LOCK MANOEUVRES: PRACTICAL CASES IN EUROPE AND PANAMA

K Eloot, Flanders Hydraulics Research, Ghent University, Belgium
M Vantorre, Ghent University, Belgium
J Verwilligen, Flanders Hydraulics Research, Belgium
D Bus, R Cleeren and **E Gheyle**, Flemish Pilotage, Belgium
E Veche, Station de Pilotage de Dunkerque, France
E Heugen and **J van Drongelen**, Dutch Pilotage, the Netherlands
R Salas, Panama Canal Pilots, Panama
R Detienne, Brabo, Belgium

SUMMARY

Lock manoeuvres are daily practice for the ships in their approach to harbours worldwide. The experiences of five pilotages operating in Europe (Belgium, France and the Netherlands) and Panama are brought together in a paper describing the operation of pilots in the entrances to and in the locks. A division is made concerning locks with approach walls at one or both sides of the lock and locks without approach walls. The lock construction and the approach areas are described and compared for the locks in Panama, in Dunkirk (Charles de Gaulle lock), in Terneuzen (West lock) and in Antwerp (Berendrecht lock). Correspondence between the lock manoeuvres and the use of tugs can be recognised and shows that lock effects must be overcome by developing and maintaining a good strategy in pilotage which can be shared all over the world.

1. INTRODUCTION

Lock manoeuvres are daily practice for ships in their approach to the Flemish harbours. The Berendrecht lock – the largest lock in the world – receives Ultra Large Container Ships from the Mediterrean Shipping Company on their way to the Delwaide dock. With a cumulative overall clearance of 3 m between ship sides and lock walls (fendering not taken into account) the West lock in Terneuzen is accessible for 37 m wide bulk carriers [1], [2].

Lock manoeuvres are daily practice worldwide with the well-known Panama Canal locks since 1914. The design of the new locks which are presently under construction and which will allow the transit of Post-Panamax vessels with lengths up to 366 m and beams up to 49 m is based on a drastic modification in the lock operations, as ships making use of the new locks will not be assisted by locomotives, but only by tugs. To prepare this operational change the Panama Canal Pilots have contacted their colleagues worldwide.

Experiences obtained by a shipping company in one harbour are often extrapolated for the access of their vessels to other harbours. Based on the research for the access of wide-beam ships to the West lock in Terneuzen the port authorities and the pilotage of Dunkerque have contacted the Knowledge Centre Manoeuvring in Shallow and Confined Water (www.shallowwater.be) for a comparable study for entrances to the Charles de Gaulle lock as has been done for entrances to the West lock.

These modified operations in new locks and the need of increasing the ship sizes in existing locks require a multidisciplinary investigation in which simulation techniques are widely used by institutes as a research tool and by pilotages as a training tool. Transfer of knowledge and expertise helps in defining the similarities and differences between lock operations in Europe and Panama and how to speed up the accessibility issue making use of the research results and the operational processes in use in other harbours.

Based on contacts between the Flemish, Dutch, French and Panamanian pilotages the Knowledge Centre Manoeuvring in Shallow and Confined Water is presenting a collection and description of the lock operations in the existing Panama locks, the Charles De Gaulle lock in the port of Dunkerque (France), the West lock in Terneuzen (The Netherlands) and the Berendrecht lock in Antwerp (Belgium). A comparison of the lock constructions and the access channels from a ship hydrodynamics point of view will be made. The lock effects experienced by the pilots and the operation of tugs will be summarised and combined with full scale measurements executed by Flanders Hydraulics Research and the pilotages. The paper is therefore a multidisciplinary document illustrating the pilots' view on lock operations and lock effects.

2. LOCK APPROACH DESCRIPTION

2.1 LOCKS WITH APPROACH WALL

2.1 (a) Locks on the Panama Canal

Construction
The lock system of the Panama Canal consists of three lock complexes (Figure 1), one on the Atlantic side (Gatun Locks) and the other two on the Pacific side (Miraflores and Pedro Miguel Locks). The purpose of the lock system in the Canal is to raise vessels to Gatun

Lake, which is 26.5 m above sea level, so that they can cross the Isthmus through the lake.
The locks at Gatun have three levels, and each level raises/lowers the vessels 8.8 m in height. The locks at Pedro Miguel have one level which raises/lowers vessels 9 m to/from Gatun Lake/Miraflores Lake. The locks at Miraflores have two levels which raise/lower vessels 17 m from/to the Pacific Ocean/Miraflores Lake.

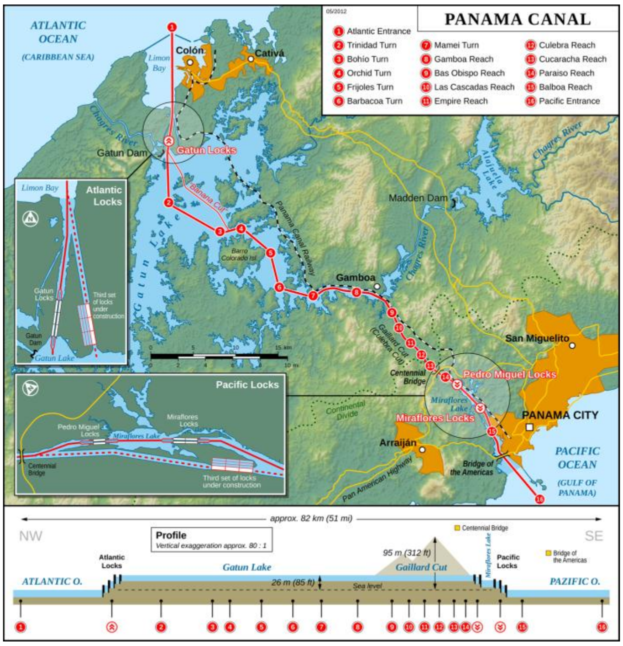


Figure 1: Lock complexes at the Panama Canal [3]

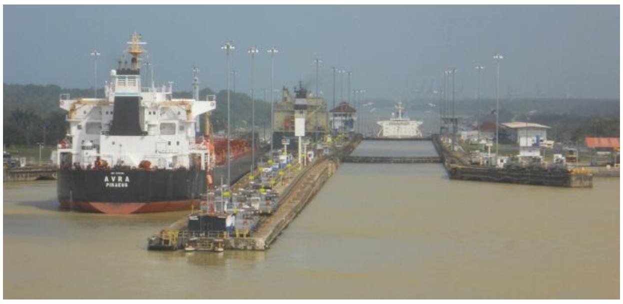


Figure 2: Solid approach walls and locks at the Panama Canal


Figure 3: Detail of the solid approach wall with rubber fenders

All the lock chambers have the same dimensions, 320.12 m in length and 33.54 m in width. The maximum dimensions of vessels allowed in the Panama Canal have changed through the years, finally coming up with the well-known Panamax vessels. The maximum length overall for commercial vessels is 289.6 m, except for passenger and container ships which may be up to 294.2 m. The maximum beam for commercial vessels allowed for transit is 32.31 m. The maximum allowable draft in the Panama Canal is 12.04 m Tropical Fresh Water.

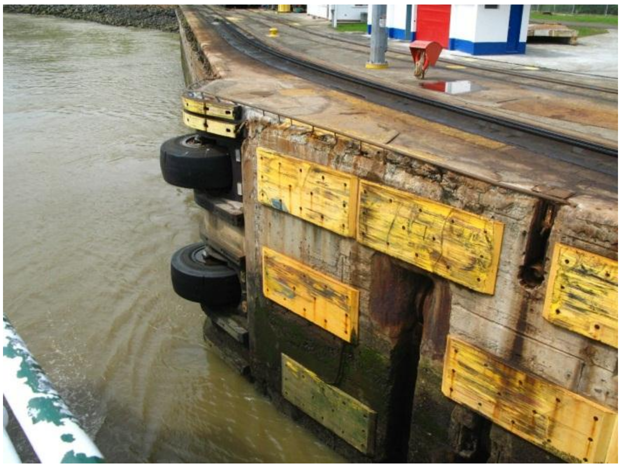


Figure 4: Detail of the wheel fenders at the opposite side of the approach wall

This draft provides a safe under keel clearance of at least 1.5 m over certain shallow areas in the Canal. It also allows for a clearance of 0.50 m over the south sill of Pedro Miguel Locks, which is the shallowest point in the Canal.
There are two sets of locks (Gatun and Miraflores) which have sea accesses, and are, therefore, subject to density currents and tidal currents. Pedro Miguel Locks and the lake entrances of Gatun and Miraflores Locks are mainly subject to the wind and, occasionally, to currents generated by dams or spillways located near the locks.

All sets of locks have solid approach walls (Figure 2), which assist pilots to guide large vessels inside the locks. These walls also act as staging areas to increase the efficiency of the Canal by having vessels in position to go inside the locks when they are ready to accommodate them.
The lock walls inside the locks do not have fenders. Only the approach walls have a combination of rubber fenders and sliding fenders (Figure 3) and wheel fenders at the opposite side of the lock approach wall (Figure 4).
All the locks are fitted with tracks for locomotives or “mules” that assist vessels through the lockage. Each of these locomotives are capable of exerting a pull of approximately 40 tons, and they can go up to 4.8 km/h while working a vessel. The use of locomotives has allowed the transit of vessels through the locks in expedient but safe manner. This is something that will greatly differ from the new design of locks that are being built in the expansion. The use of locomotives have also allowed the Panama Canal to increase the size of the

ships going through the locks, maximizing the use of the lock dimensions to the point that only 12 m can be left between the lock gates and the vessel's bow and stern, and less than 1 m on each side.

Manœuvre

All vessels of 24.39 m in beam and over are assigned two pilots and one tug which is usually placed on the shoulder to assist them to the locks. Those of 27.74 m in beam and over are assigned an additional tug. Vessels of 274.39 m in length overall and larger are assigned a third pilot, bow pilot, to assist in the lockage itself.

Figure 5: Bow tug on the shoulder of a bulk carrier

Figure 6: Stern tug in cut style assisting a container ship

<u>Entrances sea side</u>:

Pilots usually make tugs fast about three nautical miles from the locks. The bow tug (Figure 5) is made up on the shoulder, either port or starboard, depending on the lane where the vessel will be locked in. The length of line used will depend on the flare of the ship, but it has been found that the shorter the line, the more effective the use of the tug. The stern tug (Figure 6) is made up "cut style", which consists of having the tug placed right aft, in line with the centreline of the vessel, with its lines preferably sent through the chocks at either side of the stern. The pilots prefer the same principle of keeping the tug as close as possible to the vessel's hull as possible.

The heading of the approach to Gatun Locks is the same as the heading of the locks, but the approach at Miraflores Locks consists of a turn of about 25 degrees in a reach of 0.33 nautical miles (Figure 1).

Sea entrances in Miraflores and Gatun Locks are subject to density and tidal currents, in addition to the wind. Most pilots in the Panama Canal do one of two manoeuvres when approaching sea entrances: a *straight in* or *stemming the current* approach. Both of these approaches use the density current, which has the most effect on vessels near the locks, to assist with the manoeuvre. In the *straight in* approach, the pilot aligns the vessel in the same heading as the locks before arriving, and manoeuvres the vessel alongside the approach wall, using the current, the ship's engine and rudder, as well as the tugs to adjust. *Stemming the current* approach is exactly described as the pilot manoeuvring the vessel so that the bow stems the current head on, and pivots around the "soft nose" of the approach wall (Figure 7). This manoeuvre takes into account the possibility of the current, setting the ship strongly towards the approach wall before the vessel passes the end of the wall. Both of these manoeuvres should be made at less than two knots of speed. Care must be taken of not going too slow or the current could take over the ship.

Figure 7: Stemming the current approach along the approach wall

If the situation allows for it, pilots request the lockmaster to keep the lock sea gates closed until they have the vessel flat alongside the approach wall, with its locomotives made fast (three of them at this point, two at the bow and one at the stern) holding the ship tight and with the tug boats pushing the vessel against the wall. Most pilots do not request the gates to be open until about 75 m of the vessel are inside the jaws of the approach walls (i.e. the initial area where the vessel meets both walls). The reason for this is to avoid the effects of the density current at that critical point of the manoeuvre, where the current sets the vessel strongly against the knuckle. The effect of the current is so strong in this area that two locomotives of 40 tons of pull each and two tugs of at least another 40 tons each are required to keep the vessel alongside. The effect of the current, in addition to the piston effect at the locks, makes it necessary to enter the locks with full ahead on the ship's engine in most loaded bulkers or tankers. It is known that sometimes pilots had to wait for the density current to dissipate to be able to enter the locks.

Entrances lake side:
Lake entrances at the locks are not affected by density currents, but are subject to the wind and to currents created by spillways/dams.
An example of this current occurs while manoeuvring towards Miraflores Lock lake entrance (northern entrance), coming from Pedro Miguel Locks, and passing through Miraflores Lake. Pilots have come to describe this lake as a "downhill" lake due to the fact that vessels tend to gain speed while heading south because of the constant spilling of water through Miraflores Dam during the rainy season, which lasts nine months of the year.
Tugs are mostly made up the same way as in the sea entrances, and the approaches are made taking into account predominantly the direction and speed of the wind. There are no operational limits for the existing locks regarding wind force or direction. The need for additional resources (i.e. tugs) is up to the pilot.

The northern entrance of Pedro Miguel Locks has the additional difficulty of the hydrodynamic effects of the banks at the Gaillard Cut.
The objective at the lake entrances is the same, to manoeuvre the vessels alongside the approach wall so that they pick up the locomotives and proceed inside the locks.
Once inside the locks, the pilots use the locomotives to tow the vessel inside, assisting with the ship's engine and rudder. The locomotives also keep the vessel away from the lock walls, helping the pilot to counteract the hydrodynamic effects that result from the solid lock walls and the ship's hull. The effective use of the ship's rudder and engine are absolutely necessary for the same reason.

Hydraulic Assist
The *Hydraulic Assist* procedure is a special lockage procedure utilized only at Gatun and Pedro Miguel Locks. It is a means for assisting large vessels to leave the lock chamber, when completing a down lockage, by admitting water into the chamber behind the vessel as it moves out. This procedure is available, upon pilot request, for vessels having a beam over 30.2 m and draft over 11.3 m TFW. The net effect of this procedure has been measured by locks personnel to raise the water up to 90 cm below the vessel, which results in the vessel leaving the lock faster and with less resistance due to the increased under keel clearance. Pilots have especially found this procedure helpful when manoeuvring loaded bulkers and tankers out of Pedro Miguel Locks, where the smallest under keel clearance is found.

2.1 (b) Charles de Gaulle lock in Dunkirk (Figure 8)

Construction
The orientation of the lock is 260° with an approach wall of 212 m which alignment differs from the lock wall alignment with a value of 0.008° (Figure 9). This deviating orientation of the approach wall will provoke a small effect when the ship is entering the lock. The breadth of the lock is 50 m, reduced by the fenders which consist of tires spread over several lines on the height of the wall. The length of the lock between outside gates is 364.36 m.

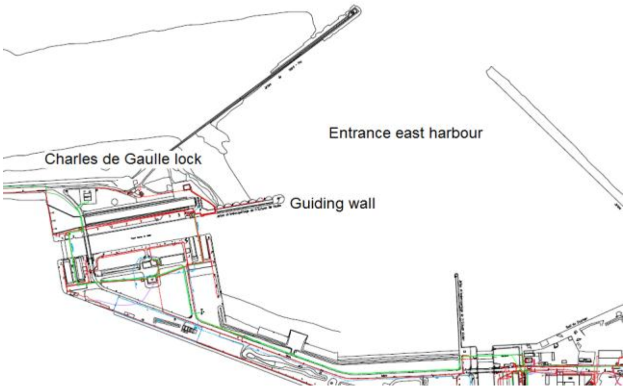


Figure 8: Charles de Gaulle lock at the port of Dunkirk


Figure 9: Approach wall of the Charles de Gaulle lock in the port of Dunkirk

The dredged bottom depth is -13.5 m in the entrance channel to the lock and alongside the approach wall.

Manoeuvre
Until today, the Charles De Gaulle lock at Dunkirk allows access to the port of Cape size ships (292 m to 45.05 m) with a maximum draft of 14.35 m (generally 14.2 m). Most ships are unloaded to this maximum draft at the western harbour and two pilots are on board while approaching the eastern harbour.

Entrance sea side: The entrance of Cape size ships is at mean tide only permitted 2 hours after high water (HW, with a tidal coefficient of 85, tidal range 4.7 m and bottom depth varying between -13 and -16 m at the breakwaters) to be able to combine sufficient clearance for the draft and a flow current speed reduced to less than

1 knot for turning the ship while passing the breakwaters (Figure 10).
After having passed the last couple of buoys (DW29 / 30) nearby the breakwaters, the ship executes a 10 minutes turning manoeuvring over 90° in a flood current pushing to the east with a ship's speed fall from 6-7 to 4-5 knots.

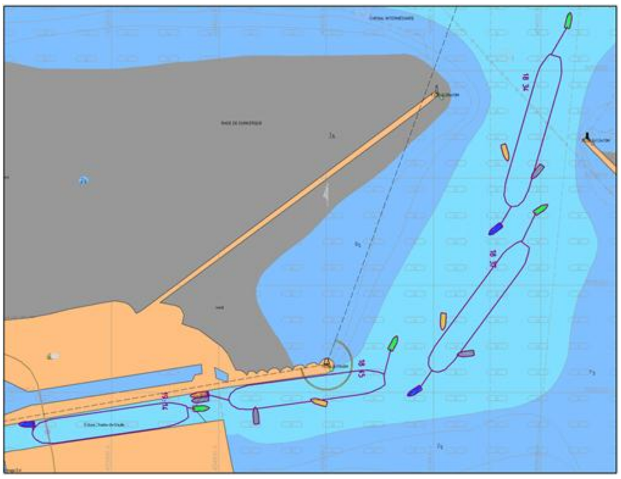


Figure 10: Entrance manoeuvre of the MV Cape Aster on 2012/12/05 in the port of Dunkirk

While passing the breakwaters, the engine may not be stopped as long as the flow current interacts with the ship's stern. At a stabilised course of 195°, the engine is put to half or even full astern in order to reduce the speed to 1.5-2 knots on a distance of less than one ship's length (270 m). With a bottom depth of -13.5 m and the water level generally decreasing by 25 cm every 15 minutes (e.g. Figure 11), the manoeuvre takes place in an emptying harbour with a modified current to the north. Passing the extremity of the approach wall, the ship swings to the orientation of the lock, pushed alongside the approach wall fitted with a sliding wood fender (Figure 9). The speed may not exceed 1.5 knots.

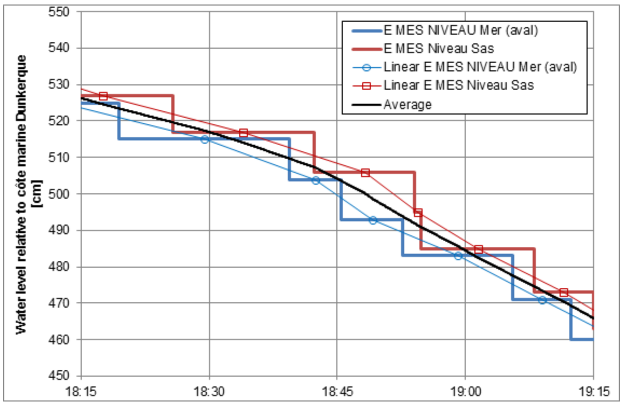


Figure 11: Water level change in cm during lock entrance with MV Cape Aster on 2012/12/05 18:46 (entrance of the bow)

Taking into account the falling water level and the available water depth, the underkeel clearance (UKC) in the lock entrance will generally be restricted to a maximum of 3.5 m (25% of the 14.2 m ship's draft) giving a modified tidal window at neap tide (passing the breakwaters in advance, 1h30 after HW) and spring tide (2h30 after HW).
The underkeel clearance during the entrance manoeuvre on the 5th of December 2012 was 30% due to a tidal level of 5.0 m while entering with the bow.
The tug assistance is shown on Figure 10 and is typical for Cape size vessels: two 41 ton tugs pulling fore and aft and two 70 ton tugs pushing first at both sides during the manoeuvre from breakwater to approach wall and next pushing the vessel at the port side against the approach wall.
The maximum wind force during the entrance of Cape size bulk carriers depends on the wind direction and differs from the limitations for container ships as the lateral wind area is much smaller for a bulk carrier (e.g. approximately 4,000 m² for a height above water of 13 m and a draft of 14.2 m) at loaded condition. For the ship alongside the approach wall the most unfavourable wind direction is sector north so that the maximum accepted wind force corresponds to a wind speed of 40 knots (20.6 m/s, 8 to 9 Bft) for the sector northwest to northeast and 45 to 50 knots (23 to 25.7 m/s, 9 Bft) for the sector southeast to west. The northern wind hinders additionally the turning manoeuvre from the sea to the harbour through the breakwaters and makes it impossible for the aft tug to assist due to the swell. For the wind coming from the north the approach wall reduces the lateral wind area of the vessel with one quarter so that for 40 knots wind speed 80 ton (lateral wind coefficient C_{WY} of 1.0, wind area A_L 3000 m²) bollard pull tug assistance is necessary to counteract the wind lateral force.

Lock: When a ship with a maximum length of 292 m enters the lock with a tug fore and three tugs aft (1 towing and 2 pushing tugs), the clearance between ship and tug combination and the lock extremities once the ship is moored in the lock, is only 12 to 15 m. The lock is filled by valves at the bow side of the ship pushing the ship back so that the mooring arrangement or a kick ahead on the engine must prevent the ship from hitting the tugs at the aft ship. When the dock side gate is opening, the sea water of the lock sinks and is replaced by brackish water (due to evacuation of the inland rainwaters by the port); this exchange creates a mascaret (density wave) which has a strong pushing effect on the ship going astern. This effect is stronger when the ship is larger and thus the free space in the lock is restricted so that the pushing tugs pass through another lock to avoid collision with the ship.

Entrance dock side: The Cape size bulk carriers leaving the eastern harbour have generally a draft of 10 m and thus an increased height above water of 17 m. The ships are moored port side along the quay and execute a swinging manoeuvre at approximately one ship length from the lock. The ships are assisted by four tugs, one fore and one aft and two pushers at both sides of the vessel (Figure 12, tug configuration during the entrance).

Once the swinging manoeuvre is accomplished the ship's motion is stabilised by the two pushers and stopped in line with the axis of the lock followed by the engine set to ahead propulsion. The piston effect is not felt while entering the lock as the underkeel clearance tends to medium deep water (90% UKC) but an external current flow from the cooling water of an electrical plant disturbs the entrance manoeuvre into the lock. The lack of an approach wall at the dock side increases the difficulty of the entrance manoeuvre compared to the manoeuvre at the sea side.

Figure 12: Simulator image of the entrance of the Charles de Gaulle lock from the dock side at Dunkirk harbour

Due to the increased vessel's wind area, the wind force from all directions, except from the east, complicate the entrance manoeuvre. The maximum wind speed from the sector north is 40 knots (20.6 m/s) and for all other sections 45 knots (23 m/s).

2.2 LOCKS WITHOUT APPROACH WALL

2.2 (a) West lock in Terneuzen

Construction

The principal dimensions of the West lock in Terneuzen are presented in Table 1.

The West lock, connecting the ports of Ghent and Zeeland through the canal Ghent-Terneuzen, is generally accessible for ships with a maximum length of 265 m, a beam of 34 m and a draft of 12.5 m (fresh water draft, 1 m keel clearance in the canal). In 2008 a trial period started to evaluate the accessibility of Kamsarmax vessels with a maximum length of 230 m and a larger maximum beam of 37 m. The Alam Permai was the first 36.5 m wide vessel that sailed to the Arcelor Mittal Plant in Zelzate on 2008/11/20 with a departure in ballast condition (draft 9.0 m) on 2008/11/24 (Figure 13). After a trial period of two years the regulations were modified to accept 37 m wide ships in the West lock and on the canal on a regular base.

Table 1: Principal dimensions of the West lock in Terneuzen [2]

Parameter	**Unit**	**Full scale**
Chamber length	[m]	290.0
Max. chamber length	[m]	378.5
Lock width	[m]	40.0*
Bottom of lock	[m NAP]	-12.82
Sill on river side	[m NAP]	-12.82
Sill on canal side	[m NAP]	-11.37
Water level river side	[m NAP]	-3.50 to 5.75
Water level canal side	[m NAP]	2.13

(NAP = Normaal Amsterdams Peil / Normal Amsterdam Level, absolute height reference in the Netherlands)
* almost 38 m between the floating fenders (Figure 13 and 14)

Figure 13: Departure manoeuvre with the Kamsarmax vessel Alam Permai in the West lock in Terneuzen on the 2008/11/24

Manoeuvre

Entrance river side: The Outer Harbour in Terneuzen (Figure 15) is reached from the Western Scheldt through the breakwaters and has a total length of 1500 m from the breakwaters to the lock. The mean water depth is -11.5 m LAT (Lowest Astronomical Tide) or -14.19 m NAP in the Outer Harbour. In Figure 15 the entrance position of the Petalon in front of the breakwaters and the assisting tugs are shown. This vessel is a 230 m long and 36.85 m wide Kamsarmax vessel lightered to a draft of 12.5 m freshwater at Terneuzen Roads in order to reduce the vessel's draft for entering the West lock and the canal.

Entering the Outer Harbour to the West lock will be in a tidal window around HW to avoid maximum flow current on the river and to ensure sufficient UKC. A minimum UKC of 1 m is required in the lock.

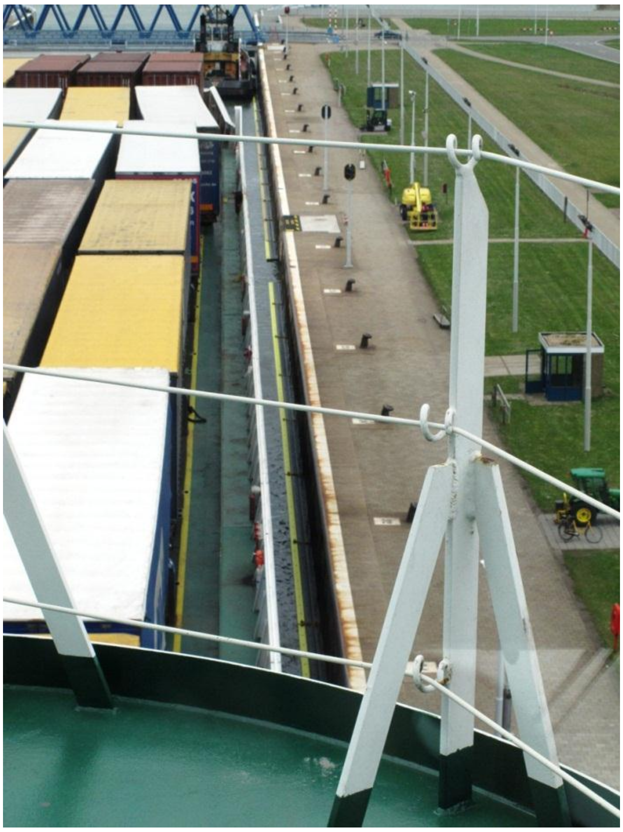


Figure 14: Floating fenders along the lock wall in the West lock in Terneuzen

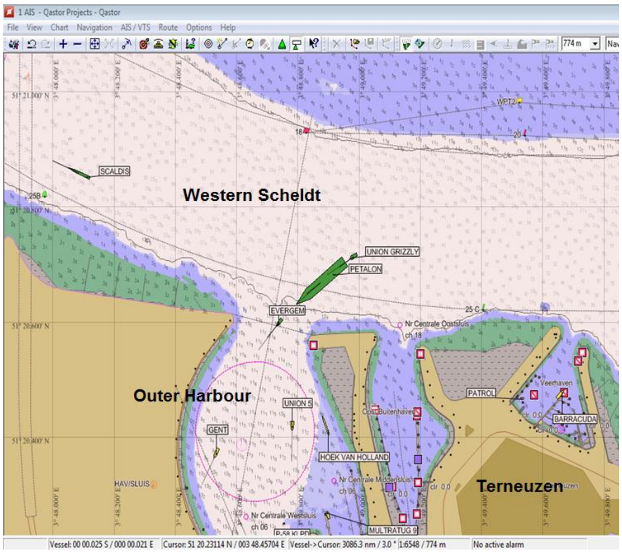


Figure 15: Portable Pilot Unit and Schelde Navigator Marginal Ships with highly accurate Qastor positioning system used by the pilots at Terneuzen

For Kamsarmax vessels passing the West lock it is compulsory to:

- Have two pilots on board, using a dedicated portable pilot unit, the 'Schelde Navigator for Marginal Ships' (SNMS);
- Be assisted by four tugboats (Figure 15), one centre lead forward (e.g. Evergem 37 ton), one centre lead aft (e.g. Union Grizzly 60 ton), and two pushers at both sides (e.g. Gent and Union 5 respectively 40 and 45 ton); the tug configuration in Figure 15 can modify at the ship's stern with minimum one tug of 39 ton for a dead slow vessel's speed of less than 5 knots and a maximum wind force of 5 Bft and at least two tugs of each 30 ton or one tug of 60 ton for a wind force of 6 Bft regardless of the dead slow speed.
- Allow a maximum wind force to the lock in loaded condition of 6 Bft and in (heavy) ballast condition of 5 Bft;
- Have a minimum required visibility of 1000 m.

When the vessel has entered the Outer Harbour the speed is reduced to approximately 4 knots and the vessel will be positioned in the centreline of the lock (Figure 16, survey on the Koutalianos). The tugs assisting at port / starboard side will be positioned at one third of the ship length nearby the bow.

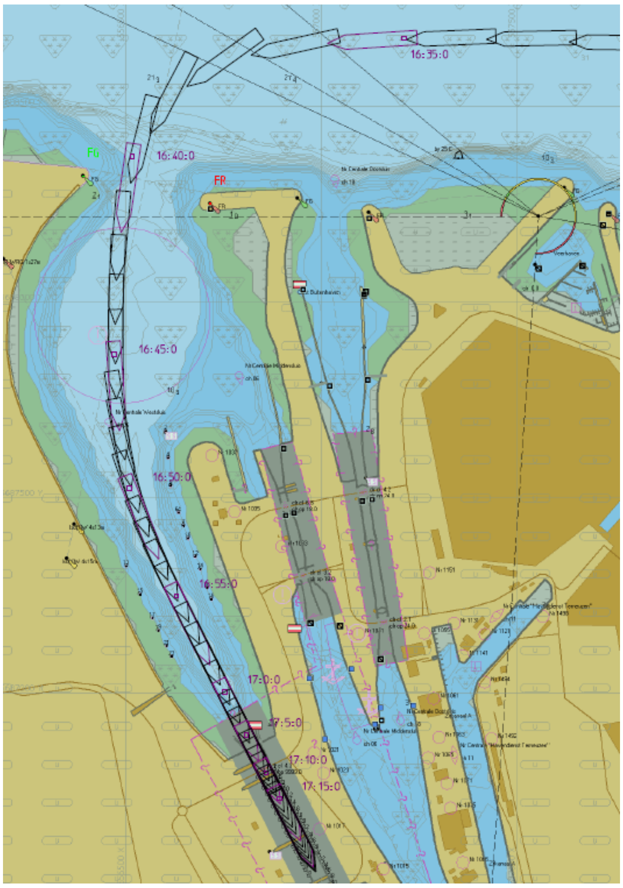


Figure 16: Arrival of the Kamsarmax vessel Koutalianos in the West lock in Terneuzen on March 30th 2010 (tugs not presented)

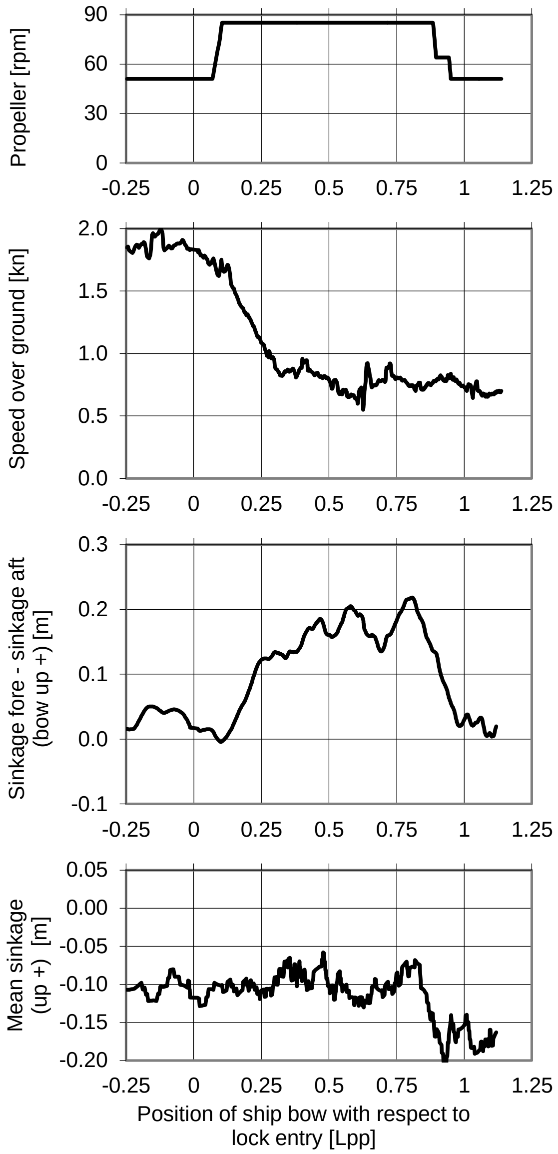


Figure 17: Propeller rpm, speed over ground, trim and mean sinkage measured on inbound Koutalianos during the survey in the West lock in Terneuzen [2]

The speed will be further reduced to approximately 1.5 knots (Figure 17). The engine will be at Dead Slow Ahead approaching the lock. As the bow enters the lock the speed will drop significantly and the engine will be ordered Half Ahead. This so-called plunger or piston effect causes a significant reduction of the speed and requires more rpm to enter the lock. The tugs on port/starboard side will assist to manoeuvre the vessel in the centreline of the lock. The margin for entering the lock is approximately 0.5 m between the fenders at both sides. Entering the lock halfway the speed will increase again, the engine will be ordered Dead Slow Ahead and the aft tugboat will start to control the vessel's speed in order to stop the vessel at the right position.

A full description of the manoeuvre executed by the Koutalianos from river to West lock can be found in [2].

Entrance canal side: (Figure 18) The entrance from the canal side only differs from the entrance from the river side in the decreased (and rather negligible) piston effect for the heavy ballasted Kamsarmax vessel. Due to the increased wind effect on a ballasted ship the maximum wind force is also restricted to 5 Beaufort.

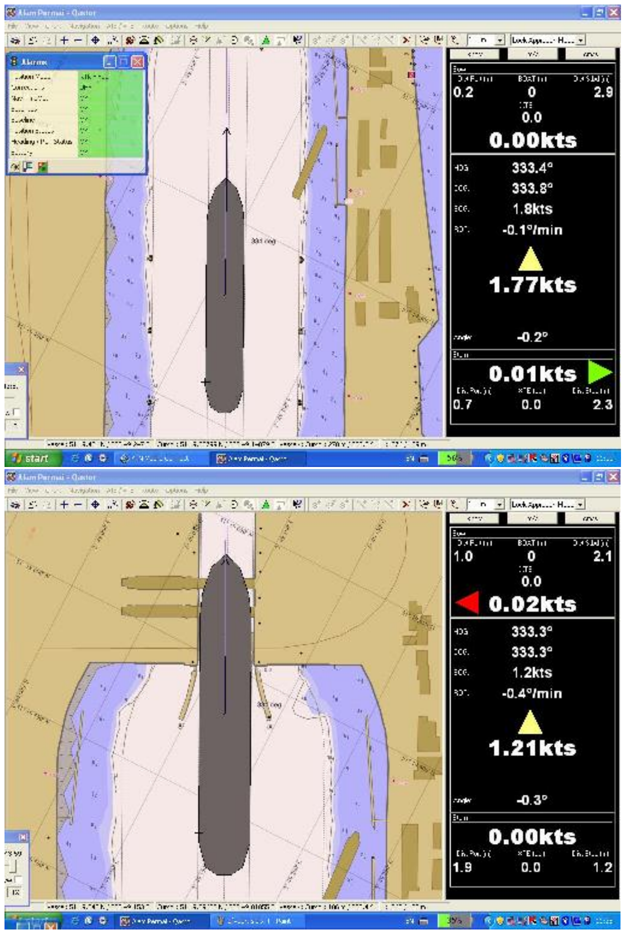


Figure 18: Full SNMS for the Alam Permai at ballast condition during the entrance of the West lock from the canal side

2.2 (b) Berendrecht lock in Antwerp

The port of Antwerp has actually six locks leading to the docks on the right and left bank (Figure 19). Four of them are used by seagoing vessels, while the two others are mainly for barges and inland ships and occasionally used by seagoing vessels when another lock is out of use. A new lock is under construction at the end of the tidal Deurganck dock to give a second entrance (actually only Kallo lock) to the Waasland harbour on the left bank. The Berendrecht lock is the largest of the lock complexes in the port and in length and width still the largest in the world.

Flemish and Dutch (river) pilots boards a vessel at Flushing roads, 36 miles away from the nearest lock. At the time of boarding in Flushing, generally the assigned lock for the vessel is not known. The Antwerp Port

Coordinator is monitoring the incoming vessels and assigns them a lock based on various criteria such as size, draft, destination in the docks and availability of the locks.

While underway, the pilot is informed about the assigned lock, his turn into the lock, the mooring side and the approximate time the lock will be ready. This planning is affecting the sailing on the river taking into account for example the reduced ship's speed for matching the arrival at and the availability of the lock.

Slowing down means that wind and current have more impact on the vessel's track and implicates that other ships destined for a lock upwards the river sometimes have to overtake.

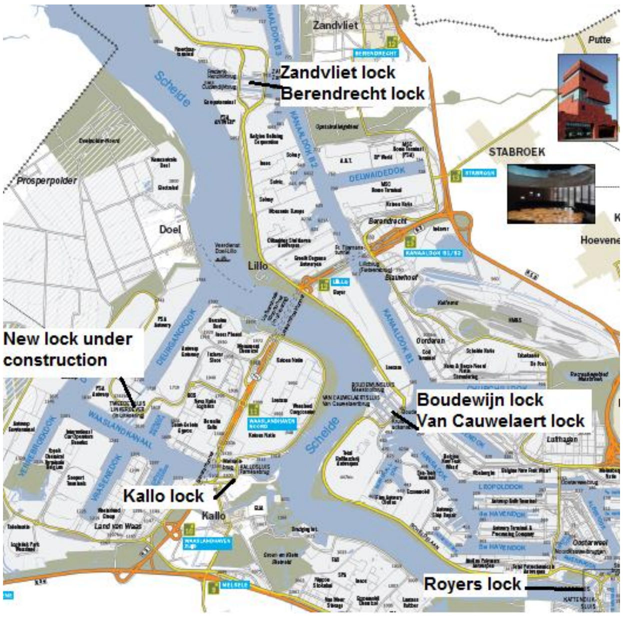


Figure 19: Lock complexes at the port of Antwerp (Belgium) with the Berendrecht lock the largest lock anno 2013 [8]

With the enlargement of ship sizes (length, beam as well as draft) in the last decade (growing to ULCS with lengths up to 400 m) overtaking or being overtaken must be closely controlled as only certain spots on the river admit this time-consuming and difficult manoeuvre which has been examined by real-time simulation tests.

Construction (Figure 20)

Figure 20: Berendrecht - Zandvliet lock complex

The Berendrecht lock, built in 1989, connects the Western Scheldt (river side) with the Canal dock B2 (dock side) and has a length of 500 m, a width of 68 m and a depth of -13.58 m TAW (Tweede Algemene Waterpassing, a reference height for infrastructure in Belgium) or -12.89 LAT which means that deep drafted ships can only enter thanks to the tidal level. The new lock at the end of Deurganckdock will have the same horizontal dimensions but a depth of -17.80 m TAW. From the river side the lock is mostly approached from the north while turning from the river with tidal current to the entrance of the lock. From the dock side with a mean canal level of 4.25 m TAW (depth at lock sill is thus 17.83 m) a turning manoeuvre from and to the canal dock B2 (south of the lock) is required so that at both sides the approach area is only over a short distance in line with the lock axis requiring important tug assistance. The corners of the Berendrecht lock are equipped with wheel fenders to protect the lock construction and the ship's hull during contact.

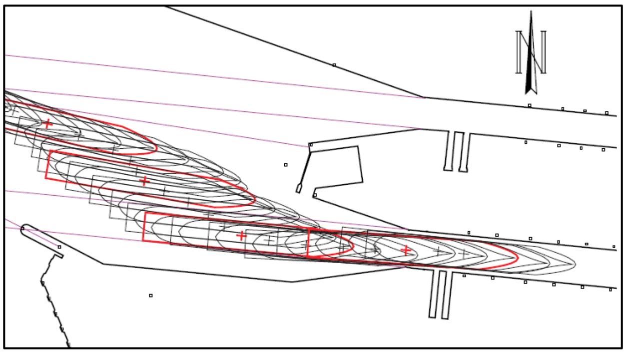


Figure 21: Entrance of the Berendrecht lock from the river side during a simulation run with a 380 m containership (beam 51.6 m, draft 13.1 m) at N 6 Bft and one 45 ton fore tug and two 60 ton aft tugs

Figure 22: Entrance of a 366 m Ultra Large Container Ship in the Berendrecht lock at the port of Antwerp

Manoeuvre

<u>Entrance river side</u> (Figure 21 and 22): Although a planning is made, the availability of the lock on arrival can be uncertain. Mostly ships are scheduled to depart

from the same lock the arriving vessel is heading to. Hence, the time the lock will be ready merely depends on the time the departing ships are moored into the lock. Delay of the departing vessels means waiting in front of the lock and finding a place where the vessel can be kept in position, countering wind and current and sparing enough room for the departing vessels to safely leave the lock. Sometimes tugs are scheduled to take out the departing vessels first and later serve the arriving vessel.

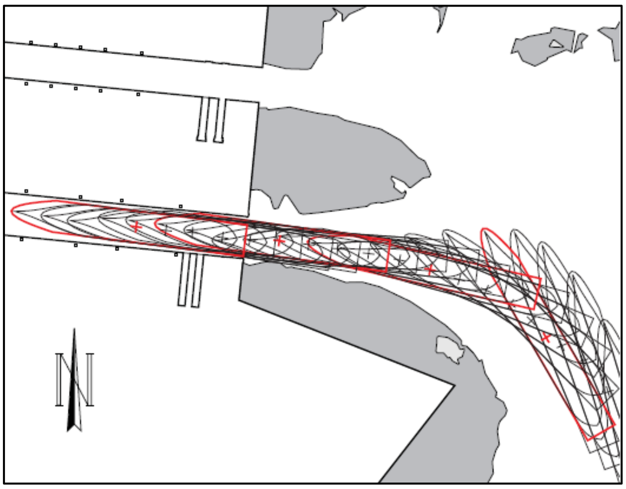


Figure 23: Entrance of the Berendrecht lock from the dock side during a simulation run with a 380 m containership (beam 51.6 m, draft 13.1 m) at NE 6 Bft and three 55 ton tugs

Although a distinction can generally be made for a lock entrance during flood or ebb tide, no single lock has the same approach pattern. When the ULCS started to call to Antwerp (more specific the Berendrecht lock) the pilotage decided not only to make a tidal window to cope with the draft of the vessel but also a current window was determined to avoid a lock entrance at strong ebb tides. Thanks to the learning process on the simulator these ULCS are actually entering Berendrecht lock at any tide, with two pilots on board for ships with length up to 300 m.
For the ULCS with large lateral windage area the maximum wind condition had to be reduced. The wind limitations for ULCS can be summarised as:

- for a ship length from 300 to 340 m no limitations;
- for a ship length from 340 to 360 m, maximum 7 Bft;
- for a ship length larger than 360 m, maximum 5 Bft although for the Deurganck dock (no lock entrance) a higher wind force of 6 Bft can be maintained for an inbound and 7 Bft for an outbound manoeuvre.

Although ahead or following wind directions during a lock approach are more favourable, the orientation of the approach channel at both sides of the Berendrecht lock does not accept higher values for the maximum wind force.

The tug assistance for a manoeuvre with a 366 m container ship to the Berendrecht lock is composed of:

- Inbound: two 60 ton tugs aft and one 45 or 60 ton fore; for strong winds from south or north the tug assistance can be increased with an additional 45 or 60 ton fore; the tugs pull with the aft tugs fastened at starboard or port side while the fore tug uses the centre lead hawser.
- Outbound: one 60 ton tug center lead aft and one 45 or 60 ton tug center lead fore. At minimal wind force the fore tug can be omitted in favour of the bow thruster.

The bollard pull of the tug fleet in the Flemish harbours is increasing with some 80 ton tugs available so that the tug configuration nowadays changes compared to the configuration used during the simulation studies in Figure 21 and Figure 23. The tugs start their fastening procedure about two miles from the Berendrecht lock.

<u>Entrance dock side</u> (Figure 23): The approach of the Berendrecht lock from the dock side is planned in the same way and suffers from the same problems in manoeuvring space (except the tidal current) as at the river side. After the use of Full SNMS by the river pilots operating on the Western Scheldt to the port of Antwerp the dock pilots also introduced the personal pilot units as Full SNMS to ensure safe manoeuvring.

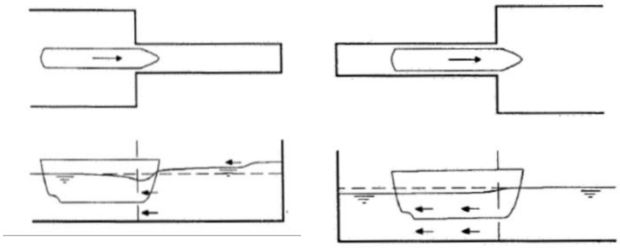
At the dock side an ULCS has to approach right in front of the lock after turning from the canal B2 dock, as it is impossible for such ship to enter the lock from another angle. If these ships encounter strong winds (more than 5 Bft), the ship's bow has to be kept to the wind in order to avoid damages. In case of southern or northern winds exceed 6 Bft, entering the lock with an ULCS should be avoided, because of the tugs (especially the fore tug) not being able to pull full power in the approach of and in the lock itself.
When leaving the lock to the docks the vessel speed must be strictly controlled so that the turning manoeuvre from the lock to the canal B2 dock can be executed safely with enough reserve to other ships in the docks.
At the dock side, the tug configuration consists of Voith-Schneider tugs. For ships of 366m and more the use of at least two tugs is compulsory. In most cases two tugs with a bollard pull of 50 tons will be provided, if required this number will be increased to three or four.

3. LOCK EFFECTS DESCRIPTION

The ship-lock combinations described in chapter 2 are characterised by a large blockage factor, i.e. the ratio of the ship's section to the lock section, giving an increased effect of the hydrodynamic forces while approaching and leaving the lock. Although the lock effects are specific for each lock, a description will be based on the practical information from the four geographically spread locks in Belgium, The Netherlands, France and Panama.

3.1 TRANSLATION WAVES

The translation waves are the waves generated in the lock and the approach channel due to the forward ship motion while entering or leaving the lock (Figure 24). The water volume taken by the ship must be replaced inside the lock and the approach causing a wave profile running with the ship and an increased return flow alongside the ship's sides and thus an increased ship's resistance. The wave system and the return flow also affect the inflow to the propeller and the rudder which can lead to vibrations of the propeller if the clearance in the lock is limited (e.g. Charles de Gaulle lock in Dunkirk). The translation waves and return flow depend among others on the hull form, the blockage, the approach channel section (symmetry) and the ship's speed. [5]



Entering a lock — Leaving a lock

Figure 24: Translation waves in different situations [4]

The effect of the translation waves is clearly seen during all described manoeuvres in the different locks on the speed fall while entering the lock and must be tackled by decreasing the ship's speed in advance (1 to 3 knots) combined, if necessary, with an increased propeller rpm to maintain the desired entrance speed. Additionally vertical motions are induced: when a bulk carrier enters the lock chamber in the West lock in Terneuzen or the Charles de Gaulle lock in Dunkirk, the bow is pushed upwards, but gradually the ship will undergo a general sinkage (Figure 17) [1], [2], [5]. Touching the lock sill is avoided by guaranteeing a minimum UKC at the lowest tidal level of at least 1.0 m (except Pedro Miguel locks in Panama, where only 0.5 m is required) for the drafts in the respective locks which vary between 12.0 (Panama) and 15.6 m (Antwerp).

3.2 BANK AND CUSHION EFFECTS

Due to the low ship's speeds while approaching and leaving locks with an asymmetric approach channel at starboard and port side of the ship, the bank effects acting on the ship will generally be overcome, but take a major part in the difficulty of an approach when a more closed approach wall (Panama Canal and the Charles de Gaulle lock) influences the hydrodynamic pressure field around the ship's hull drastically. Bank effects are generally characterised by a lateral force towards the bank or vertical wall and a bow-out yawing moment. In close proximity of a bank an additional hydrodynamic effect, called cushion effect, occurs due to the incompressibility of the surrounding water forming a cushion between the physical limit of the lock approach area and the ship's side.

The ship's motion alongside the approach wall of the Charles de Gaulle lock induced despite of the northwesterly wind (with a turning moment to starboard), a turning moment to port while entering the lock with the bow (compare the two pictures taken at 18h46 and 18h47 on Figure 25).

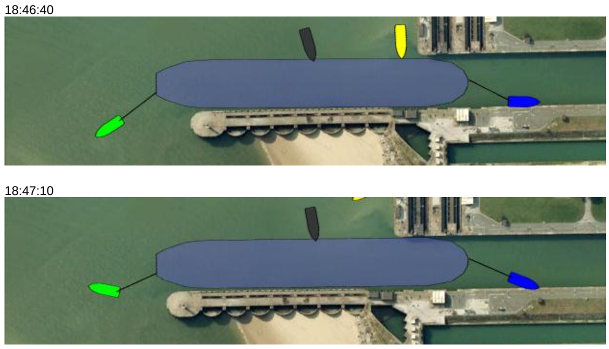


Figure 25: Entrance of the Cape Aster in the Charles de Gaulle l5ck alongside the approach wall

The influence of different types of approach walls has been examined by Flanders Hydraulics Research (FHR, [1], [6]) for the new locks in Panama during the conceptual design phase, showing the influence on lateral force and yawing moment in Figure 26 (ship entering the lock in the axis line). A comparison is made between a completely symmetric situation without approach wall; a solid, closed wall; a permeable wall consisting of a surface-piercing beam supported by elongated elements; and finally a series of piles, referred to as 'invisible wall'. It is observed that even the configuration without approach wall is not free of asymmetry, because of the turning direction of the propeller, and the fact that in these confined waters the slightest asymmetry is amplified. A solid structure causes an effect similar to a bank or quay wall: attraction to the wall combined with a bow-out moment. The effect of a permeable wall is completely different: the lateral force tends to push the ship away from the structure (but only when the ship is already entering the lock chamber, not during the actual approach), while the yawing moment is fluctuating, but takes much lower values. The 'invisible' wall hardly affects the approaching vessel.

It has been clear that the following parameters have a major influence on the accessibility of locks for specific ships:

- the approach wall;
- the underkeel clearance;
- the eccentricity;
- the ship type;
- the type of manoeuvre.

Although the absence of an approach wall on the dock side of the Charles de Gaulle lock and of the related hydrodynamic effects, the Dunkirk pilots prefer the

availability of an approach wall as this fixed alignment helps in counteracting the wind force by using the appropriate tug assistance. The approach wall exact position, alignment and construction type is nevertheless important as the desired increase of the maximum ship's beam from 45 m to 47 m in the Charles de Gaulle lock could be complicated by the presence of the approach wall and the fender constructions. The new locks in Panama will also be equipped with approach walls of which the design is under investigation.
Comparing the tug configuration at the sea and dock side of the Charles de Gaulle lock the presence of the approach wall requires another configuration for the assisting tugs, the pushers in particular.

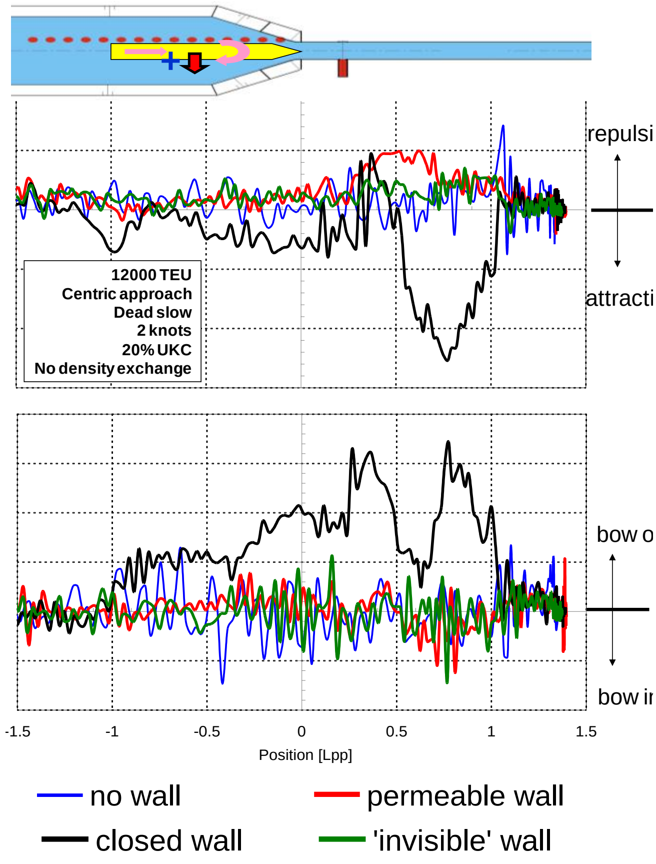


Figure 26: Lateral force (above) and yawing moment (below) on a self-propelled guided ship model during lock approach: effect of approach wall layout. Zero position is sketched above, figure taken from [1]

3.3 DENSITY CURRENTS

Density currents and their effect on the lock manoeuvres are most important for the seaside entrances of the locks in Panama, Dunkerque and Terneuzen (Figure 27).

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. An example is given in Figure 27 for the West lock in Terneuzen where the density exchange is minimised by the use of an air bubble curtain resulting in a combination of a density flow (mainly at the river side of the lock) and a turbulent flow caused by the air bubble curtain (available at both sides of the lock). Due to the effectiveness of this curtain in hindering the salt intrusion into the Canal Ghent-Terneuzen, the disturbing effect of the air bubble curtain is compensated by the use of floating fenders all along the lock walls.

Figure 27: West lock in Terneuzen: density currents modifying the lock manoeuvres

In order to investigate the effects of discharge and gate opening, a research was executed at FHR with a model scale lock equipped with a gate that could be opened according to a realistic opening law, and spilling outlets constructed in front of the lock gate (Figure 28) [1] [7].
While brackish water was used in the approach channel (density: 1012 kg/m³) during the entire experimental program, the lock was filled with fresh water during density exchange current tests. The fresh water was dyed so that its flow is visible during recording. During these tests the ship could be waiting along the approach wall (static test) or already be approaching the lock (dynamic test, with as significant parameter the waiting time between the opening of the gates and the entrance of the vessel). Reflecting floats were present on the water allowing to assess the magnitude and direction of the surface flow velocity.

A density current flow during the opening of the lock gate or spilling causes longitudinal and lateral forces and a yawing moment of which the lateral force can take extremely high values in the presence of a closed approach wall. Due to the unpredictable and mainly asymmetrical nature of the density flow (even for a symmetric approach channel), which may affect approaching vessels for a considerable time, e.g. 20 minutes and more for a large sea lock, the pilots and skippers must be aware of the effect and anticipate in using the controls and tug assistance.

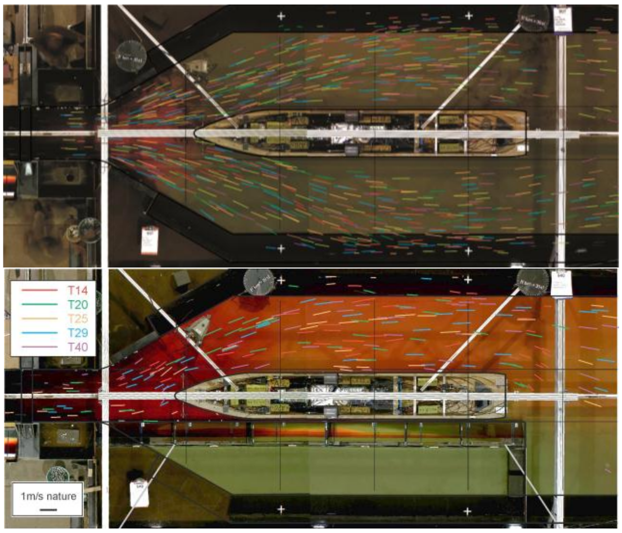


Figure 28: Effect of approach structure configuration on surface current pattern due to density exchange flow: no wall (above) – closed wall (below) [1]

3.4 FENDERING

Different types of fenders are used in the respective lock complexes and are described in chapter 2.

The West lock differ from the other three locks (at the Panama Canal, the Charles de Gaulle lock and the Berendrecht lock) due to the use of floating fenders alongside the total length of the lock walls. The use of these floating fenders is mainly attributed to a fluent entrance and exit of the ships in the lock with a diverse fleet of maritime and inland vessels operating in disturbing density and air bubble flows.

All other locks are characterised by the use of wheel fenders or other fixed fenders to protect the lock corners and for the Charles de Gaulle lock tyres are present all along the lock walls at intermediate distances to prevent from direct contact between the ship's hull and the concrete walls. Although fenders are available, most of the time contact between the vessels and the fenders is avoided as each contact induces damage (from painting to structural damage to the fender or the ship's hull). The contact forces are function of the vessel's longitudinal and lateral approach speed, the contact area and ship's and fender's structural characteristics.

4. CONCLUSIONS

The aim of the paper is to give some insight in lock operations for maritime vessels in Panama, Dunkirk, Terneuzen and Antwerp from a pilot's point of view. The lock and approach channel are described for each lock complex and the manoeuvres executed by the different pilotages. A comparison is difficult to make as some operational parameters (such as the locomotives at the Panama locks) are specific but it could be interesting to make some summarising tables. In Table 2 the lock length is based on the maximum length between the outer lock gates. The depth is rather a minimum (Panama: lock sill of the Pedro Miguel locks, West lock and Berendrecht lock: 1 m UKC) or an averaged value according to the tidal level (Dunkirk) at the sea side. The ship dimensions are actual maximum sizes of the vessels in the lock.

Table 2: Lock and ship dimensions

	Length (m)	Width (m)	Depth/draft (m)
Panama locks			
Lock	320.12	33.54	12.54
Ship 1	289.6	32.31	12.04
Ship 2	294.2	32.31	12.04
Dunkirk: Charles de Gaulle lock			
Lock	364.36	50	17
Ship	292	45.05	14.35
Terneuzen: West lock			
Lock	378.5	40	13.5
Ship 1	265	34	12.5
Ship 2	230	37	12.5
Antwerp: Berendrecht lock			
Lock	500	68	16.6
Ship	366	51.2	15.6

In Table 3 ratios of the lock-ship dimensions are calculated for each lock. The smallest ratios are found for the existing Panama locks where the use of the locomotives accepts a smallest width and depth/draft clearance of 4% of the ship's dimensions. Also in the longitudinal direction a clearance of less than 11% is used between the ship and the lock doors. For an accessibility of the locks with tug assistance the length clearance will be larger than with locomotives but a 25% clearance as in the Charles de Gaulle lock in Dunkirk is possible and lower values are also in use.

The width clearances are, besides the small values for the existing locks in Panama, between 8 and 11% for the wide beam ships passing the West lock and Charles de Gaulle lock while more general values are found for the smaller ships in width in the West lock and for the actual ships in the 2013 still largest lock of the world, i.e. Berendrecht lock. The width clearances increase to 18 and 33%. For all locks the depth/draft clearances or underkeel clearances are small with values of 6 and 8% in the Berendrecht and West lock and higher values

(although lower values occur with lowering tide) of 18% for the Charles de Gaulle lock.
For all lock operations with wide beam ships compared to the lock dimensions two pilots are onboard and work together in communicating relevant information or if available using a full SNMS or pilot unit for exact positioning and controlling the speed during lock approach.

Table 3: Lock and ship dimension ratios

	Length ratio	Width/ Beam	Depth/ draft	UKC
	(-)	(-)	(-)	(m)
Panama locks				
Lock-ship 1	1.11	1.04	1.04	0.5
Lock-ship 2	1.09	1.04	1.04	0.5
Dunkirk: Charles de Gaulle lock				
Lock-ship	1.25	1.11	1.18	2.65
Terneuzen: West lock				
Lock-ship 1	1.43	1.18	1.08	1.0
Lock-ship 2	1.65	1.08	1.08	1.0
Antwerp: Berendrecht lock				
Lock-ship	1.37	1.33	1.06	1.0

The number of tugs is smallest (two) for the existing locks in Panama (where assistance is also provided by locomotives) and grow to four for the West lock and Charles de Gaulle lock. The presence of an approach wall requires another tug configuration and has probably also an influence on the maximum acceptable wind forces during lock approach. In the Charles de Gaulle lock the accessibility of the lock is guaranteed up to 8 and 9 Beaufort while at the West lock and the Berendrecht lock for wide beam ships the maximum wind force is restricted depending on the loading condition to 5 or 6 Beaufort.

All considered lock manoeuvres are characterised by external hydrodynamic (ship-bank/approach wall interaction, (density) current, shallow water) and aerodynamic effects (wind-sheltering) of which some effects induced by translation waves, density flow and asymmetrical approach are described more in detail in the paper. The advantage of a fixed approach wall in accepting higher wind forces during approach is counteracted by additional hydrodynamic lateral force and yawing moment which must be overcome by the ship's controls or tug assistance. So far all these effects are tackled by the pilots and did not restrict them in accepting new challenges in lock approach with larger and ever growing ships. Although this is not described in this paper, the use of simulation tools and thus a realistic description and prediction of all involved external effects are required to set and check the limits in accessibility for each lock. The new locks being built in Panama and the modification of the lock operation from locomotives to tugs contain many new challenges which must be examined in detail although as is shown in this paper lock operations with only tugs are, despite their diversity in local customs, common practice worldwide.

5. REFERENCES

1. VANTORRE, M., and RICHTER, J., ‘Maneuverability in lock access channels, “What's new in the design of navigation locks?”’, *2nd International Workshop, PIANC*, New Orleans, 2011.

2. VERWILLIGEN, J., RICHTER, J., REDDY, D., VANTORRE, M., and ELOOT, K., ‘Analysis of full ship types in high-blockage lock configurations’, *Proceedings MARSIM*, Singapore, 2012.

3. http://upload.wikimedia.org/wikipedia/commons/9/91/Panama_Canal_Map_EN.png

4. VRIJBURCHT, A. ‘Vertical motions of ships sailing into or out of locks and the related water motions’, *Delft Hydraulics Publication 461*, 1991

5. VERGOTE, T., ELOOT, K., VANTORRE, M. and VERWILLIGEN, J., ‘Hydrodynamics of a ship while entering a lock’, *Proceedings International Conference on Ship Manoeuvring in Shallow and Confined Water*, Ghent, 2013.

6. DELEFORTRIE, G., WILLEMS, M., VANTORRE, M.; LAFORCE, E., ‘Behavior of post panamax vessels in the Third Set of Panama locks’, *International Conference on Marine Simulation and Ship Maneuverability (MARSIM 2009)*, Panama, 2009.

7. DELEFORTRIE, G., WILLEMS, M., LAFORCE, E., VANTORRE, M., DE MULDER, T., DE REGGE, J., WONG, J., ‘Tank test of vessel entry and exit for third set of Panama locks’, *The Proceedings of the International Navigation Seminar following PIANC AGA*, pp. 517-530, 2008.

8. Worldwide web: http://www.portofantwerp.com/sites/portofantwerp/files/POA-0841-Havenkaart_Kaart.pdf

6. AUTHORS BIOGRAPHY

Katrien Eloot holds the current position of senior expert at Flanders Hydraulics Research and guest professor at Ghent University. She is responsible for simulation studies and fundamental research related to ship hydrodynamics and especially manoeuvring in shallow and confined water.

Marc Vantorre, naval architect, is full senior professor of marine hydrodynamics and head of the Maritime Technology Division at Ghent University, Belgium. His research focuses on ship behaviour in shallow and confined waters, mainly in close co-operation with Flanders Hydraulics Research in Antwerp. He is member of PIANC Working Groups and former member of the ITTC Manoeuvring Committee.

Jeroen Verwilligen holds the current position of nautical researcher at Flanders Hydraulics Research. He is experienced with simulation studies and full-scale measurements on several vessels to Flemish Harbours. He is responsible for initiating CFD research at FHR.

Dirk Bus is river pilot (operating on the Western Scheldt) of the Flemish Pilotage in Flanders, Belgium.

Rudi Cleeren is river pilot (operating on the Western Scheldt) of the Flemish Pilotage in Flanders, Belgium.

Erwin Gheyle is canal pilot (operating on the entrance to the Terneuzen complex and the canal Ghent-Terneuzen) of the Flemish Pilotage in Flanders, Belgium.

Eric Vèche is pilot at the Station de Pilotage de Dunkirk, France.

Eugene Heugen is pilot at the Dutch Pilotage, the Netherlands.

Jos van Drongelen is pilot at the Dutch Pilotage, the Netherlands.

Rainiero Salas is Panama Canal Pilot, Panama.

Ronny Detienne is director of the pilotage CVBA BRABO, operating in the docks of the Port of Antwerp, Belgium.