DETERMINATION OF HAWSER FORCES
USING NUMERICAL AND PHYSICAL
MODELS FOR THE THIRD SET OF PANAMA LOCKS STUDIES

by

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1. THE PANAMA THIRD SET OF LOCKS PROJECT

1.1 Main issues of the project

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 set of larger locks, 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 and a width of 55m. The design ship is a so-called Post-Panamax 12000 TEU container carrier ($348 \times 48.8 \times 15.2 m^3$; $C_B = 65\%$). Because water consumption is a major issue, each of the 6 new Locks will be equipped with 3 Water Saving Basins (WSB).
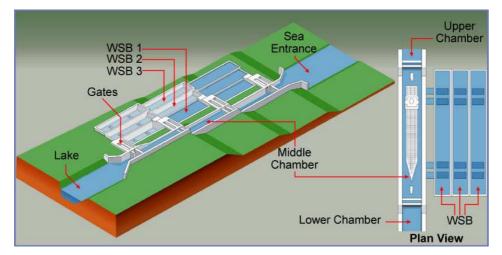

Figure 1: Third Set of Locks structure – Overall view

This "3 locks & 9 WSB" configuration will help saving 87% of the water required for the transit of one ship between the Gatun lake and the ocean. Even if the New Locks will be larger and longer than the existing locks, they will consume 7% less water than them when the WSB will be used.

1.2 Studies performed between 2002 and 2008

From 2002 to 2008, the Consortium Post Panamax (CPP) has performed several studies for ACP in order to achieve the preliminary design of the new Locks.

The sketch hereunder give an overview of the studied carried out during this period and presents briefly the kind of model used for every phase:

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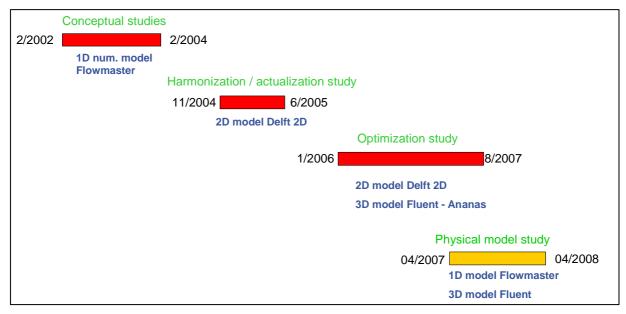[6] Autoridad Del Canal de Panama, Panama, Jwong@pancanal.com

Figure 2: Studies sequence between 2002 and 2008

1D, 2D & 3D numerical models studies were firstly carried out to select and pre-optimize a filling & emptying system. After its completion, the physical model study has been started in order to validate the system selected.

The validation was based on the two main issues which were to maximize the transit throughput and, at the same time, to limit hawser forces under an acceptable maximum threshold value.

1.3   Description of the numerical models used during the study

Three mains software are used in the hydraulic study:

> Flowmaster2 Software: 1D numerical model used for calculation of filling and emptying times;

The 1D calculations performed to design the basis of the F/E system have been run with the Flowmaster2 software. The code is able to predict the pressures, velocities and flow rates, the valves operating schedule, the water levels variations and consequently the F/E times, that occur in the F/E system. It can be run either in steady state and transient simulation. Owing to the resulting data, it has been possible to compare different emptying/filling lock designs and to define the main components of the system.

> Delft3D numerical model: used for the calculation of the water movements in the lock chamber and the assessment of the hydrostatic component of the hawser forces;

The model has been set-up by Flanders Hydraulics Research based upon an accepted, state-of-the-art, commercial, software package for shallow water flow (Delft3D software). The assumption of shallow water flow is acceptable because the horizontal dimensions are much larger than the vertical ones (hence vertical acceleration terms in the equations can be neglected.).

This 2D numerical model solves the 2D shallow water equations (i.e. the so-called Saint-Venant equations) for the water flow in the lock chamber. It has been used in order to calculate the evolution in time of the water levels in the lock chamber and to determine the hydrostatic pressure field acting on the ship hull during filling or emptying operations.

> Fluent Software: 3D numerical model used for the design of the most complex hydraulic shapes, for the calculation of head losses in those components and for the calculation of the hydrodynamic forces acting on the vessel during a filling and emptying operation

Fluent is a commercial 3D numerical flow simulation software package. It solves partial differential equations of fluid mechanics (Navier Stokes equations) using the finite volumes method.

The 3D calculations of the hydrodynamic forces acting on the vessel have been carried out meshing the whole lock chamber, a section of the F/E system and the design vessel. Fluid structure interaction and interface tracking (using the VOF method) have been taken into account.
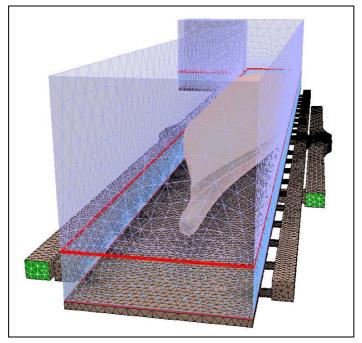

Figure 3: Meshing of the chamber, F/E system and vessel

1.4   Description of the physical model

A physical model at scale 1/30 has been built in order to complete the design of the F/E system and to validate the two main issues that were the F/E times and the hawser forces.

The model was composed of:

- 2 lock chambers,

- 3 WSB associated with the lower lock chamber,

- a 250 m fore bay (Gatun lake side),

- a 250 m tail bay (ocean side).

This "2 chambers & 3 basins" configuration allows to carry out all type of filling/emptying operations, with and without the WSB.
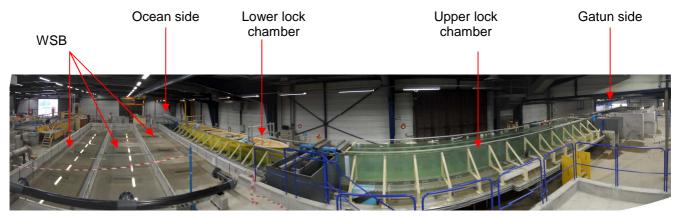

Figure 4: General view of the physical model

The model is equipped with different types of sensors in order to measure:
- the water levels in lock chambers, WSB, fore and tail bays;
- the longitudinal and transversal differential water levels in lock chamber;
- the velocities and flow rate in culverts;
- the pressure in the culverts and downstream the valves;
- the valve positions;
- the longitudinal and transversal hawser forces (i.e. the longitudinal and transversal components of the hydrodynamic force exerted by the water on the ship's hull).

A ship model, a Post-Panamax container vessel with 12,000 TEU nominal capacity, has been built at scale 1 to 30 to be used in the physical model of the locks. The ship model is neither equipped with propulsion, nor a rudder since only filling and emptying operations are simulated on the physical model.

Figure 5: View of the Post-Panamax container ship model

2. DEFINITION OF HAWSER FORCES AND SETTING OF AN HAWSER FORCES CRITERION

2.1 Definition of the term 'Hawser forces"

The term "hawser forces" can have multiple definitions which need to be detailed and 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 opposing to the ship displacement and needed to sustain the ship in a given position in the lock chamber. They depend on the external forces exerted on the vessel (hydrodynamic forces, wind forces for example) and on the vessel positioning system itself (number, size and position of the mooring lines).

These are not the forces measured on the physical model since it would require representing the real configuration of the mooring lines system (which leads to many technical problems).

Anyway, they can be predicted by a numerical mechanical model of the ship and its vessel-positioning system, fed with time series of measured forces on the ship's hull).

The threshold value for the reaction can not be given if the mooring line system is not defined.

➢ Hydrodynamic forces exerted on the ship's hull

They are 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 (with two components: a longitudinal one and a transversal one).

There numerical prediction required a 3D numerical model with a very refined mesh and taking into account Fluid Structure Interaction aspect (which means long and costly numerical calculations).

➢ Hydrostatic forces exerted on the ship's hull

They are 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 Delf2D numerical model during the previous studies (Delft2D numerical model was solving the Shallow Water Equations in the lock chamber taking into account the discharge calculated with the 1D Flowmaster numerical model). The numerical calculations give the longitudinal and the transversal component of the hydrostatic forces.

These are only one component (generally the main) of the hydrodynamic forces.

➢ Forces deduced from the water level slopes

They can be used as an approximate estimate of the hydrostatic forces exerted on the ship 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 with which a vessel is attached.

The water slopes measured on the physical model can be compared to the "hawser forces" also measured in order to find out a relevant correlation between the two parameters.

2.2 The "hawser forces" criterion

To evaluate the design of a F/E-system, a hawser force criterion is applied. Basically, this is simply an attempt to quantify that the filling (and emptying) process should be sufficiently 'tranquil' or 'smooth' such that the ship's moored in the lock chamber do not suffer from unacceptable displacements and/or ruptures of mooring lines. Emptying in general gives rise to lower hawser forces than filling (since the energy dissipation takes place outside of the lock chamber). Therefore, only filling will be considered in this report.

Traditionally the hawser force criterion is formulated by requiring the longitudinal force F_x not to exceed a certain threshold value, which is expressed (in promille) as a fraction of the ship's displacement weight Δ.

Verification of this criterion goes as follows:

➢ In the conceptual design phase, the maximum force $F_{x,max}$ (only the hydrostatic force component) is estimated with a 1D or (in the present methodology) a 2D shallow water solver.

➢ In the design phase, the maximum force $F_{x,max}$ (including forces of other nature than the hydrostatic force component) is measured with a physical scale model.

If $F_{x,max}$ (expressed in promille as a fraction the ship's displacement weight) is below the threshold value, then the F/E-system is said to comply with the hawser force criterion. If $F_{x,max}$ exceeds the threshold value, then the design of the F/E-system should be modified.

Note that traditionally, neither in the numerical model, nor in the physical scale model, the real vessel-positioning system, which consists of several mooring lines, is explicitly taken into account in the calculation resp. measurement of $F_{x,max}$. Stated in another way, both in the numerical and the physical models, the design ship is kept in position by means of an artifical 'vessel-positioning system', which is only meant to quantify the forces on the ship's hull.

Yet, the real vessel-positioning system does play a role in the hawser force criterion, i.e. it determines the threshold level value.

For inland navigation vessels, standard hawser force threshold values are put forward by international (e.g. PIANC) or national authorities. In some references in literature, different threshold values are specified, depending on the size of the vessel and on the vessel positioning system (e.g. different values for filling with mooring lines attached to fixed bollards vs. mooring lines attached to floating bollards).

For ocean-going vessels, however, the references in literature related to hawser force threshold values are very scarce.

This fact necessitates reflection upon the different strategies that could be adopted to define appropriate – i.e. reliable but not overly conservative – hawser force threshold values for large maritime locks in general and for the new post-panamax locks in particular.

2.3 Methodologies available to determine the hawser forces threshold value

In any case, the definition of a threshold value for the hawser forces requires previously having a fair idea on the mooring lines system to be used. In the case of the Post-Panamax locks, we considered a vessel-positioning system for ocean-going ships consisting of several mooring lines attached to fixed mooring bits on top of the lock wall and to winches on the vessel's mooring deck. The vessel is supposed to be centred in the lock chamber.

For the aforementioned system, different methodologies exist to put forward threshold level values for the hawser forces in the (conceptual) design phase.

➢ *Authority-based methodology*

This first method is to rely upon the authority of estimated (international or national) bodies, which suggest specific threshold values. Unfortunately, no such specifications were available by now in literature for Post-Panamax locks.

➢ *Water surface slope-based methodology*

The second method to determine threshold values, is to get inspiration from in situ observed (end-to-end) water surface slopes in (post-)panamax locks, in which no operational problems related to hawser forces are known to the respective port or canal authorities:

  o Berendrecht lock (Port of Antwerp, Belgium): up to 0.40 ‰

  o Miraflores lock (Existing lock on the Panama Canal): up to 1.30 ‰.

In theory, the water surface slope, if measured between bow and stern, is a good measure for the (longitudinal component of the) hydrostatic force acting on the ship's hull. This fact is exploited to estimate the hawser force by means of numerical models, based upon a (1D or 2D) solver for the shallow water equations.

➢ *Force-based methodology*

The third alternative methodology consists of a rational way to quantify the hawser force threshold values for the aforementioned system, taking into account the characteristics of the vessel-positioning system. More specifically, the forces in the mooring lines are required to remain below certain limits, imposed by the vessel-positioning system.

In the longitudinal direction, the threshold value, i.e. the maximum external force $F_{x,max}$ that can be sustained by the reaction forces in the mooring lines, is given by:

$$F_{x,\max} = \frac{T_u}{f_s f_m} \sum_i \cos(\theta_i) \cos(\phi_i)$$

,

where:

  o T_u denotes the minimum tensile strength of the lines,

  o f_s the safety factor (with respect to T_u),

  o f_m the magnification factor to account for the dynamic effects in the mass-spring system formed by the vessel and its mooring lines. A reasonable value is $f_m=2$.

  o $\sum_{i=1}^{N} \cos(\theta_i) \cos(\phi_i)$ is the geometrical efficiency (in the longitudinal direction) of the mooring lines, accounting for their geometrical orientation at the beginning of the filling process. The orientation is expressed by two angles θ_i and ϕ_i, which depend on the geometry of the lock chamber, the geometry of the vessel and its mooring deck, the (centred) position of the ship in the lock chamber and the water level at the beginning of filling. The optimal orientation of a mooring line is horizontal and aligned with the longitudinal axis of lock chamber and ship: $\cos(\theta_i)\cos(\phi_i) = 1$. If a given mooring line configuration consists of 2N lines in total, then only N lines of it are active (i.e. are elongated and under tension) in sustaining an external force (e.g. in the direction of the positive x-axis, i.e. the longitudinal axis). If those N lines were optimally oriented, then the maximum geometrical efficiency would be obtained: $\max\left(\sum_{i=1}^{N} \cos(\theta_i)\cos(\phi_i)\right) = N$. For the hawser force threshold value in the transversal direction, a similar expression has been derived.

> *Motion-based methodology*

Besides the previous force-based reasoning, one should also verify whether the ship's motion (which is the response to the external forces acting on the ship's hull and to the reaction forces of the mooring lines) is within acceptable limits. This is not investigated in the classical numerical model studies. It requires an additional dynamic analysis model to calculate the ship's motion (for which the classical numerical model studies might give the input time series of forces and moments acting on the ship's hull).

To illustrate the motion-based methodology, Prof.dr.ir. M. Vantorre (division of Maritime Technology, Ghent University, Belgium) set up a model to simulate the degrees of freedom of the 12,000 TEU design container vessel in the new third lane lock chamber. The mooring lines act e.g. as linear springs, with limitation of forces.

The time series of (hydrostatic) forces and moments on the ship's hull - as calculated by the 2D numerical model for the water flow in the lock chamber (in which a ship is present) - are used as an input to the dynamic model.

3. HAWSER FORCES MEASUREMENT AND CALCULATION METHODS

3.1 Assessment of the forces based on the calculation of the water slope

In the conceptual design phase, the hawser forces analysis boils down to the calculation of the longitudinal component, F_x, of the hydrostatic force on the ship's hull. It is common to make F_x, non-dimensional by taking the ratio of the force and the displacement weight of the design ship.

In order to evaluate the variation of F_x in time, one needs the variation in time of the water level difference at bow and stern of the design ship. That's why the 2D numerical model, described in section 1.3, has been set-up to calculate the evolution in time of those water levels.

This 2D numerical model solves the 2D shallow water equations (i.e. the so-called Saint-Venant equations) for the water flow in the lock chamber.

The whole lock chamber, including the gate recess, the rolling gates and all of the 40 ports (20 in each lock wall, is meshed. Discharge time series previously calculated by means of the Flowmaster 2 software, are applied as boundary conditions to the 2D model at the port position. The computational grid is shown in Figure 6, and consists of square cells with size 1 meter.
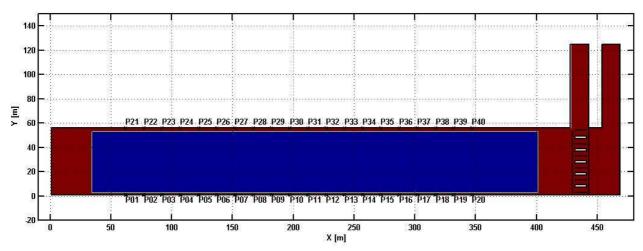

Figure 6: Computational grid for 2D simulation of water flow in lock chamber

The presence of the design ship is taken into account by defining a fictitious 'atmospheric pressure field' on top of the water surface. For the first calculations, that pressure field was dimensioned as a box-shaped (left picture in figure 7), the dimensions of the box being the length, the beam and the

draft of the ship. The pressure field has been then adjusted in order to represent the exact shape of the Post-Panamax hull (right picture in Figure 7)
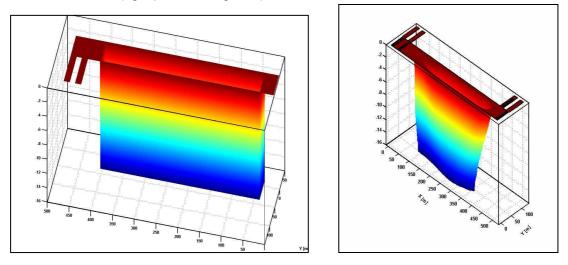

Figure 7: Fictitious atmospheric pressure field in order to simulate the presence of the ship's hull in the lock chamber

After running the 2D model, in each point of the computational grid time series of the water (as well as time series of the two components of the depth-averaged water velocity) are available. From these water level time series, the hydrostatic forces upon the ship's hull, and in particular the longitudinal component F_x, can be calculated. Figure 8 shows an example of results achieved after a simulation:
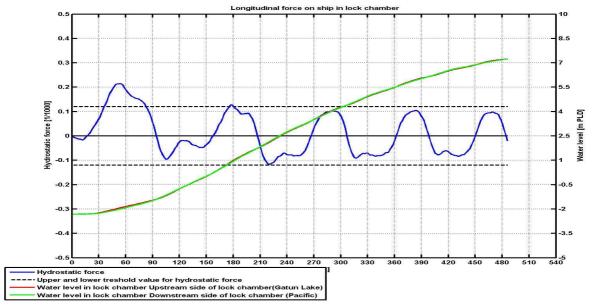

Figure 8: Upstream & downstream water levels variation in the lock chamber and longitudinal hydrostatic force exerted on the ship hull

An estimate of the transversal component F_y of the hydrostatic force can also be calculated from the differences in water level along the ship's hull.

This methodology based upon 2D and 1D models allows to assess the hydrostatic forces resulting from the water movements in the lock chamber rather quickly. Nevertheless, it can not take into account the hydrodynamic component of the forces acting on the ship hull. It is consequently very efficient if used for comparison purposes rather than for accurate predictions of hawser forces.

3.2 Calculation of the forces with 3D numerical model

3.2.1 Selection of the numerical model

In the conceptual design studies, the calculations were performed using both Flowmaster (1D software) and a Delft3D software model that solves the 2D shallow water equations in order to assess the so-called hawser forces and to compare different configurations of the lock filling and emptying system.

After the calculations performed with Flowmaster and Delft3D software, 4 systems has been retained. It was then decided to carry out additional analysis with 3D numerical CFD tools (Fluent and Ananas) solving partial differential equations of the fluid mechanics (Navier Stokes equations) using the finite volume method in order to finalize the F/R system design and to retain one configuration to be studied on physical model.

The calculation domain that had to be taken into account included several specificities which required analysis and validation on other cases. The analysis should consider the accuracy of the model but also the calculation time and cost.

The questions that were raised and that had to be answered were mainly:

- o What type of numerical model should be used, Large Eddy Simulation (LED) or Reynolds Average Navier Stokes (RANS)?

- o How to take into account the water/air interface tracking in the calculation? Indeed, the water level is rising during the filling operation and need to be adjusted at every time step. The Volume Of Fluid (VOF) and Level Set method have been compared and used for this problem,

- o How to take into account the Fluid-Structure Interaction (FSI)? It can be understood that the vessel and the water in the lock chamber interact on each other during a F/E operation. This FSI affects the magnitude of the forces acting on the ship hull and it was necessary to evaluate the effect on the final results.

- o How to take into account the dynamic meshing? Indeed, since the water level and the ship hull are both rising during the simulation and so the boundary conditions are "moving". It implies that the mesh has to be rebuilt at every time step which is a very costly and time consuming procedure.

The capacities of several 3D CFD codes have been compared in order to select the most suitable tool for these simulations, especially the ANANAS-Lemma code. It benefits from the most recent and efficient developments based on the works by Inria and the French university. It provides as standard features an implicit FSI model and a "Level set" interface tracking model.

In addition, validation tests have been carried out by simulating the filling of the Zandvliet lock. Comparisons have been done with results achieved on physical model.

By the end, it has been decided to run the calculation using the ANANAS-Lemma code with a Euler model for the simulations requiring fluid-structure coupling and the Fluent code with a RANS model to calculate purely free surface flows without fluid-structure interaction (using also the VOF method and an unstructured mesh that permits mesh deformation without remeshing).

3.2.2   Application to the Panama Locks

The calculation domain considered, in Figure 9, includes the lock chamber and the filling system. The lock chamber and the gate recesses are represented. The filling system comprises the main culverts, the secondary culverts, the central distributors and 20 ports on each side of the chamber.
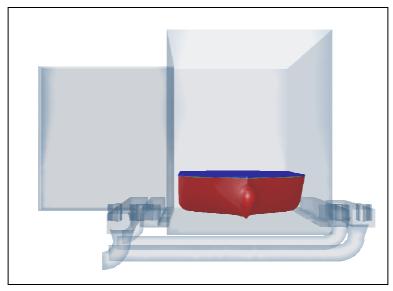

Figure 9: Calculation domain

The meshing was composed by about 1 800 000 tetrahedral elements and 430 000 points.

The discharge time series issued from the 1D model hydrograph were set as limit condition in both main culverts. The initial level in the lock chamber was set to 18.30 m.

The calculations allow to determine the flow distribution through the ports, the water movements in the lock chamber and to calculate the hydrodynamic forces exerted on the ship hull for each of the F/E system retained after the conceptual design studies.
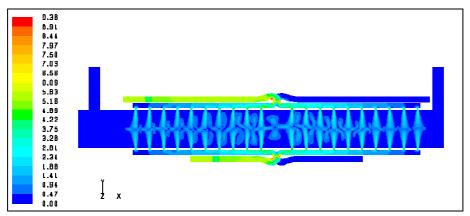

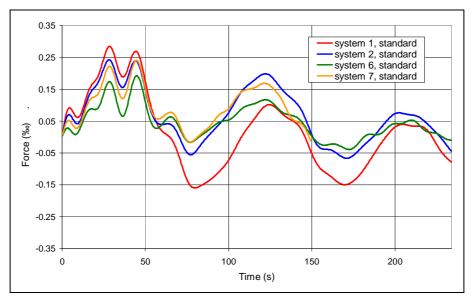**Figure 10: Example of flow distribution through the ports**

Figure 11: Longitudinal forces exerted on the ship hull during a filling operation

This method gave results accurate enough to compare the 4 different configurations of the F/E system. The calculations also led to assess the magnitude of the expected forces acting on the ship and to evaluate the effect of the Fluid-Structure Interaction on these forces (forces have to be increased by 25% if FSI is not included in the model).

Anyway, due to the calculation times and costs, it does not allow to carry out simulations for every F/E scenarios taking into account all the hydrodynamic phenomenon (FSI, turbulence, drag force) in order to define with the required accuracy the hawser forces.

That is why a third method, coupling physical model measurements and mathematical model calculation has been set up.

3.3   Combination of physical model measurement mathematical model (motion-based methodology)

3.3.1 Physical model measurements

By now, the physical model seems to be the best tool to represent faithfully all the hydraulic phenomenon that occur in the lock chamber and that generate and/or interact with the ship movements (provided the scale has been correctly chosen and the ship model is well modelled).
Anyway, the physical model of the lock itself does not permit to measure the forces in the mooring lines because of technical difficulties. Indeed, it is hardly feasible to maintain the mooring lines tight on the model while the vessel is rising or lowering by almost 35 cm during a lockage operation.
Moreover, the forces in the mooring lines are very sensitive to the geometric parameters (angles, length), to the number and type of lines which means that the results of every test is unique and can hardly be generalised. For instance, any changes in the lines position would require carrying out a new test in order to update the result.

Consequently, the methodology that has been retained consisted in:
1- Measuring the forces exerted on the ship during a F/E operation (which means the force measured depend only on the hydraulic conditions such as initial head and on the ship position; not on the type, number or position of the mooring lines);
2- Using these results in a mathematical model developed to calculate the forces in the mooring lines and the ship motion.

The longitudinal and transversal forces were measured on the physical model by means of 3 dynamometers (2 for the transversal forces and 1 for the longitudinal forces) and positioned as shown on Figure 12.
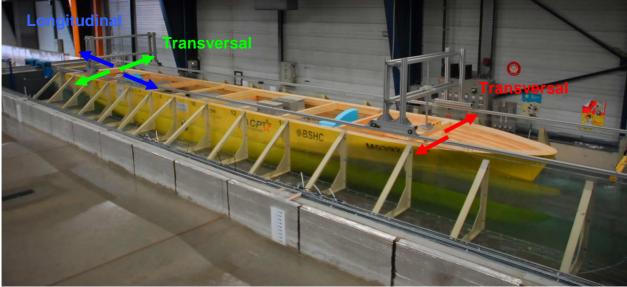

Figure 12: Location of the dynamometers

The system allows the vessel to move vertically around vertical bars fixed into the lock bottom floor. The dynamometers are fixed on a plate maintained rigidly on the ship as shown in Figure 13.
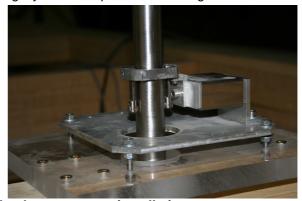

Figure 13: Details of the dynamometers installation

This system does not model the elasticity of the mooring lines and all the forces exerted on the vessel are completely transferred to the measurement system.

3.3.2 Calculations of the forces in the mooring lines

By means of a simplified mathematical model for the ship dynamics (set up by prof. M. Vantorre), ship motions and hawser forces due to the longitudinal and lateral forces and the yawing moment measured on the horizontally fixed ship model has been simulated. Calculations have been performed for the most critical F/E scenarios.

In the analysis, the response of a moored ship to the measured forces and moment has be simulated making use of constant estimated values for the added inertia and hydrodynamic damping coefficients. The vertical motion of the vessel during the lockage operation has been taken into account.

The simulations are based on time histories of the vertical motion, the longitudinal force, the lateral force and the yawing moment acting on the ship during the lock operation. For each of the considered operations, two sets of time histories have been applied to the moored ship:

- o the time histories as measured during the tests;

- o a modified time history, obtained by calculating a running average over a time span of 25 s for the lateral force and the yawing moment, while the original measured signals are used for the longitudinal force and the vertical motion.

Prior to the calculations, a mooring arrangement has been considered, taking into account the following requirements and hypotheses:

- o the ship's own winches and mooring lines are used;

- o a manual control of each winch by a simple, realistic criterion has been applied;

- o during lock filling/emptying, the ship is kept centred in the lock chamber.

The selected mooring configuration consists of eight mooring lines of the type Samson Proton-8 (2"1/4) lines, see Figure 14:

- - four breast lines (fore starboard, fore port, aft starboard, aft port)

- - four spring lines (fore starboard, fore port, aft starboard, aft port)

Figure 14: Mooring lines arrangement

For a number of representative cases, the mooring line configuration defined here above was proven to be acceptable to stabilize the vessel position during lock filling/emptying.

Given the force maxima for the considered scenario's and given the suggested mooring line orientation – in which a separate subset is dedicated to the transversal hydrodynamic forces (4 breast lines) and a separate subset (4 springs) is dealing with the longitudinal hydrodynamic forces – it was advocated to define two independent threshold values for assessing physical model results:

> ➢ a longitudinal threshold value of 50 ton, which can directly be applied to the measurements of a physical model

> ➢ a transversal threshold value of 30 ton, which has to be applied to each of the running average (time span of 25s) of the transversal force components measured in a physical model.

This methodology, mixing both numerical and physical model, has permitted to validate the selected F/E system. Based on the results of physical model for the most critical hydraulic scenarios, it lets to the designer a good flexibility for the choice of the mooring line system.

ACP finally used the resulting values from the model studies to define the performance criteria required for the final design and construction of the Third Set of Locks, to insure that the works meet the navigational safety, time performance and system capacity necessary for project success.

References

TO1-Task1.2.5-CNR-R012 Numerical model of variations for the selected F/E system, CPP, AUGUST 2008

TO1-Task1.2.5-CNR-FHR-R013 Specification of hawser force criteria FINAL REPORT, CPP, SEPTEMBER 2007

TO5-Task5.1-CNR-R001 NTERIM REPORT VALIDATION TESTS, CPP, MARCH 2008

TO5-Task5.1-CNR-R002 OPTIMIZATION TESTS REPORT, CPP, JUNE 2008

Mooring Layout for Lock Filling/Emptying Operations, Prof. M. Vantorre, MAY 2008