Physical Model for the Filling and Emptying System of the Third Set of Panama locks

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ABSTRACT

The Panama Canal Authority (ACP) extension plan includes the construction of a third lane with new locks at both sides of the Canal. The design ship is a so-called Post-Panamax 12 000 TEU container carrier.
In order to maximize the vessel throughput of the new locks, and at the same time, to safeguard the vessel during the lockage, many numerical studies and two physical model studies have been carried out.
In a first phase, the Filling and Emptying (F/E) system of the locks has been pre-optimized with numerical models (1D, 2D and 3D models). In a second phase, a physical model study has been carried out at Compagnie Nationale du Rhône Hydraulic Laboratory, Lyon, France, operating as member of the consortium CPP (Technum – Tractebel – Coyne-et-Bellier – CNR).
The F/E system is a “double culvert” sidewall and ports system composed of: a main culvert connected by a central flow divider to two secondary culverts in the middle section of the lock chamber. Each secondary culvert is equipped with 10 ports which feed the lock over 80% of its length. In order to limit water consumption, each lock is connected to 3 Water Saving Basins (WSB).
The scale model (1:30) represents two locks chambers, 3 WSB associated with the lower chamber, a fore and a tail bay. The Post-Panamax container ship vessel is also modelled.
A special emphasis is put on the hawser forces measurements and in the definition of a threshold value as no standard values presently exists for Post-Panamax locks given such operating conditions (use of water saving basins or not, hydraulic heads ranging from 3.5 m to 20 m).

The experimental setup and the scenarios of tests are described and an overview of the main results (F/E times, times series of water levels with and without ship in the lock chamber, time series of hydraulic efforts on the ship hull) are given.

INTRODUCTION

The Panama Canal Third Set of Locks, the new approach lanes and the widened and deepened Canal will allow the transit of Post-Panamax size vessels and will significantly increase the capacity of the Canal. Triple lift type locks with double sets of rolling gates have been designed by the Consortium CPP and selected for construction. Each new lock chamber will have a length varying between 427m and 488m, depending on the gate operation. The width of each chamber was set at 55m. The design ship is a so-called Post-Panamax 12000 TEU container carrier (length over all 366m, beam 48.8m, draft 15.2m; block coefficient 0.7).
The Filling & Emptying system (F/E) will be able to operate with and without using the Water Saving Basins (WSB). When the WSB are not used, the maximum hydraulic head can reach 20 m in extreme operating conditions.

One of CPP's task orders under ACP contract "*Engineering Services for Additional Studies and Technical Assistance for New Locks"* consists of construction and operation of a physical model to validate the F/E system that was selected and pre-optimized during several numerical model studies.
The validation is based on the two main issues which are **maximizing the vessel throughput** (capacity) and **limiting hawser forces** for a given positioning system to an acceptable maximum threshold value in normal operating conditions.

The main target design criteria for the F/E system were initially set at:

- Maximum total chamber F/E time without using the WSB : 10 minutes
- Maximum total chamber F/E time with WSB: 17 minutes (5 minutes for lake-lock, lock-lock or lock-ocean operation, and 4 minutes for each WSB-lock or lock-WSB operations).
- Limitation of hawser forces under acceptable values
- Limitation of average water velocities in culverts and ports to 7 m/s for all F/E operating scenarios.

HAWSER FORCES CRITERIA

It is rather difficult to set a maximum hawser force criteria since no standard values presently exist for Post-Panamax locks, subject to specific operating conditions (water saving basins operated or not, hydraulic heads ranging from 3.5 m to 20 m). An authority- based design criteria methodology (relying on threshold values suggested by international or national technical bodies) is not possible.
In addition, the wording "hawser forces" can be attributed multiple definitions which need to be specified in order to define a threshold value. The following definitions have to be distinguished:

- Forces exerted on the mooring lines: these are actually the reaction forces which are needed to sustain the ship in a given position in the lock chamber. These forces are not measured on the physical model since it would require modelling the real configuration of the mooring lines system (which is considered as not feasible).

- Hydrodynamic forces exerted on the ship's hull: resulting from all the water movements exerted on the ship's hull (pressure force due to the difference of water level, drag forces issued from the flow around the hull, turbulence force due to the energy dissipation in the lock chamber). These are the forces measured on the physical model.

- Hydrostatic forces exerted on the ship's hull: resulting from the hydrostatic pressure distribution along the ship's hull (i.e. the water level differences along the ship's hull). These forces are the ones predicted by the 2D-Delft numerical model (solving the Shallow Water Equations in the lock chamber) during the previous studies. The numerical calculations give the longitudinal and the transversal component of the hydrostatic forces, being only one component (generally the main) of the hydrodynamic forces.

- Forces deduced from the water level slopes: can be used as an approximate estimate of the hydrostatic forces exerted on the ship's hull, with two components: a longitudinal one and a transversal one. They allow to carry out rapid and easy evaluation of the "hawser forces" in situ since it is far easier to measure water surface slopes in the lock chamber than reactions forces in the mooring lines. The water slopes measured on the physical model will be compared to the measured hydrodynamic forces in order to determine a relevant correlation between the two parameters.

During the pre-optimization numerical studies, a conservative value of 0.12 ‰ has been adopted as a target value for the longitudinal hydrostatic forces. This value has been further evaluated during the physical model study.

EXPERIMENTAL SETUP

Model scale

The choice of the scale is defined by the Froude law of similarity (i.e. conservation of the ratio between the forces of inertia and gravity in prototype and in the mode). It takes into account the degree of accuracy expected for the results and the size of the elements to be modeled.
However, since the flows in the F/E system are under pressure, one must also check if the state of flow is fully turbulent (Reynolds number > 5000) so that the velocities, flows and, consequently, the F/E times and the forces on the vessel are adequately modeled.
An undersized scale would lead to laminar flows in the model causing higher energy losses and thus providing erroneous results.
The geometric scale (E_G) retained for the model is 1/30th. It leads to the following scales:

- geometrical scale E_G = model scale/prototype scale = 1/30

- velocity scale $E_V = (E_G)^{1/2} = 1/5.47$
- discharge scale $E_Q = (E_G)^{5/2} = 1/4\ 929$
- time scale $E_t = (E_G)^{1/2} = 1/5.47$
- force scale $E_F = (E_G)^3 = 1/27\ 000$

As such, the dimensions of a 460 m long and 55 m wide chamber will be 15.3 m in length and 1.80 m in width on the physical scale model.
A velocity of 7m/s in prototype will coincide with a velocity in the model of 1.3 m/s.
Finally an operation which takes 10 minutes in prototype will be simulated in about 2 minutes on the physical model.

General design

Figure 1 shows an overview of the physical model.

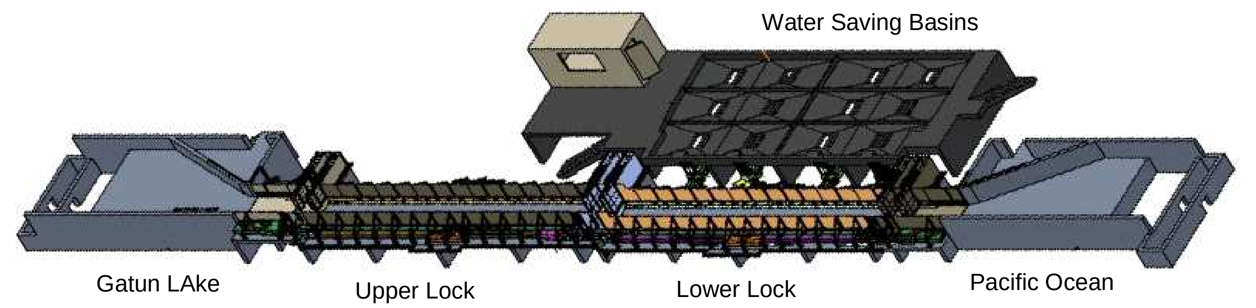

Figure 1: View of the physical scale model.

It is composed of:

- 2 lock chambers,
- 3 WSB connected to the lower lock chamber,
- a 250 m fore bay (Gatun lake side),
- a 250 m tail bay (ocean side).

This “2 chambers & 3 WSB” configuration allows to carry out all the F/E operations, with and without the WSB, and allows to reduce the model construction time and cost.
The 3 water saving basins are built in connection to the lower chamber.
A 12 000 TEU container ship model has been built at scale 1 to 30 in order to perform the force measurements (displacement 160,000 T, block coefficient 0.7).
The ship model is neither equipped with propulsion, nor a rudder since only filling and emptying operations are simulated on the physical model. Tugs are not simulated.

Filling and Emptying system

The Filling and Emptying system to be validated with the physical model has been selected and pre optimized by means of several numerical model studies (1D, 2D and 3D models).
The F/E system is a double culvert sidewall system with central connection to the lock chamber (see Figure 2). The main culvert is connected to a secondary culvert equipped with 20 ports (10 upstream and 10 downstream) at each side of the lock chamber. In

order to limit water consumption, each lock is equipped with three Water Saving Basins (WSB).

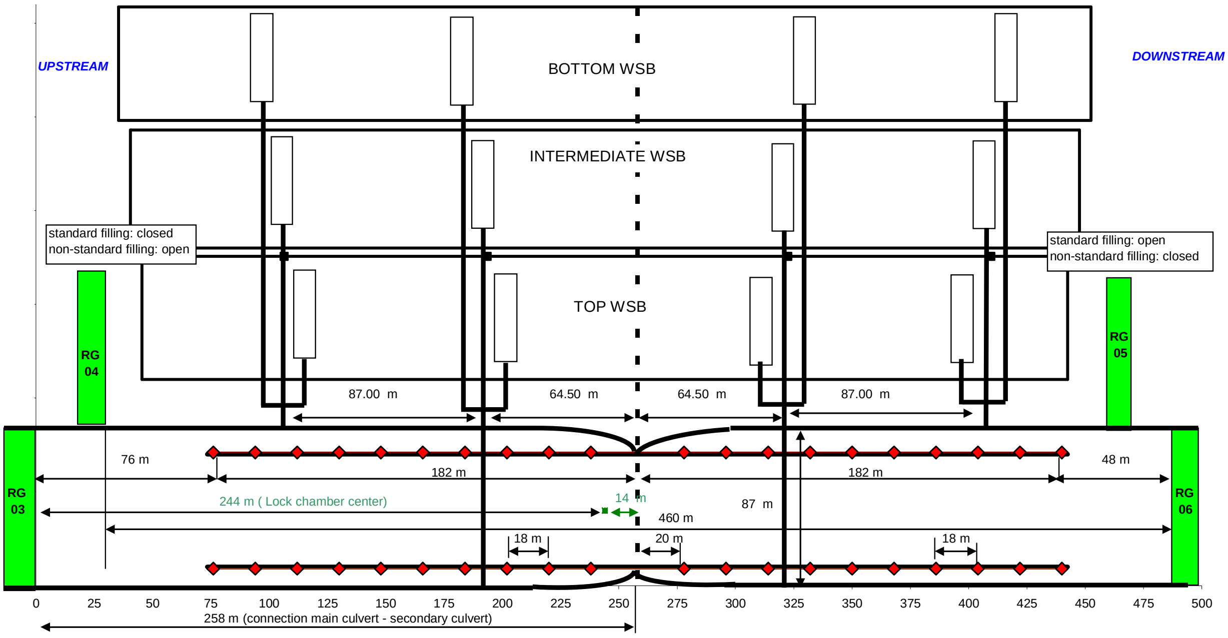

Figure 2: F/E system layout

Due to different operating modes for the rolling gates that need to be considered (standard and non standard cases); several configurations of the sidewall F/E system have been tested by means of 2D numerical models in order to optimize the position of the central connection between the main and secondary culverts and the dimensions, position and spacing of the side ports.

For each considered system the objectives were to:

- minimize hawser forces whatever the gate operation/position,
- minimize the filling and emptying times,
- maintain a symmetry in the connection between the WSB conduits and the main culverts,
- maintain the same culvert length between each WSB valve and the central connection.

Both numerical 2D and 3D studies showed that gate recesses have a noticeable influence on the slope of the water level (and consequently on hawser forces), and need to be taken into account in the models.
Finally, as a consequence of the gate recesses dissymmetry and the different gate operations, the system selected and represented in the physical model is slightly shifted (14m) downward of the geometric center of the lock chamber.

Main manifold features:

Position of the port axis: .... 258 m from the upstream gate (14 m shifted from the centre of the lock chamber)
Number of ports: .... 20 ports per side
Port size:.............................. 2 m x 2 m
Upstream port spacing: .... 18 m
Downstream port spacing: ... 18 m
Port shape: .... rounded corners (entrance)
Total filling length: .... 364 m (79.2 % of the lock chamber length – 460m)

Physical model equipment

The model is equipped with different sensor types to measure:

- the water levels in lock chambers, basins, fore and tail bays;
- the longitudinal and transversal differential water levels (=water slopes) in lock chamber;
- the velocities and flow rate in culverts;
- the pressure in the culverts and downstream of the valve positions;
- the valve opening schedules;
- the longitudinal and transversal forces.

The definition of the F/E operations, the control of the valve schedule and the acquisition of data is done by an application developed with the Labview software. All the data are also visible in real time on multiple screens in the control and command room.

Focus on the measurement equipment for hawser forces analysis

The model is equipped with 8 differential sensors for the measurement of the longitudinal and transversal water slopes in the lock chambers.
The longitudinal and transversal forces are measured by means of 3 dynamometers: 2 for the transversal forces, one at bow and one at stern and 1 for the longitudinal forces at stern (see Figure 3). The ship is guided by vertical tubes going through the ship's hull and allowing the vertical translation of the ship, together with the pitch and roll motions. All the hydrodynamic forces applied on the ship hull are completely transferred to the forces measurement system.

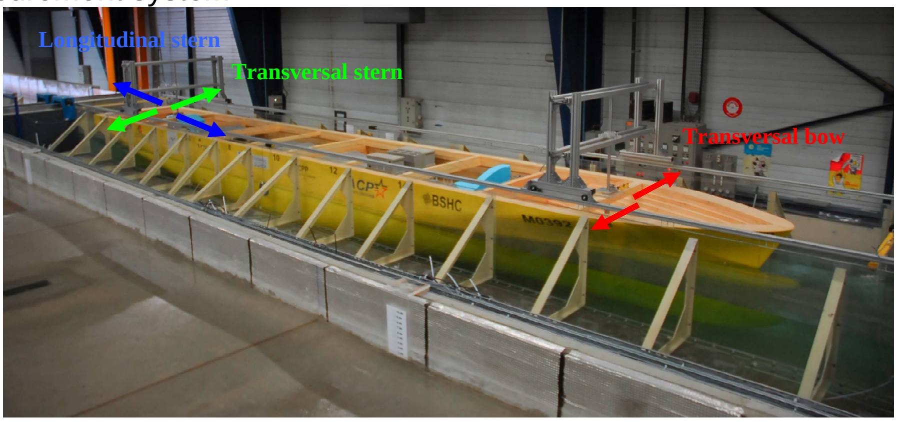

Figure 3: Post-Panamax and forces measurement system

Free ship motion measurements

In addition to the forces measurements, F/E tests have been carried out with a 3D optical tracking system, the ship being totally free in the lock chamber.

This technology allows determining the six degrees of freedom at given points of the vessel (see Figure 4)

- 3 translational motions: surge, sway and heave;
- 3 rotational motions: roll, pitch and yaw.

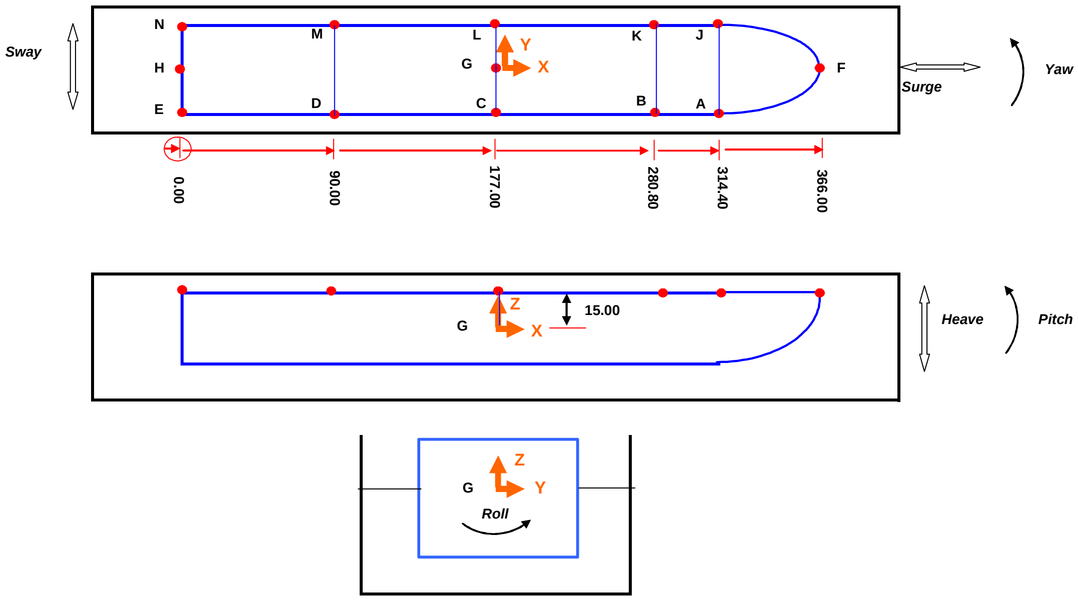

Figure 4

One objective is to calculate accelerations (longitudinal, transversal and vertical) of the vessel during F/E operations for the given points. These values are deduced by differentiating two times the displacement function.

On this basis, and considering the relation between acceleration and forces (F=mA), one can calculate at each time, the equivalent force needed to keep the vessel in position (at any point of the vessel) at every moment during the F/E operation.

NUMERICAL OPTIMIZATION OF F/E SYSTEM COMPONENTS

In order to save time during the test phase, numerical pre-optimization of some parts of the F/E system has been undertaken in overlap with the physical model conception phase.

This study has been carried out with Fluent, which is a 3D CFD code. Following components have been studied:

- the WSB intakes;
- the connection between the WSB conduit and the main culvert;
- the converging shape of the WSB conduit at the downstream side of the valves;
- the lake intakes;
- the ocean outlets.

PHYSICAL MODEL TEST SCENARIOS

Tests in steady flow conditions

The tests in steady flow condition were carried out in order to measure the flow distribution in the ports and consequently to determine the efficiency of the central flow divider (i.e. to verify whether an equal flow distribution is reached between the upstream and downstream part of the secondary culverts).

The measurements are carried out setting constant upper and lower water levels, and constant valve opening ratio during the entire test duration. Consequently, the flow rates in culverts and ports are also constant and are easier to measure. Three cases of discharges in the main culvert were considered.

The efficiency of the central flow divider (see figure 5) has been assessed and the divider has been optimized. The 3D CFC software (Fluent) has been used to modify the shapes of the divider.

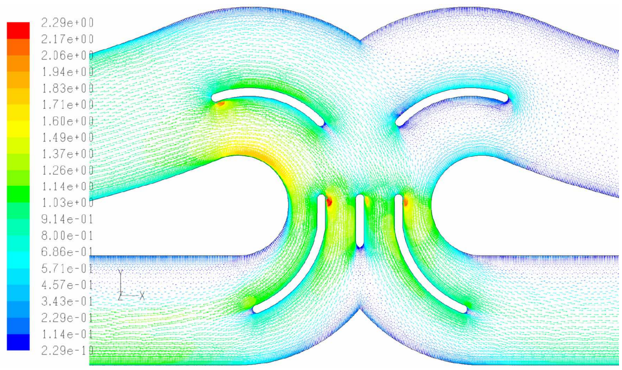

Figure 5: Shape of the central flow divider

Tests for filling-emptying operations

Cases have been simulated with the ship and without the ship in the lock chamber, taking into account various situations (and combinations) of:

- lock chamber operations : lake Gatun to lock, lock to lock, lock to ocean, WSB to lock, lock to WSB,
- hydraulic operations : filling or emptying of the chamber
- initial hydraulic head : max, mean, max with WSB,
- gate configuration : standard and non standard

Emptying and filling tests with the ship in the lock chamber

For each case of operations, F/E times, maximum flow rates (and consequently velocities), extreme water slopes (longitudinal and transversal) have been measured.

F/E times measured during the tests carried out on the physical model are, for most of the cases, slightly longer than those calculated with the 1D numerical model used during the pre optimization studies. The valve operation schedules were then adapted to adjust the results of F/E times, so as to comply as much as possible with the target design criteria.

Hawser forces analysis in the longitudinal direction

Time series of water level differences measurements (end to end in the longitudinal direction of the lock chamber) have been registered. Time series of longitudinal forces have also been measured.

The ship seems to follow quite well the changes in the longitudinal water slope. It is well known that the longitudinal component of the hydrostatic force on the ship's hull is in good approximation given by the water level slope between bow and stern. A good correlation is found (see figure 6) between the longitudinal water level slope (i.e. the end-to-end slope measured in absence of a ship in the lock chamber) and the longitudinal component of the total hydrodynamic force on the ship's hull (measured, of course, in presence of the ship in the lock chamber).

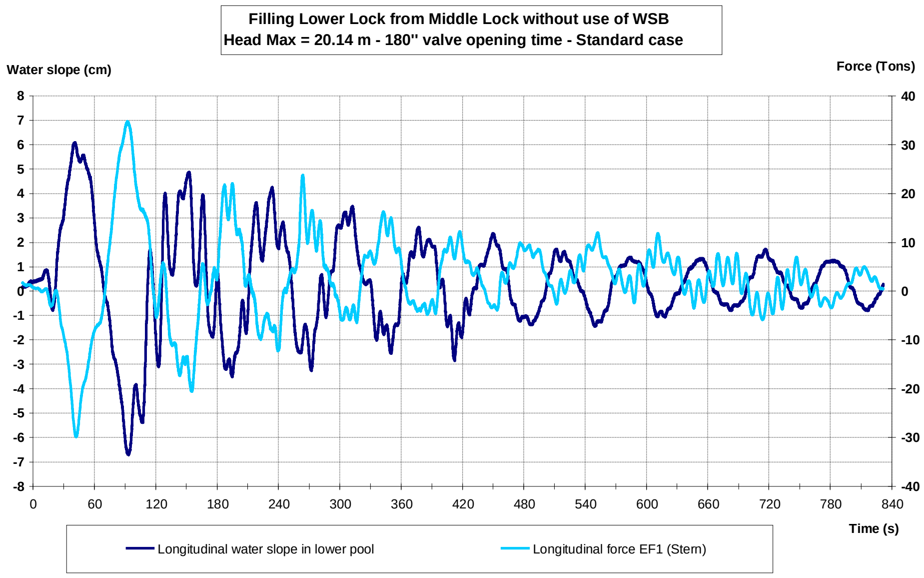

Figure 6: Longitudinal water slope vs longitudinal force on the vessel

Longitudinal forces are well correlated with the longitudinal water slope measured with the ship in the lock chamber. A correlation can also be found with the water slope without ship in the lock chamber. It allows determining a threshold value for the water slope without ship in the lock chamber in order to limit the longitudinal forces.

Hawser forces analysis in the transversal direction

Time series of water level differences measurements (in four cross sections of the lock chamber) have been registered. Time series of transversal forces (at bow and stern) have also been measured. The period of the signal is about 10s (10 times less than the longitudinal slope).

An analysis has been started in cooperation with Prof. dr. eng. Marc Vantorre (Division of Maritime Technology, Ghent University, Belgium) in order to assess the forces exerted on the mooring lines given the forces and measured on the physical model using a mathematical model.

PRELIMINARY CONCLUDING REMARKS

At the time this article is written, the test phase is still in progress. A lot of valuable data have already been collected concerning F/E times, forces exerted on the ship during F/E operation and many other hydraulic parameters (discharges, pressures, velocities and head losses).

Concerning the evaluation of the hawser forces in the mooring lines, different measurements technologies have been used in order to corroborate the measurements between each other. It finally leads to an original methodology to predict hawser forces in a well defined vessel positioning system.

The tests phase should be finalized in May 2008.

REFERENCES

VANTORRE Marc: Hawser forces during lock filling. Marine Technology Division Ghent University, Ghent Belgium (on behalf of CPP). March 2008.