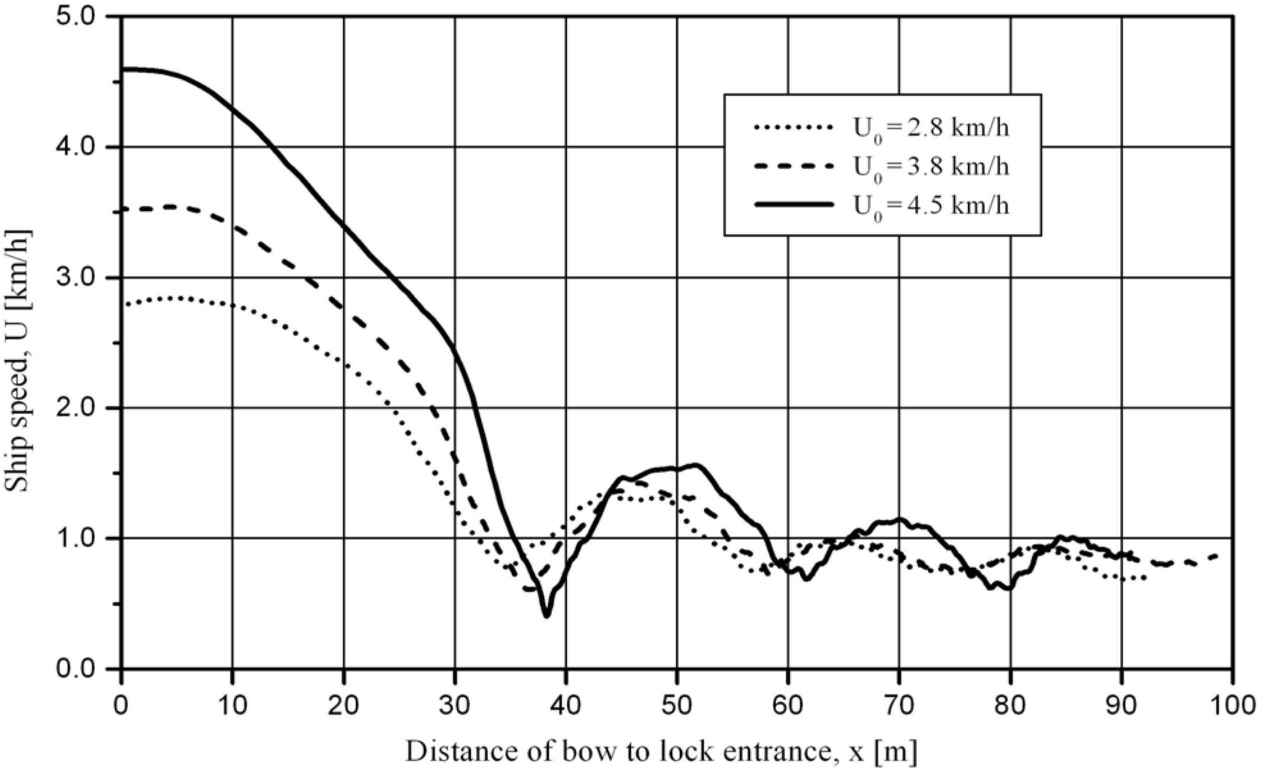

Figure 5 – Numerical simulation for different approach speeds for MS "Loetschental" entering the Lüneburg ship lift from the downstream side

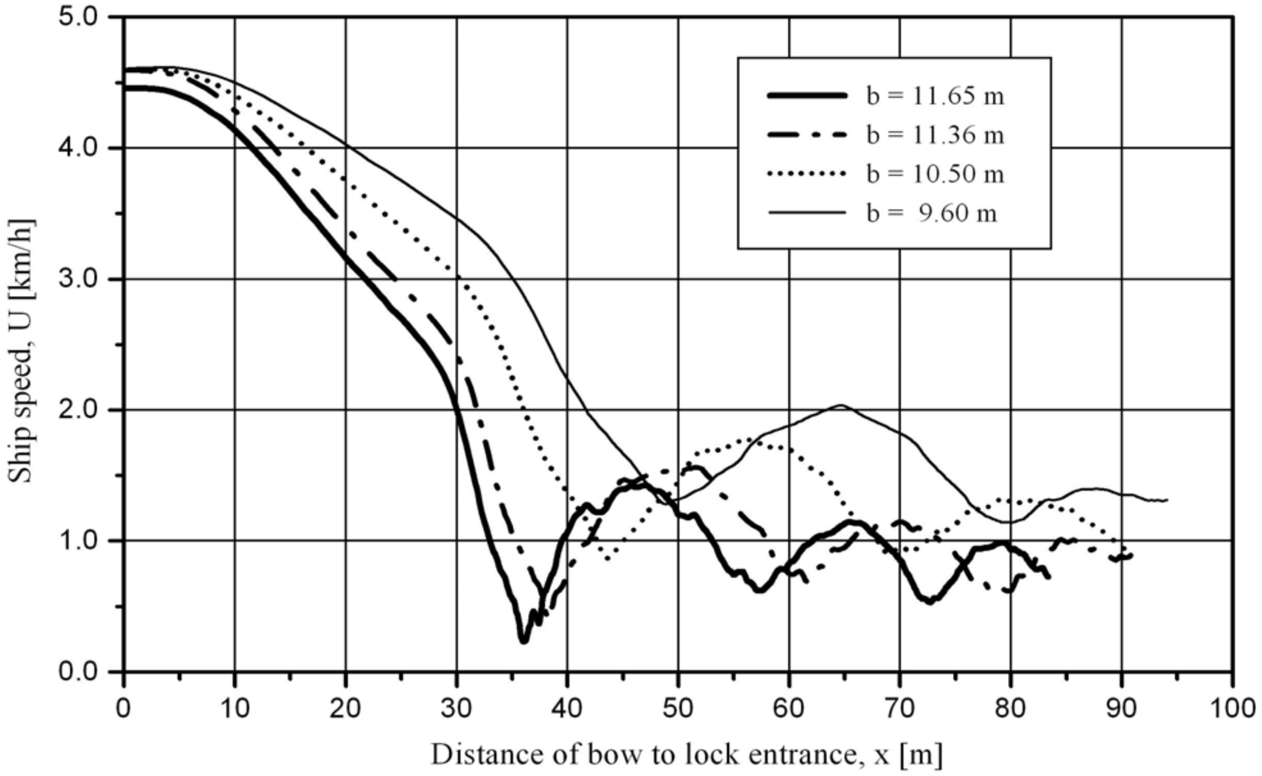

Figure 6 – Numerical simulation of the effect of the beam of vessels on the sailing speed during entry of Lüneburg ship lift from the downstream side