ANALYSIS OF FULL SHIP TYPES IN HIGH-BLOCKAGE LOCK CONFIGURATIONS

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Abstract: In order to increase the capacity of waterways and harbours located behind locks, waterways and port authorities may consider to increase the allowable values for ship beam and draft. By extending the operational limits of existing locks in this way, the blockage of the lock increases which may significantly influence the governing hydrodynamic effects. In order to assess the accessibility of larger bulkcarriers to the Terneuzen West Lock, giving access to the port of Ghent, the entering manoeuvre of full form ships into a lock has been analysed by means of model testing, full scale trials and real-time simulations.

1. INTRODUCTION

Over the course of time, ship sizes have increased and continue to increase to fulfil the demand of goods all over the world. Harbours need to accommodate these larger ships to stay competitive, but their access is often restricted by navigation locks, which usually cannot easily be extended because of social, environmental and financial issues, of which a few are mentioned here. Besides of the building costs, private property might need to be expropriated. A larger lock also involves higher maintenance costs and more water interchange. For locks that connect the hinterlands with the sea, this can even signify a larger salinisation of the fresh water and soil. Therefore, it is desired to continue using existing locks as long as possible.

Allowing modern vessels into navigation locks which were originally planned for smaller ships, results in very high blockage values. This does not only affect the ships behaviour, but also reduces the tolerance for inaccuracies and mistakes during approach, entry and exit manoeuvres. To prepare pilots and captains, but also to determine the feasible margins of ship-to-lock ratios, the ship behaviour should be analysed by means of model testing. The results can be interpreted to give advice about critical main dimensions to corresponding authorities or they can even be converted to mathematical models for real-time simulators. Simulations can then be used to further assess the scenario or for training of the pilots.

A recent example of increasing blockage in navigation locks is the West lock, located in the city of Terneuzen in the Zeeland Province of the Netherlands that connects the river Scheldt with the Ghent-Terneuzen Canal. The canal links the port of Ghent in Belgium to the port of Terneuzen, and the river Scheldt, thereby providing an access to the North Sea for sea-going vessels.

The West lock is primarily intended for sea-going vessels, although occasionally inland vessels are locked as well. This happens only for reasons of efficiency and optimal use of the lock-through capacity. Normally, inland vessels are locked through one of the two other locks available in Terneuzen (Mid lock with main dimensions of 110 m by 18 m or East lock with dimensions of 280 m by 23 m).

The actual maximum allowed beam of vessels passing through West lock is 37 m. This value was allowed after extensive simulator studies at Flanders Hydraulics Research (FHR) and full scale trials, conducted by Marin and FHR.

In the scope of this paper, experiments and simulations are described for a vessel of a full scale beam of 38 m to verify whether it can still manoeuvre safely through the lock and to determine possible constraints, such as minimal under keel clearance. Furthermore full scale measurements on a 37 m wide bulk carrier to the West lock in Terneuzen will be presented to line out the differences with model test results.

2. MODEL TESTS

2.1 Model setup

Entry and exit manoeuvres of a full ship hull are tested on a 1/60.6 scale model of the river side of West lock, Terneuzen (main dimensions given by Table 1 and Fig. 1). A ship model of Esso Osaka, scaled by the factor 60.6 to the dimensions given by Table 2, is used. Although Esso Osaka is actually a tanker, the main dimensions and block coefficient of the model are also representative for bulk carriers, which (besides of RoRo vessels and car carriers) usually frequent the West lock, Terneuzen.

Table 1. Principal Dimensions of the West lock Terneuzen

Parameter	Unit	Full scale	Model scale
Chamber length	[m]	290.0	4.785
Max. chamber length	[m]	378.5	6.246
Lock width	[m]	40.00	0.660
Bottom of lock	[m NAP]	-12.82	-0.212
Sill on river side	[m NAP]	-12.82	-0.212
Sill on canal side	[m NAP]	-11.37	-0.188
Water level river side	[m NAP]	-3.50 to 5.75	-0.058 to 0.095
Water level canal side	[m NAP]	2.13	0.035

(NAP = Normaal Amsterdams Peil / Normal Amsterdam Level, absolute height reference in the Netherlands)

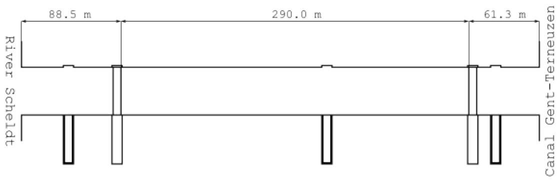

Fig. 1 Principal Dimensions of the West lock Terneuzen

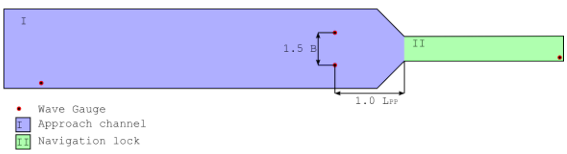

Fig. 2 Wave gauge position (not to scale)

Table 2. Principal dimensions of model ship

Parameter	Unit	Full scale	Model scale
Length b/w perpendiculars	[m]	231.73	3.824
Length over all	[m]	244.82	4.040
Beam	[m]	38.00	0.627
Draught (ballast)	[m]	9.00	0.149
Draught (maximal)	[m]	12.50	0.206
Block coefficient (ballast)	[-]	0.8037	0.8037
Block coefficient (maximal)	[-]	0.8204	0.8204
Orientation	[° N]	153.6°	-

The lock model is described in detail by Delefortrie et al. (2009). It is equipped with a guiding railing that keeps the ship model on a straight path while entering the navigation lock. The original lock model needed to be narrowed and shortened to correspond to the main dimensions of the West lock. Features such as the removable floor inside the lock, the outlets to model lock spill and the salt water tank for salinity exchange simulations are, at this time, not used either. To keep the frictional scaling errors at a minimum the surface roughness of the lock is reduced by building it in glass. A positive side effect is its transparency which allows a better observation of the model tests. The waves are measured at the end of the lock and at one ship length before the lock, both on port and starboard side at 0.75 ship beams from the centreline (Fig. 2).

The ship model is ballasted to two representative draughts at even keel, which correspond to an empty ship (full scale draught of 9 m) and the maximal allowed draught on the canal Ghent-Terneuzen (full scale draught in fresh water of 12.5 m). At bow and stern, lateral forces and sinkage are measured. The forces are measured by dynamometers directly at the guiding railing and sinkage is measured as the vertical distance between the ship and the railing. The longitudinal position is measured and, together with time information, translated to speed. Furthermore, the bow wave, propeller rate, thrust and torque as well as the longitudinal forces delivered by air fans (representing tug boats), which are mounted on top of the vessel, are logged.

To facilitate the switch between entry and exit manoeuvres, a mechanism is provided at the other end of the test tank to disconnect vessel and guiding railing, so that the ship model can be turned with little effort. Additionally, different eccentricities of the vessel with respect to the navigation lock and static rudder angles can easily be set.

2.2 Model test series

The following parameters have been varied during the model tests.

Direction: all conditions have been tested both for entering and exit manoeuvres.

Eccentricity: besides of the centric case (full scale space of 1 m between hull and lock walls), eccentricities of 0.5 m and 0.25 m between hull and closest lock wall have been conducted towards starboard side only. As confirmed by tests at one under keel clearance, the difference between port and starboard eccentricity is negligible.

Drift: most tests have been carried out at zero drift; in the maximal draught case a drift angle of 0.4 deg has been applied additionally.

Draught: model tests have been conducted at ballast draught (full scale draught of 9.0 m) as well as maximal allowed draught on the canal side of the West lock (12.5 m). Although the river side of the lock is modelled the deeper canal side draught is used because:

- This draught is deeper and therefore more critical;
- The allowable draught on the river side depends on the current salinity level, and is therefore not a fixed value;
- In the model tests, no transition from salt to fresh water is made.

Under keel clearance (ukc): in the ballast case, tests have been done with under keel clearances of 80% and 50%. In the maximal draught case, the model is run at ukc's of 30%, 15% and 8%.

Propeller rate: full scale propeller rates of 22, 33, 43, 53 rpm are estimated to achieve speeds in the approach channel (at 80 % ukc) of 1, 2, 3 and 4 knots respectively. With various under keel clearances propeller rates are maintained instead of speed. Additionally, tests are carried out with an increase of propeller rate to 85 rpm (engine setting: "half") inside the lock. At very low clearances, 22 and 33 rpm are not tested as the model could not accelerate from zero speed.

Tugboat assistance: all conditions have been tested without tugboat assistance. In addition to that, the average speed of the ship inside the lock was determined at each condition and used as set-point for the desired speed inside the lock for model tests with tug assistance. In these tests, the software automatically sets the tugboat propeller forces to reach and maintain the desired speed as long as the ship model is inside the navigation lock.

3. FULL SCALE TRIAL

3.1 Measurement and processing

In March 2010 Flanders Hydraulics Research performed full scale measurements on the inbound bulk carrier MS Koutalianos (Table 3) during her journey through the West lock in Terneuzen. The measurement equipment consisted of a pair of RTK-GPS antennas mounted on a precalibrated inertial measurements unit (IMU). In this IMU the accelerations and orientations were measured in six degrees of freedom by means of accelerometers and gyroscopes. When fed with RTK-correction signals from reference stations, the measurement equipment has accuracies as indicated in Table 4. The actions of rudder, engine and tugboats were registered.

In post processing the vertical position of the keel was referred to the reference level NAP by means of the geoid model RDNAPTRANS^{TM}2008. By subtracting the vertical position of the keel from the bottom profile derived from recent surveys the under keel clearance was calculated.

The vertical position of the keel with respect to the water surface (dynamic draught) was calculated by subtracting the vertical position of the keel referred to NAP from tide measurements registered in the harbour of Terneuzen. After adapting the initial draught at zero speed (12.35 m) to the varying water density during the lock approach, this value was subtracted from the dynamic draught to calculate the sinkage of the ship.

Fig. 3 MS Koutalianos entering the West Lock in Terneuzen on March 30th, 2010 (real view)

Table 3: Principal dimensions of MS Koutalianos

Parameter	Unit	Full scale
Length b/w perpendiculars	[m]	221.6
Length over all	[m]	229.5
Beam	[m]	36.92
Draught (river side)	[m]	12.35
Draught (canal side)	[m]	12.50

Table 4: Accuracy of measurement equipment applied

Parameter	Unit	Accuracy
Horizontal position	[m]	0.010
Vertical position	[m]	0.015
Roll angle	[°]	0.06
Trim angle	[°]	0.01
Heading	[°]	0.05

3.2 Ship behaviour during lock entrance

Environmental conditions: The approach of the MS Koutalianos to the West Lock of Terneuzen was performed at minor current velocities and at a moderate wind condition of 3 to 4 Beaufort from south-western direction. MS Koutalianos reached the outer harbour of the lock at 65 minutes past high tide (spring tide). This resulted in an under keel clearance equal to 2.5 m (20% of the draught) both in the lock and during the lock approach.

Lock Entrance: The bow of the MS Koutalianos reached the lock entrance at speed 1.8 kn resulting in an even keel sinkage of ca. 0.10 m (Fig. 4). This speed resulted from a propeller rate 51 rpm increased to 64 rpm shortly before entering the lock and from astern tug assistance. During the lock approach two aft tug boats with bollard pull 40 tons were ordered to pull 50% at 180°.

In order to moderate the loss of speed due to lock effects, the propeller rate was increased shortly after entering the lock. At the same time the aft tugs were ordered to pull with minimum power.

Ship partly in the lock: During the penetration of the first ship half in the lock, the ship speed decreased to 0.7 kn and the ship experienced a bow up trim increasing up to 0.22 m. At the same time the mean sinkage remained at 0.10 m leading to a maximum sinkage of 0.21 m at the stern.

When half the ship length had entered the lock a constant ship speed and trim remained until the ship had completely entered the lock.

Ship in lock: when the stern entered the lock, a high blockage acted both on bow and stern. The trim angle decreased again to zero while the mean sinkage of the ship increased to 0.19 m. The ship's resistance appeared to decrease when the stern enters the lock. For a short time this resulted in an increase of speed which was countered by decreasing the propeller rate.

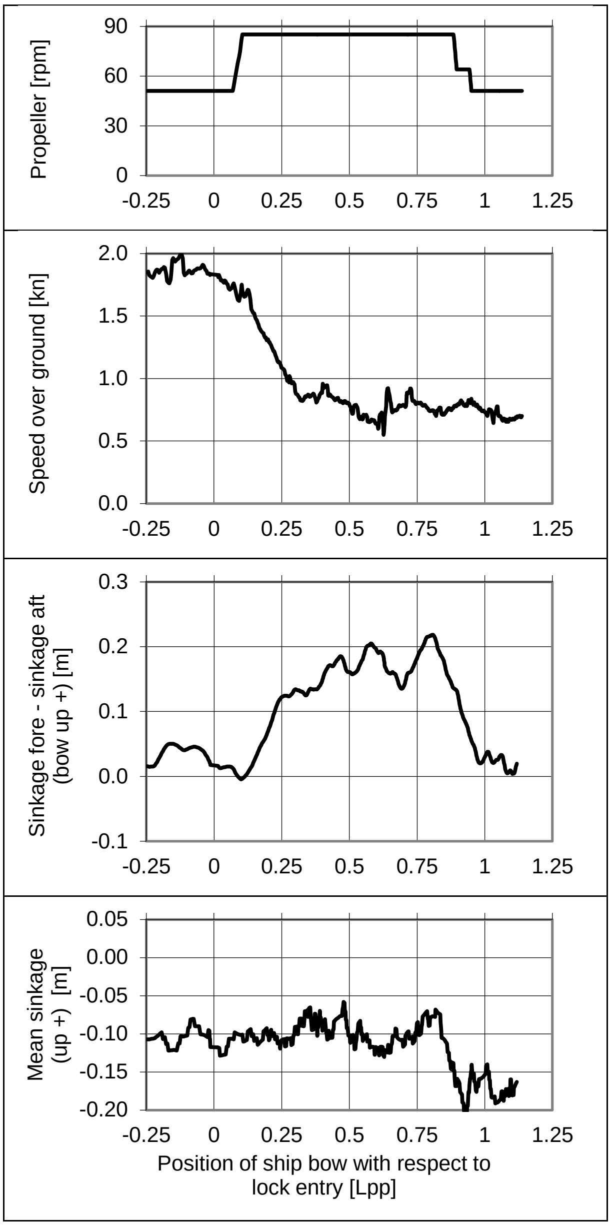

Fig. 4 Full scale measurements on inbound MS Koutalianos entering the West lock in Terneuzen

Table 5: Conditions at arrival of MS Koutalianos to West Lock Terneuzen compared to model test conditions. All dimensions with respect to full scale

		MS Koutalianos	I0_M15_255SHALF	I0_M30_255SHALF
Speed at lock entrance	[kn]	1.8	1.6	1.8
Propeller rate during lock approach	[rpm]	51	33	33
Propeller rate during lock penetration	[rpm]	85	85	85
UKC	[%]	20	15	30
Ship beam	[m]	36.9	38	38
Ship draught	[m]	12.35	12.5	12.5
Blockage	[%]	76.9	82.6	73.1

Fig. 5 MS Koutalianos entering the West Lock in Terneuzen on March 30th, 2010 (copyright J.W.P. Prins)

3.3 Comparison full scale to model scale

From the dataset of model tests described above, those tests were selected that correspond the best with the arrival of the MS Koutalianos to the West lock in Terneuzen. The conditions tested in model tests I0_M30_255SHALF and I0_M15_255SHALF were selected (Table 5). Fig. 6 presents the ship behaviour during the selected model tests

Propeller: both in full scale trials and model tests the propeller rate was increased to 85 rpm during lock entrance. The application of the propeller was similar in full scale trials and model tests.

Speed: Fig. 6 reveals the under keel clearance has a major effect on the ship speed. The model test performed at the lower under keel clearance (15%) involved an entrance speed of 1.6 kn. Due to lock effects the speed decreased to 30% of the initial speed. During the model test performed at a higher under keel clearance (30%), the initial speed was 1.8 kn and the velocity loss due to lock effects resulted in a stationary lock speed of 40% of the initial speed. Furthermore the ship speed decreased more gradually at the higher under keel clearance and present higher variations at the lower under keel clearance.

The full scale trial was performed at an intermediate under keel clearance (20%). The speed measured during the full scale trial corresponds very well to the model test performed at an under keel clearance of 30%.

Trim and Sinkage: Both trim and sinkage measured during model tests reveal significant variations during lock entrance. These variations result from translation waves propagating in the lock chamber between ship bow en lock door. Fig. 6 shows that the effect of translation waves on trim and sinkage increases with decreasing under keel clearance.

Comparison with Fig. 4 shows that the effect of translation waves on the vertical motions were much more moderate during full scale trials than they were during model tests. A possible explanation is the larger ship beam applied in model tests.

If the variations due to translation waves are filtered from the trim and sinkage the average evolution of sinkage and trim is similar for both full scale trials. The magnitudes for trim and sinkage are similar for both under keel clearances tested at model scale but correspond to different ship speeds.

When arriving to the lock model the mean sinkage of the ship is very small (0.02 m full scale) and the ship is trimming to the bow. When entering the lock the trim increases until the ship almost completely entered the lock. Apparently, the bow up trim in the model tests remained when the aft ship entered the lock, while during full scale trials at that point the trim restored to its initial value.

Despite variations due to translation waves the mean sinkage remained small when the ship had not completely entered the lock. When the stern enters the lock the mean sinkage increased significantly. The general evolution of sinkage is similar for full scale trials and model tests.

Conclusion: Although the full scale trial was executed at an intermediate blockage with respect to the selected model tests, the effect of translation waves are considerably larger for the model test results. A possible explanation concerns the smaller ship beam (36.9 m) of the ship MS Koutalianos compared to the beam of the ship model (38 m). Furthermore the model tests reveal that also the under keel clearance has a major effect on the translation waves in the lock.

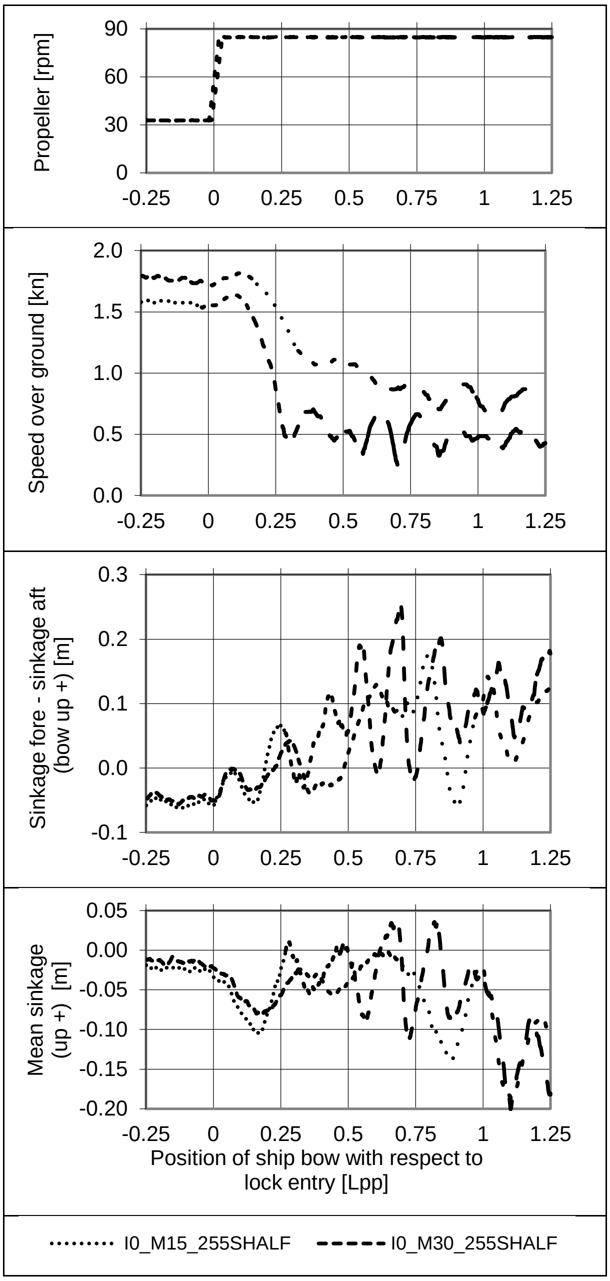

Fig. 6 Results from model tests I0_M15_255SHALF and I0_M30_255SHALF

4. SIMULATION

4.1 Simulator study

FHR studied the accessibility of the West lock in Terneuzen for bulk carriers with a beam of 38 m (Table 6) by means of six days of simulation on a full mission bridge simulator (SIM 360+).

The simulation conditions were based on the actual regulation for bulk carriers with a maximum beam of 37 m. This regulation determines the maximum wind force, corresponding tug assistance and visibility.

4.2 Simulation of model lock effects

An overview of additional effects that have to be included in the mathematical model of a ship manoeuvring simulator in order to perform real-time simulation runs with a sufficient degree of realism and reliability is given by Vantorre and Richter (2011).

In this paper, only the longitudinal motion and the vertical displacement will be discussed. These phenomena are dominated by the translation waves during lock entrance, which were simulated by means of a ship-lock interaction module based on Vrijburcht (1988). This numerical model calculates the propagation of six translation waves through the lock and in the approach canal resulting in a longitudinal force on the ship. By integrating the wave heights around the ship hull, the sinkage and trim of the vessel can be derived from the wave system.

Table 6: Principal dimensions of 38 m wide bulk carrier used for simulation study to West lock Terneuzen

Parameter	**Unit**	**Full scale**
Length b/w perpendiculars	[m]	232.4
Length over all	[m]	240.0
Beam	[m]	38.00
Draught (river side)	[m]	12.30
Draught (canal side)	[m]	8.00

Table 7: Conditions at which simulations were performed of lock entrance at conditions similar to those in Table 5. All dimensions with respect to full scale

		Simulation 1	**Simulation 2**	**Simulation 3**
UKC	[%]	20	15	30
Ship length over all	[m]	230	240	240
Ship beam	[m]	37	38	38
Ship draught	[m]	12.5	12.3	12.3

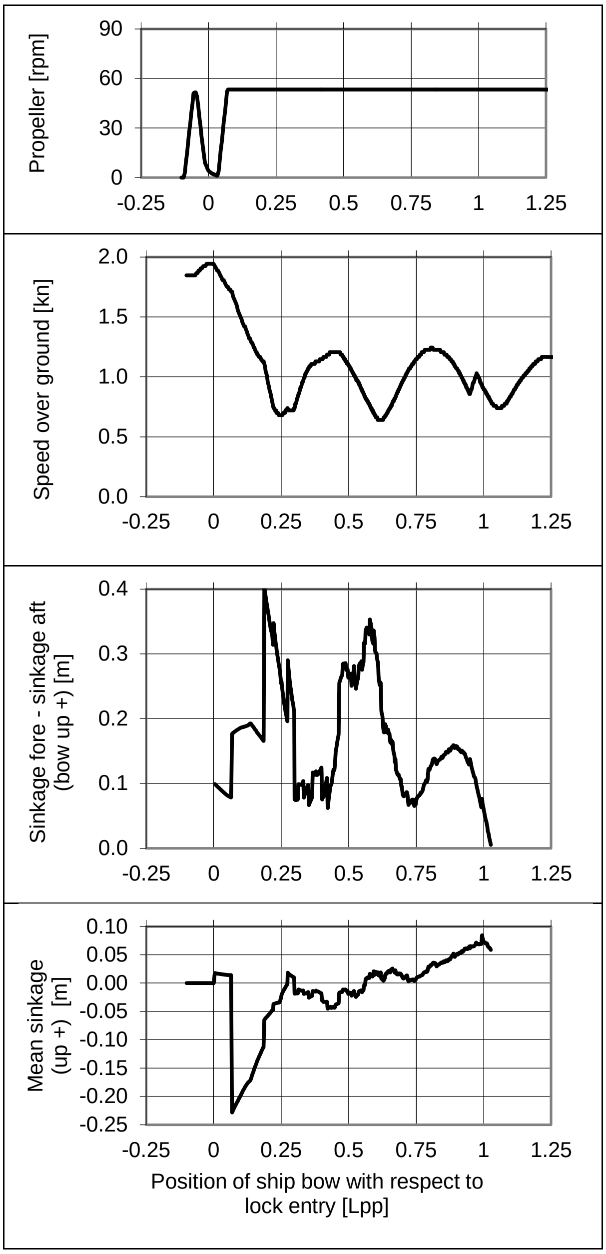

Fig. 7 Simulation of inbound 37 m wide bulk carrier entering the West lock in Terneuzen at UKC 20%

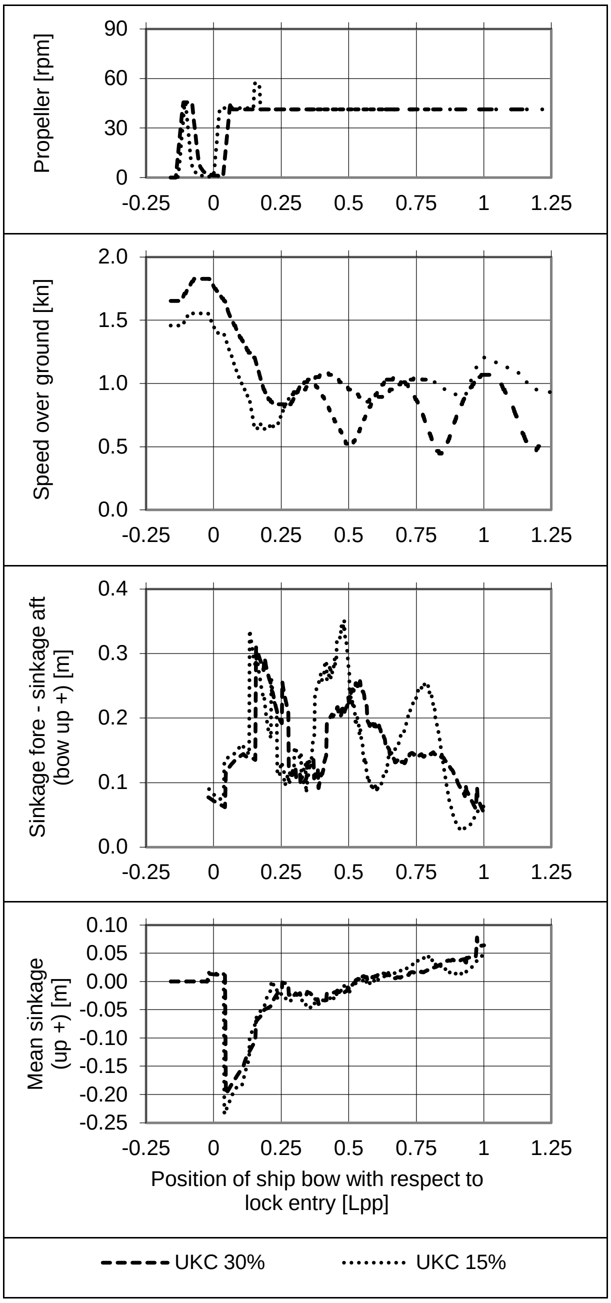

Fig. 8 Simulations of inbound 38 m wide bulk carrier entering the West Lock in Terneuzen at UKC 15% and UKC 30%

In order to clarify the different magnitude of translation waves during the full scale trial on the MS Koutalianos and the model tests, simulation runs were performed at similar conditions as shown in Table 5 (see Table 7). The results of the simulations are shown in Fig. 7 and Fig. 8.

During the simulations the propeller rate was operated manually to achieve similar speeds as in the corresponding full scale trial or model test. No tug assistance was applied during the simulations.

Propeller: The simulations show that significant smaller propeller rates were applied during the simulations to obtain a similar evolution of the ship speed during lock entrance in full scale trials and model tests.

Speed: Both in simulations performed with a 37 m wide bulk carrier as in simulations performed with a 38 m wide bulk carrier the effect of translation waves on speed evolution during ship entrance is significant. Based on the simulation model the translation waves seem to be mainly affected by under keel clearance more than by ship beam.

Trim and sinkage: Although the magnitude and sign of trim calculated during lock entrance simulations is similar to the trim during full scale and model scale experiments, the evolution of this parameter during the manoeuvre differs significantly from simulation tests. However, the evolution of the mean sinkage during lock entrance is completely the opposite of the sinkage derived from experiments.

Conclusion: Using the Vrijburcht ship-lock interaction module allows to simulate the translation waves in a lock chamber resulting in a loss of speed depending on the under keel clearance. The results are comparable to those obtained from model tests. Nevertheless the simulation model does not explain the smaller effects of translation waves during lock entrance of a 37 m wide bulk carrier and the vertical motion cannot be calculated accurately. These discrepancies can be explained by the fact that Vrijburcht (1988) investigated the entry of inland barges into a lock, which is characterized by a very sudden increase of the blockage. The latter increases more smoothly during the entry of a sea-going vessel, even for full-form ships such as bulk carriers.

Fig. 9 MS Koutalianos entering the West Lock in Terneuzen (simulated view)

5. CONCLUSIONS

Based on model test series recommendations regarding under keel clearance and blockage during entrance of bulk carriers to a high blockage lock configuration are presented. The model test series reveals that lock effects significantly increase when the under keel clearance is 30% or less. Nevertheless in model tests performed at under keel clearances smaller than 30% the ship speed during lock entrance remains positive when a combination of low speed during the approach and increasing propeller rate when the ship enters the lock, is applied.

Registration of a marginal bulk carrier sailing to the West lock in Terneuzen demonstrates that also in reality this strategy is applied. When comparing parameters as ship speed, trim and sinkage in both full scale trial and model tests at similar conditions, it seems that effects from translation waves propagating in the lock chamber between ship bow and lock door are significantly larger in model tests. A possible explanation is that the wave system in the lock depends more on the horizontal clearance than on the under keel clearance. The presence of floating fenders in the Terneuzen West Lock, which were not included in the scale model, might affect the wave propagation as well.

To assess the accessibility of 38 m wide bulk carriers to the West lock in Terneuzen a simulation study was performed on a full mission bridge simulator.

In order to clarify the different magnitude of translation waves during the full scale trial on the MS Koutalianos and the model tests, the simulation model for calculation of translation waves was applied in conditions similar to those in full scale trial and model tests. Based on the comparison between model tests, full scale measurements and simulations, it was concluded that the effect of translation waves on the speed history can be satisfactorily simulated with the present mathematical model, which is not the case for the vertical motion of the ship during lock entry.

6. FUTURE WORK

Model tests – both with self-propelled and captive ship models – have proved to be a valuable research tool to gain insight into the physical phenomena dominating a ship's behaviour during lock entry. In order to determine the operational limits of such a manoeuvre in terms of relevant parameters such as under keel clearance, blockage, speed, propulsion and ship shape, there is a need for additional systematic model test series. The results of such a test program will provide valuable data to generate or validate a more general ship-lock interaction module for real-time simulators. The development of mathematical models suited for simulating lock manoeuvres is challenging, as most of the phenomena are non-stationary, while most of the simulation models follow a quasi-steady approach; on the other hand, the complexity of the calculations should be limited to allow real-time simulations.

An increased interest in ship behaviour in locks and their approach channels, both for sea-going and inland vessels can be observed recently. In 2011, the Inland Navigation Commission (InCom) of PIANC established a new working group "Ship behaviour in locks and lock approaches" (InCom WG no. 155). In 2013, Flanders Hydraulics Research and Ghent University, supported by the Royal Institution of Naval Architects, will focus their Third International Conference on Ship Manoeuvring in Shallow and Confined Water (Ghent, 3-5 June 2013) on the topic of ship behaviour in locks (www.shallowwater.be).

With respect to simulation models and numerical calculation methods to determine forces and moments due to phenomena typical for manoeuvres in locks or their approach channels, Flanders Hydraulics Research has made a selection of model test results available as benchmark data. The experimental data were acquired in 2007-2008 in the preparation phase of the third set of locks for the Panama Canal, when model tests on scale 1/80 were performed at FHR with a ship model entering and leaving a lock chamber. These tests were performed on behalf of the Consorcio Pos Panamax (CPP) for studying the behaviour of ships transiting the future locks as a part of the ACP Contract Engineering Services for Additional Studies and Technical Assistance assigned by the Panama Canal Authorities. The selected tests concern lock manoeuvres with the design vessel for the new Panama Canal locks, a post-panamax 12000 TEU container carrier, with different approach wall configurations, under keel clearances and eccentricities, with and without density currents. Through the availability of open data the organisers of the conference mentioned above wish to stimulate the research on hydrodynamics of ships in locks and their approach channels in order to improve mathematical models for simulation of lock manoeuvres. The open data can be acquired by means of a publication dedicated to this topic which is available on the web site www.shallowwater.be.

7. ACKNOWLEDGEMENT

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