What's new in the design of navigation locks?

– PIANC Workshop –

In the framework of the
PIANC Report n°106 - INCOM WG29

- ABSTRACTS -

13th – 14th September 2011

New Orleans – USA

PIANC – www.pianc.org

Editor: Prof. Ph. RIGO, INCOM WG29 Chairman

This 2nd international workshop presenting the **Innovations in Navigation Lock Design -** PIANC Report n°106 was organized on 13th and 14th September2011 in New Orleans, USA. The first workshop in September 2009 in Brussels, Belgium was a huge success, with more than 100 participants, and therefore, it was decided to offer follow up events.

This 2nd international PIANC workshop on **Innovations in Navigation Lock Design** will be held in conjunction with the SMART-RIVERS 2011 Conference in New Orleans, Louisana.

On 13th Sept 2011, there was a detailed presentation of the main innovative issues highlighted in the PIANC 2009 report (n°106). This workshop differs from the 2009 one in that new speakers presented their experience with respect to innovative lock design, including the new Panama Locks.

On 14th Sept. 2011, the workshop was dedicated to "*Ship behavior in locks and lock approaches*".

For info about SMART RIVERS 2011: http://smart11.pianc.us

Workshop proceeding

The Workshop proceeding (including all the PowerPoint presentations given during the workshop – in PDF version) is release on the PIANC web site (www.pianc.org) and on
www.anast.ulg.ac.be ,
www.anast.ulg.ac.be/index.php/fr/nouveautes/40-categorynews/102-pianc-whats-new-in-the-design-of-navigation-locks

Proceedings of the 1st PIANC workshop (Brussels 2009) are available at:
www-new.anast.ulg.ac.be/index.php/en/news/40-categorynews/94-pianc-workshop-innovations-in-navigation-lock-designq
and
www.pianc-aipcn.be/figuren/verslagen%20activiteiten%20Pianc%20België/fotoboekjes/workgroup/locks/Locks/index.html

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WORKSHOP - TECHNICAL AGENDA

13th Sep 2011 (Tuesday)

8:00 **WORKSHOP INTRODUCTION**
By Prof. Ph. RIGO (BE), INCOM Vice chairman
and J. CLARKSON (U.S. Army Corps of Engineers, member of INCOM WG29)

8:30-10:00 **WORKSHOP PART 1 – THE PANAMA LOCKS**
THE DESIGN OF THE PANAMA LOCKS
By M. NEWBERY (USA) and J. AUGUSTIJN (NL)
Chair: Ph. RIGO (BE)

NUMERICAL SIMULATIONS AND EXPERIMENTAL MODELS: THE EXPERIENCE OF THE NEW PANAMA MODEL
By S. ROUX (Fr)
Discusser: R. STOCKSTILL (USA)

10:30-12:00 **WORKSHOP PART 2 – PIANC 2009 - Report n°106 - on Locks**
INNOVATIONS IN NAVIGATION LOCK DESIGN
General Presentation of the PIANC Report n°106 on Locks (2009)
By Ph. RIGO (BE) and P. HUNTER (UK),

A SELF-CONTAINED HIGH-LIFT LOCK WITH WATER-SAVING BASINS
By C. THORENZ (D)

INNOVATION IN LOCK FILLING AND EMPTYING SYSTEMS
By R. STOCKSTILL –(USA)
Discusser: D. BOUSMAR (BE)

CONSTRUCTION METHODS
By D. MILLER (USA)
Discusser: WU. PENG (China)

13:30 – 15:00 **WORKSHOP PART 3 – PIANC 2009 - Report n°106 – on Locks (cont.)**
COMPUTER FLUID DYNAMICS IN LOCK DESIGN
By T. DE MULDER- (BE)
Discusser: C. THORENZ (D)

NEW CONCEPT OF LOCK GATES
- Use of synthetic materials and the comeback of sliding gates versus rolling gates
  By R. DANIEL (NL) and J. AUGUSTIJN (NL)
- New materials and systems in the design of miter gates
  By R. DANIEL (NL)
- Innovation in lock equipment
  By O. HOLM (Fin) and J. BODEFELD (D)

15:30 – 17:00 **WORKSHOP PART 4 – CHALLENGES OF TOMORROW**
DESIGN FOR MAINTENANCE: DREAM OR REALITY? THE EXPERIENCE OF THE NEW PANAMA LOCKS – LIST OF REQUIREMENTS (20 min + 10 min questions)
By R GORDON and J. WONG (ACP)
Chair: J. BODEFELD (D) and P. HUNTER (UK)

IDENTIFICATION OF THE CHALLENGES OF TOMORROW
PANEL MEETING
Coordinator: Ph. RIGO
Panelists: J. AUGUSTIJN (NL), J. BODEFELD (D), R. DANIEL (NL),
R GORDON & J.WONG (ACP), M. NEWBERY (USA), R. THOMAS (BE)

17:00 – 17:30 **PROJECT REVIEWS and their value in realising innovations**, By E. PECHTOLD (NL)
17:30 **CLOSURE** By Ph. RIGO (BE)

14th September 2011 (Wednesday Afternoon)

8:30 – 12:00 **SMART-RIVERS Conference**
Keynote addresses and Plenary Session on Hurricane Surge Barrier

12:00 – 13:30 Lunch – with keynote speaker from EU commission (invited)

13:30 – 15:30 **WORKSHOP PART 5 : MOORING FORCES AND VESSEL BEHAVIOUR (in locks)**
EXPERT PANEL SESSION – Ph RIGO (BE)
The experts present their experience on this issue, which is the main focus of the new PIANC WG 155 (having their inaugural meeting during the SMART RIVERs Conf.)

Presentation of new innovative concepts for navigation locks
By S. KWOK (St. Lawrence Seaway, Canada)
Experience in Belgium
By T. DE MULDER, M. VANTORRE (BE)
Experience in China
By WU PENG (China)
Experience in France
By S. ROUX (Fr)
Experience in Germany
By C. THORENZ (D)
Experience in The Netherlands
By J.J. VELDMAN (NL)
Experience in USA
By R. STOCKSTILL (USA)

Discussion : Coordinated by Ph RIGO (BE)

15:30 – 16:00 **Break**

16:00 – 17:00 **WORKSHOP PART 6 : VESSEL BEHAVIOUR (in locks)**
Chair: WU PENG (China)

INTERACTION between SALT WATER INTRUSION and NAVIGATION (in locks)
By M. SAS (BE)
MANEUVRABILITY IN LOCK CHANNELS
By M. VANTORRE (BE)

17:00 -17:30 **WORKSHOP CLOSURE**
By PIANC USA Representative
PIANC HQ Representative
Prof. Ph. RIGO, Workshop Chairman and Coordinator

What's new in the design of navigation locks?

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The Post-Panamax Locks

The Design of the Panama Canal Third Set of Locks

M. Newbery
Design Manager - CICP, and Vice President - MWH
J. Augustijn
Rotterdam Design Center Engineer- CICP, and Project Manager – Iv-Infra

ABSTRACT: This paper provides a high level summary of some key design elements of the Atlantic and Pacific Third Set of Locks. It describes the evolution of the design from the tender design to final designs. Particular emphasis is placed on the design challenges posed by the technical requirements for the lock rolling gates together with CICP's solutions as presented in the accepted final designs.

1 INTRODUCTION AND TENDER DESIGN

The Panama Canal Third Set of Locks is being constructed for the Panama Canal Authority under a design-build contract. The contract was awarded in August 2009 to Grupo Unidos por el Canal (GUPC), a JV consortium of Sacyr (Spain), Impregilo (Italy), Jan de Nul (Belgium) and CUSA (Panama). The project is scheduled to be completed in October 2014. The award was made on a best value basis (combination of qualifications and price); GUPC was rated highest of the three bids in both catagories. The tender design was prepared by CICP Consultores Internacionales (CICP), a design JV led by MWH (USA), along with member firms Tetra Tech (USA) and Iv-Infra (Holland).

The design team (several of whom have worked on the expansion project for ACP since 1999) evolved the ACP's concept design through innovations in the hydraulic design, the concrete structures, and the lock gates. Hydraulics were simplified for the intakes, outlets, and water saving basin conduits. Structures were optimized through detailed soil-structure modeling and FEM analysis. Lock gate operating speed was increased for additional capacity. These improvements resulted in the highest technical ranking and were key to reducing the construction cost.

2 FINAL DESIGN

Final design by CICP has been on-going since 2009. The designs are being prepared at design centers in Chicago, Bellevue, Buenos Aires, Rotterdam and Milan and cooridinated though CICP's Design Integration Office (DIO) co-located with GUPC's staff in Panama. Design staffing levels are peaking in 2011 (with both design and construction on-going) at around 250 full-time equivalent engineers and support. Design centers are linked for collaboration by a dedicated server system on which all designs, documents and drawings are stored. Work products are delivered to GUPC via the Aconex document management system. Multiple design tools are employed for the production of around 10,000 permanent works drawings. These include Revit, AutoCad, Civil 3-D, Microstation and Tekla. Navisworks is used to integrate the various models and perform clash detection in real-time.

Fig. 1. Revit Model, Atlantic Lock Complex

Hydraulic design comprised developing a complete 3-D numerical model using OpenFoam, performing additional optimizations, and extensive physical model testing (by CNR in Lyon, France, at 1:30 scale). The modeling resulted in adjustments to the conduit/secondary culvert connection, the water saving bason intakes/outlets, and the culvert valve elevations. All filling and emptying requirements were met or exceeded, including criteria for maximum ship hawser forces for two design vessel types.

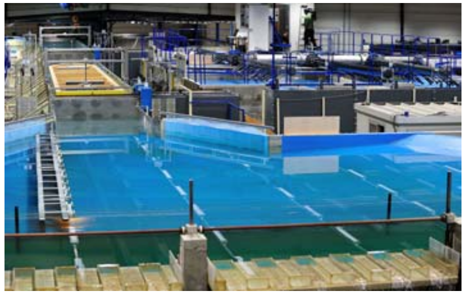

Fig. 2. Hydraulic Model of Post Panamax Locks

Geotechnical studies comprised development of 3-D topography and excavation models in Microstation, stability analyses, foundation characterization, seepage and drainage analysis and design and development of seismic loading for both the Atlantic and Pacific lock complexes. To better characterize seimic loads, deconvolution was used to modify seven seismic outcrop time-histories for use as input to the structural modeling.

Structural design of the nearly 5 10^6 m^3 of concrete comprises extensive 2-D and 3-D modeling of the lock chamber monoliths and lock heads using Abaqus software. Non-linear finite element analysis (FEA) models were developed for the analysis including a 3-D combined lock head and lock gates model, believed to be a first. Analysis included a combination of static and seismic loads. Results for the seven seismic time histories were averaged to obtain analysis results. Run times on super computers for the non-linear seismic analysis exceeded 48 hours per time history for the larger lock head FEA models.

Fig. 3. Image of Pacific Lock Middle and Lower Chambers superimposed on aerial photograph.

Fender systems are still under development at the time of writing, but are likely to include multiple horizontal fenders in the lock chamber to faciliate sliding during ship movement from chamber to chamber. Unique articulated multiple wheel fenders are proposed for the corner fenders. Approach wall fenders are proposed as hybrid cone panel units.

Control of the lock filling and emptying system is a key design challenge, accomplished through sixty-four 6.5m x 4.5 m culvert valves, 72 6.5m x 4.2m conduit valves along with 16 4.0 m x 3.0m equilization valves, providing complete redundancy. Valve opening and closing times can range from 1 minute to 6 minutes, with actuation of hydraulic cylinders by means of continously variable hydraulic power units (HPU's). Each complex has a total of 42 operations buildings which are now under final design. The mechanical, electrical and controls systems also provide complete redundancy to provide the high degree of reliability and availability required by the technical specifications. Because only a single lane of Post-Panamax locks is provided, a high availability of 99.6% is mandated.

3 LOCK ROLLING GATE DESIGN

Each three-lock chamber complex includes four lock heads housing the rolling gates. Redundant gates in each lock head makes for a required 16 gates in total for the two lock complexes. The gates are 60 m wide, up to 10 m thick and 30 m high. The average weight is around 3,000 Tonnes. With an average lift of around 9 m between lock chambers, the lock gates must hold as much as 20 m of differential head.

However, it is not just the sheer size that makes the design of these gates unique. The project's location in a highly seismic area requires that the lock gates be designed using the current state of practice, whereby both seismic design spectra and the suite of seven time histories are used in the analysis. The time history analyses were carried out using super computers in a complex multi-component model containing the lock head, its backfill and the two rolling gates. The model not only includes non-linear interfaces between lock head and the gates, it also incorporates the complex hydrodynamic loadings of the water. Following extensive research the water is modeled in the form of lumped added masses calculated with the Westergaard formula.

The added water mass under seismic loading is around ten times the weight of the gate. To confirm the applicability of the Westergaard formulation, CICP performed extensive analyses. These included computer simulations, several full scale tests shaking existing gates at their own frequency, and a laboratory scale model test. Through these state-of-practice analyses, it was concluded that the Westergaard formula is applicable.

To service the expected high demand for Canal transits, the envisaged use of the Third Set of Locks is significantly higher than that of typical locks - on the order of 15 to 20 operations per day over their 50 year design life. This high level of usage means that the amount of lock gate load cycles are such that fatigue loading is in many cases a governing normal load case. In addition to these 'normal' load cases, special load cases such as dry outages and ship impact have been investigated and considered in the design.

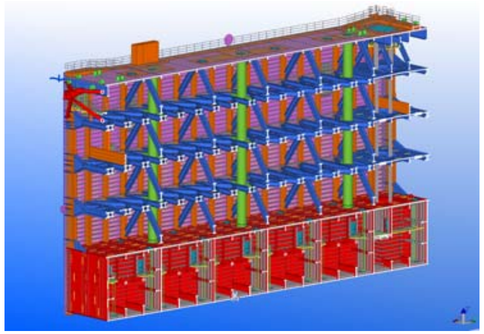

Fig. 4. Longitudinal section of a lock rolling gate showing buoyancy chambers, trusses and the upper support bracket. Tekla 3-D model.

Structurally, the lock gates are similar to a ship or submarine hull in design. As such, they are equipped with a buoyancy chamber, a submerged steel box filled mostly with air, which reduces the operational weight of the gate to about 7% of its actual weight. A key requirement for the gates is that they are able to be floated out for repair or relocation. This is a conventional requirement for the design of this type of lock gates, but it is complicated by the need to design for low chamber water levels. As a result, the buoyancy chambers need to be located near the bottom of the gate making it impossible to float the gate in a stable manner. This problem was solved by the introduction of a flotation hull, which can be formed by inserting watertight panels at the top of the gate structure, thereby increasing buoyancy and, with addition of ballast at the bottom of the lock gate, providing stable flotation.

The lock gate drive system consists of a duplicate set of winches and wire ropes. The design of the reeving system is such that the force driving the gate always acts on the centreline. The winches are connected to gearboxes that are driven by electrical motors. Acceleration and deceleration of the motors are accomplished by a variable frequency drive. If one motor/gearbox or winch fails, the other set can take over, adding to the reliability of gate operations.

During movement the operational weight of the gate is carried by two wagons in a so-called "wheelbarrow" arrangement. The 'upper' wagon carries one end of the gate via a bracket, and rolls over a set of rails located in the top of the lock head.

The upper wagon is connected to the drive system and pushes or pulls the gate during operation. The other end of the gate is supported by the lower wagon running on a rail track located in the lock head sill. The lower wagon is connected to a column which carries the gate's operational weight near the top. The design of the wagon attachments - specifically the column for the lower wagon and the bracket to the upper wagon - makes it possible to replace either wagon within four hours. Extreme loads on the wagons, for example due to leakage after a ship collision or due to a major earthquake, are controlled by a load limiting device. This device consists of a set of pre-stressed springs that behave rigidly up to a threshold value, and then elastically when this value is exceeded. The elastic behavior of the springs at high loading enable the gate to settle to the lock head floor on vertical bearing blocks. This prevents the load on the wagons from exceeding the maximum allowable value.

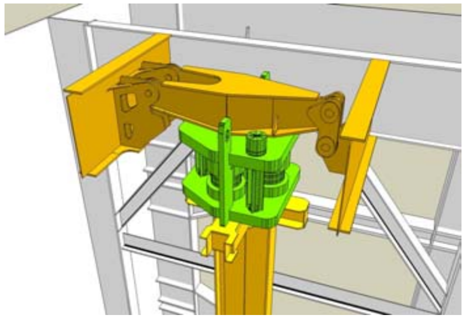

Fig. 5. Load limiting device arrangement at the top of the lower wagon column. Tekla 3-D model.

Horizontal water loads on the gate are transferred to the lock head by the guide and bearing system. When the lock gate is in the closed position and retaining water, load transfer to the lock head structure is accomplished by a set of lateral bearing blocks along the vertical edges and along the bottom of the downstream side of the lock gate. During movement, the remaining horizontal forces (e.g., those due to residual differential head, salinity differences, wind and wave loads) are transferred to the lock head by guide blocks located near the corners of the lock gate.

For the guide and bearing blocks, ultra high molecular weight polyethylene (UHMW-PE) has been selected for its strength and low-friction properties. Because of their good combined sliding properties, the combination of UHMW-PE and stainless steel has been chosen for the guide system. The UHMW-PE guide blocks are attached to the gates, while the bearing plates are stainless steel embedded in the lock head sill. Apart from carrying loads, the bearing plates also serve as a sealing surface. Due to stringent requirements with regard to leakage, the bearing and sealing surfaces are separated, withseparate rubber seals applied.

The lock gates are designed to be maintained within their recesses, with a recess closure and dewatering system provided for this purpose. For maintenance, the gate can be floated up in the recess and suspended on maintenance supports. Maintenance can then take place in the recess, without interruption of the operation of the lock, a key requirement to meet the availability criteria.

4 NEXT STEPS

Construction is underway with excavation and foundation preparation advanced at both sites. Structural concrete placement should also be advancing at both sites by September 2011. Lock gate fabrication by Cimolai (Italy) has commenced as has valve fabrication by Hyundai (South Korea).

Design is focused on completing the water saving basins, approach walls and wing walls together with the project control system, buildings and electro-mechanical systems. In addition, design now includes review of shop drawings, reinforcement and embedment drawings, as well as a quality assurance role in reviewing construction and major equipment suppliers.

An evolving construction plan for both sites has led to changing design priorities with associated coordination challenges – to be expected on a design-build project. Standing up a quality management system across 3 companies, 3 continents, 5+1 design centers has been critical to the technical success of the project. Having highly qualified key technical staff has been, is and will be essential to the succesful outcome of the project design.

The Panama Locks – Numerical simulations & experimental models: the experience of the new Panama model

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ABSTRACT: The combined used of physical and numerical model gives birth to a very powerful "hybrid" model that helps the designer to minimize the calculation time, cross-check the results, access to a large number of data and improve the prediction of the hydraulic performance of the prototype. In the case of the final design study of the Post-Panamax locks, the combined use of a physical model, 1D, 2D & 3D numerical models have proven to be a very efficient tool through a lot of cases which are presented in this paper for some of them.

1 INTRODUCTION

In the frame of the construction works of the New Locks of the Panama Canal, the final design of the locks F-E system has been carried out using both a physical scale model and a set of 1D, 2D and 3D numerical models. The physical model has been run in the Laboratory of the Compagnie Nationale du Rhône in Lyon while the numerical model studies were performed by MWH in Buenos Aires. Initially, numerical models had been run to fix the design to be tested in the physical model. Then, each model were run at the same time, allowing to cross-check the results and minimize the time to achieve the validation of the hydraulic performance of the F-E system.

2 DESCRIPTION OF THE PHYSICAL MODEL

A scale model, 60 m long and 10 m wide, representing two lock chambers, three WSB associated to the lower chamber, one fore bay and one tail bay has been built at scale 1/30 in CNR laboratory.

This model has been equipped with about 100 sensors in order to measure:

- The water levels in the lock chambers, basins, fore and tail bays;
- The longitudinal and transversal differential water levels in the lock chamber (i.e. the longitudinal and transversal water slopes);
- The velocities and flow rate in the main culverts and WSB conduits;
- 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).

Figure 1: General view of the physical model

A set of three Post-Panamax ship models at scale 1:30 were used for carrying out the tests in the physical model aimed at measuring the total forces exerted on the ship's hull and calculate the hawser forces and vessel displacements.

3 PRESENTATION OF THE NUMERICAL MODEL USED DURING THE FINAL DESIGN STUDY

State-of-the-practice software was used to study the different problems:

- Local head losses at the different system components were computed using 3D models based on OpenFOAM, a formerly commercial code that has become freely available. Its main advantages over comparable commercial software are its high-performance (Linux-based, parallel processing), access to a worldwide forum to request support, and its flexibility to introduce new features, if needed.
- The filling/emptying times and maximum flow velocities were calculated with a 1D model based on the commercial software FlowMaster V7.
- The hawser forces were inferred from the water surface slope values correlated during previous design phases. The water surface slopes were obtained using a 2D model based on Hidrobid software (a numerical code developed by Instituto Nacional del Agua) which is similar to other software like Mike 21 – by DHI –, or Delft2D.

All the models went through calibration or validation processes. The validation of OpenFOAM was based on comparisons with existing experimental results. The 1D model was first calibrated by comparison with experimental results from measurement carried out on the conceptual design physical model and with the results of the 3D models. Then, also the results of the physical model were used. The 2D model was validated by comparing its results with the results obtained with software Delft2D, and with measurements performed in the physical model.

4 EXAMPLES OF COMBINED USE OF PHYSICAL AND NUMERICAL MODELS

4.1 Calibration of the 1D model of the lock F-E system

The entire F-E system has been modeled with the Flowmaster 1D software, representing and setting the parameters of every component such as reservoirs, culvert, bends and valves. Anyway, some components such as the central flow connection present a very complicated hydraulic shape whose head losses coefficient can not been set without additional calculations with 3D model and measurements carried out on the physical model.

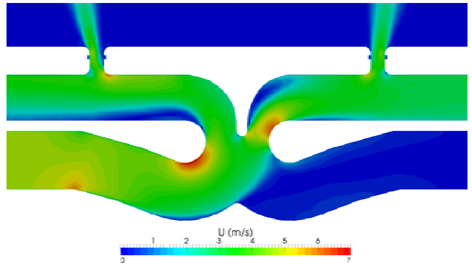

Figure 2: central flow connection

Once the 1D model has been calibrated, it becomes a very efficient tool allowing to perform fast sensitivity analysis, in order to define the operating parameters (i.e. valve opening schedule) before testing them on the physical model.

The construction of two 1D numerical models, one at scale 1/30 and the other at prototype dimensions, also gave very valuable information on the scale effects.

4.2 Assessment of the flow distribution through the lateral ports

Achieving a balanced flow distribution along the lateral ports is something of first importance in order to have smooth filling conditions. Before running all the F-E scenarios, a lot of measurements were carried out on the physical model in steady flow condition to assess the symmetry of the flow entering into the lock chamber.

These measurements have been completed by 3D numerical calculations that gave valuable data, such as distribution of the flow in every port, difficult to obtain by simple measurements on the physical model.

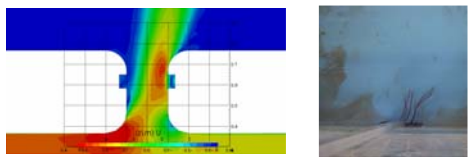

Figure 3: numerical calculation Vs observation on physical model

All this set of data allowed to get an accurate and comprehensive knowledge of the flow conditions in every port and to validate the efficiency of F-E system regarding the flow distribution.

4.3 Upgrade of some components of the F-E system Tender design

The combined use of physical and numerical model has demonstrated its full efficiency through the modification of one main culvert valve layout.

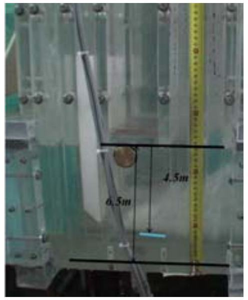

Figure 4: Air entrainment under a valve

After having detected visually on the physical model that some air was sucked in the main culvert downstream of one valve, a 3D numerical model of the valve has been implemented. It was validated on the basis of data measured on the physical model (especially pressure).

A new configuration of the valve layout has then been studied with the numerical model and the retained configuration has been installed on the physical model for validation.

This methodology has permitted in a very short time to ensure the results by cross-checking the data on both model and to optimize the F-E system modification from a financial point of view.

PRESENTATION OF THE PIANC REPORT n°106 ON LOCKS

Ph. Rigo

Chairman of INCOM WG29, Prof. ULG-ANAST, Belgium

P. Hunter

Member of the INCOM WG29, HR Wallingford, UK

ABSTRACT: This introductory paper presents the PIANC report n° 106 (2009) on "Innovations in Navigation Lock Design". Main objectives and issues are highlighted in this paper. This PIANC report has been achieved by the INCOM Working Group 29 of PIANC from 2006 to 2009.

1 INTRODUCTION

Locks are key structures for the development of navigation in canals and in natural rivers where weirs regulate water levels to enable navigation. They may also be strategic infrastructure for port development.

In lower elevation regions, such as New Orleans and the Netherlands, locks are structures in dikes and also have an important task in flood defence.

In 1986, PIANC produced a comprehensive report of 445 pages on Locks (PIANC, 1986). For about twenty years this report has been considered as a world reference guideline, but it now needed updating to include new design techniques and concepts. PIANC decided in 2006 to launch a new Working Group (WG) to update the report, and this present report is the result.. The new report must be considered more as a complement to the 1986 report than a replacement version, and focuses on new design techniques and concepts that were not reported in the former report. It covers all the aspects of the design of a lock but does not duplicate the material included in the former report. Innovations and changes that have occurred since 1986 are the main target of the present report.

The core of this report has three major parts. The first part (Section 3) presents an exhaustive list of design goals associated with locks. This section is particularly important for decision makers who have to launch a new project. The second part (Section 4) reviews the design principles that must be considered by designers. This section is methodology oriented. The third part (Section 5) is technically oriented. All main technical aspects (hydraulics, structures, foundations, etc.) are reviewed, focussing on changes and innovations occurring since 1986. Perspectives and trends for the future are also listed. When appropriate, recommendations are listed.

Major changes since 1986 concern maintenance and operational aspects, and more specifically how to consider these criteria as goals for the conceptual and design stages of a lock. Renovation and rehabilitation of existing locks will be an increasingly important topic for the future.

In natural rivers, locks are usually associated with movable weirs, and in coastal areas with flood protection structures. In 2006 PIANC published the InCom-WG26 report "Design of Movable Weirs and Storm Surge Barriers" (PIANC 2006). That report can be considered as a companion report to the present report as locks and weirs have many design aspects in common. Some design aspects are not discussed in this report since they have already been developed in the InCom WG26 report on weirs (for instance: multi-criteria assessment for comparison of design alternatives, ...).

Section 2 of this report also includes more than 50 project reviews of existing (and planned) lock projects describing them and their innovative aspects. Some innovative and untested concepts are also mentioned as references although with no guarantee of validity.

2 AIMS OF THE INCOM-WG29 AND TERMS OF REFERENCE

The objectives of the InCom-WG29 were defined by the Terms of Reference (ToR) proposed by the

Inland Navigation Commission (InCom) and approved by the PIANC Executive Committee (ExCom) in late 2005. The ToR required establishing a comprehensive review of modern technologies and research results used to design and build navigation locks. A clear commitment was that only concepts and technologies not discussed in the previous PIANC 1986 report were to be considered and reported in this new report.

So, topics investigated here include:

a) Design objectives and optimization goals for locks
b) Innovative lock design concepts
c) Innovative technical solutions.

Recent lock projects of interest are listed, reviewed and analyzed.

Recommendations for studies needed at the conceptual and design stages of a lock are established.

In addition, maintenance and **operational** requirements are discussed and listed.

A detailed **reference list** is included in the new report. Documents were analysed and compared by the WG to give engineers, designers and authorities a reference list allowing them to access relevant information to solve their problems.

To assist continuity and to avoid duplication of existing PIANC material the former 1986 PIANC Report on Locks is included on the DVD attached to the report (Directory A3). In addition, its Table of Contents is printed in Annex I of the report. These should be used as support to this report and as a baseline of standard practice.

3 DVD of the PIANC REPORT n°106

Due to publishing constraints the number of pages of the PIANC n°106's hardcopy report was limited. Therefore additional information has been saved on a companion DVD (attached to the PIANC hardcopy report) - see list here after. Care should always be taken to use the current versions of standards and other publications that might supersede the versions on the DVD.

4 FUTURE WORKS

Continuing developments in lock design will be assisted by further PIANC WGs on related topics.

The WG155 on behaviour of ships in locks, the WG151 on seismic effects and ship impact on lock gates and the WG154 on design and operation of miter gates have started, and future other topics need to be prioritised.

The DVD of the PIANC Report 106 includes the following directories:

- A1: The Project Reviews of 56 lock projects.
- A2: PIANC 2009 Lock Report (pdf)
- A3: PIANC 1986 Lock Report (pdf) – in French and English
- A4: PIANC Dictionary on Locks & Waterways
- A5: LIST of LOCKS (Worldwide list)

- Additional information to various sections of this report (Directories B) such as:
  - B4.6.1: Salt Water Intrusion
  - B4.6.5: 3D Video Modelling of Construction Process
  - B5.2: Hydraulic (Manoeuvring, Fendering, ...)
  - B5.5: Gates and Valves
  - B5.7: Lock Equipment
  - B5.8.5: Lubricants and Bio Oils

- Various technical guidelines (Directories C) :
  - C1- Estoril'2006 - PIANC Congress Papers
  - C2- Beijing'2008 - AGA-2008 Papers.
  - C3- Navigation Lock - Ecluse de Navigation (by N.M Dehousse, 1985) in French
  - C4- Corps of Engineering, USA - Reports on Innovation
  - C5- Chinese Codes
  - C6- French Guidelines - Lubaqua (CETMEF)
  - C7- Fish Passage In Lock
  - C8- Corrosion Protection
  - C9- Planning of Lock Maintenance (example)
  - C10- European Code For Inland Waterways (CEVNI)
  - C11- Ship Impact
  - C12- Seismic Impact of Lock Gates
  - C13- ISPS Code 2003 - IMO (Safety and Security of Ship and Port)
  - C14- Panama Third Lock Lane
  - C15- Seine Nord Europe Canal (France)
  - C16- Three Gorges Locks, China
  - C17- Specifications for Lock Design (Lanaye Lock, Belgium)

A SELF-CONTAINED HIGH-LIFT LOCK WITH WATER SAVING BASINS

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ABSTRACT: This paper presents the concepts for a high lift lock with integrated water saving basins, which is planned to be fully self-contained, i.e. doesn't exchange water with the adjacent reaches.

1 INTRODUCTION

The Elbe Lateral Canal connects the port of Hamburg, located at the river Elbe, with the Mittelland Canal, one of the most important canals in the network in Germany. The Elbe Lateral Canal has to overcome a height difference of 61 m. This is done in two steps, first with a double ship lift at Scharnebeck with 38 m lift height, than with a lock with 23 m lift height at Uelzen (both finished in 1976). The latter was originally a single lock with 185 m usable length (Uelzen I) which was later extended (finished in 2006) with a second lock of slightly larger dimensions (190 m x 12.5 m). Due to the increase in both traffic and typical ship length, the rather short caissons of the ship lift (100 m usable length) are no longer sufficient. Thus, investigations were started by the local planning authority (Neubauamt Hannover, NBA-H), whether an additional ship lift or instead a lock with water saving basins would be the most viable addition to the old ship lift.

2 HYDRAULIC CONCEPT

In the last two decades, several locks with water saving basins in Germany have been built with a filling-emptying system which is based on a pressure chamber beneath the lock chamber for the fluid distribution. This system was shortly described in PIANC Report 106 "Innovations in navigation lock design". At the time given, this system can be regarded as a de-facto standard in Germany for high lift locks with water saving basins. Figure 1 shows the permanent formwork for the nozzles, which connect the equlibrating pressure chamber with the lock chamber.

Picture 1: Permanent formwork for the pressure chamber of Sülfeld lock

Already in the 1960s, in the planning phase for the Elbe Lateral Canal, the Federal Waterways Research Institute (BAW) researched the possibility to build a lock at the place where later the ship lift was built. A concept was derived for a lock with six layers of integrated water saving basins (thus saving ~71% of the water). Due to the fact that surge waves in the canal had to be reduced, additional basins were placed in the construction for storing the residual water (which normally would be taken from or given into the canal). These basins (at the bottom and at the top) were connected with a pump network, which pumps the water back during the locking process. This lock was tested as a laboratory model in the BAW and the final report (1968) states that it would be possible to fill a self-contained lock

with 38 m lift height in ~14 minutes. It must be stressed that the filling time was optimized to its maximum, because of the concurrency situation against a ship lift (which later was chosen for realization). I.e. the culverts to the water saving basins were of extraordinary size, the valves were operated with very fast overlapping schedules etc.. These investigations showed the general feasibility of the concept and were the basis for the recent considerations.

3 RECENT INVESTIGATIONS

Based on the investigations from the sixties and the newer locks with pressure chamber filling system, the NBA-H and the BAW started to investigate the possibility to construct a larger self-contained lock next to the smaller ship lift of Scharnebeck. At the time given, the concept features eight to twelve saving basins (subject to financial optimization) and two additional exchange basins for the residual water in an integrated construction ("O" and "U" in Figure 2). For the system both symmetric and asymmetric placement of the water saving basins has been considered. It was decided that a symmetric placement leaves too little space for the concrete construction between the layers of the water saving basins. Due to considerations about fault conditions (i.e. direct connection of a water saving basin to the upstream reach) the more sturdy construction with asymmetric basins was selected.

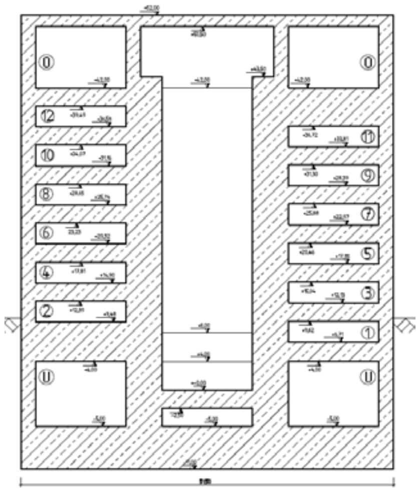

Figure 2: Cross-section of the lock with integrated water saving and exchange basins

The lock will have an usable length of 225 m and a width of 12.5 m. The upstream water table is at 42 m over mean sea level (MSL), the downstream water table varies between 4 m+MSL and 8 m+MSL.

For this system, initial calculations of the hydraulic system were performed. These show that the feasibility of the concept for the larger dimensions is given, too. An acceptable filling time of 20-28 minutes was achieved for different dimensions of the filling system.

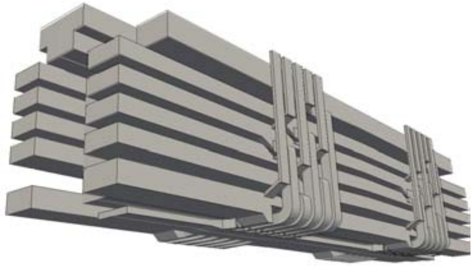

Figure 3: Hydraulically relevant surfaces of the lock

Figure 3 shows the hydraulic system, here in a variant with eight layers of water saving basins (staggered on left and right side of the chamber) and two culverts per basin.

In this presentation the basic constraints, the developed system and the achieved results of the preliminary hydraulic tests will be presented.

INNOVATION in LOCK FILLING and EMPTYING SYSTEMS

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ABSTRACT: The U.S. Army Corps of Engineers is planning navigation improvements for many projects to meet predicted increases in tow traffic. Some of these improvements include the addition or replacement of the navigation lock. Innovative design and construction techniques are being investigated to try and reduce construction costs as well as operation and maintenance costs. Two locks employing the In-Chamber Longitudinal Culvert System (ILCS) have recently been constructed. Both the new McAlpine Lock on the Ohio River and the new Marmet Lock on the Kanawha River are ILCS designs. This paper overviews features of the new locks and provides essential ILCS design guidance. A list of references is given for design details such as culvert location; port size, location, and spacing; port extensions; culvert-roof overhang; and wall baffles.

1 BACKGROUND

The U.S. Army Corps of Engineers (USACE) is in the planning, design, and construction phase of several lock improvement projects. These improvements, needed to meet future traffic increases on waterways of the United States, consist of lock additions, lock enlargements and/or repairs to existing locks. New designs are being considered for these projects to save construction, and operation and maintenance costs. Various lock extension ideas have been proposed to retrofit existing 180-m auxiliary locks to 360-m chambers. Ohio River projects are considering addition of culverts within the chamber of extended auxiliary locks. Mississippi River projects are developing ways to add a lock while minimizing traffic interruptions during construction. These novel designs have been tested in site-specific physical models of the particular projects, but no generalized design guidance has been extracted from the studies.

Two of the newest locks constructed by the USACE have employed the innovative In-chamber Longitudinal Culvert System (ILCS). Both the new McAlpine Lock on the Ohio River and the new Marmet Lock on the Kanawha River are ILCS designs. The ILCS was developed as part of research conducted by the USACE at the Engineering Research and Development Center (Hite and Stockstill 2004, Hite 2003, and Stockstill 1998).

While the ILCS was mentioned in a paper presented at the previous PIANC "Innovations in Navigation Lock Design" workshop (J. Webb, Paper 5, part A), the current paper provides ILCS hydraulic design guidance. The paper also describes project features such as intake manifolds and valve configurations found on the McAlpine and Marmet Locks.

The primary metrics for evaluation of a lock's hydraulic performance is operation time and hawser forces. USACE guidance limits hawser forces during operation to a maximum of 4.5 t (metric tons) (USACE 2006 and 1995). The allowable hawser force can be viewed in terms of water-surface slope. The water-surface slope that produces a 4.5 t hydrostatic force on a 3-wide by 5-long flotilla of jumbo barges (each 59.4 m long by 10.7 m wide) drafted at 2.7 m, moored in a nominal 360-m by 33.5-m lock is 0.0002.

2 INTAKE MANIFOLDS

The intake is designed for hydraulic efficiency while limiting the tendency of vortex formation. The original ILCS design concept used "through the sill" intake and outlet configurations. Butterfly valves located on the face of the intake ports were used to control the flow. Maintenance concerns ruled out

the submerged valve idea and the valves were relocated to the miter gate monoliths. The Marmet Lock intakes are in the sill and the culverts curve outward so that the vertical lift valves are outside the chamber walls. The McAlpine design has more conventional wall intakes although the design is unsymetrical.

Fig 1: Intakes at new McAlpine Lock during construction

3 FILLING AND EMPTYING MANIFOLDS

The design pools (lift) and expected operation times for each project are given from hydrologic and economic studies, respectively. The culvert size is set by the lift and target operation time. Culvert manifolds are designed to provide uniform flow distribution and dissipation of port jet energy. Good flow distribution along the lock chamber length is required to limit the longitudinal water-surface slope. Jet energy reduction reduces chamber water surface roughness which leads to safer navigation for smaller craft.

Hydraulic efficiency of locks can be quantified with the dimensionless lock coefficient. The lock coefficient gages the efficiency integrated over the operation cycle including the effects of inertia, valve characteristics, and head losses in the culverts, intakes, discharge ports, and valves. This coefficient provides a convenient means of comparing differing lock systems, sizes, and lifts. An ILCS may require larger culverts than a comparable side-port system because it is less efficient (Hite and Stockstill 2004). This is particularly true for filling operations where the lock coefficient is about 0.72 for the side-port systems and about 0.64 for the ILCS.

The main hydraulic features of the ILCS are the longitudinal culverts, ports, port extensions, and wall baffles. A practical port size is 0.381 m wide by 1.067 m high (Stockstill 1998). The ports should be located within the middle half of the chamber lengthwise and with half the total number of ports centered about the third points lengthwise of the chamber. Port extensions are provided on the upper ports to direct flow toward the center of the chamber. Ports on the opposite culverts should be staggered. The location of the port groupings affects the port spacing. The ports should be spread over as much of the lock chamber length as possible yet close enough to maintain even distribution of port flow along the culvert. The number of ports is such that the sum of the port areas is equal to about 0.97 times the culvert area. Wall baffles are used to diffuse the port jets at the lock chamber floor.

Fig 2: In-chamber longitudinal culverts, McAlpine Lock

4 VALVE INFORMATION

Experiments were performed with three types of valves. Butterfly valves were used in the experiments conducted by Stockstill (1998), vertical lift valves were used in the study by Hite (1999), and reverse tainter valves were used in Hite (2000). Each of these valves has slightly different operating characteristics. Valve operations directly affect the lock chamber performance. Variable speed valve operations, wherein the valve is opened at a slower rate during the initial lock filling, reduces the hawser forces. Once there is cushion of water in the chamber, the valve speed can be increased.

Acceptable filling times and chamber performance for the ILCS have been achieved with normal valve speeds ranging from 4 to 8 min. Valve speeds faster than 4 min are not desirable especially for lifts over 4.6 m. Fast valve operations cause excessive downstream hawser forces shortly after the valve is opened. This is inherent in a longitudinal culvert where inertia causes the upper ports to flow first.

REFERENCES

Hite, J. E. 2003. "In-chamber Longitudinal Culvert Design for Lock Filling and Emptying System," *ERDC/CHL TR-03-8*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Hite, J. E. 2000. "New McAlpine Lock Filling and Emptying System, Ohio River, Kentucky," *ERDC/CHL TR-00-24*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Hite, J. E. 1999. "Model Study of Marmet Lock Filling and Emptying System, Kanawha River, West Virginia," *Technical Report CHL-99-8*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hite, J. E. and Stockstill, R. L. 2004. "Hydraulic Design of a Longitudinal Culvert for Lock Filling and Emptying Systems," *Journal of Hydraulic Engineering*, Vol. 130, No. 5, pp. 381-388.

Stockstill, R. L. 1998. "Innovative Lock Design, Report 1, Case Study, New McAlpine Lock Filling and Emptying System, Ohio River, Kentucky," *Technical Report INP-CHL-1*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers, 2006. "Hydraulic design of navigation locks," *Engineer Manual 1110-2-1604*, Washington, D.C.

U.S. Army Corps of Engineers, 1995. "Planning and design of navigation locks," *Engineer Manual 1110-2-2602*, Washington, D.C.

CONSTRUCTION METHODS

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ABSTRACT: This contribution reviews the construction methods developed and implemented since the publication of the 1986 PIANC Report on Locks and reported in PIANC report n°106 (2009). This section discussions additional means and methods of construction, particular improvements in "in-the-wet" construction thru the use of Ciasson Excavation, Heavy Lift and Float-in methods.

1 INTRODUCTION

Traditionally locks were constructed "In-The-Dry" by use of cofferdams, diversions or other means to allow construction using conventional construction means and methods. However, this method requires the time and expense to keep water from the site during construction. The cost of the diversion structure or cofferdam is significant and can add many months if not years to the construction schedule. This induces a larger footprint than the final lock requires with a consequent increase in environmental and real estate impacts. It also impacts access to the site by navigation.

In-the-wet construction methods have improved greatly over the last decade with improvements in underwater concrete placement and curing techniques, improvements in measurement and position systems and development of connection techniques and designs that allow high quality connections to be made underwater. As sites get more congested and navigation traffic grows – In-the-Wet construction allows the designer more flexibility in minimizing the construction impacts to navigation traffic.

2 IN-THE-WET CONSTRUCTION

All of the In-the-Wet construction methods begin with preparation of the foundation in advance of installation of the concrete or steel structures. Dredging is used to remove unsuitable material and to shape the bottom surface. Sheet pile walls, jet grouting or other methods can be used to prepare for a seepage cutoff connection to the future foundation. If the structure is pile founded the piles can be driven to final grade with an underwater hammer, the use of a follower or removable pile extension or by driving a longer pile than necessary and then cutting off the upper section of the piles after driving with a diver. A number of alternatives have been developed for the construction of the lock substructure, possibly including the superstructure as well. These technics include:

Float-in Construction. The structure is fabricated off-site either in a graving dock or on a floating drydock. It is designed to be buoyant on its own or to make use of supplemental buoyancy, such as an air bladder or an additional barge that is connected to the structure. After construction the structure is transported to the site on its own or placed on a barge and towed to the site. It is then moved into position using prepared alignment guides such as guide piles, dolphins or prepared anchors, or guides, such as horned guides. Water ballast is used to lower it into position and then connections to the foundation are made, typically via the placement of tremie concrete (concrete placed under water). The Braddock lock and dam is a good example of this technique.

Heavy Lift Construction. Heavy lift construction is similar to float-in, however the fabrication site needs to be near the final installation site, or the fabricated elements need to be small enough to place on a barge for transport to the final installation site. In this case the fabricated construction is not buoyant and a large crane is used to transport the unit from its construction or offloading site to its final position in the structure. The Olmsted dam is a good example of this technique.

3 PNEUMATİC CAİSSON METHOD

This method has been used for several projects in The Netherlands with good success. In this method the lock structure is built at the existing ground level and after completion – the ground is excavated from beneath the lock and is methodically lowered into its final position. This is not available for all lock construction because it requires a particular combination of subgrade conditions and topography. The Lith and Almere locks are good examples.

4 LOCAL COFFERBOXES

This technique allows for a very small dewatering footprint of a small element of the structure, such as a single lock wall monolith to allow construction to occur in the dry without the cost and expense of a full cofferdam.

5 CONSTRUCTİON MATERİALS

Several improvements in materials and component fabrication have also lead to advancement of construction over the last several decades. These include:

- Improvements in precast concrete components and connections
- RCC – Roller Compacted Concrete and its use in mass concrete
- Improvements in mix designs for underwater concrete placement
- New Light Weight Fill materials such as expanded polystyrene, expanded clay such as Argex,
- Fiber Reinforced concrete

6 CONCLUSİON

Many of the individual techniques and materials have been available for decades, but their acceptance and the broader acceptance of the viability, limitations and applicability have added greatly to the tools available to the engineer and contractor in the current design, construction, operation and maintenance of lock and dam structures today.

Computational Fluid Dynamics (CFD) in lock design: Progress and challenges

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ABSTRACT: Different types of numerical models are used nowadays in the hydraulic design of navigation locks. At the upper end in terms of physical complexity and computational effort, are the three-dimensional models based on the Navier-Stokes equations, usually referred to as CFD (Computational Fluid Dynamics) models. Here, a short overview is given of the main features, progress and challenges of CFD modelling for (lock) design purposes.

1 INTRODUCTION

During the first International PIANC Workshop on "Innovations in Navigation Lock Design" (Brussels, 15-17 October 2009) C. Thorenz (BAW, Federal Waterways Research Institute, Germany) gave an excellent overview of the state-of-the-art of Computational Fluid Dynamics in lock design (Thorenz, 2009).

Two years later, this contribution to the successor workshop (New Orleans, 13-14 September 2011) will dwell on the same theme, with some difference in focus.

Inevitably, the points of view expressed will be coloured by the specific background (De Mulder, 1997) and experience of the author, including other fields of application of fluid mechanics (than hydraulics and lock design) and other tools (than numerical models). As a consequence, it will **not** be **a mere apology** to the present or future capabilities of computational hydraulics (as is sometimes the case in similar overview papers) but an attempt to present a **more balanced view** upon progress and challenges.

2 TERMINOLOGY

For some people, **Computational Fluid Dynamics** is a generic term referring to all kinds of numerical simulation of fluid flow. A classification of the types of numerical models adopted in navigation lock design has been presented in (Thorenz, 2009), based on the spatial dimensionality of the models: zero-dimensional, one-dimensional, two-dimensional and three-dimensional.

For other people, however, the term Computational Fluid Dynamics - with acronym **CFD** - solely refers to the **three-dimensional models** which are based on the most general fluid dynamics equations, i.e. the **Navier-Stokes equations**.

In this paper, the term Computational Fluid Dynamics will have the latter connotation. Examples of CFD codes are: Fluent, CFX, Flow3D, Star-CD/Comet, OpenFOAM, NaSt3DGP (Thorenz, 2009), ADH (Stockstill, 2009),…

3 CFD MODELS: SOME FEATURES

3.1 Ingredients

First, some important **ingredients** of CFD modelling will be introduced:

- Velocity-pressure formulation
- Free surface modelling
- Turbulence modelling
- Boundary (and initial) conditions
- Mesh generation and optimization
- Fluid-structure interaction
- Numerical diffusion and dispersion
- Convergence
- Source code
- Computer platform
- CFD practitioner
- CFD client

Some of the ingredients will be separately commented upon in the following paragraphs. The issue of turbulence modelling will get the major attention. It should be clear from the onset, however, that most of the ingredients are **strongly coupled**.

3.2 Velocity-pressure formulation

Most hydraulic engineers are familiar to models for rivers, channels, estuaries,… which are governed by the so called **shallow water equations** (SWE). This approximation is valid the vertical acceleration is negligible, hence if the streamlines are only gently curved and the pressure varies quasi linearly over the water depth (i.e. a **hydrostatic pressure distribution**). The unknowns of an SWE model are the water depth and the (depth-averaged) velocity.

CFD models, however, are based on the more general **Navier-Stokes equations**, in which the pressure itself is an unknown, in addition to the (local) velocity, see e.g. Figure 1. As a consequence, flows characterized by **any pressure distribution** can be simulated by means of CFD codes, yet at the computational price of calculating (at every timestep) the complete pressure field.

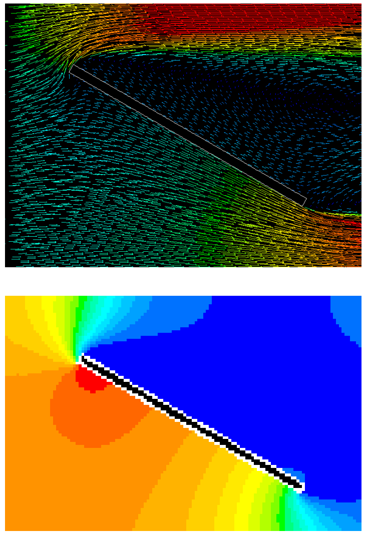

Figure 1 : Velocity vectors (top) and static pressure contours (bottom) around valve in culvert

3.3 Free surface modelling

Originally, CFD codes were developed for **internal, pressurized flow** (like e.g. Figure 1). Later on these codes were extended to be able to simulate **free surface flow**, again causing an increase of the computational effort and burden.

To mitigate the latter problems, often use is made of a "rigid lid" approximation.

Many experienced CFD practitioners come from outside the "open channel flow community". This can be an asset, but in case of free surface flow simulations it might lead to less correct estimates of "turn-around times" (which is detrimental in design processes) as well as to loss of accuracy.

3.4 Turbulence modelling

3.4.1 General overview

In principle all turbulent flows can be described by the Navier-Stokes equations, supplemented with proper boundary and initial conditions. Since most practical flow problems are characterized by large Reynolds numbers, there is a large ratio between the largest and the smallest turbulent length scales (eddies). As a consequence, the **Direct Numerical Simulation** (**DNS**) requires an extremely fine mesh size and timestep in order to resolve all scales (and large memory/storage). The corresponding computational cost is tremendous. Hence, DNS is only applicable in academia (i.e. for relative schematic flow domains with a relative low Reynolds number) and is not suited for engineering applications, let alone for design purposes.

Since many decades, it is common for engineering applications to rely upon the **Reynolds-averaged Navier-Stokes** equations (**RANS**), which allow (only) the time average flow to be resolved on the mesh. Due to the averaging procedure, however, the so called Reynolds stresses appear in the equations. Several classes of models are available to model these stresses, e.g.:

- **Reynolds Stress Models** (**RSM**), which lead to six extra scalar transport equations, i.e. one for each of the Reynolds stresses.
- **Eddy Viscosity Models** (**EVM**), which require less computational effort, i.e. the number of extra transport equations is generally reduced to two (or even one).

Thanks to the increase in computational speed and resources, **Large Eddy Simulation** (**LES**) is more and more being applied for engineering purposes. Contrary to DNS, only the large (energetic) eddies are resolved on the mesh in case of LES, leaving the subgrid scales to be modelled. LES is significantly less computationally expensive than DNS, though still a tremendous amount of grid points (hence computational effort) is required to fully resolve the viscous wall boundary layer. To mitigate this problem, research is going on nowadays to develop **hybrid LES/RANS** methods in which RANS models (and the corresponding flaws, cf. section 3.5) are relied upon near walls, whereas LES is adopted in the rest of the computational domain.

3.4.2 Two-equation models

Notwithstanding the progress in various other approaches to model turbulent flows, two-equation EVM are still the "workhorse" for engineering calculations (especially in a design context).

In EVM, the exchange of momentum due to turbulent eddies is modelled in analogy to the molecular exchange of momentum. This requires the definition of a turbulent or eddy viscosity ν_t [in m²/s] (in analogy to the kinematic viscosity ν of the fluid [in m²/s]). Based on dimensional reasoning and empiricism, the eddy viscosity is defined as the product of a turbulent velocity scale u [in m/s] and a turbulent length scale ℓ [in m], see Table 1. The most popular **two-equation** EVM are:

- the **k-ε model**, based on the turbulent kinetic energy (per unit weight) k [in m²/s²] and its dissipation rate ε [in m²/s³]
- the **k-ω model**, which is based on k and its specific dissipation rate ω [in 1/s].

Table 1. Definition of turbulent scales in two-equation Eddy Viscosity Models

model	turb.velocity scale u	turb.length scale ℓ
$k-\varepsilon$	$\sqrt{k}$	$k^{3/2}/\varepsilon$
$k-\omega$	$\sqrt{k}$	$k^{1/2}/\omega$

The empirical constants in the "standard" versions of the k-ε and k-ω models have been "tuned" for flat plate boundary layer flows. For other and more complex type of flows, important flaws have been observed. As a consequence, numerous ad hoc corrections and variant models have been developed. This is indicative of the search for something better and/or something more "universal".

3.4.3 Validation studies

To illustrate the relative strengths and weaknesses of numerical predictions based upon various turbulence models, the reader will be referred to some **benchmark cases** in **literature**:

- **plane/round free jet flow** (Bardina et al., 1997)
- **3D wall jet flow** (Launder & Rodi, 1983 ; Craft & Launder, 2001)
- **impinging jet flow** (Craft et al., 1993)
- **separated flow in a 2D diffuser** (Iaccarino, 2001)
- **separated flow in a 3D diffuser** (Cherry et al., 2006 ; Karvinen & Ahlstedt, 2008)
- **flow in 90° bends** (Crawford et al., 2009).

As is illustrated in Figure 2 to Figure 4 (cf. infra), the selected benchmark cases are relevant for lock design, i.e. for prediction of head losses in components of the filling-emptying system or the water flow in the lock chamber and even the hydrodynamic forces on a vessel.

From the abovementioned validation studies, it can be concluded that there might be significant **discrepancies between** the **numerical predictions and** the **experimental data** (making abstraction of the intrinsic accuracy of the latter, which is – unfortunately – rarely quantified in validation papers). In addition, it turns out that there is **no single turbulence model** that **is superior** to others for all types of flow. Hence, one could say that turbulence modelling is still not (and will never be ?) a mature domain.

Moreover, the **quality** of a numerical prediction is not only related to the choice of the turbulence model, but **also depends on** various **other "ingredients"** (e.g. the wall treatment, the numerical parameters etc.). Hence, thinking of turbulence model selection in terms of "an Olympics" is pointless.

Nevertheless, it is a burden for the CFD practitioner to choose amongst the available turbulence models in his/her code. On the other hand, it is strongly recommended to exploit this feature and carry out a **sensitivity analysis** by adopting more than one model.

For the sake of completeness, it should be mentioned that **many practical flows** are highly 3D and are to a large extent **governed by inviscid pressure driven structures**. For such type of flows, turbulence stresses (hence turbulence modelling) become less important.

3.5 Boundary conditions

In any numerical model, the computational domain has to be constrained somewhere, i.e. boundaries have to be defined and the influence of

the "outside world" onto the flow domain has to be expressed by means of conditions imposed at the domain boundaries.

The definition of the **boundaries** and the associated **boundary conditions** need to be given sufficient consideration, since the (quality of the) solution depends to a great extent on them (and not only of the governing equations).

In a CFD code, several types of boundary conditions are available. The CFD practitioner should be aware that some conditions assume **idealized types of flow** (like e.g. fully developed flow) at a given boundary. Sometimes the assumed flow type is not realizable in the simulation, because the flow domain has been constrained too much (in order to minimize the computational efforts).

Special attention should be given to the treatment of (no slip) **wall boundaries** from the point of view of **turbulence modelling**. Close to a wall, the turbulence tends to zero in the viscous boundary layer. Fully resolving the latter layer requires an extremely fine mesh and requires that the "traditional" **two-equation turbulence models** (k-ε, k-ω,…) need to be modified into so called low-Reynolds number versions, since the "traditional" versions are only valid in regions of developed turbulence. To bypass these "problems", so called "universal" **wall functions** have been developed. One should be aware that this "trick" implicitly assumes that the first mesh point nearest to the wall is situated outside the viscous sublayer, i.e. in a (local equilibrium) turbulent boundary layer for which the velocity profile is known to be described by a "universal" (log-law) function of the distance to the wall. It is obvious that in complex near-wall flows (with strong pressure gradients or complex strains) this is not always a good approximation. Moreover, the wall function approach ideally requires the flow to be known into advance, i.e. at the moment of mesh generation. For the sake of completeness, one should add that more advanced wall function approaches have been proposed in literature, attempting to overcome some of the weaknesses of the classical approach.

It is good to know that even when "more advanced" turbulence models – like **RSM** and even **LES** – are adopted for engineering applications, similar wall treatment approaches – with rather comparable flaws – are relied upon.

3.6 Mesh generation and optimization

The mesh (or grid) defines the subdomains in which the flow domain is discretized, hence the discrete points in which the (finite number of) unknowns of the flow problem will be calculated for.

The **finer** the **mesh** size (for a given flow domain), the **more unknowns**, hence the **larger** the **computational effort**. Very often, CFD practitioners generate one mesh that is "felt" to be both sufficiently fine to guarantee an acceptable quality of the results and sufficiently coarse to allow fast turn-around times. Especially in design processes, the **grid dependency of** the **results** is rarely verified, whereas in validation studies the mesh resolution is shown to have a significant impact on the predicted values (e.g. Karivenen & Ahlstedt, 2008 ; Thorenz, 2009).

In case of applications with a large range of spatial scales, local grid refinement (e.g. in areas with strong gradients in flow variables) is often sufficient (as opposed to a global mesh refinement throughout the flow domain, which leads to a drastic increase in computational effort). From this point of view, **unstructured grids** including adaptive grid refinement can be advantageous (see e.g. Stockstill, 2009).

Another aspect which is often overlooked is that a **mesh** does not only have to be **generated** – which can be quite a time-consuming job, especially in case of complex flow domains – but might also need some **mesh optimization** in order not to degrade the accuracy of the results due to lack of smoothness (i.e. a sudden transition from fine to coarse mesh cells), too "skew" mesh cells, etc.

3.7 Numerical diffusion and dispersion

In a CFD code, partial differential equations are solved in discretized form. Several "schemes" are available to approximate the distinct terms (advection, diffusion etc.) in the governing equations.

Some discretization schemes for the advection terms introduce large amounts of "numerical" – i.e. spurious – diffusion, which adds up to the "physical" – i.e. real – diffusion expressed by the diffusion terms in the transport equations. As a consequence, **gradients** in the solution are excessively **"smeared out"** and the amplitude of wave components gets excessively damped.

Likewise, some discretization schemes suffer from numerical dispersion, which means that the numerical propagation speed of wave components differs from the physical one, and **spurious oscillations** in variables might appear.

In some codes, the CFD practitioner can select **alternative discretization schemes**, and consequently have impact onto the amount of numerical diffusion and dispersion. One should point out that the amount of numerical diffusion and dispersion also depends on the mesh size and timestep selected by the CFD practitioner.

3.8 Convergence

In a CFD code, (at every timestep) a set of **coupled, non-linear equations** has to be solved. This requires an **iterative solution technique** in which the successive approximations to the "final" solution should (after a sufficient number of iterations) gradually become closer - i.e. "converge" - to the latter.

To **monitor** the convergence process, at every iteration some numerical indicators (e.g. the "residuals" of the equations) are put at the disposal of the CFD practitioner. However, the rate at which numerical parameters (i.e. the indicators) converge can be different from the ones of physical parameters (like e.g. pressure coefficients or head loss coefficients).

The higher the degree of nonlinearities and coupling in the set of equations, the more difficult the convergence process might be. As a consequence, the particular choice of e.g. a turbulence model or a free surface model, might influence the convergence rate.

Sometimes the **convergence** process in a CFD simulation is **slow or** even **stalled**. If in these circumstances the iterative process is stopped "prematurely", one should be aware that the "best" approximate solution which is available at that instant, still might deviate significantly from the (yet unknown) "fully converged" solution.

3.9 CFD practitioner

From the foregoing sections, it is obvious that the role of the CFD practitioner is extremely important. The **selection of** the CFD code **"ingredients"** directly influences both the **quality** of the predictions and the associated **computational efforts** (CPU time and memory requirements).

A fair trade-off needs to be found, for every single CFD application.

3.10 CFD client

Section 3.9 implies that the CFD client also has an extremely important role. If too tight **time constraints** are imposed on the CFD practitioner, it might (unintentionally) lead to lower quality results.

Moreover, if the CFD client can not (directly or indirectly) provide **experimental data** for his/her application at stake, a proper judgement of the quality might not be feasible.

In short, the CFD client should play a **critical** but **constructive** role in order to make CFD become something else than "Colourful Fluid Dynamics".

3.11 Closure

An important lesson to keep in mind is that CFD is synonymous to **large computational efforts,** even if "ingredients" are chosen which somewhat minimize the effort.

It is obvious that the higher the physical complexity that is required, the higher the computational effort will be.

Of course, thanks to tremendous evolutions in hardware and software, nowadays simulations are possible which were considered prohibitive a number of years ago.

Making abstraction of specialist discussions on how fast the computational power will exactly increase over the coming decades, a naïve belief that this will solve all problems and lead to perfect predictability is not advocated.

Moreover, advanced models which are applicable in a **(fundamental) research** context, are not always an option for **design** purposes, where the emphasis is on **simplicity**, computational **speed**, and **robustness**.

4 USE OF CFD IN DESIGN

4.1 Aeronautical design

It is often instructive to enlarge one's angle of view. Therefore, the situation in **aerodynamics** and **aeronautical design** will first be briefly reviewed, based upon the information provided in (Deconinck et al., 2003) .

Aeronautics has always been (and still is) an important driving force for developments in advanced numerical (flow) modelling, According to (Sermeus & Deconinck, 2003) **CFD** is **not yet a mature technology**, at least not in the way that Computational Structure Mechanics (CSM) and Computer Aided Engineering (CAD) are. The underlying reason is that CFD has to deal with multiple length scales, turbulence and (sometimes) chemical reactions, which require complex physical models and significantly greater computer resources. Consequently, **CFD** is **not yet** a **component of** an **integrated virtual prototype environment** used by an aircraft design engineer, but CFD simulations are

carried out by highly-specialized CFD practitioners, who are well experienced in making grids that are tailored to the flow problem and in calibrating their physical models to get an acceptable answer.

A more effective use of CFD tools in the aerodynamic design process requires the **computational and manpower costs** to become acceptable, but it is also a matter of being able to ensure a **sufficient and known level of accuracy**.

A large body of fundamental **research** in CFD deals with the eternal quest for better, like e.g. more accurate discretization methods, and with the development of ever more refined physical models, most notably turbulence models. Before new methods and models can be accepted, however, questions concerning with **accuracy**, **reliability** and **efficiency** must be answered, **in absolute terms** and/or **in relative terms** with respect to existing methods and models, before they can be used with confidence.

In terms of **accuracy**, the **customer requirements** in this field of engineering are rather **high**: predictions of e.g. the drag coefficient of an airplane should be possible within ± 0.0001. The critical "ingredients" to achieve this goal (sooner or later) by means of CFD based predictions, are according to (Van Dam, 2003):

- computational models that include all the pertinent geometrical details
- large meshes with high grid resolutions in relevant areas of the flow field
- well-developed numerical solvers that don't swamp the flow solutions with numerical diffusion
- fully-converged numerical solutions
- boundary-layer transition locations that match those encountered on the real configurations
- turbulence models that are validated for the flows that are encountered
- employing a drag evaluation methodology that is complete.

Note that this list contains virtually the same elements as the "ingredients" discussed in section 3.1 of this paper.

4.2 Lock design

The situation in **lock design** is to a great extent comparable to the one in aeronautical design, though the requested predictive accuracy in case of lock design might in general be called somewhat less ambitious. Moreover, the prototype under design is virtually always unique and does not give rise to mass production.

The lock designs in which the author was involved, are mainly situated in Belgium/Flanders. There, the role of CFD is still limited, but growing.

Yet, the involvement as an hydraulic consultant to the Autoridad del Canal de Panama (ACP) during the conceptual design of the **third set of Panama Canal locks** by Consorcio Pos-Panamax (CPP) – see e.g. (Roumieu et al., 2008) ; (Roux et al., 2010) – as well as during the design by Consultores Internacionales (CICP) on behalf of Grupo Unidos por el Canal (GUPC) – see e.g. (Roux & Badano, 2011) – also offers a valuable source of information with respect to current use of CFD ; some illustrations thereof are given in Figure 2 to Figure 4. Of course, additional information is also drawn from literature (e.g. Stockstill et al., 2005 ; Stockstill, 2009 ; Hammack & Stockstill, 2009 ; Thorenz, 2010).

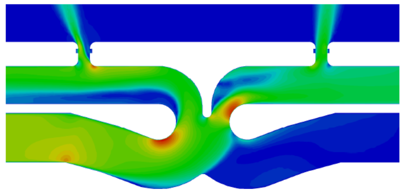

Figure 2 : CFD flow simulation in component of filling-emptying system (Courtesy: GUPC/CICP)

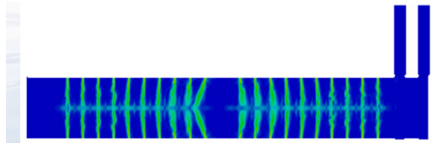

Figure 3 : CFD flow simulation in lock chamber (Courtesy: GUPC/CICP)

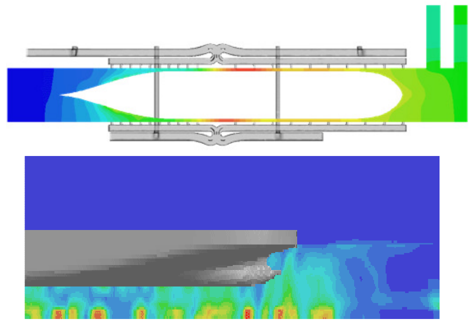

Figure 4 : CFD flow simulation around vessel in lock chamber (Courtesy: CPP)

There is no doubt that **CFD can nowadays contribute to lock design**, e.g. for prediction of head losses in (geometrically complex) components of the filling-emptying system, though complete predictions of hydrodynamic forces on ships in the lock chamber ("hawser forces") and moving bodies (like e.g. valves) are still somewhat beyond reach for design (and certainly for conceptual design) purposes.

Yet, especially the combined use of **numerical models** – including CFD – and **physical models**, seems to be a powerful **"hybrid" methodology** for the hydraulic design of navigation locks, see e.g. (Hiver, 2009) and (Roux & Badano, 2011). CFD can e.g. assist in the set-up of physical models.

Hybrid modelling also allows to minimize the time (and money) needed to achieve a design which meets specific hydraulic performance criteria.

CFD can also provide continuous information in the flow domain, yielding a more comprehensive set of flow parameters than the information in discrete (measurement) points gathered in a laboratory study. This is beneficial for analysis of the phenomena and for trouble-shooting.

Moreover, cross-checking of physical and numerical model results contributes to the confidence in the design. Physical models indeed provide an additional **trust** factor because they have been used for so long by hydraulic engineers, are palpable and visible to all observers.

The question arises as to what is the use of CFD in (conceptual) designs of locks for which (because of various reasons) no physical modelling is adopted. In order to gain confidence in the potential role of CFD in those circumstances, it would be wise if the "CFD community" were to devote more efforts to **quantification of** the **uncertainty** of CFD simulations, rather than concentrating (solely) on extending the scope of applications (in terms of geometrical, physical and computational complexity). For design purposes, it is indeed of utmost importance to rely upon tools which have a known and acceptable **accuracy**, for a given amount of acceptable (computational and manpower) **costs**.

Of course, this requires e.g. the availability of reliable and relevant experimental **benchmark** data, collected either by means of laboratory studies or prototype measurements. It is true that in literature (both inside and outside hydraulic engineering) numerous validation studies have already been published (see also section 3.4.3), but best practice would be that every **CFD practitioner** feels impelled to take up this (lifelong ?) task, fully aware that accuracy is an intricate function of (particular) choices of all the "ingredients" listed in section 3.1.

Though uncertainty quantification is more common in the experimental community - and tradition is at their side - it is hoped that the aforementioned efforts needed for CFD validation would also inspire the **physical modelers** to critically reflect upon the influence of their (particular) choices of "ingredients" on to the accuracy of the "physical model predictions".

5 CONCLUDING REMARKS

CFD modelling is certainly useful in hydraulic design of navigation locks. Its role will increase in future, without making physical modelling or lower-dimensional numerical models obsolete. However, a prerequisite is that more efforts are devoted to validation and uncertainty quantification. The key to reliable predictions remains that the CFD practitioner has a sufficient **knowledge of the flow solver and** - above all - of **the flow phenomena**.

Of course, even when these conditions are fulfilled, the question remains whether current **design criteria** (e.g. with respect to "hawser forces"), against which model predictions are to be compared, are sufficiently adequate and well-founded (especially in case of new or non-standard situations) to guarantee a safe, a comfortable and an economic lock design (see e.g. De Mulder, 2009 ; De Mulder et al., 2010). In this respect, it seems logic to invest more in prototype observations and measurements, as well as in "tests at prototype scale" (e.g. investigating alternative valve opening/closing laws in existing locks). Due attention should also be given to enquiries of important "stakeholders", such as pilots/skippers and lockmasters.

With respect to design criteria and how they should be verified, it is hoped that the newly erected **PIANC Working Group 155** will set the course.

6 REFERENCES

Bardina, J.E., Huang, P.G. & Coakley, T.J. (1997). Turbulence modelling validation, testing, and development. NASA Technical Memorandum 110446, April 1997, 98 p.

Cherry, E.M., Iaccarino, G., Elkins, C.J. & Eaton, J.K. (2006). Separated flow in a three-dimensional diffuser: preliminary validation. Annual Research Briefs, Center for Turbulence Research, p. 31-40.

Craft, T.J., Graham, L.J.W. & Launder, B.E. (1993). Impinging jet studies for turbulence model assessment – II. An examination of the performance of four turbulence models, International Journal of Heat and Mass Transfer, Vol. 36, Issue 10, p. 2685-2697.

Craft, T.J. & Launder, B.E. (2001). On the spreading mechanism of the three-dimensional turbulent wall jet. Journal of Fluid Mechanics, vol. 435, p. 305-326.

Crawford, N., Spence, S., Simpson, A., Cunningham, G. (2009). A numerical investigation of the flow structures and losses for turbulent flow in 90° elbow bends. Proc. of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, Vol. 223, p. 27-44.

Deconinck, H., Sermeus, K. & van Dam, C. (2003) (editors). CFD-based aircraft drag prediction and reduction. Proceedings of VKI Lectures Series 2003-02, von Karman Institute for Fluid Dynamics.

De Mulder, T. (1997). Stabilized finite element methods for turbulent incompressible single-phase and dispersed two-phase flows. Ph.D. thesis. Cath.University Leuven & von Karman Institute for Fluid Dynamics.

De Mulder, T. (2009). Mooring forces and ship behaviour in navigation locks. Paper 7 in International Workshop on "Innovations in Navigation Lock Design", PIANC-Brussels-Belgium, 15-17 Oct. 2009.

De Mulder, T., Verelst, K., Vercruysse, J., De Cock, W. & Haegeman, M. (2010). On hawser force criteria for navigation lock design: Case study of maritime locks in Port of Antwerp. Paper 290 in PIANC MMX Congress, Liverpool-UK, 10-14 May 2010.

Hammack, E.A. & Stockstill, R.L. (2009). Evaluation of a lock culvert valve using a computational flow model. Proceedings of 33rd IAHR Congress: Water Engineering for a Sustainable Environment, p. 1092-1099.

Hiver, J.-M. (2009). Numerical simulations and experimental models: how to choose ?. Paper 11 in International Workshop on "Innovations in Navigation Lock Design", PIANC-Brussels-Belgium, 15-17 Oct. 2009.

Iaccarino G. (2001). Predictions of a turbulent separated flow using commercial CFD codes. Journal of Fluids Engineering, Vol. 123, No. 4, p. 819-828.

Karvinen, A. & Ahlstedt, H. (2008). Comparison of turbulence models in case of three-dimensional diffuser. Proceedings of Open Source CFD International Conference 2008, Berlin, Germany, 4-5 December 2008, 17 p.

Launder, B.E. & Rodi, W. (1983). The turbulent wall jet – measurements and modelling. Annual Review of Fluid Mechanics, Vol. 15, p. 429-459.

Leschziner, M.A. (2003). Turbulence modelling for aeronautical flows. Proceedings of VKI Lectures Series 2003-02 on CFD-based aircraft drag prediction and reduction. von Karman Institute for Fluid Dynamics.

Roumieu, P., Roux, S., De Mulder, T., De Regge, J. & Wong, J. (2008). Physical model for the emptying and filling system of the third set of Panama locks. Pages 531-545 in proceedings of International Navigation Seminar following PIANC AGA 2008, Beijing-China.

Roux, S., Roumieu, P., De Mulder, T., Vantorre, M., De Regge, J. & Wong, J. (2010). Determination of hawser forces using numerical and physical models for the third set of Panama locks studies Paper 151 in PIANC MMX Congress, Liverpool-UK, 10-14 May 2010.

Roux, S. & Badano, N. (2011). The Panama Locks - Numerical simulations & experimental models: the experience of the new Panama model. 2nd International Workshop on "What's new in the Design of Navigation Locks", PIANC-New Orleans-USA, 13-14 Sep. 2011.

Sermeus, K. & Deconinck, H. (2003). Drag prediction validation of a multi-dimensional upwind solver. Proceedings of VKI Lectures Series 2003-02 on CFD-based aircraft drag prediction and reduction. Von Karman Institute for Fluid Dynamics.

Stockstill, R.L., Berger, R.C. & Hite, J.E. Jr. (2005). Application of computational hydraulics for the evaluation of navigation structures. PIANC Magazine n° 119, April 2005, pages 31-35.

Stockstill, R.L. (2009). Computational model of a lock filling system. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IX-18. Vicksburg, MS. U.S. Army Engineer Research and Development Center.

Thorenz, C. (2009). Computational Fluid Dynamics in lock design – State of the art. Paper 10 in International Workshop on "Innovations in Navigation Lock Design", PIANC-Brussels, 15-17 Oct. 2009.

Thorenz, C. (2010). Numerical evaluation of filling and emptying systems for the new Panama Canal locks. Paper 77 in PIANC MMX Congress, Liverpool-UK, 10-14 May 2010.

Van Dam, C.P. (2003). Critical factors in CFD-based drag prediction. Proceedings of VKI Lectures Series 2003-02 on CFD-based aircraft drag prediction and reduction. Von Karman Institute for Fluid Dynamics.

USE of SYNTHETIC MATERIALS and the COMEBACK of SLIDING GATES VERSUS ROLLING GATES

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SUMMARY: Designers and constructors of navigation lock gates and other hydraulic structures have more and more high-tech synthetic materials at their disposal. Those materials often improve the performances of hydraulic gates and extend their service life. This introductive paper contains an outline of the presentation on this issue given by the authors on the 2nd International Workshop "What's new in the design of navigation locks" in New Orleans, LA, in September 2011.

1 INTRODUCTION

Developments in material technology introduce new chances for lock gate design and engineering. Perhaps the most spectacular is the breakthrough of synthetic materials. These materials are in two ways increasingly interesting in lock gate design:

- as materials of entire gate structures;
- as materials of some crucial components.

This presentation gives an overview of the latest gate designs employing synthetic materials in both mentioned ways. The authors represent public and private sector in the Netherlands – a country of the most intensive inland and sea navigation in Europe.

2 GATES OF SYNTHETIC MATERIALS

The materials which can be used for constructing entire gates are fiber reinforced polymers (FRP's). Compared to e.g. structural steel, the advantages of these materials for gate design are mainly:

- high strength;
- low maintenance (no corrosion);
- favorable environmental properties.

Both advantages are discussed in the presentation. This does not mean that FRP's can someday replace steel entirely; they also have disadvantages like high price and relatively low elesticity module. But the share of FRP's in gate construction wil likely grow in the comming years.

In the Netherlands, one navigation lock already operates with miter gates constructed of FRP's (Fig. 1). There are plans to construct other, larger FRP gates, e.g. a 30 m wide vertical lift gate in the new complex of sluices in the Afsluitdijk dam. These and other examples are included in the presentation.

Fig. 1. FRP gate of a lock near Werkendam

3 SYNTHETIC HINGES AND OTHER DETAILS

As synthetic materials in general and FRP's in particular are fully engineered materials, they have a potency to meet high mechanical requirements. This is especially interesting in heavily loaded details like pivots, hinges, tracks, front and heel post linings etc. In the Netherlands, two families of synthetics are particularly successful in this field:

- Reinforced thermoset resins with additives;
- High molecular polyethylene, e.g. UHMPE (also abbreviated UHMWPE or UHMW).

Other synthetics, like PTFE, polyamide, diverse polymer alloys – reinforced or not – are also "in the lift", but in a less spectacular manner. Yet, this can possibly change because there is much development going on in this field.

While UHMPE successfully performs e.g. in slide tracks of rolling and vertical lift gates (Fig. 2, left), the reinforced thermosets win ground in heavily loaded gate pivots and other bearings (Fig. 2 right). In both cases, however, the engineers should take account of some phenomena and material properties which substantially differ from conventional tracks and bearings employing metallic contacts. This issue is highlighted in the presentation.

Fig. 2. UHMPE guides of the Hartel Canal Barrier and Tenmat® pivot bushings of the Naviduct miter gates, Enkhuizen

4 SHARING THE KNOW-HOW

The experience in synthetic material applications that was collected by Dutch engineers has broadly been used in other countries. An example is two spectacular recent projects: the Malamocco Lock in Venice, Italy, and the rolling gates of the new set of locks in the Panama Canal.

The combination of stainless steel or Titan and UHMPE at the interface of the fixed and moving part of gates and valves provides excellent durability and low wear. If the proper combination and surface condition is chosen, guide tracks can be designed entirely maintenance free.

In the design of the Malamocco Lock in Venice, the vertical loads from the sliding gates are carried by a UHMPE track. The two sliders are constructed as hydro-feet: During the movement, water is pumped at high pressure through four separate canals to the area under the hydro-foot, lifting it a fraction of a millimeter from the track. The film of water between the track and hydro-foot serves as lubrication, leading to extremely low friction values. As friction is a major component in the total drive force, the reduction of it can reduce the required capacity of the drive system. This is benificial both at the moment of construction (direct cost), but also during the life of the system (maintenance costs), because it limits the energy consumption. With the smaller machinery, spare parts are also smaller. These advantages have been confirmed in practice on the sliding gates of the Prince Willem-Alexander Lock in Amsterdam.

The horizontal guide and bearing surfaces for the Venice as well as the Panama Canal gates consist of a combination of UHMPE and stainless steel.

The choice of the position of materials is usually driven by direct investment costs and maintenance costs. A lay-out with UHMPE as sliding track and stainless steel sliders gives such limited wear, that this situation has the best life cycle ecomomics. However, there are often other design criteria, such as the limitation of leakage and constructability, that can influence this choice.

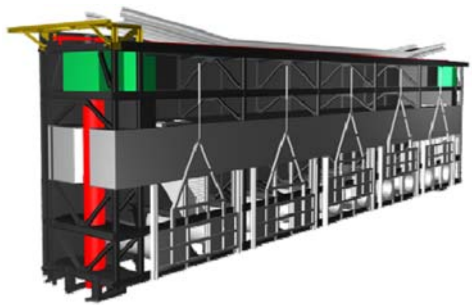

Fig. 3. Lay-out of Malamocco Lock gate in Venice, showing one hydro-foot tube in red.

4 CONCLUSIONS

The applications of high-tech synthetic materials form a strong tendency in hydraulic gate projects. The advantages of these materials are undenyable and have been proved in practice. We will likely see a growing number of such applications in the nearest future. New materials make it also possible to apply new structural principles and systems. One of them is the replacement of traditional rolling supports (in both rolling and vertical lift gates) by slide supports - a step that significantly reduces the construction and maintenance costs of hydraulic projects.

NEW MATERIALS AND SYSTEMS IN THE DESIGN OF MITER GATES

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SUMMARY: Favored by both ship captains and lock operators, miter gates are the most frequently used gate system in the world. Nonetheless, also miter gates have their limitations. Going beyond them requires the courage to apply new, modern materials and to perform some system modifications. This introductory paper draws the main tendencies in innovative miter gate designs in the Netherlands, the most intensively navigated country in Europe, as presented by the author on the 2nd International Workshop "What's new in the design of navigation locks" in New Orleans, LA, in September 2011.

1 INTRODUCTION

Dutch engineers often say that "nature itself holds water on a miter gate". There is little exaggeration in these words. Hydraulic load keeps indeed the gate closed and takes, in a sense, care of its own control. This environmentally favourable principle has been used by hydraulic engineers for at least 6 centuries. It does not, however, rule out modifications. New technologies, materials and ideas make remarkable developments of miter gates possible. Two groups of such developments can be distinguished:

1. Performance extensions within conventional system functionality, e.g. by using modern, high-tech materials and technologies.
2. Functionality extensions beyond conventional system limits, e.g. allowing reverse water heads on a mitre gate or extending its feasible width.

The intention of this paper and the presentation is to show the highlights of these developments – most of them from the author's engineering practice.

2 NEW MATERIALS AND TECHNOLOGIES

In regard of new material applications, two fields of developments can be recognized:

- New materials for entire mitre gate structures;
- New materials for crucial details, in particular gate bearings and supports.

The materials which in both fields proved to be particularly interesting are high-tech synthetics. The applications of those materials originate from other disciplines and structures, like automobile industry, shipbuilding and energy production. Winning the markets there increased the supply and quality of those materials and decreased their price. This, in turn, made them interesting for construction market. As newcomers with potency to develop, they will be more and more significant for lock gate construction and maintenance in the future.

An example of new materials for an entire gate is the FRP miter gate (Fig. 1 left) of the Spiering Lock in Werkendam. This gate has been presented in more details in the preceding paper. More gates of FRP's are currently under consideration in the Netherlands.

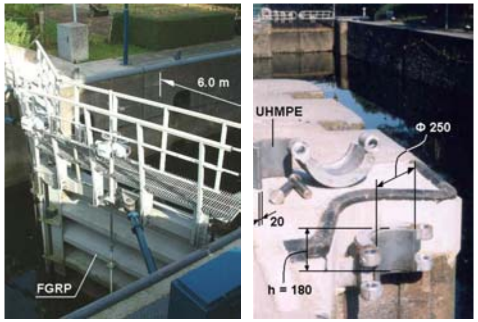


Fig. 1. FRP gate of the Spiering Lock, Werkendam (left) and UHMPE top hinge of the Tilburg Lock in Wilhelmina Canal (right)

Interesting are the applications of new materials in gate details, such as bearings, heel and front post linings, sill supports, walkways etc. One can observe gradual turning back from traditional materials like steel, other metal alloys and timber, to the materials like ultra high molecular polyethylene (UHMPE) or fibre reinforced resins with additives. The preceding paper presents an example of the latter. Polyethylene gate bearings have, e.g., been used in the Tilburg Lock on the Wilhelmina Canal (Fig. 1 right). Both polyethylene and FRP's have also successfully been applied in post supports, sluice valves, vessel guides on gates, walkways and other details.

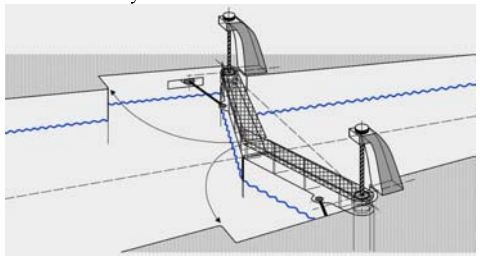
3 NEW SYSTEM FUNCTIONALITIES

Netherlands is a country in the delta of three great European rivers. This results in a large and complex waterway system, with varying flow directions. In consequence, lock heads and gates must usually bear hydraulic loads from any of the two directions. The conventional way of solving this problem in a mitre gate was to install two, reversely directed gates (4 leaves) at each lock head. In diverse recent projects, however, this task has been accomplished using only one gate (2 leaves) in a lock head. An example is the gate system of the Naviduct, lock on an aqueduct, in Enkhuizen (Fig. 2). The employed technology has been presented by the author on different occasions. This contribution focuses on practical performances of that technology, as the discussed systems have already been operating for about 10 years.

Fig. 2. Miter gates of the Naviduct in Enkhuizen, carrying reverse water head

A critical aspect of miter gates is the performance of their hinges. In particular, the hinge that carries the horizontal and vertical reaction during rotation (usually bottom pivot) presents a wear problem. The system midification that helps handling this problem is the replacement of the vertical reaction to the top hinge. There are already locks in the Netherlands with the gates supported at their top hinges, which gives better maintenance assess to that detail. A definite solution, however, would be a gate that does not load the hinges vertically. This leads to the idea of a suspension gate (Fig. 3)

Fig. 3. Suspension miter gates with hinges bearing only horizontal loads



Another "bottle neck" problem of the miter gate system is that it can hardly be used for very wide sea lock chambers. Even if buoyancy tanks are applied, the loads on hinges, proper closing of the two gate leaves and gate drive present then major problems. These problems have recently been encountered in the project of a new, 60 – 70 m wide IJmuiden lock, offering a wide access to the Amsterdam harbor. The available space there is narrow, which does not favor a rolling gate system. Therefore, a number of miter gate system modifications with far end supports will be considered for this project. Examples of possible options are sketched in Fig. 4.

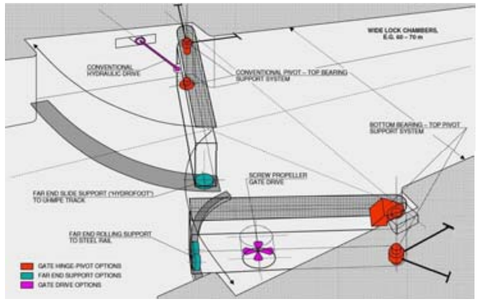


Fig. 4. Options of miter gates with far end supports for very wide lock chambers

4 CONCLUDING REMARKS

These and other miter gate material and system options – both realized and still under consideration – are discussed in the presentation. They all indicate that there is space for innovations in this type of lock gate. The idea of employing the water head potential energy for its own control is also appealing enough to continue looking for more new solutions and to give innovations a chance. We will hopefully see the results of it in the nearest future.

INNOVATIONS IN LOCK EQUIPMENT

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ABSTRACT: As locks do not work without any equipment, these are important components although their monetary value is small compared to the construction itself or the lock gates. Mooring equipment, gate protection, illumination and aids to navigation are the main types of equipment looked at in this paper. Since the 1986 PIANC report some development was done improving mainly the serviceability and the durability. Several innovations –mainly already in use- are described.

1 INTRODUCTION

Lock equipment is not only a vital part of efficient lock operations and navigation safety, but also a vital part of safety and security of both lock personnel and general public. Since 1986 PIANC report on locks there has been major development in some lock equipments, which are described in following chapters.

2 MOORING EQUIPMENT

Vessels generally use bollards, mooring pipes or rings as means of securing during levelling. Design, size and positioning of fixed or floating mooring equipment depend on the vessel size and type and its vulnerability. Mooring and unmooring, and adjusting mooring lines during levelling, all need to be possible without danger of lines or mooring equipment getting stuck.

Mooring bollards can be fixed or movable ones or in some cases bollards can be replaced by a floating pontoon inside the lock. There are nowadays some examples of horizontally travelling bollards in use. Another innovation with higher level of service is an automatic mooring system for fixing ships in sea locks. It is working on a magnetic or vacuum principle. One of the basic requirements is more or less uniform ship types that are using the lock as the flexibility is limited.

Presently there are also many design codes for design of mooring equipment.

3 GATES PROTECTION AND GATE MAINTENANCE EQUIPMENT

Gate should be protected from damages in bot open and closed position. In open position the protection is usually wooden planking. In closed position gates can be protected by pumpers or by special protection structure, which hinders vessels from colliding the gates. In some cases, double set of gates is also in use.

Locks are typically equipped with bulkheads to enable dewatering of the lock for inspections and repairs. Some locks are equipped with special inspection systems (such as tunnels) to minimize the need of lock dewatering.

Some locks are also used in flood control. In this case, the gates must be equipped with gate locking device.

4 SIGNALLING, MARKING AND ILLUMINATION

Signaling should be executed according to the stipulations of any regional regulations on inland navigation. Signal indication and lock illumination choices should be adjusted to terrain illumination of the lock for the benefit of color recognition; it should have sufficient attention value.

White markings are a good and inexpensive tool for obtaining sufficient contrast in the dark while using little light. Marking vertical surfaces, such as

guiding structures and guard walls, to support the visual guidance of navigation is very effective.

At night visibility decreases and orientation is more difficult which requires extra effort for safe navigation for the ship's crew. This effort has to be kept as low as possible in order to prevent decreased safety. For this purpose, suitable and economically sound illumination of the lock complex is essential.

5 AIDS TO NAVIGATION

Aids to navigation are usually prescribed in national or international standards or legislation. Positions, size, colors etc. are usually prescribed in detail and should be followed. In addition for a lock some extra aids to navigation can be applied which often do not fall under these standards.

Typical additional lock extra aids are:

- Stop stripes
- Marks on the gates
- Distance marks

6 SECURITY

Terrorism and security can be a major issue in lock design in some locations.

The design of safer facilities should try to use an approach similar to that used for railway stations and airports. During the lock design stage these features should be integrated into the structure while keeping in mind the aesthetics of the local environment and avoiding a fortress appearance. The design of fencing and barriers should include consideration of the color and texture of the surrounding area. Electronic monitoring equipment should be fully integrated to lessen its visual impact. The design should reduce or control access by pedestrians and vehicles to the facility by providing check points.

7 SAFETY FOR PUBLIC, USERS AND PERSONNEL

Typical safety risks in locks are possibility of falling in the lock, accidents during the lock operation or maintenance or repair work caused by moving lock gate, fire or spill of hazardous cargo or vandalism.

Risks to the public and risk of vandalism can be reduced with the measures of security i. e. controlling the access to the lock area and monitoring. There must be also enough life rescue equipment (life buoys, rails, ladders etc.) in the lock to enable rescue of a person that has fallen in the lock.

The lock operation system should be designed in a way, which prevents the misuse of the lock gates during maintenance and repair works. There should also be safety sensors, which stop the gate movement, if something is in between the gates.

In addition to these in locks, which are operated remotely or by waterway users, there should be enough cameras for the monitoring of lock traffic and a possibility to take over the lock operation at any stage from the operation/monitoring room. There should also be guiding signs, loudspeakers to give instructions from the operation/monitoring room and a possibility for the waterway users to contact the operation/monitoring room.

To enable the firefighting there should be enough extinguishers and other firefighting equipment in the lock area as well as routes for the fire brigade both from land and water side of the lock. There should be at least two separate escape route from the lock area to guarantee the safe evacuation of the lock area.

Ships can carry hazardous types of cargo which can require special technical features at the lock complex and require special operation of the lock complex. These requirements are generally imposed by codes for the transportation of dangerous goods. The requirements may concern distances from other vessels, other facilities and public. They may also set demands for lock operations (for instance separate locking of ships carrying hazardous cargo) as well as requirements for lock equipment or escape routes.

PROJECT REVIEWS
and THEIR VALUE IN REALIZING INNOVATIONS

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ABSTRACT: This paper highlights the value of using Project Reviews (PR's) as a tool to acquire experience in innovative solutions. PIANC Report n°106 offers a useful starting point with its 56 PR's. A web based online database with PR's may become a useful tool for the nearby future.

1 INTRODUCTION

In an upgrading project for 3 locks in the Netherlands some pre-designs were made for a lock wall with floating bollards rising higher than the upper level of the lock. What was unknown at that time was that comparable solutions had already been designed and built in France and in the US. This was a typical example of reinventing the wheel.

In such cases not only is the design and construction done twice, but the same mistakes may also be made twice in the process towards the best solution.

Cost reduction plays a key role in infrastructural works and it would be very useful to know about the existence of similar solutions before starting.

2 PROJECT REVIEWS.

To provide a good overview of the international experience of different design aspects it is valuable to have an extensive number of recent worldwide Lock Project Reviews available. For an effective use it is important to have a clear register to simplify the search for relevant aspects.

One reason that this is particularly valuable for locks is the limited frequency of lock projects. It is hard to maintain an optimal level of knowledge and experience, when this is based only on the projects within one country. As we all know this is one of the reasons why the existence of PIANC is so important.

Benefits of Project Reviews (PRs):

- PR's make it easier to investigate possible solutions .
- PR's make it possible to compare the specific situation with others in the world: what problems occurred, what were the risks, what solutions were found, and also what did it cost in terms of time and money.
- To determine and to minimize the uncertainty of innovative solutions. Often innovations are not implemented because they are considered to be too risky. This is due to the lack of experience. By making the relevant aspects of worldwide lock projects available, and also their performance, this can be used as indicator for the feasibility of innovative solutions, and also help to determine the actual value of the uncertainty of a solution.

- Actual reference projects provide a quick reference to convince decision makers that innovative ideas really are feasible.
-

3 PROJECT REVIEWS IN THE PIANC REPORT 106.

PIANC Report 106 includes a total of 56 detailed project reviews in which the practical use of innovations is presented.

Representative samples of each lock type included in this document are summarized in chapter 2 of the report. Case studies of each of these locks are included on the attached WG 106-CD-Rom (Directory A1).

The case studies include a more complete description of the locks, foundations, gate types, hydraulic systems, construction methods and, where available, construction costs. Photographs and selected engineering drawings are also provided for many of the locks.

Each project was reviewed and the innovative features applied in the project are described.

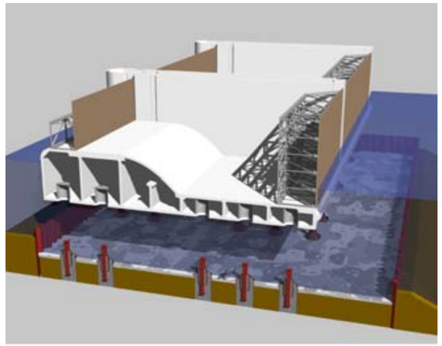
The innovative features were ranked into five general classifications. The innovations and their classifications are shown in Table 2.1 in the report.

	Hydraulics		O & M		
Project Reviews	Filling and Emptying Systems	Water Management (Water Saving Basins)	Energy Management	Life Cycle Cost	Maintenance
1 1-01 Kallo Sea Lock					PT
2 1-03 Self-Propelled Floating Lock					
3 1-04 High-Rise Navigation Lock	AC				
4 1-05 Van Cauwelaert Lock					
5 2-01 Tucurui Lock		PT			

Figure 1. Layout of Table 2.1 in the report

The project reviews included are not meant to cover all the different aspects, but are representative for the innovations currently in use or in the phase of research or design.

Members of WG 106 selected projects in which they or their associates were involved in the lock design or construction. Many of the projects fall under multiple categories in their areas of innovation.



In order to show the areas of innovation in a systematic way, five major categories and appropriate subcategories were created:

1. Hydraulics
2. Operation and Maintenance
3. Environmental
4. Design / Construction
5. Miscellaneous

Each project summary includes a table showing the project innovations. The innovations are categorized to indicate the type of innovation. The following definitions are used.

- Proven innovations (constructed/evaluated)
- Unproven concepts (idem but not evaluated)
- New concepts (construction planned)
- Advanced concepts. (research status)

4. CHALLENGES FOR THE FUTURE

The limitation of the available reviews is that not all lock projects are covered and that the actuality of innovative features is limited by the release date of the report.
It would therefore be useful to look for a means of sharing actual project data in an effective way.

In addition to sharing project information in congresses and papers like this workshop, one can also think of periodically updating lists with project reviews, or better: creating a database.

Together with other PIANC-members some investigation has been undertaken into the feasibility of such a database.

One possibility is to create an on-line Wikipedia-like database on the PIANC-website.

- Containing project information for locks worldwide.
- Easily accessible for PIANC-members
- a search function for relevant entries
- to be updated by designers themselves
- PIANC members can act as webmaster

An instrument like this fits perfectly in a modern media approach and would make the information easily accessible in the future.

DESIGN FOR MAINTENANCE
The Experience of the New Panama Canal Locks

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Project Manager, Third Set of Locks - Pacific, Panama Canal

ABSTRACT: This paper presents some of the design considerations implemented for the Panama Canal Third Set of Locks to achieve optimum operations, reliability, durability and maintenance of the new facilities and equipment. Two years into the project under this DB contract, these requirements are being incorporated into the final designs, procurement and actual construction of the new locks.

1 INTRODUCTION

Twelve years ago, the Panama Canal organization began conducting studies in search for alternatives to today's operation at nearly full capacity of its Panamax locks. A total of more than 120 studies were integrated into a Master Plan (2005-2025) that would lead to an optimum solution for the Canal Expansion by means of a Third Set of Locks. (See http://www.pancanal.com/eng/plan/index.html).

As the different studies on marketing, finance, water resources, environment, infrastructure, navigation advanced and were integrated, decisions were made as to the best configuration to expand the Canal's future capacity. These decisions included life-cycle cost analyses of the initial investment, operation costs and maintenance costs for the options under consideration.

Also, since the decision was to build only one additional lane of locks consisting of one Post-Panamax lock complex at each end of the Canal and a new Pacific Access Channel, high performance and reliable operations would be required to continue providing Canal customers with expedite and safe transit service between the Atlantic and Pacific oceans.

In October 2006, Panamanians approved the project by a margin of three to one. Funds for the program were secured and tendering of the different projects under the Expansion Program began. Dry excavation and dredging work to deepen and widen the navigation channels started in 2007.

Four international consortia were pre-qualified for the main project - the design and construction of the new set of locks. The contract was awarded in July 2009. Since then, the intermediate and final designs for all elements of the locks structure and equipment are advanced, excavation work is progressing and concrete placement has started.

Two years into the locks project, we can say that the Panama Canal's Third Set of Locks is no longer a dream. It is a reality scheduled to be completed by October 2014.

2 CONCEPTUAL STUDIES

The Panama Canal has more than 90 years of experience operating, maintaining and improving the existing Panamax locks and navigation channels. The new challenge required expert guidance and the Panama Canal Authority (ACP) contracted technical assistance from CPP, a French-Belgium consortium and Project Management firm to develop conceptual studies and to help in the preparation of procurement documents.

The Panama Canal also embarked in benchmarking with worldwide owners and operators of canals and locks systems, such as USACE. Technical groups, and visited different Post-Panamax lock complexes in Europe, including, German locks that operate with water-saving basins. ACP experts have joined and participated in PIANC congresses and work groups. The ACP has also established strategic alliances with port and government authorities such as the Port of Antwerp (BE) and the Rijkswaterstaat (NL).

The conceptual studies allowed the Panama Canal to study and select options at a high-decision level and to prove the feasibility of the project as well as to better estimate quantities and costs.

Marketing studies were used to help determine the design vessel as a 13,000 TEU containership, which in turn helped to determine the dimensions of

the Post-Panamax locks, limiting gate size to practical standards.

One of the main decisions was to build the locks with three lifts, which not only require only two thirds of the water to operate, but also minimizes saltwater intrusion. On the technical considerations, a three-lift lock reduces gate size to a practical limit.

Concurrently, it was also decided to incorporate three water-saving basins per lift, or nine per lock. This unique combination required numerical and physical model studies to optimize filling and emptying times, limit water velocities, chamber water slopes and hawser forces.

The Filling and Emptying system selected includes longitudinal culverts, side filling ports, and a secondary culvert. The main advantage of the system is the ability to isolate one culvert for repairs or maintenance, without the need of lane outages.

For ease of maintenance all culvert and conduit valves were standardized along with their operating equipment.

For increased reliability, the culverts were split for two valves in parallel and two in series. Each set of valves has bulkhead slots to isolate and block it while the rest of the Filling and Emptying system remains operational. The contractor will supply bulkheads and dewatering pumps.

The Panama Canal chose to use rolling gates as most Post-Panamax locks in Europe. One of the main advantages of using rolling gates is their ability to retract into the gate niche to then be sealed using bulkheads and drained to perform repairs or maintenance without the need of lane outages. Design specifications enable quick replacement of the roller buggies whenever required.

For increased reliability and safety of operations, double sets of rolling gates are required at each of the four niches for a total of eight gates per lock. The middle gates are standard. The top of lake and ocean gates should allow traffic of maintenance vehicles.

The Panama Canal has the only lock system in the world that uses electrical towing locomotives to assist ships in navigating through the locks. However, it was decided to use tugs to assist ships in the new locks, just as in other Post-Panamax locks in Europe, because these are more standard equipment, easier to buy, replace, repair and maintain.

Durability of the civil structures is critical. For example, different levels of severity must be complied with for seismic requirements, including minor damage, but fit for service. The concrete design mix must also comply with physical characteristics of strength and permeability to guarantee 100 years of service life.

Other requirements include the life span of coatings and corrosion protection, and the capability to perform a lock outage. In consultation with Panama Canal pilots regarding navigation requirements, the issues discussed include maximum surface water velocity at discharge, permeable approach walls, knuckle fenders, and chamber fenders that need to be effective and allow for ease of replacement.

3 PROCUREMENT

The Panama Canal decided on a Design-Build contract to minimize contract risk, among other considerations. This type of contract required more detailed performance specifications. The FIDIC yellow book was used as a standard document to allow for international bids.

During the tender process, Panama Canal officials and technical groups met with the pre-qualified consortia to make the document more biddable and to refine the technical specifications. This process resulted in a total of 24 amendments.

The bids were evaluated on the basis of best value, allotting a weight of 55% to the technical package and 45% to the financial proposal. The contract was awarded slightly below the ACP amount of allotted funds.

4 CONCLUSION

Two years into the contract, the work is progressing, excavation drawings have been completed and more than 18 million cubic meters of material have been excavated from a total estimate of 46 million cubic meters. Concrete mix designs have proven compliant with requirements and placement started in early July with a total estimate of 4.8 million cubic meters to be placed in less than three years at both Atlantic and Pacific lock complexes.

Gate intermediate designs are compliant and final and fabrication will start in October. Culvert valve final designs are being completed. Both valve and gate embeds are already being received at the lock sites.

The locks filling and emptying system has already been modeled and its performance complies with all design parameters.

The electrical, mechanical and control designs are progressing, whereas high reliability is required for its analysis by means of a fault-tree analysis. The electrical and control systems have two feed loops for redundancy and reliability. Three lock crossunders are being built to house these and other systems. Standard off-the-shelf parts and current technology will be procured, installed and tested.

Prior to acceptance, commissioning tests for the operation and control equipment and systems based on their performance and reliability will be conducted.

The date of completion of the locks construction is scheduled for late October 2014. Once completed, the contractor will have to provide three years of maintenance of the locks, which includes parts, labor, tools and accessories, as well as training for ACP personnel, operation and maintenance manuals, and as built drawings. With all the wheels in motion, we can now say that the new Panama Canal Third Set of Locks is a dream come true.

IDENTIFICATION OF THE CHALLENGES FOR TOMORROW

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International PIANC Lock Experts

ABSTRACT: This New Orleans workshop is the occasion to identify the pending issues, which remain in 2011 key challenges for the design of navigation locks. A panel of PIANC experts will discuss about their experience in order to highlight what they consider to be the relevant topics requiring more extensive researches and maybe new PIANC working groups.

1 IDENTIFICATION OF THE CHALLENGES FOR TOMORROW

Within the challenges that will be discussed by the experts during the panel meeting (*), we will have:

- The seismic effect, which is currently investigated by PIANC WG151,
- Ship entrance/maneuvering and ship behavior in locks, which will be investigated by PIANC WG155,
- Ship impact on lock gates, which is currently investigated by PIANC WG151,
- Reliable design and operation of miter gates, which will be investigated by a new PIANC WG 154,
- Use of composite material for the design of locks,
- Design of monolith lock (versus a structure with joints),
- High rise navigation locks (above 40 m),
- Water management (lack of or too much),
- Salt water intrusion,
- Life cycle cost including maintenance (Design for Maintenance),
- Durability of structures,
- Maintainability of equipment and structures,
- Environmental and social aspects,
- Stakeholders' management,
- Etc.

(*) Note that these challenges only concern navigation locks.

2 SPECIFIC CHALLENGES FOR LOCK GATES

When the focus concerns lock gates, some specific challenges are:

1. Reliability under all conditions. Sometimes engineers complicate their systems too much, increasing in fact the probability of failures.
2. Service life (durability and maintainability) of gate components like tracks, wheels, hinges, seals, buffers and heel posts (mitre gates); and not the main structures that usually serve long enough.
3. Maintainability in the sense of: low, easy, safe, healthy and environment-friendly maintenance.
4. Vessel-friendly service. How to improve the comfort and safety of the vessels and their passengers (crews)?
5. Etc.

MOORING FORCES and VESSEL BEHAVIOUR IN LOCKS – EXPERIENCE IN BELGIUM –

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ABSTRACT: This paper presents the approach adopted in Belgium to assess the quality of the filling and emptying process in navigation locks. It is based on physical and numerical modeling, as well as in situ measurements.

1 INTRODUCTION

Belgium, though only 30000 km² large, has a number of maritime ports and a dense network of waterways. As a consequence, numerous maritime and inland navigation locks are operational, most of them having a low lift height (< 10m) and some an intermediate lift height (10 to 15m).

Here, a brief overview will be given of the role of mooring forces and vessel behaviour in the design of these locks.

2 MOORING FORCES

Traditionally, the concern of "smooth" filling and emptying during navigation lock design is translated into a so-called "hawser force criterion". This criterion imposes an upper limit (hereafter referred to as a threshold level) to the hydrodynamic force that the water exerts on a vessel in the lock chamber. Hence – contrary to what the name of the criterion suggests – the resulting forces in the hawsers (mooring lines) or other elements of the vessel-positioning system, are not explicitly used as a design criterion. This approach was meant to simplify the classical methodology for the verification of the criterion, i.e. a physical model of the lock, with a (centrally-positioned) vessel being attached to an (artificial) force measurement set-up, rather than to (a scaled version of) a realistic vessel-positioning system.

The threshold level is usually expressed as a fraction (in per mille) of the vessel's displacement weight. Most of the time, only threshold levels for the longitudinal component of the force are considered.

Figure 1: Measuring forces on push-tow combination in scale model

The values for the threshold level have evolved over the course of time. For quite some time, 1 ‰ was a popular value in Belgian designs. Since the nineteen eighties or so, values were adapted to evolutions in guidelines of neighbouring countries, in which the threshold level depends (somewhat) on the displacement weight of the vessel and on the

characteristics of the mooring system (e.g. fixed vs. floating bollards).

Nowadays, not only physical models in the hydraulic laboratories of the Belgian regional Waterway Administrations – i.e. the "Waterbouwkundig Laboratorium" in Antwerp and the "Laboratoire de Recherches Hydrauliques" in Châtelet – are employed as verification tools (Figure 1), but also numerical models.

One type of numerical model is based on the shallow water equations to describe (in 1D or 2D) the water motion in the lock chamber in presence of vessels (modelled by artificial fields of atmospheric pressure). The time series of filling and emptying discharges that are (pre)calculated by hydraulic network models are used as boundary conditions. This type of model is applicable to (roughly) estimate the force on the vessel (Figure 2), when the longitudinal component of the hydrostatic force on a vessel (i.e. the slope of the water surface between bow and head of the vessel) is the dominant force component. Often (too often ?) this is assumed in literature.

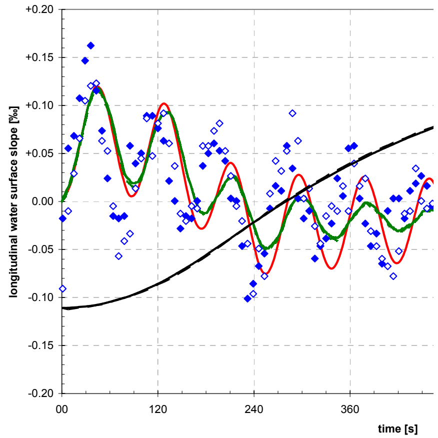

Figure 2: Comparison of numerically predicted (red line: LOCKSIM ; green line: DELFT3D) and in situ measured (blue markers) water surface slope

Since the nineteen eighties, a dedicated calculation programme for F/E systems with gate openings and slides has been developed in The Netherlands by Delft Hydraulics and Rijkswaterstaat. The so-called LOCKFILL programme allows e.g. to calculate the different longitudinal force components on a vessel. Based on the LOCKFILL literature, a similar in-house programme has recently been developed and validated at Flanders Hydraulics Research. During validation efforts, it turned out that the parameterization of the direct effect of the concentrated filling flow (jet) on the bow of a ship (which is moored relatively close to the filling gate) is afflicted with some uncertainty.

With respect to design of F/E systems for navigation locks where also recreational craft might be present in the lock chamber, the use of numerical models is somewhat limited so far. The reason is not only the lack of a proper validation of predicted "hawser forces", but neither is it obvious how to (additionally) assess the sensitivity to "turbulence" that is stated in literature for these small crafts. Moreover, recreational vessels might be moored close to the filling gate (i.e. ahead of professional vessels in the lock chamber, in order to avoid the effects of the propeller wash of the latter), where the impact of local flow phenomena is larger.

3 VESSEL BEHAVIOUR

In the framework of the conceptual design of the new Panama Canal locks, a reflection has been made on the specification of "hawser force criteria" for the associated numerical and physical modelling work (De Mulder, 2007 and 2009). Inspired by the work of (Partenscky, 1986) and (Vrijburcht, 1994), criteria for the maximum allowable force on the design vessel have been sought which take into account characteristics of the vessel-positioning system.

Additional to these efforts, a full dynamic analysis has been made of the vessel motion and the forces in the mooring lines (Vantorre, 2008; Roux et al, 2010), under the action of the hydrodynamic forces during lock-filling, which were (previously) predicted by numerical models and/or measured in the physical model. The purpose of this analysis was to assess whether these hydrodynamic forces could be considered as acceptable. Eventually, a mooring configuration making use of the ship's own winches and lines (four springs and four breast lines) was considered, controlled by a very simple algorithm that could potentially be used during manual control, to keep the ship more or less centred in the lock chamber by means of line forces that are within 20% of the minimum breaking load. Criteria for the magnitude of the horizontal forces could be formulated; for the lateral force and yawing moment, which showed significant oscillations, it was concluded that the importance of the peak values was rather limited, and that a running average over, in this particular case, 25 s could be applied without affecting the controllability of the design vessel.

So far, the abovementioned efforts that were triggered by the conceptual design of the new Panama locks, have not yet been applied subsequently in the design of new Belgian locks, for which still more "classical" approaches are adopted.

Nevertheless, the issue of mooring forces and vessel behaviour is still an active research topic in Belgium. Frequently, in situ measurements of the water surface slopes during lock filling/emptying – which are a measure of the hydrostatic forces on vessels moored in the lock chamber – have been carried out (see e.g. De Mulder et al., 2010). More recently, both the hydraulic research laboratories in Antwerp (Figure 3) and in Châtelet (Bousmar, 2011) attempt to measure the associated vessel motion during lock-filling.

All these research efforts are not only meant to collect validation data for models, but – more importantly – aim at getting more insight into the phenomena and (eventually) better-founded design criteria, which are not overly conservative while still assuring safe and comfortable lock transits. In this respect, it is felt that also sufficient weight should be given to "testing at prototype scale" of e.g. alternative valve opening schedules.

Figure 3: In situ measurement of vessel motion

4 REFERENCES

De Mulder, T. (2009). Mooring forces and ship behaviour in navigation locks. Paper 7 in International Workshop on "Innovations in Navigation Lock Design", PIANC-Brussels-Belgium, 15-17 Oct. 2009.

De Mulder, T., Verelst, K., Vercruysse, J., De Cock, W. & Haegeman, M. (2010). On hawser force criteria for navigation lock design: Case study of maritime locks in Port of Antwerp. Paper 290 in PIANC MMX Congress, Liverpool-UK, 10-14 May 2010.

De Mulder, T. (2007). Specification of hawser force criteria. Report TO1-Task 1.2.4-CNR-FHR-R013 of Consorcio Pos-Panamax, commissioned by the Autoridad del Canal de Panama.

Partenscky, H.-W. (1986). Binnenverkehrs-wasserbau – Schleusenanlagen. Springer-Verlag, Berlin.

Vrijburcht, A. (1994). Troskrachtcriteria in schutsluizen, report Q1443, Delft Hydraulics.

Vantorre, M. (2008). Mooring layout for lock filling/emptying. Annex 3-22 in report TO5-Task5.1-CNR-R002 of Consorcio Pos-Panamax, commissioned by the Autoridad del Canal de Panama.

Roux, S.; Roumieu, P.; De Mulder, T.; Vantorre, M.; De Regge, J.; Wong, J. (2010). Determination of hawser forces using numerical and physical models for the third set of Panama locks studies. PIANC MMX Congress, Liverpool, UK, May 2010.

Bousmar, D. (2011). In-situ measurements of vessel behavior during lock operation. Proceedings of Smart Rivers 2011 Conference, New Orleans-USA, 13-14 Sep. 2011.

Schohl, G.A. (1998). User's Manual for LOCKSIM – Hydraulic simulation of navigation lock filling and emptying systems, Tennessee Valley Authority, August 1998.

MOORING FORCES and VESSEL BEHAVIOUR in LOCKS
- Experience in China -

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ABSTRACT: The relevant regulations concerning the safe mooring of vessels in chamber and in waiting area near the lock are introduced. The forces acting on the vessel depend mainly on the design of the hydraulic system of the lock. Fine design could evidently reduce the forces. Some examples are given.

1 INTRODUCTION

In China, we have a set of technical codes for the design of locks used by inland vessels. The contents concerning the safe mooring of vessels in chamber and in waiting area near the lock are included the *Design Code for Filling and Emptying System of Shiplocks*[1].

The relevant regulations by the Chinese code and some study results will be introduced below.

2 SAFE MOORING

Allowable mooring forces of vessels in lock chamber and near the approach channel are referred in Table 1.

The vessel tonnage means the deadweight of the motor barge. For a push train it means the deadweight of one barge of the train. Allowable mooring force on a push train shall be determined by the minimum barge tonnage in the train. When the fixed bollard or hook is used the mooring force shall be multiplied by $\cos\beta$, where β refers to the maximum angle of the hawser and water level.

For locks with only fixed mooring equipment, the maximum water surface lifting speed in lock chamber during filling and emptying shall not exceed 5-6 cm/s. When floating bollards are used, there is no similar limitation.

To simplify the problem the vessel forces are used to compare the acceptable mooring forces of vessels and to evaluate the design of filling and emptying system of the lock.

The vessel forces are usually got by analytical method for short culvert system and physical model for more complicated system.

For the short culvert system the vessel forces could be calculated by the following formula. In the process of filling:

$$P_1 = P_B = \frac{k_r \omega DW\sqrt{2gH}}{t_v(\omega_c - \chi)} \qquad (1)$$

In the process of emptying:

$$P_1 = P_i + P_V \qquad (2)$$

In the above formula, P_1: Hydrodynamic forces on ships (kN); P_B: Wave force in the initial stage of filling (kN); P_i: Force produced by water-surface gradient during the emptying process (kN); P_V: Force produced by longitudinal velocity in lock chamber; k_r: Coefficient concerning valve configuration (could be 0.725 for a plate valve); ω: Sectional area of culvert with valve (m^2); D: Wave force coefficient; W: ships displacement (t); H: Design lift height (m); t_v: Valve opening time (s); ω_c: Sectional area of lock chamber at the initial water level (m^2); χ: Area of wetted cross section of vessels (m^2); g: Acceleration of gravity (m/s^2). *P_1 should not be more than P_L* which is horizontal longitudinal components of allowable mooring force (kN), see Table 1.

3 HYDRAULIC CRITERION FOR APPROACH CHANNELS

In addition to the allowable mooring forces criterion, the requirements of vessels moving and berthing in approach channel should be satisfied.

Table 1: Acceptable mooring forces of vessels

Vessel Tonnage (t)	3000	2000	1000	500	300	100	50
Horizontal longitudinal components of allowable mooring forces (kN)	46	40	32	25	18	8	5
Horizontal transverse components of allowable mooring forces (kN)	23	20	16	13	9	4	3

The under keel clearance of vessels should be big enough to allow the water surface lowering in approach channel during filling and emptying the lock. So the water depth in approach channel should be decided as follows.

$$\frac{H_0}{T} \ge 1.50 \qquad (3)$$

Where H_0: the water depth in approach channel at the lowest navigation level (m); T: full loaded draft of design vessel (m).

Then the current velocity should be limited to guarantee vessels safe manoeuvring in approach channel. In upper pool the maximum longitudinal current velocity in approach channel shall not exceed 0.5-0.8m/s and in the waiting area the velocity shall not exceed 0.5m/s. In downstream approach channel current velocity shall not exceed 0.8-1.0m/s.

4. REDUCING THE FORCE ON VESSEL

The forces acting on the vessel are determined by the water level differences around the vessel, the flow velocity and friction on the vessel. The forces acting on the vessel depend mainly on the design of the hydraulic system of the lock. Fine design could evidently reduce the forces.

In the longitudinal filling system, the transverse force on vessels is limited. A new type of short culvert system is used in Shihutang lock in China[2]. The forces acting on vessel during filling and emptying are mainly longitudinal and some results got from laboratory model test are shown in Table 2.

Table 2: Forces on vessel of Shihutang lock (chamber dimension 180×23×3.5m)

Lift (m)	F/E time (min)	Max. longitudinal force	Max. transverse force
11.14	11.2 (F)	30.8	15.2
	8.4 (E)	31.4	5.6
10.54	10.76 (F)	31.4	8.7
	7.53(E)	24.1	3.8
9.77	9.63 (F)	29.4	9.4
	6.72(E)	23.5	3.0

Note: Acceptable longitudinal force is 32 kN and transverse force is 16 kN.

But in the wall culvert side port system, the longitudinal force could be reduced by a fined design to the port size. Along the flow direction the port size could be divided into three groups. The height of all ports can be the same and the width can be narrower along the water flow direction during filling and emptying[3]. This makes the water into the chamber more uniform in the longitudinal direction and reduces the slope of the water surface during filling. So the longitudinal mooring force becomes smaller.

For example, there are 24 ports on one side wall. All have the same height of 0.85m. They were divided into three groups which has the width of 0.80, 0.74 and 0.68m separately. In the test the width of the third group of ports was reduced from 0.68m to 0.52m. The maximum longitudinal force acting on vessel was reduced from 16.2kN (tab. 3) to 8kN.

Table 3: Forces on vessel with a wall culvert side port system

Lock name	Naji	Changzhou 2nd lane
Chamber dimension	190×12×3.5m	190×23×3.5m
lift	13.9m	15.5m
Filling time	8.3min	9.8min
Max. longitudinal force	12kN	16.2kN
Max. transverse force	15kN	15.6kN

Note: Acceptable longitudinal force is 32 kN and transverse force is 16 kN.

So for the wall culvert side port system we should pay more attention on the transverse force on vessel. The deflector in front of port is effective to dissipate the water energy (see the presentation of hydraulic system, discussion at the Brussels PIANC workshop, 2009).

REFERENCES

[1] Design Code for Filling and Emptying System of Ship Lock (JTJ 306-2001), China Communications Press, 2001 (English version available in PIANC report No. 106 "Innovations in navigation lock design", DVD- Directory C5

[2] WU PENG, XUAN GUO-XIANG, (2008): "An Innovative Short Culvert Filling and Emptying System for Navigation Locks", PIANC AGA'2008, Beijing, China,

[3] PIANC report No. 106 "Innovations in navigation lock design", DVD-project review PR-03-04

MOORING FORCES and VESSEL BEHAVIOR in LOCKS
- Experience in France -

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ABSTRACT: This paper gives an overview of the methodology applied during the recent studies of locks filling and emptying system design in order to calculate the forces exerted in the mooring lines and the vessel displacements.

1 INTRODUCTION

The determination of the expected forces exerted on the vessel and its mooring lines during a lockage is something of first importance since it concerns directly the safety of the ship, the sealers and the lock structure.

That is why the so called "forces in the mooring lines" are with the filling & emptying times the two main criteria usually retained to approve the design of a lock F-E system.

Anyway, the force in a mooring line is a parameter that can not be measured so easily than the F-E time and that requires a dedicated measurement methodology.

2 NUMERICAL OR PHYSICAL SCALE MODEL?

The lock designer has two different tools at his disposal in order to assess the forces in the mooring lines: the numerical model and the physical model.

The numerical model offers a very large panel of investigation, from the simplest, such as a 2D model used to calculate the water movement in the lock chamber and to assess the hydrostatic components of the total forces exerted on the vessel, to the more advanced such as a 3D model including the lock F-E system, the lock chamber, the vessel and its mooring lines system, also taking into account the fluid-structure interaction. The more complete is the numerical model, the more expansive and the longer the computations times are.

The physical scale model takes into account all the hydraulic components of the forces exerted on the vessel (hydrostatic component, friction on the ship's hull, jet effects…) and consequently, the tests perform on a model with the vessel in the lock chamber give access to the total hydrodynamic forces.

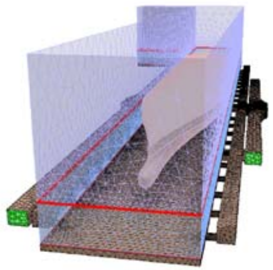

Figure 1: 3D model of the lock chamber, its F-E system and the design vessel

Anyway, the measurements carried out on the model are most of the time the forces applied on the ship and not the forces in the mooring lines since the mooring lines system itself is difficult to model.

Figure 2: Post-Panamax ship model

3 RECENT EXPERIENCE IN FRANCE

During the last design studies of locks F-E system carried out in the CNR laboratory the longitudinal and transversal forces are measured on the physical model by means of 3 dynamometers (2 for the transversal forces and 1 for the longitudinal force).

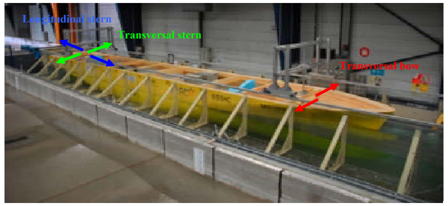

Figure 3: Forces measurement system

The system allows the vessel to move in a free way vertically but constraints it in the horizontal plan.It does not model the elasticity of the mooring lines and all the forces exerted on the vessel are completely transferred to the measurement system.

After carrying out a test, the data available are the longitudinal and transversal components of the hydrodynamic forces exerted on the vessel and the yaw moment.

The forces time series have then been injected in a numerical model, developed by Sirehna, of the ship and of the set of mooring lines built on the basis of the MSC-Adams software. In the framework of the New Panama Locks study, the model included:

- The ship modeled as a rigid body,
- The ship inertial and hydrostatic characteristics,
- The ship added masses and damping coefficients (set experimentally from model tests by an identification approach),
- The mooring lines fixed to the ship and to the lock based systems, with the appropriate stiffness and Minimum Breaking Strength (MBS) characteristics and lines pre-tensions,
- The capability to take into account the ship lift and descent, after setting the mooring lines operating conditions,
- The contact detection between the ship and the lock walls (even if the contact itself is not modeled accurately).

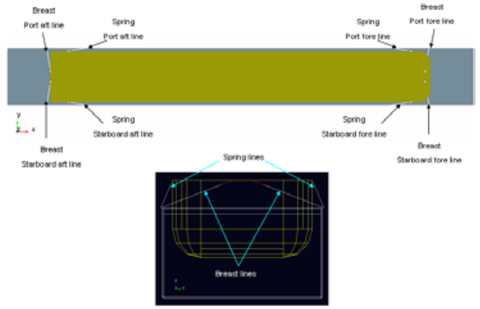

Figure 4: Mooring lines system configuration set in Adams software

This methodology gives access to the forces exerted in the mooring lines and to the vessel displacements, but its main advantage is based on its flexibility since it allows to compare different mooring lines systems for one given hydraulic scenario (i.e. initial head and valves opening schedule fixed).

4 TESTS ON COMPLETION: PREDICTION OF THE FORCES EXERTED ON THE VESSEL FROM THE WATER SLOPES

After the construction of the F-E system, the lock owner may ask for F-E operations tests in order to check that the hydraulic performances comply with the requirements. For many reasons, it is not always easy to put a vessel in the lock chamber and to measure directly the forces in the mooring lines.

During the design study of the Post-Panamax Locks, additional investigation have been carried out in order to try to predict the expected forces that will be applied on the vessel according to the water slope measured in the lock chamber without the vessel.

This study gave interesting results that will be used during the tests on completion, allowing to predict the range of the expected forces without putting a Post-Panamax vessel in the lock chamber.

MOORING FORCES and VESSEL BEHAVIOUR IN LOCKS
- Experience in Germany -

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ABSTRACT: This paper presents the methodology applied in Germany in order to judge the quality of the filling- and emptying process of locks. It is based on a combination of theoretical considerations about the relationship between ship forces and allowable hawser forces and both physical and numerical model tests.

1 INTRODUCTION

In the dimensioning process for navigation locks, two main constraints govern the design of the hydraulic system: The requested filling-emptying time for the lock and the allowed forces acting on the vessel. Thus, for locks of lower importance (i.e. with low traffic) a simple hydraulic system, which would lead to inacceptable ship forces if operated fast, can be acceptable for a slower lock operation (Figure 1).

Figure 1: Through-the-gate filling on a canal near Chester / Great Britain

For locks of higher importance it is necessary to evaluate in advance the generated forces thoroughly, in order to keep the hawser forces below the allowable limits. For some locks it might even be requested to adjust the filling-emptying system so accurately that hawsers are not required at all.

2 METHODS FOR EVALUATION

In Germany, the forces are evaluated on the basis of the hydraulic forces on the hull of the ship. These were derived by Partenscky [1], who related allowable hawser forces with hawser pretension, hawser elasticity and ship mass. He ended up with an allowable longitudinal force of 23 kN on the hull for a vessel with a weight of 30.6 MN.

Nowadays, the fulfilment of this criterion will in many cases be tested with a physical model (Figure 2). This type of model gives the opportunity to evaluate for example many variants of valve schedules etc. in a short time once the model is completed. In the model, the lateral movement of the ship hull (yellow in Figure 2) is restricted (in the x-y-plane) while the vertical movement is free. The measured forces in the x-y-plane and the torque around the z-axis are the criteria for the acceptability of the filling process.

Figure 2: Laboratory model for measuring ship forces in the lock

This approach has the disadvantage, that the properties of the hawsers and the lateral movement of the vessel are not part of the model, but are part of a mathematical evaluation. On the other hand it has the advantage that the reproducibility of the model is much better, as the handling of the hawsers introduces a lot of uncertainty in the process (both in the physical model and in reality). Therefore different variants can be tested much better against each other for the described methodology.

On the other hand, numerical models have gained a lot of impact on the design process. In the BAW three dimensional numerical models are being used for the early design stages, where singular parts must be optimized and furthermore for the modelling of the fluid behaviour in the filling system and the lock chamber itself. The quality of the numerical results for the sloshing of the water in the lock chamber can be very good nowadays. But the movement of the ship within the lock chamber and its interaction with the water (and maybe additionally with the hawsers) is still difficult to evaluate numerically in an efficient manner.

For locks with a bottom filling system, experience has shown that the water table gradient gives an acceptable estimate for the ship forces. Thus, for those locks the water table gradient is currently being used as the relevant design criterion in the early design phase, were numerical models are being used.

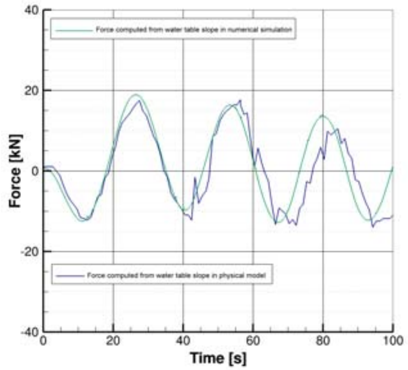

Figure 3: Ship forces computed from water table slope of physical and numerical model

Figure 3 shows the estimated ship forces as they were computed from the water table slope in the physical model (blue line) and the forces computed from the water table in the numerical model. Obviously the quality of the numerical model is excellent in this case. But it must be stressed that the movement of the ship is not yet incorporated in the numerical model presented here.

Due to the necessary computation times it is still much more effective to perform e.g. optimization of valve schedules in the physical model. The trial-and-error process can be handled much quicker, as a physical model run takes only some minutes while the numerical computations can last many hours or even days.

3 RECENT DEVELOPMENTS

The experience with the high lift locks built in the past decades in Germany (Uelzen I and II, Henriechenburg and many locks at the Main-Danube canal) have shown that the criteria presented above seem to be very strict. The lockage process in some of those locks is so smooth, that the ships use no hawsers at all. Obviously, higher forces on the ships could be acceptable. Thus, a revision of the presented criteria should be started.

Comparison with other European countries has shown that the force criteria differ from country to country. It would be worthwhile to evaluate the criteria from different countries and eventually derive a new set of guidelines.

4 REFERENCE

[1] Partenscky, H.-W., Binnenverkehrswasserbau Schleusenanlagen, Springer, Berlin 1986

MOORING FORCES AND VESSEL BEHAVIOUR IN LOCKS - Experience in The Netherlands -

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ABSTRACT: This introductive abstract on "Mooring forces and vessel behaviour in locks" introduces developments and some experience in the Netherlands on the hydraulic tranquillity in and around the lock chamber during lock-levelling, the response of the vessels and the resulting mooring forces.

[1] Alkyon Hydraulic Consultancy & Research is a trade name of ARCADIS Nederland BV

1 INTRODUCTION

In many waterways locks are the key structures to enable navigation through a waterway corridor with water bodies at different levels. For carrying a vessel from one to another level, the water level in the lock chamber should be levelled. The levelling should be organised in such a way that the hydraulic forces on the vessel in the lock chamber are acceptable, while on the other hand the levelling time and therewith the time delay for passing ships is minimised. As such the design of a levelling system requires to find the optimum between: levelling time, forces and motion on the vessel and the costs for the levelling system.

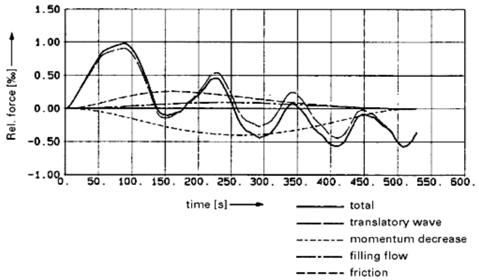

Fig 1: Forces on vessel during filling (RWS, 2000)

2 LOW-LIFT LOCK LEVELLING MODEL

İn the Netherlands the lift of most locks is not more than a few meters. İn these situations the levelling system consists of openings in the lock gates or short culverts with stilling basin in the lock heads. The program LOCKFILL was developed in the last century as a design and verification tool for lock levelling systems (WL,1994). LOCKFILL simulates the lock levelling and the hydraulic forces on the vessel in the lock chamber. The following hydraulic forces on the vessel are computed (see also Figure 1):

1. Translatory waves in the lock chamber;
2. Momentum decrease over the vessel length;
3. Jet of filling flow at the bow of the vessel (only during filling); and
4. Friction along the vessel hull.

İn many situations the translatory wave provide the main contribution to the total force on the vessel in the lock chamber. This translatory wave usually consists of an average and an harmonic component that corresponds with the own-frequency of the lock in length direction.

The last few decades this well calibrated and validated program LOCKFILL was the primary tool for design and verification of the levelling systems for locks that are levelled through the heads and with a lift up to 4 metres. This complies with most of the locks in the lower elevation regions in the Netherlands.

At present various locks are renewed, elongated or newly constructed in the Netherlands, and many other countries. Many of these locks have a higher lock-lift, bottom- or side-filling systems, saving

basins, etc. that are not accounted for in the program LOCKFILL.

3 APPROACH FOR HIGH LIFT LOCKS

The need for an extension of the modelling options became urgent during the (conceptual) design of the levelling system for the high-lift navigation locks in the canal Seine Nord Europe.

Therefore the new tool based on 1-D and 2-D flow modelling and mooring-line forces have been developed based on the programs INFOWORKS-RS, DELF3D and SHIP-MOORING.

The high lift locks in the canal SNE are characterised by:

- Lock chamber for CEMT Class Vb vessels;
- Lock lift up to 30 m;
- Up to 5 saving basins;
- Levelling-time less than15 minutes; and
- Water level slope in the lock less than 0.1%.

In view of the above the levelling of the lock requires discharges of over 200 m^3/s from and to the saving basins and 70 m^3/s from and to the canal. This was enabled applying the following design philosophy:

- Levelling through holes in the bottom of the lock chamber;
- Minimise the inertia of the water in the culverts (short distances);
- Minimise the energy losses in the culverts (internally fluent, with only gradually changing cross-section, avoid sharp corners and avoid lee areas with turbulence); and
- Manipulate the valve opening speed to control the discharge (maximise the tranquillity in the lock chamber and outer harbour).

The above philosophy has been applied for the design of the elements of the levelling system: the saving basins; the culverts; the valves; and the openings in the double bottom of the lock chamber.

Most of the above elements could not be accounted in LOCKFILL. Therefore a comprehensive schematisation of all the elements of the hydraulic system including the outer harbours has been prepared in 1-D and 2-D flow models. Further the hydraulic-loss coefficients and valve opening and closing strategy have been determined.

Sensitivity runs have been executed on a number of aspects: choice of the hydraulic-loss coefficients, the distance between saving basins and lock chamber; valve opening and closing policy, etc to check the accuracy and sensitivity and also to optimise the design and the opening and closing operation of the valves. The valve operation and the related variation in the discharges appeared to have a very significant impact on the tranquillity in the lock chamber. The results of the flow simulations for the high-lift locks comprise the levelling time and the levels in the locks and in the saving basins, see Figure 2:

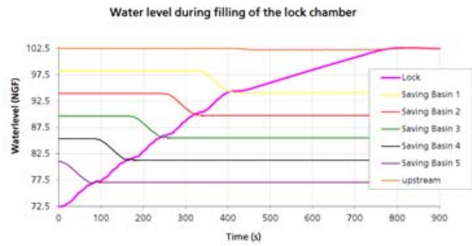

Fig 2: Levels during filling of lock

the discharges through the culverts, see Figure 3:

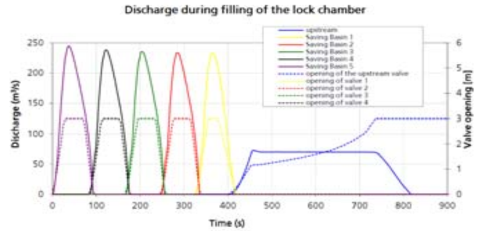

Fig 3: Discharges during filling of lock

and the water level slope in the longitudinal direction of the lock chamber, see Figure 4:

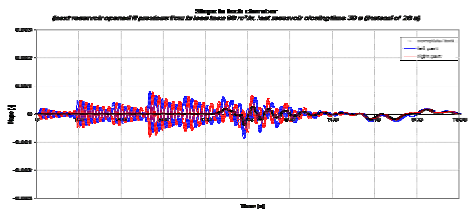

Fig 4: Slope of waterlevel during filling of lock

The computed levelling times (13 min for filling and 14 min for emptying) agreed well with the levelling time that was measured later on in the physical model (Cazaillet, 2009). Also the water-level slopes in longitudinal direction as presented in

Figure 4, agreed well slopes presented by Deleu et al. (2009) from the physical model.

4 EXTENSION TO SHIP RESPONSE

The response of the vessel has been simulated in the SHIP-MOORING model. A mathematical model of a loaded Class Vb vessel moored in the lock chamber and in the outer harbours has been considered. The water-level variations and discharges have been used for the computation of the external forces, the longitudinal motions and the mooring forces of the vessel, see Figures 5 and 6:

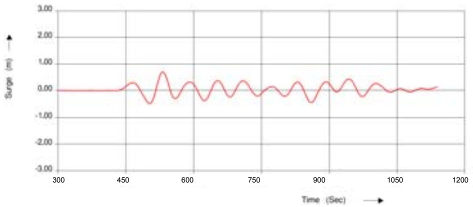

Fig 5: Vessel motions during filling of lock

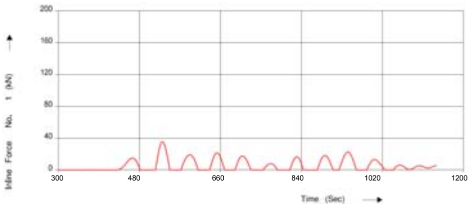

Fig 6: Mooring line force during filling of lock

The above modelling method has been applied successfully for the high-lift locks in the CSN. More recently the methodology (or part of it) has been applied for other locks in the Netherlands, including locks with filling through the lock walls.

REFERENCES:

WL, 1994; Handleiding LOCKFILL; Waterloop-kundig Laboratorium; november 1994, rapport Q1537; Delft, The Netherlands.

RWS, 2000; Ontwerp van schutsluizen, Deel 1; Rijkswaterstaat, Bouwdienst Utrecht; ISBN 90-369-3305-6; June 2000.

Cazaillet, O. 2009; Presentation 15 - CANAL SEINE NORD EUROPE MOISLAINS LOCK, PIANC International Workshop, *Innovations in Navigation Lock Design;* 15-16 October 2009, Brussels, Belgium.

Deleu, B., and Maillet, J.N; Paper 4 - Seine Nord Europe canal – Hydraulic design of locks; PIANC International Workshop, *Innovations in Navigation Lock Design;* 15-16 October 2009, Brussels, Belgium.

MOORING FORCES and VESSEL BEHAVIOR
- Experience in USA -

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ABSTRACT: The U.S. Army Corps of Engineers relies on physical hydraulic models to evaluate the performance of lock filling and emptying systems. Detailed physical models, usually constructued at a scale of 1:25, are used to ensure that a lock system will operate in a timely manner while assuring safety. Safety is assessed using hawser force criteria which is based on more than 60 years of experience in lock models and subsequent corresponding prototype performance studies.

1 USACE GUIDANCE

The U.S. Army Corps of Engineers (USACE) relies on physical hydraulic models to evaluate the performance of lock filling and emptying systems. This reliance is based on more than 60 years of experience in large-scale lock models and subsequent corresponding prototype performance studies. The lock system is designed to operate in a timely manner while assuring safety. Safety is assessed using hawser force criteria (USACE 2006). The USACE criteria is no force greater than 4.5 t (metric tons) as extrapolated from a physical hydraulic model for barge tows of various sizes and numbers in any location in the lock chamber during the locking operation (U.S. Army Corps of Engineers 2006 and 1995). Larger maximum hawser forces are allowed on displacement vessels in which case the USACE criteria is stated in terms of the vessel's displacement. Maximum hawser forces should be less than 9.1 t for ships up to 45,000 dwt and 22.7 t for ships up to 154,000 dwt.

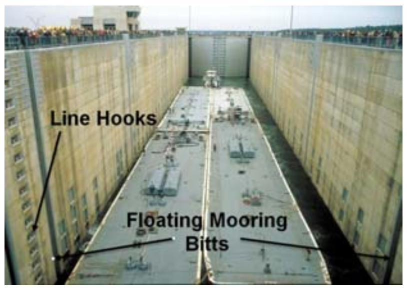

Fig 1: Tow mooring for lock filling

The hydrodynamic loads on a moored vessel consist of shear, drag, and hydrostatic forces. The later is by far the largest force exerted on a moored vessel during locking operations because longitudinal seiche can produce large differences in the hydrostatic forces at the bow and stern, yet the flow velocity is negligible. The hydrostatic force is equivalent to the product of the vessel's displacement and water-surface slope. Therefore, the USACE criteria of allowable hawser force can be viewed in terms of water-surface slope. The water-surface slope that produces a 4.5 t hydrostatic force on a 3-wide by 3-long flotilla of jumbo barges (each 59.4 m long by 10.7 m wide) drafted at 2.7 m, moored in a nominal 180-m by 33.5-m lock is 0.0003; whereas, a 3-wide by 5-long barge train moored in a nominal 360-m by 33.5-m lock is 0.0002. This shows that the hawser criteria are more restrictive on the 360-m locks in terms of allowable longitudinal water-surface slope.

The lock culvert system should provide good flow distribution along the lock chamber length to ensure that the longitudinal water-surface slope is limited. Another consideration is the roughness of the chamber water surface. Smoother conditions provide safer navigation for small craft. Performance indicators in addition to hawser forces are surface currents and turbulence, drift of free tows, and operation times.

Detailed physical models are usually constructed at a scale of 1:25. A hawser-pull (force link) device is used in physical models to measure the longitudinal and transverse forces acting on a tow in the lock chamber during filling and emptying

operations. The lock chamber water-surface elevation is measured with pressure cells.

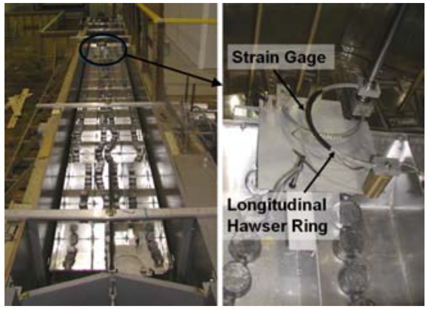

Fig 2: Hawser-pull (force link) devices

The USACE has conducted more than 60 model and 10 prototype studies of lock filling and emptying systems. The field experiments have shown that there is good agreement between hawser force measurements in physical models and corresponding prototype locks. A comprehensive evaluation of the split-lateral filling system at Barkley Lock, Cumberland River, was reported by Neilson (1975). Hawser forces measured during locking operations showed that those measured in a physical model were in "close agreement with corresponding prototype test results." Hawser forces were also measured during operation of the sideport filling system at Jackson Lock on the Tombigbee River (Dawsey et al. 1965). The prototype forces at Jackson Lock also compared favorably with the model forces.

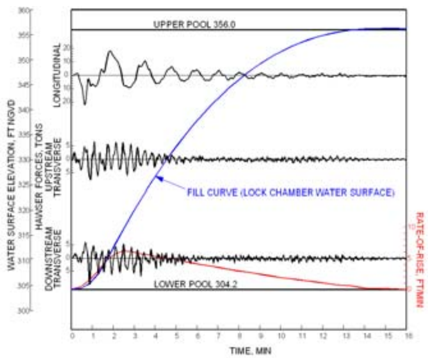

Fig 3: Physical model lock filling data

2 LOCK APPROACHES

In addition to the development of the filling and emptying system, the effect of locking operations on tows in the approaches is often investigated. The lock operation produces surges that can cause problems especially within navigation canals. These surges generate forces on moored vessels and lock gates. Therefore, intake and outlet designs are evaluated in conjunction with valve operation speeds in regard to surges produced in the upper and lower approaches.

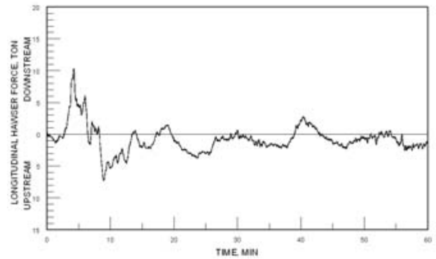

Fig 4: Hawser forces on a tow moored in the upper approach during lock filling

REFERENCES

Dawsey, J. V., Jr., Huval, C. J., and Blanton, W. C. (1965). "Prototype Hawser-Force Measurements, Jackson Lock, Tombigbee River, Alabama," *Technical Report No. 2-685*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Neilson, F. M. (1975). "Barkley Lock Prototype Tests, Cumberland River, Kentucky," *Technical Report H-75-1*1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers (2006). "Hydraulic design of navigation locks," *Engineer Manual 1110-2-1604*, Washington, D.C.

U.S. Army Corps of Engineers (1995). "Planning and design of navigation locks," *Engineer Manual 1110-2-2602*, Washington, D.C.

NEW INNOVATIVE CONCEPTS FOR NAVIGATION LOCKS

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Canada

ABSTRACT: This paper presents the Hands Free Mooring (HFM) system that is being developed and tested at the St. Lawrence Seaway. The HFM is an automated system using vacuum technology that can be used to replace the traditional mooring line handling process. While the vacuum mooring technology has been successfully used for a number of years in ports, this is the first time that it has been adopted for a lock system.

1 INTRODUCTION

The Great Lakes St. Lawrence Seaway System is a vital transportation route from the Atlantic Ocean to Lake Superior, serving the industrial heartland of North America. The St. Lawrence Seaway, which was opened in 1959, is a key component of this system consisting of navigation locks and connecting canals. It provides ship access from Montreal to Lake Erie and includes two sections: the Montreal - Lake Ontario Section (MLO), consisting of five Canadian and two U.S. locks, and the Welland Canal with its eight locks.

Since 2005, the St. Lawrence Seaway Management Corporation (SLSMC) has been exploring innovative concepts to modernize its lock operation. Vessel Self Spotting (VSS) and Hands Free Mooring (HFM) are systems that worked together to revolutionize the productivity of St. Lawrence Seaway Management Corporation (SLSMC) lock operational staff by replacing the manual lockage process with automated systems using innovative technologies. The systems also provide a major safety advantage by eliminating the risk of injury to lock and ship personnel from breaking of the mooring lines.

While the VSS have already been fully deployed, HFM has been in prototype development and trials with MoorMaster[1], the patent holding company, over the last few years.

[1] In 2007; MoorMaster joined with Cavotec Ltd and the vacuum mooring business is now known as Cavotec MoorMaster (CMM)

2 VESSEL SELF SPOTTING SYSTEM

The vessel self spotting system (VSS) was developed in 2007 as a means to provide vessels with visual information about how far they are away from their final mooring position within the lock. The system was developed to improve the lockage cycle time by having all lock personnel available for mooring operations earlier in the process. Combined with the HFM, it set the stage for potential automation of the mooring process.

Operation requirements dictate that the vessel entering the lock must be spotted at least 25m from the final mooring position when the countdown begins. The mooring position accuracy must also be 500mm or better and it must be able to work under all weather conditions.

The VSS employs a laser beam mounted at both ends of the lock to sweep the moving vessel and form a 3-D image. Vision algorithms are developed to precisely locate the foremost point of the ship bow, for ships of different shape, height, and color shading. Once locked in, the VSS determines the vessel's exact distance in meters from its final mooring position, and communicates it to the vessel captain through both a display panel and an automated radio transmission.

In 2008, the VSS was installed on one lock for field testing. An iterative process was used to perfect the software as there were many operating conditions that could not be pre-determined. Consequently, the success rate rose from 55% in June to 95% at the end of the navigation season in

December. In 2009 and 2010, the VSS were installed at all the locks.

3 HANDS FREE MOORING SYSTEM

In 2005, SLSMC and MoorMaster of New Zealand began discussions regarding the potential to adopt their vacuum mooring technology for use in a Seaway lock. While the vacuum mooring technology had been in use for a number of years, the standard units manufactured by MoorMaster were not suitable for the situation in a navigation lock.

In 2006, an order was placed with MoorMaster to develop a prototype unit that would be suitable for lock operations. This initial prototype was based on the traditional floating bollard design combined with a top-mounted vacuum mooring unit. Each unit is designed to hold a 20 kN force perpendicular to the plane of the vacuum pad and 12 kN against sliding. The unit can extend 850mm beyond the lock face to reach the vessel.

Following successful acceptance testing in New Zealand, one unit was installed in a low lift lock on the Welland Canal in early 2007. The testing confirmed the viability of the concept and identified certain improvements that could be made to the design.

To further the testing, two HFM units were installed at a high lift lock in the Welland Canal in 2008 to evaluate the system's capabilities, limitations and its impact on vessels and lockages. Each unit is equipped with continuous load monitoring function to facilitate analysis. Data gathered during the tests found that 2 units were not adequate to hold the vessels inside the lock during the lock filling operation, despite the fact that only two mooring lines, each carrying 10 kN, are used in the manual mooring process. This was due to the fact that the mooring lines allowed some slippage through either a slip clutch system or manual intervention while the HFM unit must resist the full forces.

Steel rubbing bars, which are essentially 50mm thick steel plates welded onto the haul of the vessels, were also a major problem, as they prevented the unit from creating a seal and forming a vacuum, thus rendering the units ineffective.

Figure 1 - HFM Flotation Unit

Based on the test results, two additional units were installed using a new prototype that was winch operated instead of mounting on top of a floatation tank (see Fig. 2). These units had the advantage of being able to be positioned vertically to avoid the rubbing bars on the vessel and thus greatly improved the success rate of the unit. Four units were found to be marginally adequate to hold the vessels inside the lock during filling and emptying operation. However, there were still a number of operational issues that needed to be resolved. First, maximum size vessels entering the lock in a low pool created a water gradient ahead that resulted in a hydraulic force in front of the vessel. This force was too high for the vacuum units to stop the vessel. This resulted in damage to the vacuum seal, rendering the unit unserviceable. Smaller vessels, on the other hand, faced the challenge of navigating close enough to the units to be attached using the HFM units.

Figure 2 - HFM Winched Unit

Design is currently underway to develop a fourth generation HFM unit to address the problems identified. To increase the energy absorption capacity to counter the hydraulics force generated by the vessel entering the lock, an "Active Side Shift" using pneumatic cylinders will be used to dampen vessel motion and keep the load constant at 10 kN. Each unit will also be equipped with two vacuum pads, thus doubling the holding capacity. The new unit will also be able to extend up to 2m into the lock, making it much more effective in handling smaller vessels that generally have narrower beams. A conceptual design of the new prototype is shown in Fig 3 below.

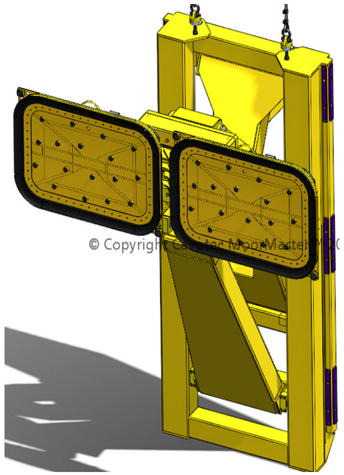

Figure 3 - Conceptual design of new prototype

4 CONCLUSION

Adapting innovative technology for the use in navigation lock is challenging as many of the factors can only be determined through testing under the operating environment. It is also important to involve vessel operators early to address any concerns in accepting the changes to traditional mooring lines, as they have been in use for a very long time.

INTERACTION between SALT WATER INTRUSION and NAVIGATION (in locks)

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ABSTRACT: This paper presents the most important aspects oft he consequences of the presence of salt water in (and around) locks : salinity and nautical aspects, based on the study oft he third set of locks in Panama, salinity and the environment, salinity and sedimentation and finally mitigating measures.

1 SALINITY AND NAUTICAL ASPECTS: THIRD SET OF PANAMA LOCKS

The Third Set of Panama Locks Project, launched by the Panama Canal Authority (ACP), comprises of the construction of a new shipping lane with locks on both sides of the Gatún Lake, at the isthmus of Panama. Ships approaching the locks navigate at a very low speed and are therefore susceptible to currents that affect the heading of the vessel. These currents can be caused by the spill released during the equalization of the locks with the ocean (spill currents) or by density currents caused by salinity differences of the ocean water and the water in the locks (exchange currents). IMDC, as part of the Consorcio Post Panamax (CPP), was assigned to carry out 3D mathematical model studies and the necessary in-situ measurements for the calibration and validation of the models. (CPP, 2007), (Sas et al, 2010)

The goal of the study was to identify and quantify the discharge and density currents that affect the manoeuvring vessels during present (Miraflores) and future (Third Set) lock operations at the Pacific side of the Panama Canal and to recommend alternatives that mitigate or eliminate the adverse effect of density currents on navigation and throughput.

A complex and innovative measurement campaign has been executed to quantify the currents and the salinity structure in the lock chambers and the tail water. The instruments (Acoustic Doppler Current Profiler-ADCP measures the 3D velocity distribution, self-Logging Multiprobe CTD instruments OBS 3A and CTD-divers that measure conductivity, temperature and pressure, a high frequency MultiSensor SiltProfiler which is a free-fall wireless profiling instrument that collects an undisturbed downcast profile of the salinity, temperature and turbidity).

Figure 1 : Opening of gates (Miraflores) and density current at surface

A far field 3D hydrodynamic model was set up and calibrated to generate appropriate boundary conditions for the 2 near field models of the Miraflores locks and the third set of locks. The former was used to calibrate the model of the salinity exchange processes during the emptying of the lock chamber and during opening of the doors, whereas the latter was used to study and evaluate different alternatives for the construction of the new approach channel to the 3rd locks (discharge point

of fresh water, lay-out of the tail bay, lay-out of the peninsula between the existing and the future navigation channel, shape of the entrance wall.

Current maps (vectors) – Fig 3- with weighted averaged velocities and transverse weighted averaged velocities (15.2 m in future approach, 12 m in present channel) have been produced and are now available to be implemented in the Navigation Simulator of ACP.

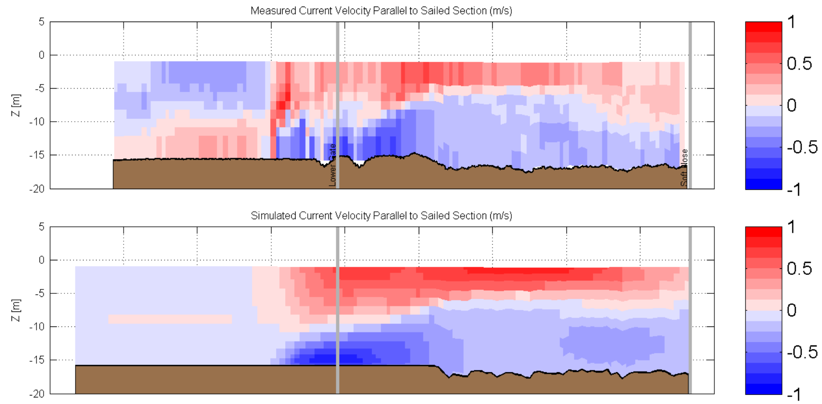

Figure 2: Typical calibration result: Longitudinal variation (at 300–1200m from upper gates) of a) measured velocity (10:45-10:53), b) modeled velocity (10:49).

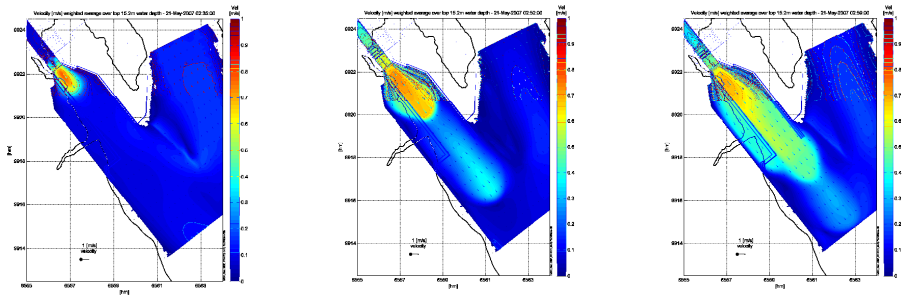

Figure 3: Illustration of draft-weighted average velocity (over 15.2 m) at different stages of the opening sequence.

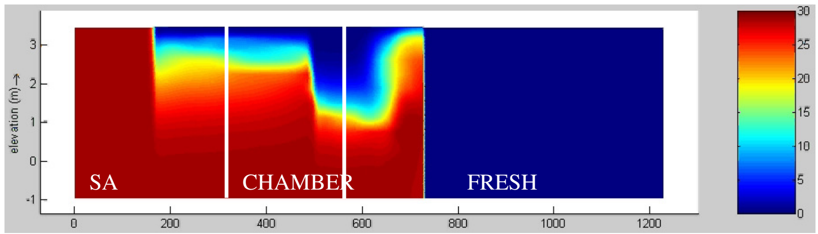

Figure 4: Modelled density flow in lock chamber fort he Seine Scheldt West Canal

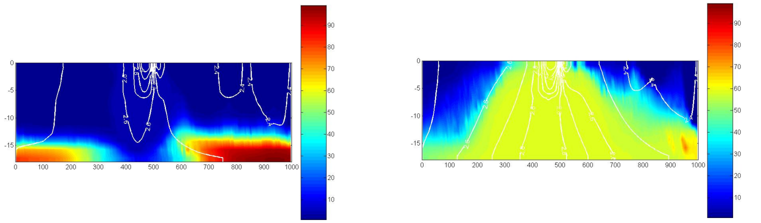

Figure 5: today's groundwater salinity through the existing canal (left); salinity 32 years after the introduction of the canal (right)

2 SALİNİTY AND THE ENVİRONMENT

Two major aspects have to be considered in assessing the environmental aspects of (sea)locks with regard to salinity.

Surface water is being used for drinking water supply, for agriculture purposes, for industry and is a characteristic element for the ecosystem. The anticipated changes in the surface water system must be identified. Illustrations will be given about saline intrusion into the canal Gent-Terneuzen (the Netherlands) and the Seine-Scheldt West canal study (Belgium), with emphasis on the salinity exchange in the lock and towards the navigation canal (Adams et al, 2010)

Changes in the groundwater in the vicinity oft he lock and along the connecting canal must be identified. It is obvious that changes in the salinity in the canal exerts an effect on the density dependent groundwater flow). Illustrations will be given about the saline intrusion analysis in the Seine-Scheldt.

3 SALINITY AND SEDIMENTATION

Salinity differences cause density currents, which entrain fine sediments into the lock chamber and into the access channels tot he locks. In general this mechanisme can contribute to even more than 50% of the sedimentation rate (PIANC, 2008).

4 MITIGATINGMEASURES

In order to minimise saline intrusion in the lock or the canal upstream, a number of mitigating measures have been studied and applied in the past (Sas M, 2009). We will briefly highlight some of these mitigating measures, such as a pumping system, the use of an air bubble curtain, gravitaional discharge of saline water via a receptor basin and complete lock chamber exchange. (Kerstma et al, 1994).

5 REFERENCES

Adams, R. Lebbe, L., Van Holland, G. De Vleeschauwer, P. Van Crombrugge, W., Sas, M. (2010), Dealing with salt intrusion and water shortage in the Seine Scheldt West connection, PIANC MMX congress, Liverpool

CPP (2007a). Task order 4: Study and 3D modeling of density and discharge currents of the third sets of locks, Task 4.1 Data Collection, Measurement Campaign Miraflores Locks 11 May – 31 May 2007. (TO4-Task4.1-TEC-R001).

CPP (2007b). Task order 4: Study and 3D modeling of density and discharge currents of the third sets of locks, Task 4.2 Numerical modeling of density currents – Pacific Approach. (TO4-Task4.1-TEC-R002).

Kerstma, J., Kolkman, P.A., Regeling, H.j., Venis, W.A. (1994) Water quality control at ship locks ; prevention of salt and fresh water exchange, Balkema Rotterdam.

Sas, M. (2009), Salinity and Locks, Innovations in Navigation Lock Design, PIANC Workshop, Brussels 15-17/10/2009.

MANEUVERABILITY IN LOCK ACCESS CHANNELS

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ABSTRACT: An overview is given of hydrodynamic effects acting on a ship approaching a lock, including approach channel and approach structure layout, density currents, translation waves, return flow, cushion effects, and retardation forces. Most of these effects have a non-stationary nature, which is challenging from the point of view of maneuvering simulation. Lock approaches are illustrated by practical examples. A selection of research tools, including simulation, model testing and full scale measurements, is discussed.

1 INTRODUCTION

Most sea-going ships are not particularly designed or equipped for approaching locks. Their main means of control, mostly propeller(s) and rudder(s), are optimized for navigation at service speed, but during harbor approach (and, particularly, lock approach), ship behavior drastically changes due to speed reduction, shallow water effects, interaction with banks and other shipping traffic, etc. Frequently, sea-going vessels are equipped with bow (and, more rarely, stern) thrusters to improve the lateral controllability during low speed harbor maneuvers, but even these vessels often require tugs to assist them during (un)berthing, turning maneuvers, and lock approach. Many inland waterway vessels, on the other hand, need to perform such maneuvers on a more than daily base, so that they are mostly equipped with powerful bow thrusters and high performance rudders to guarantee high controllability at low speed.

All phases of a ship's voyage, including access to a lock, must be performed in a safe way, i.e. with an acceptable risk, but also in an efficient way, i.e. within an acceptable timeframe and making use of a reasonable amount of resources. The success of lock approaches depends on the interaction between the ship, the channel and lock characteristics, the meteorological and hydrological conditions, the assisting tugs, aids to navigation, and all human controls involved: the pilot or captain, the wheelman and the tug captain(s). Real-time simulation techniques are commonly applied for design of new infrastructure, assessment of accessibility of existing harbors/locks for new shipping traffic, and training purposes. However, simulations are only reliable if all relevant forces acting on a vessel during the considered maneuver are taken into account in the mathematical model of the simulator program. Some of the effects should be integrated in any simulator used for harbor maneuvers, but during lock approach and entry the ship's hydrodynamics are dominated by specific effects which are often a challenge for the developers of mathematical models.

2 HYDRODYNAMICS OF LOCK ACCESS

2.1. Effect of lock approach configurations

Simulations of maneuvers in lock access channels can only be realistic if the effect of shallow water on the hydrodynamic forces and moments acting on the ship is taken into account. Furthermore, bank effects should be included to account for eccentric approach and a ship-ship interaction force module is required if encountering or overtaking maneuvers frequently take place in the approach. All these phenomena, as well as the forces induced by tugs, can be considered as standard effects for harbor maneuver simulations.

Besides these effects, interaction with the specific geometry of the ***approach channel and approach structures*** induces hydrodynamic forces and moments on the approaching vessel. Based on their origin, they can to some extent be considered as bank effects, but the way they affect the maneuver

may be quite different due to their transient character and the permeability of the approach structures.

Figure 1 displays the effect of different approach structures on the lateral force acting on a ship entering a lock along its centerline. 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.

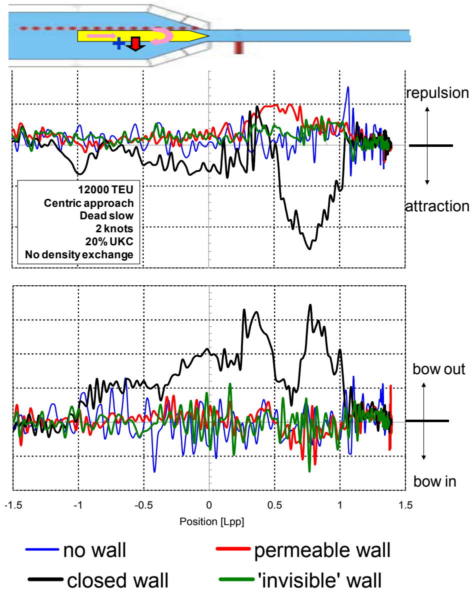


Figure 1. Lateral force (above) and yawing moment (below) on a self-propelled guided ship model during lock approach: effect of approach wall layout. Zero position is sketched above. Source: Flanders Hydraulics Research commissioned by Consorcio Pos Panamax on behalf of Panama Canal Authorities, [1], [2].

Moreover, flow asymmetry clearly continues to affect the ship after the latter has entered completely into the lock (Figure 1) or, during an exit maneuver, even before the ship has left the lock (Figure 2).

Lock approach geometries are often asymmetric, and it is difficult to predict the occurring hydrodynamic effects. This is illustrated in Figure 3, showing the oscillatory character of the forces acting on a ship approach and entering a lock.

2.2. Currents during lock approach

Although locks are mostly planned in a protected location with respect to ***currents***, approaching ships are quite sensitive to even moderate flow patterns because of their limited approach speed. Moreover, lock operations may cause additional currents due to discharge and opening of the lock gate; especially with sea locks, density differences between the approach channel and the lock chamber induce flow patterns which not only cause important forces and moments on the approaching vessel, but may also affect the assisting tugs. Figure 4 gives examples of ***density flow*** patterns around a ship waiting to enter a lock, again showing the effect of the approach structure geometry. Density currents due to lock gate opening may affect approaching vessels for a considerable time, e.g. 20 minutes and more for a large sea lock.

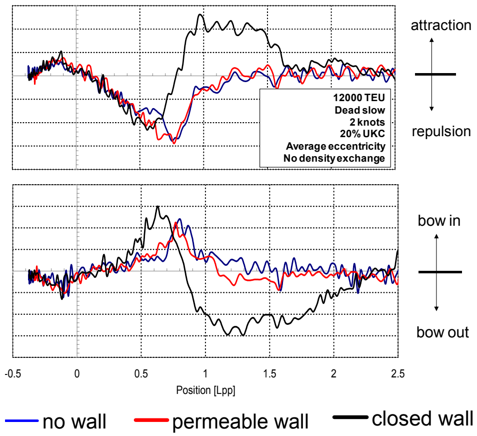


Figure 2. Lateral force (above) and yawing moment (below) on a self-propelled guided ship model during (eccentric) lock exit: effect of approach wall layout. Source: Flanders Hydraulics Research commissioned by Consorcio Pos Panamax on behalf of Panama Canal Authorities, [1], [2].

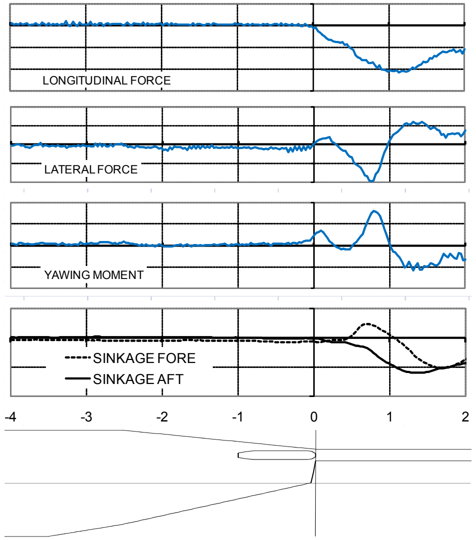


Figure 3. Captive model test with a bulk carrier entering the Pierre Vandamme Lock (Zeebrugge, Belgium) with asymmetric approach at constant speed. Longitudinal position convention: see Figure 1. Towing tank for maneuvers in shallow water (co-operation Flanders Hydraulics Research – Ghent University), Antwerp.

Large sea-going vessels are often assisted by ***tugs*** during lock maneuvers. The tug performance will also be affected by the currents generated by discharge and lock gate opening. The overall effect of currents on a tug, with limited draft, may be different compared to the assisted ship due to flow stratification, especially in case of density currents.

2.3. Lock chamber entry

Especially in the case of a large blockage factor – i.e. when the limits of the dimensions of the entering ship are (nearly) reached – the entry of a ship into a lock can be compared with the motion of a piston in a cylinder. When entering the lock, a ***translation wave*** will be generated that reflects on the closed lock gate. This transient wave system depends very much on the hull shape, and will be more pronounced in case of full form ships (tankers, bulk carriers, barges). In the gap between the ship's keel and sides, and the lock's floor and walls, a ***return flow*** will occur, increasing the frictional resistance. The wave system and the return flow considerably increase the ship's resistance (see Figure 3), affect the inflow to propeller and rudder, and induce vertical motions. The latter are also illustrated in Figure 3: when the ship enters the lock chamber, the bow is pushed upwards, but gradually the ship will undergo a general sinkage. It should be born in mind that the speed is (artificially) kept constant during this captive model test.

When the margins between the lock walls and the ship sides are small, contact with lock structures (approach structures, fenders) is almost inevitable. Lateral motions of the ship that has partially or fully entered the lock chamber are affected by so-called ***cushion effects*** due to the piling-up of water; moreover, sudden accelerations or decelerations, occurring as a result of contact, cause ***retardation forces*** due to the inertia of the water mass between wall and ship. These memory effects are very dependent on ship and lock geometry.

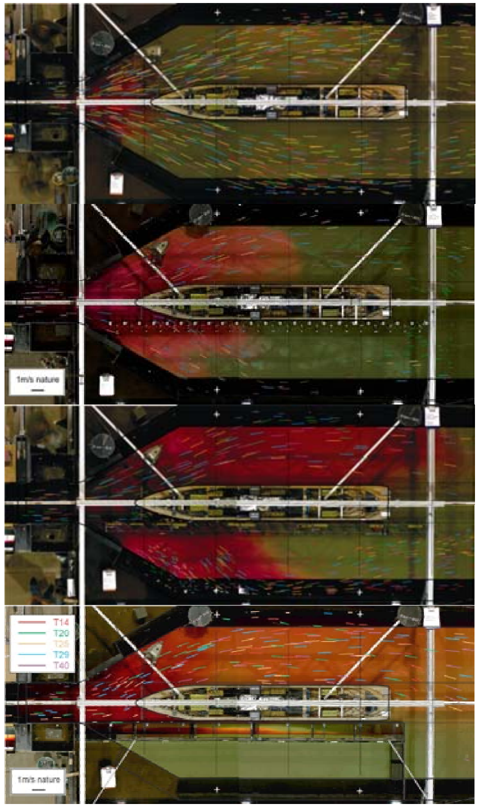


Figure 4. Effect of approach structure configuration on surface current pattern due to density exchange flow: no wall – 'invisible' wall (series of piles) – permeable wall – closed wall. Source: Flanders Hydraulics Research commissioned by Consorcio Pos Panamax on behalf of Panama Canal Authorities; [1], [2].

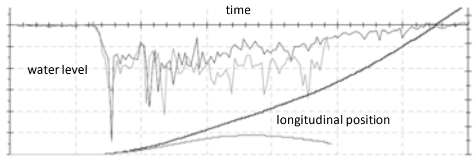


Figure 5. Results of two model tests with a self-propelled tug-barge combination leaving a lock: water level at the closed lock gate and longitudinal position of the vessel as a function of time. Source: Flanders Hydraulics Research.

2.4. Lock chamber exit

The piston effect is not only of importance for ships entering a lock, but also for ships leaving the lock chamber. The acceleration of the ship (or convoy) causes a depression of the water level between the ship and the closed lock gate, which results in a backwards suction until the water level has risen sufficiently again by the water flow along the lock walls and bottom. Figure 5 shows the results of two model tests during which a self-propelled model of a tug-barge system is leaving a lock. In one of the cases (light grey lines), the convoy is even unable to leave the lock with the given propeller settings: the water level between the closed lock gate and the ship remains low, which stops and even reverses the forward motion of the convoy. In general, the propeller rpm should be increased gradually during the acceleration phase to avoid excessive suction effects.

2.5. Other effects

Besides all these phenomena that are typical for lock maneuvers, the ship is also subject to other environmental effects, such as ***wind***. In some cases, the ship's windage area is reduced due to partial coverage by the lock construction, which decreases the wind forces and moments, but also induces time-dependent wind actions. In addition, the effects of wind gustiness is mostly more important during lock approaches compared to other maneuvers in less constrained areas.

3 PRACTICE OF LOCK APPROACH

The procedure followed during approach of large sea-going vessels to locks depends very much on the local situation. Three examples will be given: the Panama Canal Locks, the Terneuzen West Lock and the Berendrecht Lock.

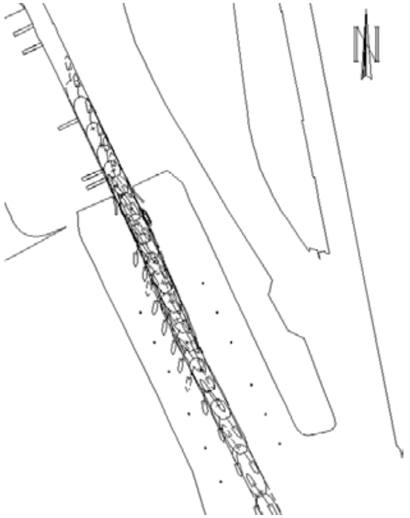
Ships approaching the present Panama Canal Locks get aligned with the lock centerline by means of tugs pushing them to the approach walls, where locomotives are attached to assist them through the lock(s), see Figure 6. This way of operation allows an efficient use of the lock capacity. The procedure for the Third Set of Locks, planned to be operational in 2014, will be different as the new locks will not be equipped with locomotives.

The Panama Canal Authorities presently allow ships with a beam up to 32.2 m in their 33.5 m wide locks. The Terneuzen West Lock (The Netherlands), giving access to the port of Ghent (Belgium), has a width of 40.0 m, but is equipped with floating fenders of 1.0 m width at each of the lock walls. Since 2008, ships with a beam of 37.0 m are allowed, after a simulation study at Flanders Hydraulics Research (Figure 7), and a number of test voyages. Alignment of the ship in the centerline of the lock is very important, and is realized with the assistance of one tug at the bow, two tugs pushing at each side and one or two tugs at the stern. The bollard pull of the stern tugs depends on the wind condition and the ship's loading condition (ballasted or loaded), but also on the speed of the vessel at dead slow ahead, as speed control is one of the main functions of the stern tugs, [4]. An increase of the allowable beam to 38 m is presently being studied.

For ships entering the Berendrecht Lock in the port of Antwerp (Belgium), the alignment might look less critical, taking account of the lock width of 68 m and the typical maximum width of the ships making use of it (about 55 m). However, due to the geometry of the access channel at both sides of the lock, it is not possible to align the ship far ahead of the lock entrance; moreover, assisting tugs have a limited free space to operate, see Figure 8 (riverside). This situation requires a completely different strategy. In order to assess the accessibility of the lock for container carriers with length up to 381 m, real-time simulations have played an important role, [5].

For facilitating the access to the locks in Terneuzen and Antwerp, the Flemish and Dutch pilots make use of a portable system SNMS (Scheldt Navigator for Marginal Ships), that allows to determine the ship's position within centimeters accuracy. In lock mode, the pilot can determine the position of the ship with respect to the lock walls.

Figure 6. Bulk carrier pushed by tugs to the approach wall before entering Gatún Locks, Panama Canal.



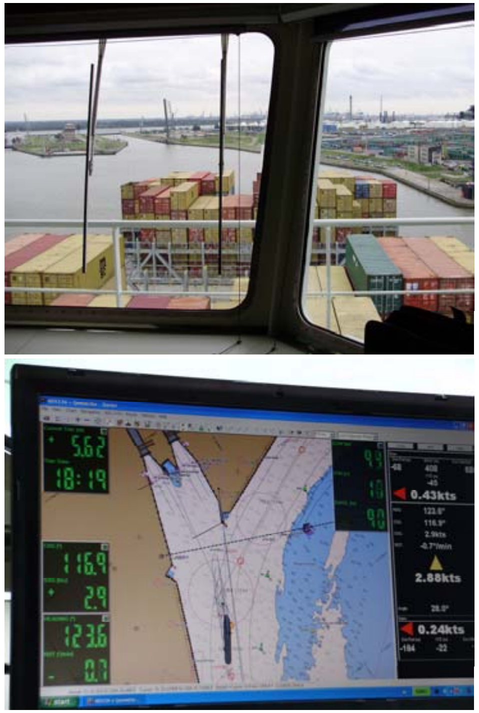


Figure 8. Ultra large container carrier approaching the Berendrecht Lock, Port of Antwerp, Belgium, from the riverside, assisted by a portable pilot assistance system.

Figure 7. Lock entry of a bulk carrier with 37 m beam to the Terneuzen West Lock: simulation and reality. Source: Flanders Hydraulics Research, [3].

4 RESEARCH TOOLS

4.1. Maneuvering simulation

For design and training purposes, maneuvering simulation has become a widespread and generally accepted tool. The realism and reliability of the simulated maneuvers and the validity of the conclusions of studies based on simulations depend to a great extent on the quality of mathematical simulation models. For studies involving lock approaches, it must be decided so as not to include the effects described in Chapter 2 into the mathematical model of a simulator suited for lock maneuvers, depending on their relative importance. The implementation of these effects requires algorithms that are sufficiently robust and not too time consuming, as the calculations have to be performed in real time. Another complication concerns the typical non-stationary character of several effects related to lock maneuvers, while most mathematical models for maneuvering simulation assume a quasi-steady approach.

For realistic simulations of lock maneuvers at Flanders Hydraulics Research, the mathematical model has been extended with modules accounting for the forces due to longitudinal translation waves, forces due to the return flow in the lock, retardation forces, and cushion effects.

Longitudinal ***translation waves*** can be modeled based on [6]. Due to the simplifications on which this model is based, i.e. the ship is considered to be a rectangular block, it gives good results for full form ships (e.g. barges, bulk carriers), but overestimates the effects for slender ships (e.g. container carriers).

The ***return flow*** caused by the forward speed of the vessel in the approach channel and the lock is taken into account based on the assumption that this flow can be considered as an external current. During lock entrance and exit, this flow varies along the ship's length, which will affect the hydrodynamic forces for which the longitudinal speed component is of importance.

Non-stationary hydrodynamic forces (***memory effects***) are implemented by replacing the hydrodynamic lateral force Y and yawing moment N due to sway and yaw acceleration ($Y = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r}$; $N = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r}$, with constant, low-frequency values for the added inertia coefficients $Y_{\dot{v}}, Y_{\dot{r}}, N_{\dot{v}}, N_{\dot{r}}$) by [7], [8], [9]:

$$Y = \mu_{yy}\dot{v} + \mu_{y\psi}\dot{r} + \int_{-\infty}^{t} K_{yy}(t-\tau)v(\tau)d\tau + \int_{-\infty}^{t} K_{y\psi}(t-\tau)r(\tau)d\tau$$

$$N = \mu_{y\psi}\dot{v} + \mu_{\psi\psi}\dot{r} + \int_{-\infty}^{t} K_{y\psi}(t-\tau)v(\tau)d\tau + \int_{-\infty}^{t} K_{\psi\psi}(t-\tau)r(\tau)d\tau$$

which implies that the kinematic history of the vessel (sway velocity v, yaw rate r) affects the present hydrodynamic forces acting on the ship.

The impulse response functions K not only depend on the ship, but also on the environment, i.e. the water depth and the bathymetry, which implies that the K functions vary during the approach maneuver. In the simulator model, a strip theory approach is implemented to take account of this effect.

The modeling of ***cushion effects*** is based on the results of captive model tests with a bulk carrier model approaching a vertical wall, which show that the effect can be implemented by multiplying the lateral force and yawing moment in open water with an amplification factor $A_C e^{-k_C \frac{d_{sq}}{B}}$, with d_{sq} the distance between the ship's side to the quay wall, B the ship's beam. As most hydrodynamic forces, A_C appears to be very sensitive to h/T, the water depth to draft ratio [10]. A strip-wise approach is applied to account for the variation of the lateral clearance over the ship length during lock entry or exit.

The realism of simulated lock maneuvers depends on the mathematical model, but also on the visuals, the simulation of tug assistance, and the 'human control'. Of course, the simulations carried out in the frame of feasibility studies, design studies, training, need to be performed by the pilots who are, or will be, in charge of the maneuvers in real life. But also the assisting crew is of great importance. For example, during the feasibility study for the admittance of bulk carriers with a beam of 37 m to the Terneuzen West Lock, the pilots preferred to involve the local wheelmen into the simulations to increase the realism.

4.2. Model tests

Model experiments are a powerful tool to investigate hydrodynamic phenomena. For developing mathematical maneuvering models in restricted waters, Flanders Hydraulics Research makes use of the *Towing tank for maneuvers in shallow water*, equipped with a planar motion carriage to perform ***captive*** model tests. The ship's kinematics are forced by the motion mechanism, while the ship's controls are predetermined as well; during a test, the horizontal forces and moments acting between the ship and the mechanism are measured. This results into a direct relationship between the ship's kinematics and controls on the one hand, and the hydrodynamic forces on the other, which is required as input for the mathematical model of a simulator as well.

An example of results of captive model tests carried out in a scale model of a lock is given in Figure 3. During this test, a constant forward speed was maintained. Although such a test offers the advantage that all relevant parameters can be selected independently, captive maneuvers are not always completely realistic. During lock entrance, the ship's speed will drop due to the increased resistance, and it is not a priori known which trajectory should be implied to obtain a realistic run.

The towing carriage and planar motion mechanism can also be used as a tracking system to perform self-propelled model tests. However, most lock entrance maneuvers with large sea-going vessels require tug assistance, which is difficult to account for during pure free-running tests. In order to investigate realistic tug assisted lock entries by means of model experiments, a lock approach facility, consisting of a scale model of a lock and its approach channel has been built at Flanders Hydraulics Research, see Figure 9. In this equipment, a ship model is allowed to move on a straight line parallel to the locks' centerline, while the lateral motions are restrained by a guiding rail to which the ship model is connected at the bow and at the stern. To sail along the beam with different eccentricity with respect to the lock axis, the frame with the wheels can be positioned eccentrically regarding the ship's axis. The lateral forces in each connection point are measured by dynamometers, while the ship is free to move in vertical direction. The ship's velocity is controlled by changing the propulsion of the ship, which is provided by its propeller or by tug assistance, simulated by small model scale airplane propellers mounted on the ship that only exert forces in the longitudinal direction. With the measured lateral forces the necessary tug assistance in any direction can be determined.

The lock access facility has been used in the frame of a feasibility study of the Third Set of Locks of the Panama Canal and for an inland shipping traffic study; at present, the test setup is used to investigate the use of the Terneuzen West Lock for bulk carriers of 38 m beam with several under keel clearances, drafts, eccentricities, propeller rates and tug assistance scenarios. The output will be used to give advice to the authorities on the regulations of entering and leaving the lock.

A general drawback of model tests concerns the scale laws: as the Froude similarity law is used, the Reynolds number is too small; hence, viscous forces are overestimated and need to be corrected.

4.3. Full scale measurements

Validation of simulators and simulation models is not straightforward, because it is not possible to assess the mathematical models directly, as forces cannot be measured at full scale; validation therefore has to be based on measurements of indirect parameters, e.g. followed tracks of maneuvering ships. Since recently, a device for the precise measurement of ship motions during operation is available at Flanders Hydraulics Research, consisting of two GPS receivers with RTK (real time kinematic) correction and an IMU (inertial measurement unit), see Figure 10. During lock maneuvers, for example, time, exact position of the vessel, her velocity and squat (mean sinkage and trim) is logged and the rudder and engine settings are monitored. The under keel clearance can be determined based on these data and the exact water levels measured at close-by stations. For an even more detailed analysis, wind, currents or even salinity information can additionally be obtained and processed, if stations are available in close proximity. The same conditions as during the full scale measurement (engine and rudder as well as environmental settings) can be used as input for either fast-time or real-time simulations in the ship manoeuvring simulators at Flanders Hydraulics Research. The results of these simulations can be compared with the measurements.

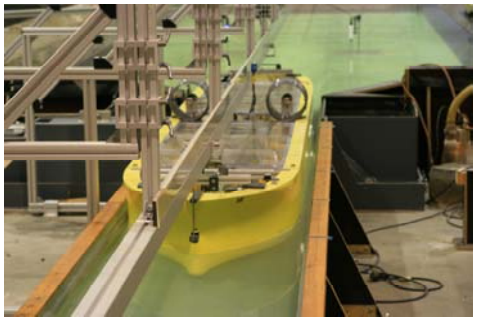


Figure 9. Lock entrance facility for self-propelled, laterally guided ship models at Flanders Hydraulics Research (photo Flanders Hydraulics Research)

Figure 10. Vessel monitoring equipment of Flanders Hydraulics Research for tracking ships during approaches and maneuvers (photo Flanders Hydraulics Research).

5 CONCLUSIONS

The safe and efficient use of locks requires an approach strategy that depends on the ship characteristics, the geometry of lock chamber and lock approach, available (tug) assistance, aids to navigation, and environmental conditions.

As human control and co-ordination between pilot/captain, wheelmen, tug masters, and lock operators play a crucial role, maneuvering simulation offer useful tools for optimizing lock design, assessing the accessibility of existing locks for new shipping traffic, and training. However, it is of great importance that all phenomena affecting and even dominating the behavior of a ship entering a lock are represented in a reliable and realistic way in the mathematical simulation model.

6 REFERENCES

[1] Delefortrie, G., Willems, M., Vantorre, M. & Laforce, E. (2009). Behavior of post panamax vessels in the Third Set of Panama locks. *International Conference on Marine Simulation and Ship Maneuverability (MARSIM '09)*, Panama City, Panama. Panama Canal Authority; International Marine Simulator Forum.

[2] Delefortrie, G., Willems, M., Laforce, E., Vantorre, M., De Mulder, T., De Regge, J. & Wong, J. (2008). Tank test of vessel entry and exit for third set of Panama locks. 517-523. *Proceedings of the International Navigation Seminar following PIANC AGA 2008*, Beijing, China. Communications Press.

[3] Vander Donckt, S., Vantorre, M., Laforce, E. (2007). Canal Ghent-Terneuzen: Maximum ship dimensions for the West Lock (in Dutch). Mod. 803-2. Flanders Hydraulics Research, Antwerp.

[4] Anon (2011). Notices to Mariners, No. 4 (February 17, 2011), Flanders Hydrography, Ostend. (http://www.meetnetvlaamsebanken.be/MVB.BaZHandler.axd?ID=c8ad396b-0244-4944-b4bd-f5079d92474d)

[5] Eloot, K., Verwilligen, J., Vantorre, M. (2010). Synergy between theory and practice for ultra large container ships. *PIANC MMX Congress*, Liverpool.

[6] Vrijburcht, A. (1988). Calculations of wave height and ship speed when entering a lock. Delft Hydraulics.

[7] Vantorre, M. (1992). Mathematical modeling of fender forces and memory effects for simulation of ship manoeuvres in confined waters. Proceedings of the 10th International Harbour Congress, pp. 5.31-5.40. Royal Flemish Society of Engineers, Antwerp.

[8] Vantorre, M. (1992). On the implementation of non-stationary forces in the mathematical model of a ship manoeuvring simulator. Design of Marine and Offshore Structures (4th International Conference on Computer Aided Design, Manufacture and Operation in the Marine and Offshore Industries, Madrid), pp. 615-632. Computational Mechanics Publications, Southampton/Boston; Elsevier Science Publishers, London/New York.

[9] Laforce, E.; Vantorre, M. (1994). Application of manoeuvring simulation techniques for dimensioning quaywall fenders. 28th International Navigation Congress, Sevilla, Section II, Subject 3, pp. 7-16. PIANC, Brussels.

[10] Vantorre, M.; Laforce, E. (1998). Experimental investigation of hydrodynamic forces acting on a ship in the vicinity of a quay wall. Symposium on forces acting on a manoeuvring vessel (MAN98), Val de Reuil.