

BEHAVIOR OF POST PANAMAX VESSELS IN THE THIRD SET OF PANAMA LOCKS

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Abstract: Flanders Hydraulics Research built a 1/80 scale model in which three different ship models have been experimented to assess the navigation behavior in the Third Set of Panama locks. The radio controlled ship models were laterally restrained, equipped with an own propulsion and longitudinally assisted by simulated tugs. During the tests forces exerted on and vertical motions of the ship, as well as water levels were recorded. A limited number of tests included density currents, which mainly occur between the first lock chamber and the ocean side. All typical lock maneuvers have been tested at different approach wall configurations, eccentricities, propeller rates, approach scenarios and under keel clearances. This article presents a selection of results of interest for lock maneuvers, among which the significant effect of density currents and the approach wall configuration on the lateral forces that act on the entering and exiting vessels. Control of lateral forces by the ship's controls and tug assistance is therefore a determining parameter.

1. INTRODUCTION

The Panama Canal Authority (ACP) plans to build a new lane along the Panama Canal that will double capacity and allow more traffic. Along with this new lane a new set of larger locks (triple lift type), referred to as the Third Set, will be built. Each lock chamber will have a length varying between 427m and 488m, depending on the opening of the inner gates. The width of each chamber will be 55m. The design ship is a so-called post panamax 12000 TEU container carrier (Table 1).

Among other task orders, ACP Contract Engineering Services for Additional Studies and Technical Assistance consisted of the execution of tank tests for investigating the behavior of vessels transiting the future Third Set of Locks. The main purpose was to determine design and operational criteria, such as the need and the configuration of lock approach walls, design criteria for fenders inside lock chambers, and required tug assistance. The task was assigned to the Consorcio Pos Panamax (CPP), which contracted Flanders Hydraulics Research, Antwerp, Belgium (FHR) to perform the model testing. Scientific support was provided by the Maritime Technology Division of Ghent University, Belgium.

In this article all data are expressed in prototype (i.e. full scale) values, unless otherwise specified. A Froude scale law is used for reducing prototype data to model data.

2. EXPERIMENTAL PROGRAM

2.1 Setup

A 1/80 scale model of the new lock with the approach channel has been built at Flanders Hydraulics Research. Scale models of the different ship types were allowed to move on a straight line parallel to the locks' centerline, while the lateral motions are restrained by a guiding rail to which the ship model is connected at the bow and at the stern.

To sail along the beam with different eccentricity with respect to the lock axis, the frame with the wheels can be positioned eccentrically regarding the ship's axis.

The lateral forces in each connection point are measured by dynamometers, while the ship is free to move in vertical direction. The ship's velocity is controlled by changing the propulsion of the ship, which is provided by its propeller or by tug assistance, simulated by small model scale airplane propellers mounted on the ship that only exert forces in the longitudinal direction. With the measured lateral forces the necessary tug assistance in any direction can be determined. The rudder of the ship model is not controlled during the tests.

Before the entrance to the lock chamber four different approach wall configurations have been tested: none, a closed wall, a permeable wall with inclined rectangular partitions, and a series of piles (see Fig. 1).

Table 1 - Ship characteristics

	Bulk carrier	8000 TEU ship	12000 TEU ship
L_{OA} (m)	282.6	348.5	369.2
L_{PP} (m)	277.2	328.5	348.0
B (m)	45.9	42.4	49.0
T (m)	15.0	14.4	15.2
C_B (-)	0.84	0.65	0.65
#blades	4	6	6
D_P (m)	7.41	8.38	9.40
P/D_P (-)	0.66	1.0	1.07
AEP (-)	0.63	0.96	1.03
Rudder area (m ²)	74.8	81.5	92.0

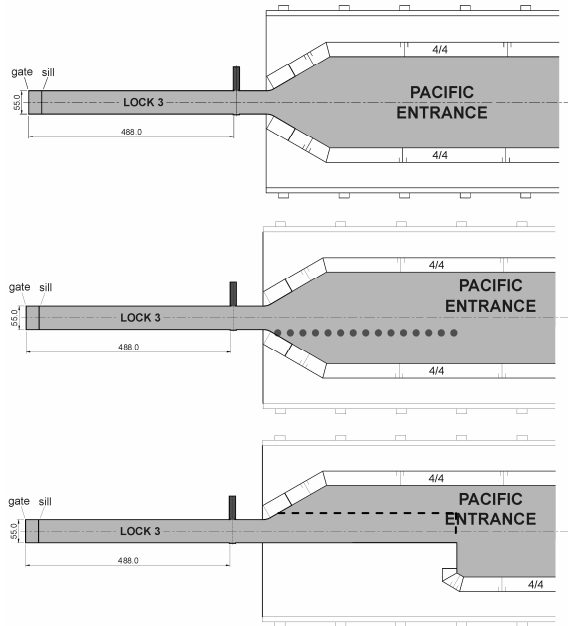


Fig. 1. Different approach wall configurations on the Pacific entrance: – No approach wall – Permeable approach wall or series of piles – Closed approach wall (closing the dashed lines allows Lock-lock tests)

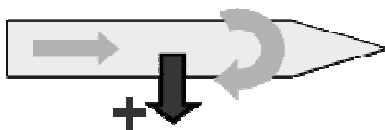


Fig. 2. Positive direction of forces and moments.

An approach wall offers the advantage of a structure where the ship can moor before the opening of the gates or helps the pilots to align the vessel with the longitudinal axis of the lock. The drawback is that its asymmetry likely induces more lateral forces on the ship.

Due to the difference in density between the water in the lock chamber and in the approach channel, density exchange currents are generated during spilling operations and during the opening of the lock gate. Some tests took into account the density current exchange. The ship could either be waiting along the approach wall (static test) or already be approaching

the lock (dynamic test).

2.2 Experimental parameters

The following parameters were varied:

- Approach wall (see Fig. 1);
- Water depth (110%, 120% and 130% of the 12000 TEU ship's draft);
- Eccentricity (along the centerline, $0.25 \cdot (55 - B)$ m and 0.6 m between the ship's hull and the lock walls);
- Ship type (see Table 1);
- Control strategy (up to 3 knots desired speed and combinations of own propulsion and tug assistance);
- Type of maneuver:
 - (Atlantic/Pacific) Ocean to Lock;
 - Lock to Lock (going up);
 - Lock to (Gatún) Lake;
 - Lake to Lock;
 - Lock to Lock (going down);
 - Lock to Ocean.
- Waiting time (in case of a density current exchange test).

Most tests were performed with the design ship (12000 TEU) to assess the different approach wall conditions at different under keel clearances and eccentricities. Lake maneuvers could be simulated by lowering the bottom in the lock chamber.

3. MEASUREMENTS

3.1 Introduction

In this chapter a comparison is made between the forces for different eccentricities, with a prototype speed of 2 knots with own propulsion at dead slow, unless otherwise specified.

The x-axis of the graphs is expressed in L_{PP} (ship length between perpendiculars). Position zero corresponds with the ship bow aligned with the knuckle, i.e. the start of the 55 m narrow section. Moments with the bow to starboard are positive, as are lateral forces to starboard (see Fig. 2).

3.2 Effect of the approach wall

When the ship enters the lock centrally along its longitudinal axis, a closed approach wall causes a lateral force towards the wall and a bow-out yawing moment. A permeable approach wall not only results into significantly smaller hydrodynamic forces, but also causes a sign change of the lateral force, see Fig. 3. The effect of an approach wall appears to be maximal when half of the ship's length is within the narrow section.

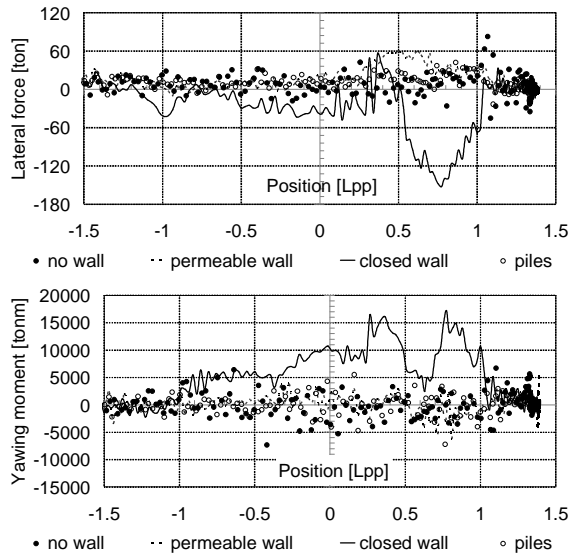


Fig. 3. Ocean-Lock test without density exchange: influence of wall configuration on lateral force and yawing moment, 12000 TEU container carrier, desired velocity 2 knots, dead slow ahead, centric entrance, 20% ukc.

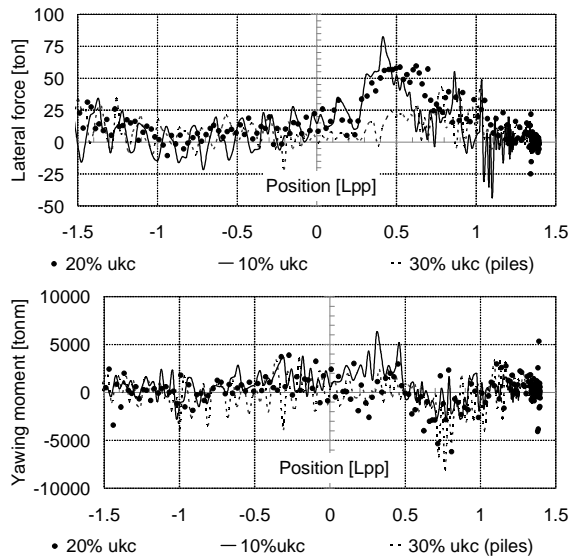


Fig. 4. Ocean-Lock test without density exchange: influence of the under keel clearance on lateral force and yawing moment, 12000 TEU container carrier, desired velocity 2 knots, dead slow ahead, centric entrance, permeable approach wall.

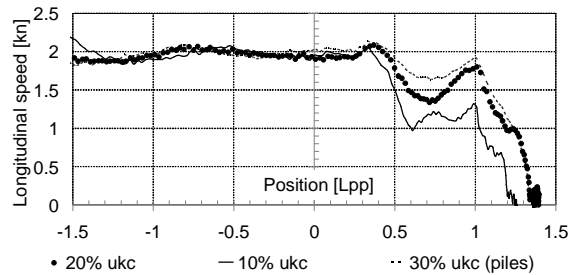


Fig. 5. Ocean-Lock test without density exchange: influence of the under keel clearance on actual longitudinal speed, 12000 TEU container carrier, desired velocity 2 knots, dead slow ahead, centric entrance, permeable approach wall.

3.3 Effect of under keel clearance

A decrease of under keel clearance has only a significant effect on the lateral force, but less on the yawing moment, see Fig. 4. The effect of the under keel clearance is even more severe when a closed approach wall is installed. Fig. 5 also shows that a sharper speed decrease is obtained at a smaller under keel clearance.

3.4 Effect of the eccentricity

Sailing eccentrically into the lock yields a remarkably larger sway force, even if no approach wall is installed. As can be seen on Fig. 6 the peak sway force is almost twice compared to the centric entrance. The more permeable the approach construction is the higher the effect of the eccentricity seems. The eccentricity also influences the yawing moment, but less outspoken.

3.5 Effect of the ship type

Entering the lock with the 8000 TEU ship under the same conditions as the 12000 TEU ship and the bulk carrier will yield a smaller lateral force and yawing moment acting on the ship before braking, Fig. 7. The forces acting on the bulk carrier have the same magnitude as those on the 12000 TEU ship. Fig. 8 shows container carriers enter the lock faster than the bulk carrier.

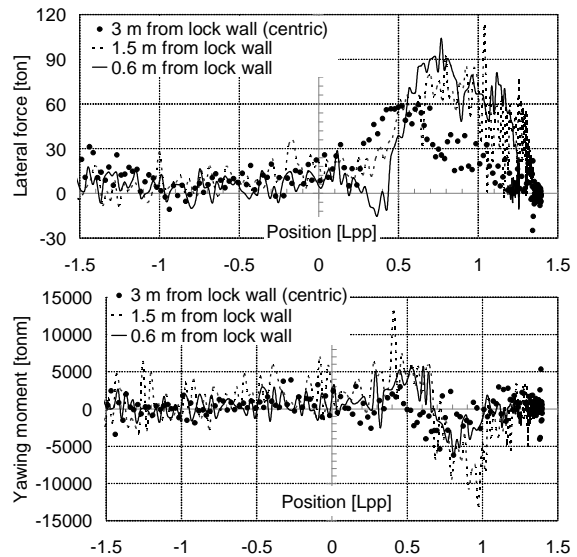


Fig. 6. Ocean-Lock test without density exchange: influence of eccentricity on lateral force and yawing moment, 12000 TEU container carrier, desired velocity 2 knots, dead slow ahead, permeable approach wall, 20% ukc.

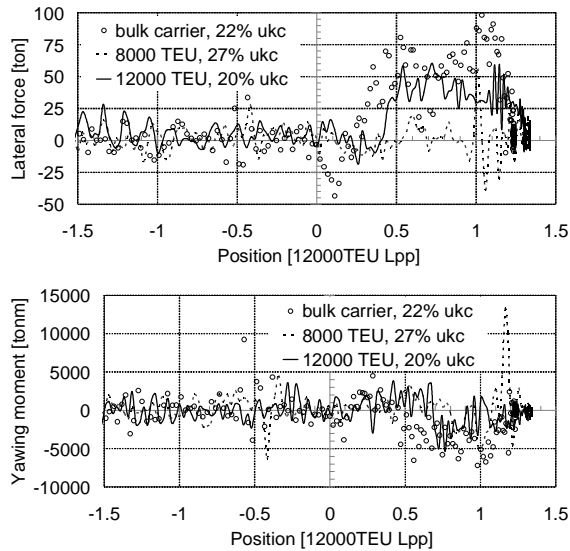


Fig. 7. Ocean-Lock test without density exchange: influence of the ship type on lateral force and yawing moment, desired velocity 2 knots, dead slow ahead, approach wall: piles, eccentric entrance of $0.25*(55-B)$ m.

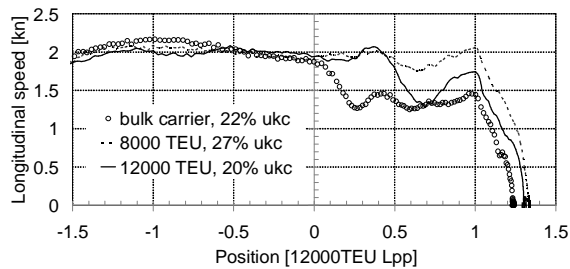


Fig. 8. Ocean-Lock test without density exchange: influence of the ship type on the longitudinal speed, desired velocity 2 knots, dead slow ahead, approach wall: piles, eccentric entrance of $0.25*(55-B)$ m.

3.6 Effect of the type of maneuver

3.6.1 Exiting the lock towards the ocean

Until now results focused on the Ocean-Lock entry, a maneuver that intuitively can be considered the most difficult. However, when analyzing the eccentric exits on Fig. 9 it is clear that while the ship is within the lock chamber comparable forces are measured as in the entry maneuver, but even larger forces occur when half of the ship has left the lock, even if no approach wall is fitted. In such case a speed reduction is required to be able to counteract the forces.

3.6.2 Lake maneuvers

Entering the upper lock from the Lake side or exiting towards the Lake has a positive effect on the forces (Fig. 10) as long as part of the ship is within the lock chamber. Indeed, the ship sails towards or from a deeper lock chamber and the larger local under keel clearance facilitates the maneuver.

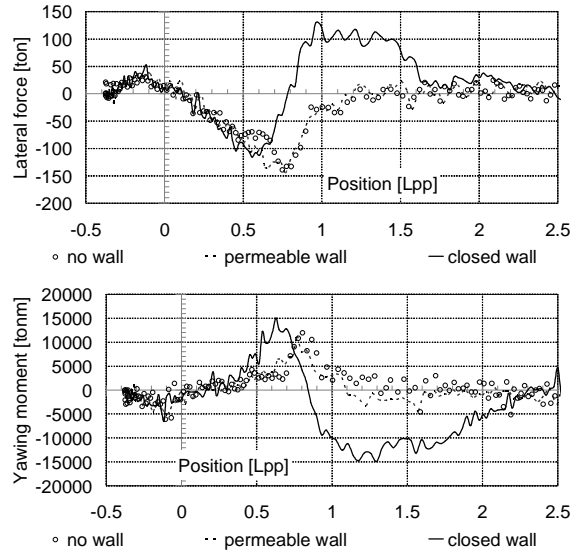


Fig. 9. Lock-Ocean test without density exchange: influence of the wall configuration on the sway force and yawing moment, desired velocity 2 knots, dead slow ahead, eccentric exit of $0.25*(55-B)$ m, 12000 TEU container carrier, 20% ukc.

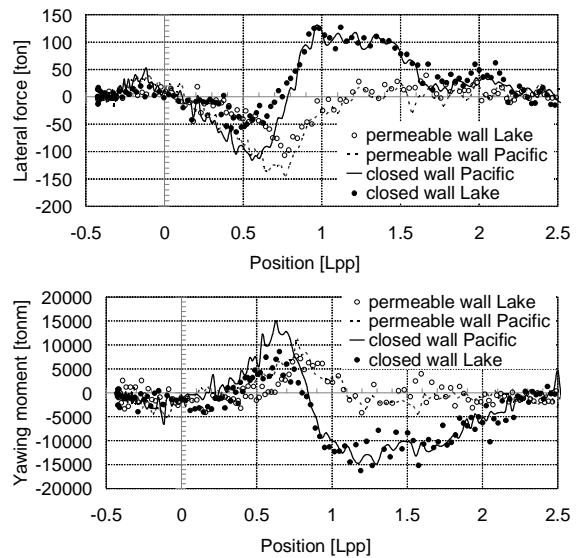


Fig. 10. Lock exit test without density exchange: influence of the wall configuration and the navigation sense (Ocean or Lake) on the sway force and yawing moment, desired velocity 2 knots, dead slow ahead, eccentric exit of $0.25*(55-B)$ m, 12000 TEU ship, 20% ukc.

3.6.3 Transition from one lock chamber to another

A transition from one lock chamber to another is usually carried out at smaller speeds. Furthermore no sudden changes of blockage occur which makes it the easiest maneuver. The navigation sense (going towards the Lake or towards the Ocean) has only a minor effect. The Lake oriented transition is usually easier because the ship starts in a deeper lock chamber facilitating the acceleration and stops in a shallower lock chamber facilitating the braking.

3.7 Effect of the density current

3.7.1 Test procedure

To operate the physical model averaged values of the salinity are taken from the measurements on the existing Panama locks [1]. This results in an averaged density difference of 12 kg/m^3 . As the density difference is the driving force for the exchange current, the approach channel in the model has a density of 1012 kg/m^3 and the lock (and spilling volume) has a density of 1000 kg/m^3 (fresh water). The fresh water was dyed so that its flow is visible during recording. Reflecting floats on the water allowed the visualization of the flow lines with DSLR cameras placed on top of the model, see Fig. 13.

In order to simulate the worst case with regard to density currents, the modeled situation is the conservative case of maximum lift without use of water saving basins. The corresponding discharge is shown on Fig. 11. In the model the discharge is created by the head difference between outlet reservoir and the water level in the entrance controlled by an opening law of the valve. This law was derived during calibration. The outlet culverts were placed on both sides near the bottom, see Fig. 12.

The opening law for the lock gate was copied from the opening law of Berendrecht lock in Antwerp and recalculated for the new Panama gate taking into account the smaller lock width.

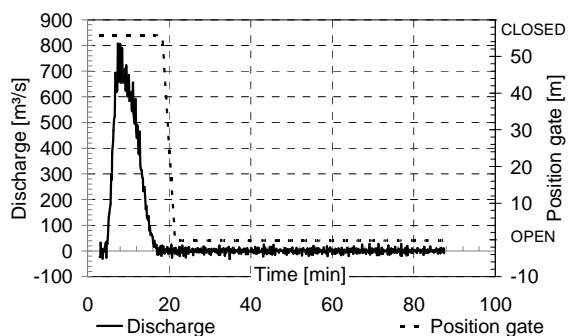


Fig. 11. Discharge and position of the gate during a static density current exchange test.

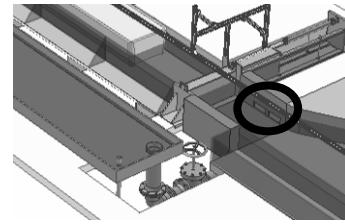


Fig. 12. Detail of lock entrance (artist impression). The outlet culverts are circled.

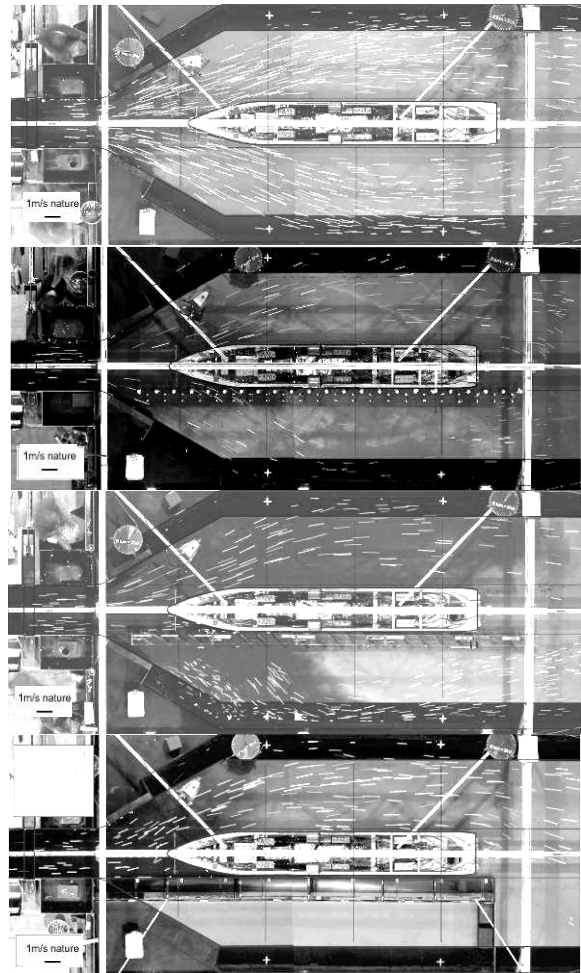


Fig. 13. Ocean-Lock test with density exchange: influence of the wall configuration (no wall – series of piles – permeable wall – closed wall) on the surface current pattern, 12000 TEU container carrier, static test, 20% ukc.

3.7.2 Static tests

During a static density current test the ship is waiting at a fixed position along the approach wall. For all tests the spill rate and opening of the gates is as shown in Fig. 11, unless otherwise specified.

The density current reinforces the asymmetry caused by an approach wall as can be seen on Fig. 13. Flow velocities up till 2.5 knots have been observed in the upper fresh water layer for any approach wall configuration.

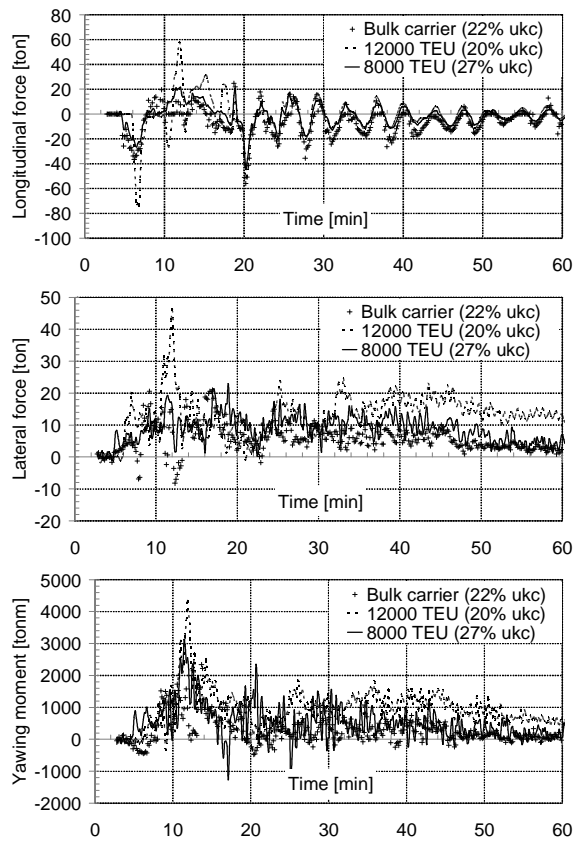


Fig. 14. Ocean-Lock test with density exchange: influence of ship type on the longitudinal force, lateral force and yawing moment, approach wall: piles, static test.

The spilling of the flow causes a peak in all force components (Fig. 14), certainly for the 12000 TEU container carrier. The forces acting on the ship when opening the gate are noticeably smaller. Anyhow the approach wall configuration has a significant effect yielding larger forces with decreasing permeability.

3.7.3 Dynamic tests

During a dynamic test spilling and opening of the gate occur while the ship is approaching the lock. An important parameter is the waiting time, being the time between the complete opening of the gate and the ship's bow passing the knuckle. The applied waiting times are 5 to 19 min prototype. A very long waiting time corresponds to a test without density exchange currents.

The sway force increases sooner with a longer waiting time due to the earlier encounter between ship and density currents, and becomes maximal when the bow passes the knuckle, Fig. 15.

On the other hand the decrease occurs at the same point for all waiting times, except when waiting very long, i.e. a test without density exchange current. A longer waiting time means that the force has to be counteracted for a longer time; as a consequence the

easiest condition is a very short or a very long waiting time. Without density currents the sway force starts to act when the bow passes the knuckle and turns maximal when the ship is already half in the narrow section. The effects of the waiting time on the yawing moment are less significant.

3.8 Squat and roll

Squat and roll never proved to reach critical values for any of the ship types. As an example the bow and stern sinkage have been shown on Fig. 16. While entering the lock the water accumulates in front of the ship's bow which causes the initial rising of the bow. A significant effect of the approach wall configuration on the sinkage cannot be observed.

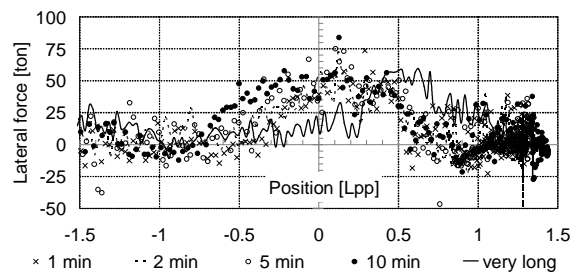


Fig. 15. Ocean-Lock test with density exchange: influence of the waiting time on the lateral force, permeable approach wall, dynamic test at a desired velocity of 2 knots, dead slow ahead, 12000 TEU container carrier, 20% ukc.

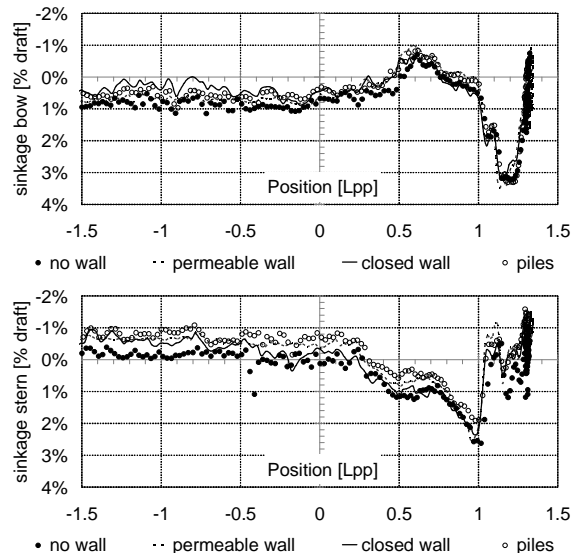


Fig. 16. Ocean-Lock test without density exchange: influence of wall configuration on the sinkage, 12000 TEU container carrier, desired velocity 2 knots, dead slow ahead, centric entrance, 20% ukc.

4. ANALYSIS OF THE RESULTS

4.1 Evaluation strategy

An analysis of the results was performed to know whether the measured forces can be counteracted given a certain tug assistance and lateral thruster assistance for the maneuver.

All ships can be assisted by 3 tugs with 60 tonf bollard pull: one at the bow and two at the stern. Two tugs at the stern are crucial to brake the ship because of the large speed modern container carriers reach at dead slow ahead.

If tug assistance is not sufficient rudder assistance is used which depends on the rudder angle and the propeller thrust. If neither is sufficient assistance of a bow and stern thruster (not for the bulk carrier) is considered. In this way runs can be assessed and an optimal balance between safety and speed can be found.

Of course the presence of an approach wall or the limitations of the lock chambers have the disadvantage that not all the available tug power can be deployed to counteract lateral forces and that longitudinal force components are generated that also have to be counteracted or that generate speed corrections, see Fig. 17.

In practice test runs are evaluated positively if all average control assistance is used at less than 90% and if the lateral force can be counteracted at any time with the given control assistance.

The average force needed to move the ship from x_0 to x_N can be determined as (t is time):

$$F_{average} = \frac{\int_{t(x_0)}^{t(x_N)} F dt}{t(x_N) - t(x_0)} \leq 0.9 F_{MAX} \quad (1)$$

The numerator in (1) multiplied with the average ship velocity between x_0 and x_N is called 'Effort' and is proportional with the kinetic energy needed to move the ship from x_0 to x_N :

$$E = \int_{t(x_0)}^{t(x_N)} F dt \frac{x_N - x_0}{t(x_N) - t(x_0)} \quad (2)$$

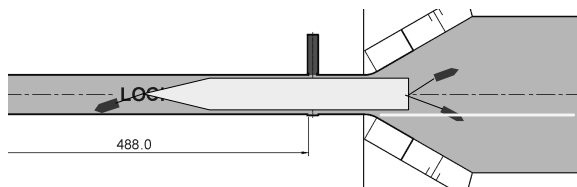


Fig. 17. Restriction on positioning of tugs.

4.2 Results

4.2.1 Preliminary remark

A "Y" above some of the bar-diagrams in this paragraph means that the run rejected because of insufficient capacity in a lateral direction.

A "B" below some of the bar-diagrams in this paragraph means that a bow thruster is required.

4.2.2 Examples

As an analysis example the Ocean-Lock entrance is discussed for the three different ship types at a desired speed of 2 knots.

The bow tug is especially used in runs where the ship does not use its own propeller, see Fig. 18. Increasing eccentricity and speed will demand more assistance. For the same approach wall and the same water level the bow tug has to work less for the 8000 TEU ship than for the 12000 TEU ship. This is not always the case for the bulk carrier compared to the 12000 TEU and once the ship uses its propeller the decrease of bow tug use will be stronger for the latter, due to the poor propulsion efficiency of the bulk carrier.

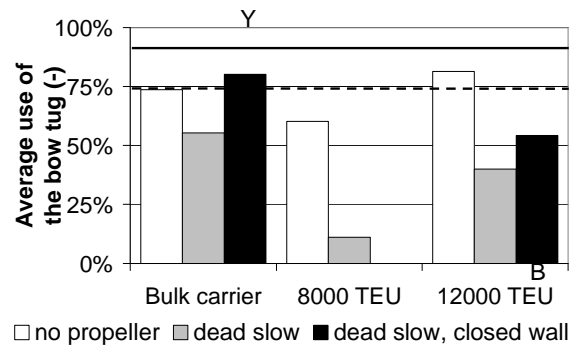


Fig. 18. Ocean-Lock test without density exchange: influence of ship type on the average use of the bow tug, desired velocity 2 knots, centric entrance, 20% ukc for 12000 TEU ship, approach wall: series of piles.

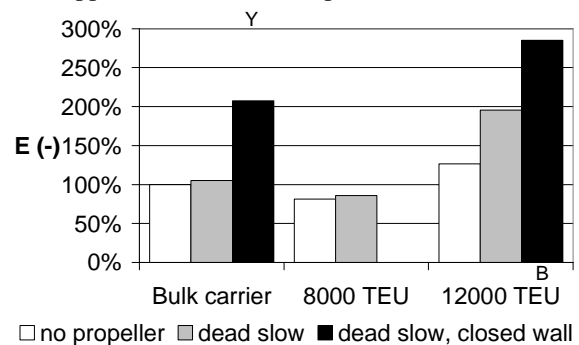


Fig. 19. Ocean-Lock test without density exchange: influence of ship type on the effort of the maneuver, desired velocity 2 knots, centric entrance, 20% ukc for 12000 TEU ship, approach wall: series of piles.

Lateral force is never problematic for the bow tug, if at least no closed wall is installed and if the ship does not enter eccentrically at high speeds. In case of the bulk carrier the lateral force can then no longer be counteracted and the 12000 TEU needs to use a bow thruster.

The global entry effort (2) in Fig. 19 has been expressed as a percentage of the global entry effort needed for the bulk carrier without propeller action. The global entry effort for the bulk carrier is positioned between the effort for the 12000 TEU ship and the 8000 TEU ship. The global efforts increase with increasing eccentricity and speed.

4.3 Navigation times

The navigation time not only depends on the speed the vessel can reach in the lock chamber, e.g. Fig. 8, but also on the lateral forces that need to be counteracted and that could generate accelerations of the ship as explained in 4.1.

In general the 8000 TEU ship will be able to maneuver faster and with less effort compared to the other ships.

Without density currents the 8000 TEU convoy – which is ship plus tugs – is the fastest entering the lock in less than 8 min. The 12000 TEU ship can enter the lock along the permeable wall in less than 9.2 min and the bulk carrier always needs more than 13 min.

Density currents affect the required time because of the extra longitudinal force the ship needs to counteract. The influence of the density currents has the largest repercussions on the entrance times of the bulk carrier (+23%). For the container carriers the increase is approximately 15%. Mind that even if waiting very long might reduce the entry time, waiting shortly – whenever possible – will improve the total transit time.

5. SIMULATION CHALLENGES

The analysis method used is mainly focused on assessing optimal navigation conditions. The implementation into a simulator is not straightforward because various criteria have to be met:

- Shallow water mathematical models for the post panamax ships have to be available, because the ships not only navigate in the lock, but also sail along the canal;

- The longitudinal movement of the ship in the lock has to be predicted. This model should include a one dimensional hydraulic component to calculate the currents and waves in the lock and approach channel;
- The lateral forces acting on the ship during a lock maneuver should be modeled;
- Lateral motion, which was not accounted for during the experiments, should be modeled. The motion itself could cause retardation effects in the forces, as well as cushion effects.
- The simulation of the density currents with a ship moving in the lock in real time is still a challenge because of the large computational times, but analysis of the experimental results could reveal a possibility to include some density current effects in the forces on the ship in the lock, as function of relative time to opening of the gate.

6. CONCLUSIONS & RECOMMENDATIONS

Results showed the approach wall configuration has a significant effect on the lateral forces that act on the entering and exiting vessels. If an approach wall is installed it should be as permeable as possible in order to avoid excessive asymmetries in the currents which lead to excessive lateral forces.

The lateral forces acting on the ship also increase with the space the ship occupies in the lock (the blockage). A larger or fuller vessel will experience a larger resistance and larger lateral forces and will require more effort to enter. Lateral forces are also influenced by density currents, which certainly need to be taken into account along the ocean side.

Eccentricity and a decreased under keel clearance have an adverse effect on the maneuvers. As most tests show that the forces are smallest when sailing in the centerline, it is advised to provide visual or electronic aid to assist the pilots. Larger, deep-drafted ships as the 12000 TEU container carrier are preferably scheduled at higher tides. It is always recommended to use the ship's propeller to assist the maneuver.

The tug assistance (number of tugs, bollard pull and the way they are connected to the ship) is extremely important to counteract lateral forces. For the experimented vessels at least two 60 tonf bollard pull tugs are required at the stern and one 60 tonf bollard pull tug at the bow. The sinkage nor the rolling of the vessels is a critical parameter.

LIST OF SYMBOLS

AEP	extended blade area ratio	(-)
B	ship beam	(m)
C_B	block coefficient	(-)
D_P	propeller diameter	(-)
E	effort	(Nm/s)
F	force component	(N)
L_{pp}	ship length	(m)
P	propeller pitch	(m)
T	ship draft	(m)
t	time	(s)
TEU	Twenty feet Equivalent Unit	(-)
ukc	under keel clearance	(-)
V	velocity	(m/s)
x	longitudinal position	(m)

REFERENCES

- [1] Delft Hydraulics, 'Salt Water Intrusion Analysis Panama Canal Locks - Existing Situation – Report A: field data collection - development and validation of simulation model - analysis of salt water intrusion', report Q3039, June 2003.