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HYDRAULIC DESIGN AND PERFORMANCE OF THE FILLING AND EMPTYING SYSTEM OF THE PANAMA CANAL THIRD SET OF LOCKS

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ABSTRACT

The Panama Canal Third Set of Locks is a three-lift lock with Water Saving Basins that have been designed to provide a safe and reliable transit system for Neopanamax vessels travelling in both directions between the Pacific and the Atlantic Oceans. The hydraulic design consists in a dynamically balanced double longitudinal culvert side port Filling and Emptying System. This paper presents the process, methodology, and tools employed to develop and validate the filling and emptying system design, from original concept through system commissioning. Main results collected during the startup and commissioning of the system and the evolution of its performance over the firsts years of operations is presented proving that the innovative designed system performs as it was required.

Keywords: Panama Canal, Locks Filling and Emptying system, numerical model, physical model, prototype tests

1 INTRODUCTION

The Panama Canal Third Set of Locks is a three-lift lock with water saving basins (WSB) that have been designed to provide a safe and reliable transit system for Neopanamax vessels travelling in both directions between the Pacific and the Atlantic Oceans. The hydraulic design consists in a dynamically balanced double longitudinal culvert side port Filling and Emptying System. It was constructed for the Panama Canal Authority (ACP) under a design-build contract awarded in August 2009 to the consortium *Grupo Unidos por el Canal*, a joint venture of four construction companies (Sacyr Vallehermoso S.A., Salini-Impregilo S.p.A., Jan de Nul n.v. and C.U.S.A.) and inaugurated in June 2016. The design was prepared by CICP *Consultores Internacionales*, a design joint venture led by Stantec (formerly MWH).

A robust and comprehensive design methodology, comprising numerical and physical hydraulic modeling, was developed and implemented to deliver the required Filling and Emptying system performance under stringent Employer's Requirements. In addition, the lane of locks must be functional, reliable, and able to operate 24 hours a day, every day of the year, and achieve a 99.6% level of availability. As a result, the system has been provided with redundant components such as culverts, conduits, valves, and operating systems. These redundant components, along with the need for the locks to be available even during most maintenance or inspection operations, involve many different operational scenarios while meeting operational safety and efficiency criteria.

This paper presents the process, methodology, and tools employed to develop and validate the Filling and Emptying system design, from original concept through system commissioning. As part of the new facilities commissioning, a prototype measurement plan was developed to demonstrate compliance with the Employer's Requirements for system performance. Main results collected during the startup and commissioning of the system and the evolution of its performance over the firsts years of operations are presented.

2 THE THIRD SET OF LOCKS

The Third Set of Locks of the Panama Canal consists of two new locks facilities, one at each end of the Canal. These are in addition to the existing two locks lanes operational since 1914. A new lock facility is located at the Atlantic end of the Canal (*Agua Clara* Locks), on the east side of the existing *Gatun* locks and the other is located at the Pacific end of the Canal (*Cocolí* Locks), to the southwest of the existing *Miraflores* Locks. The new locks are connected to the existing channel system through new navigational access channels.

Each of the new lock facilities consists of three aligned locks chambers (Upper, Middle, and Lower) separated by a pair of Rolling Gates housed in four Lockheads, through which vessels move in three steps from sea level to the level of Gatun Lake (~27m) and back down again. The chambers are 458 m (1,500') long, by 55 m (180') wide, and 18.3 m (60') minimum water depth, allowing vessel drafts of up to 15.2m (50') in tropical fresh water. Each chamber has three lateral water saving basins (WSB) totaling nine basins per lock. The three WSBs (Top, Intermediate, and Bottom) can store water when lowering the chamber water level and can supply water when increasing the chamber water level. This procedure allows the reutilization of up to 60% in each cycle reducing the fresh water consumption of the lock system.

Figure 1. View of Cocoli and Agua Clara Locks (May 2016)

Each complex is completed with the associated buildings, facilities, and other systems required for its operation. Figure 2 shows a general plan and view of the *Agua Clara* Locks, *Cocoli* Locks design have similar configuration. Figure 3 shows a conceptual transversal section of the locks.

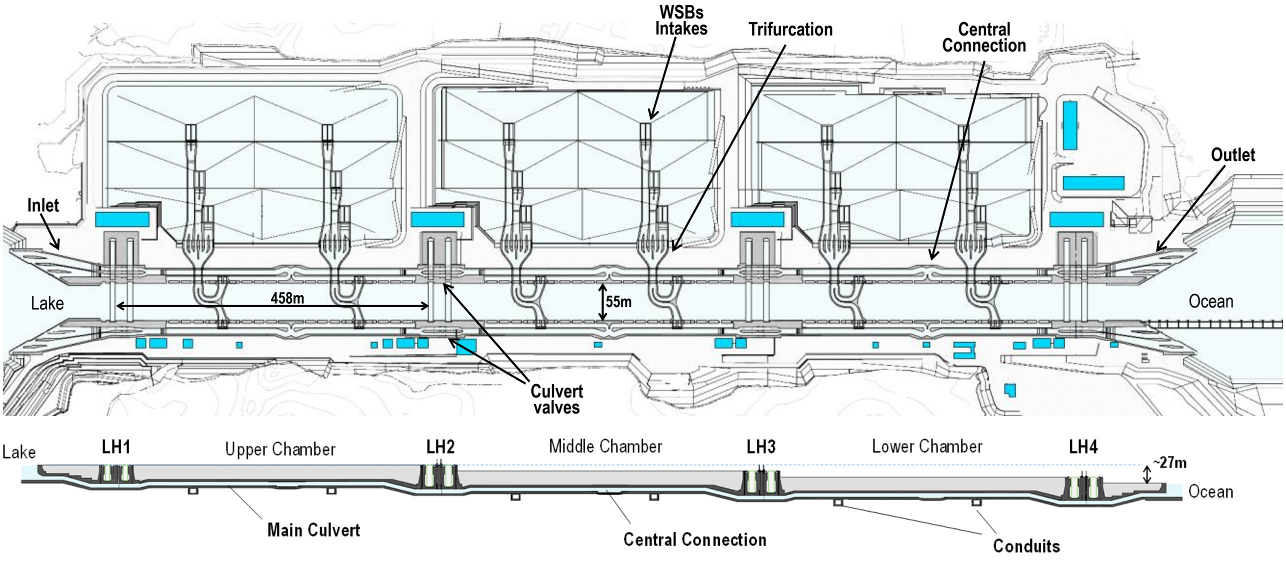

Figure 2. Project Plan and View of Agua Clara Locks

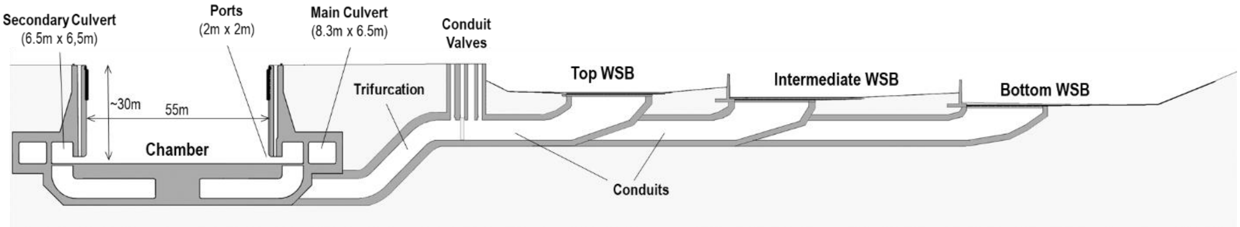

Figure 3. Conceptual transversal section of the locks

The lock systems accommodate both uplockage and downlockage vessels, with a planned reversal once per day. The lock system can operate with or without the use of WSBs. In the case of operation with WSBs, the following criteria are followed:

- When a vessel moves from the Ocean towards the Lake (i.e., from a lower level towards a higher one, or 'uplockage'), the water level at each chamber is increased in two steps: (i) by receiving all available water from the corresponding WSBs through the conduits, successively in time (starting with the Bottom WSB); (ii) by receiving water from the target reservoir (chamber or the Lake) through the culverts, until the two water levels are equalized.
- When a vessel moves from the Lake towards the Ocean (i.e., from a higher level towards a lower one, or 'downlockage'), the water level at each chamber is decreased in two steps: (i) by sending water to the corresponding WSBs through the conduits, successively in time (starting with the Top WSB); (ii) by sending water to the target reservoir (chamber or the Ocean) through the culverts, until the two water levels are equalized.

For the operation without WSBs, step (i) is skipped for both uplockage and downlockage. In addition, a reinitialization operation is required to allow the change in the direction of the transits by preparing the chambers and WSB with the appropriate initial water levels.

For a transit of a vessel through the lock complexes, a series of F-E system equalization (or leveling) operations between different water bodies are required. As for the Panamax locks, the chambers, and also the Water Saving Basins are filled or emptied through a network of culverts, conduits, ports and connections controlled by vertical lift gates (named as Valves in this project). Filling and emptying are only by gravity and does not use pumps.

The total lift between the lake and the oceans is between 24-27 m and is divided in three relatively equal pieces per chamber. The initial heads of the F-E system operations fluctuate, primarily due to oceans tides and lake levels. The average initial heads of these operations are approximately:

- 9 m for Lake to Chamber operations without the use of WSBs, and 3.6 m when the WSBs are used.
- 18 m for Chamber to Chamber operations without the use of WSBs, and 7.2 m when the WSBs are used.
- 9 m for Chamber to Ocean operation without the use of WSBs, and 3.6 m when the WSBs are used.
- 3.6 m for WSB to Chamber operations or Chamber to WSB operations.

The F-E system principally consists of the main and secondary culverts, valves and conduits. Culverts connect hydraulically with the chambers through ports, and WSBs connect hydraulically with the culverts through conduits. Hydraulic components of the F-E System include the following elements that are showed in Figure 4:

- Intake and Outlet Structures located in the locks wingwalls. Each structure incorporates four bays or openings.
- Culvert valves (4.15m x 6.5m) that control water flow from Gatun Lake, between contiguous lock chambers, and to ocean level. These valves are located in the Lockheads, where every culvert splits in two branches in parallel. Every branch has two culvert valves in series for redundancy;
- One main culvert (8.3m x 6.5m) along each side of the lock chambers, located inside the lock walls. The purpose of the main culverts is to supply and receive water through the central connection to and from the secondary culverts in the longitudinal walls of the chambers.
- Four secondary culverts (6.5m x 6.5m), two per lock side, per lock chamber. The purpose of the secondary culverts is to laterally fill and empty the lock chambers evenly. The secondary culvert is a manifold and distributes flow to the ports of the lock chambers during filling; and collects flow from the chamber through the ports during emptying. The secondary culverts are also connected to the WSB conduits to transfer water between the chamber and the WSBs in both directions.
- Ten ports (2m x 2m) per secondary culvert, connecting the lock chamber through the lock walls for a total of forty ports per lock chamber. The ports both feed water from the secondary culvert into the lock chamber during filling and in turn draw it back from the chamber into the secondary culvert when emptying.
- Two chamber conduits (9m x 6m) per chamber that connect the secondary culverts from both sides of the chamber with the trifurcations and convey water between the chamber and each one of the three WSB conduits in both directions.
- Two trifurcation structures per chamber that connect the chamber conduits (9m x 6m) with each one of the WSB conduits. Each trifurcation is connected to six conduit valves (4.5m x 6m) that regulate the flow of the three conduits that connect with the three WSB.
- The WSB conduits connect each WSB with the trifurcations. An intake/discharge structure exits at the end of every WSB conduit. Each structure includes two bays equipped with horizontal trash racks.
- Means of equalization (3m x 4m) that are provided in each Lockhead in order to enable equalization of water levels between adjacent chambers with the level between the two rolling gates in the connecting Lockhead. Also, they allow the transference of make-up water from the lake towards the oceans to adjust the water levels along the complexes if needed.

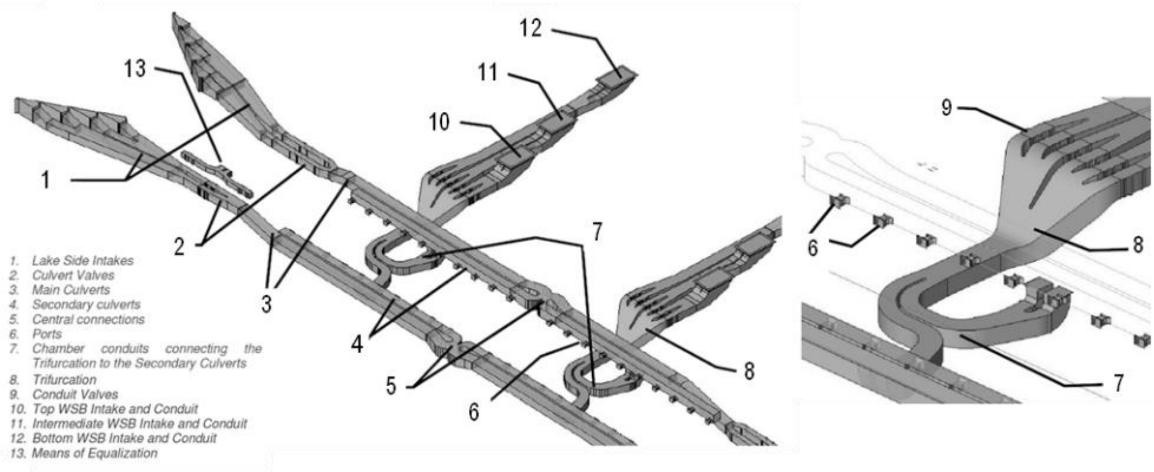

Figure 4. Filling and Emptying System scheme

3 FILLING AND EMPTYING SYSTEM DESIGN

The first attempt for the construction of the third set of locks started by the United States of America in 1939. The construction was interrupted in 1942 during Second World War and some of the excavations performed at that time have been taken in advantage for the new design of the locks.

More recently, and since 1999, ACP had performed several and comprehensive studies for the development of the Third Set of Locks for expansion the Panama Canal capacity. Numerous technical documents complete the huge background including an engineering contract to develop a conceptual design developed by the Consortium “Post-Panamax” formed by Coyne et Bellier, CNR, Tractebel and Technum. During that phase of the project, ACP defined the main features and elaborated all the tender process documents.

The tender design process started in December 2007 when ACP issued the Request for Proposals for the design and construction of the locks to the four pre-qualified tenderers. The process continued on March 2009 when the tenderers consortiums submitted their technical and economic proposals and ended in August 2009 when the contract was awarded.

3.1 Design process

During the tender design process, the F-E System was studied and optimized initially by numerical modelling resulting in the Tender Design. After the contract was awarded, an Intermediate and Final Design was developed considering the required four main objectives:

- Minimize the F-E times to increase the vessel-throughput capacity of the system,
- Minimize water slopes and hawser forces to achieve a balanced and safe process,
- Minimize the overall use of fresh lake water, and
- Maintain the vessel positioned in the center of the chamber longitudinally and transversally during the F-E process for standard lockage conditions.

A robust and comprehensive design methodology that included numerical and physical hydraulic modeling was developed. A 1:30 scale physical model was built by the laboratory of the *Compagnie Nationale du Rhône* in Lyon, France (Figure 6) while the numerical model studies were performed by CICP’s team in Buenos Aires, Argentina.

Figure 6. View of the 1:30 scale Physical model with a 14,000 TEUs containership

The set of numerical models included a 0D volume integrated numerical model developed ad-hoc of the locks system, a 1D section averaged numerical model of the entire F-E system (Flowmaster V7 code), a 2D vertically integrated numerical model of the chambers (Hidrobid code), and a 3D numerical models (CFD) of the F-E system components (OpenFoam code).

The process was initiated with the definition of the “Intermediate Design” using only numerical modeling and then, the “Final design” was validated with the interaction of the numerical and physical model results. This approach minimized the time required to accomplish the validation of the final design’s hydraulic performance of the F-E System considering that the design process, under a Design-Build contract, was challenging because of its tight schedule. For example, the contract stablished a milestone that states that the concrete could start to be poured only after the approval of the final design of the F-E system.

One of the successful strategies was the comprehensive and day-to-day interaction between both modeling approaches (numerical and physical) besides they were performed in different locations. The other was to implement “flexible” pieces for the construction of some of the more critical parts of the system using Styrofoam or similar soft materials in order to allow an efficient way to implement changes in the hydraulic shapes that were under optimization at the same time through numerical modeling (See Roux & Badano, 2011; Lecertúa et. al.; 2015 and Menéndez, 2011). This can be seen in light blue material in the physical model of the trifurcation in Figure 7 together with the numerical model and a picture during construction. In addition, the optimization had to take into account the other constrains such us the structural design of the proposed geometries. Under this methodology it was possible to simulate numerous alternatives of geometries for each particular connection or bend for the optimization of the complete F-E system before implementing it in the physical model for validation.

Finally, ACP approved the hydraulic final design of the F-E System in February 2011.

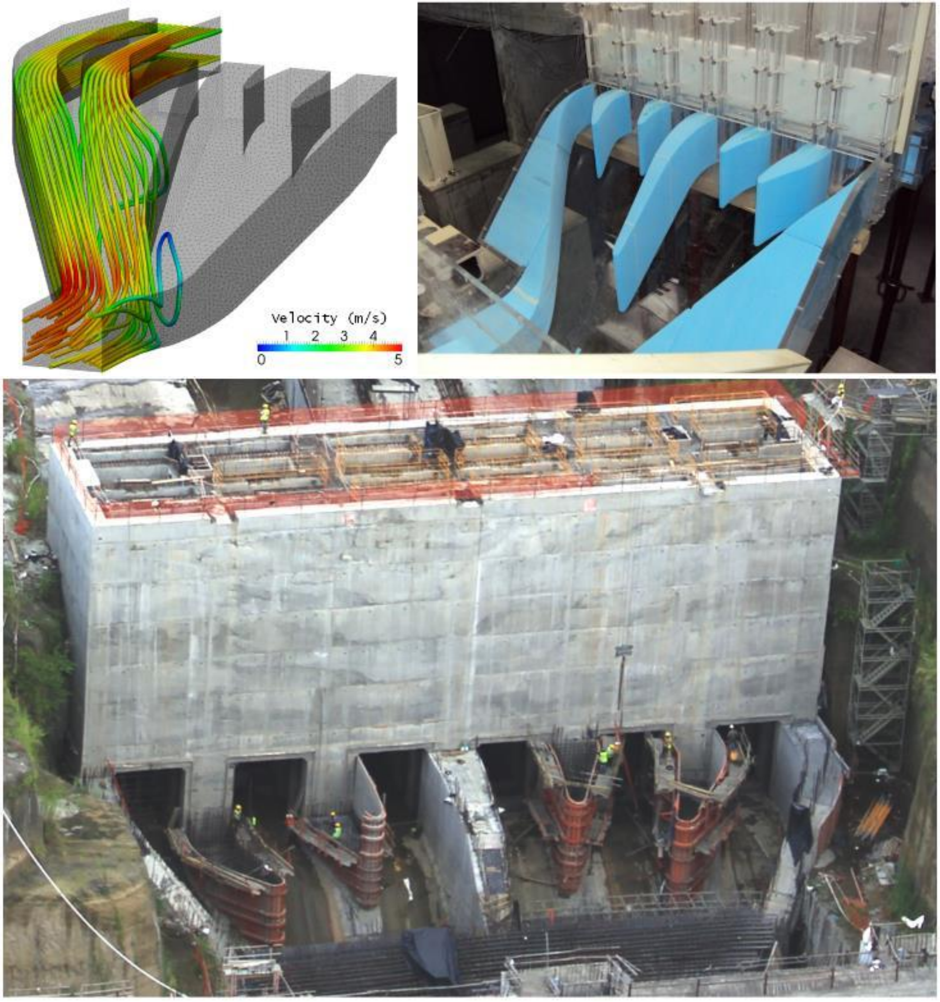

Figure 7. Trifurcation structure - CFD model, validation with Physical model and construction

3.2 Operation

The F-E system was designed as symmetrical as possible. Depending on the availability of the different components, the F-E system is operated symmetrically to prevent vessel movements causing a vessel to hit the wall, gates, tugs or other vessels inside the chamber, or introducing excessive water slopes or hawser forces. If symmetrical operation is not possible due to the lack of certain components, the F-E system is operated according to defined special rules that minimize the impact of non-symmetrical operation.

The results and understanding of the dynamics of the F-E system after the design process served as the basis for the development of the Lock Machinery Control System (LMCS) software for lockage operations. All lock operations and equalization scenarios considering chamber configurations, use of gates, lockage sequences, turnaround, initial conditions and the use of valves under various operating conditions including different maintenance or abnormal situations were developed, defined and documented using Functional Requirement Diagrams. The Functional Requirement Diagrams were coded and implemented by the control system integrator.

The valve operating parameters (opening and closing times and cycles) were based on the calculated and measured values obtained in the physical and numerical models, to comply with the Employer's Requirements regarding:

- Not to exceed Filling and Emptying Times
- Not to exceed Maximum allowed velocities (8 m/s)
- Not to exceed Maximum allowed longitudinal slopes ($0.14^{o}/_{oo}$) and transversal slopes ($0.10^{o}/_{oo}$)
- No risk of cavitation
- No air entrapment
- No water hammer effects

The valves control the flow inside the culverts and conduits that results from a differential head between two water bodies. With the closure of the valves, the flow inside the culverts or conduits starts to decelerate by the restriction produced by the valve. In contrast, during a free equalization operation (without closing the valves), the inertia of the flow would result in an overflow; that is the flow would not stop when water levels are equal on both sides of the gate, the upstream chamber would be over-emptied and the downstream chamber would be over-filled. An oscillation of the water levels would start at that point and continue until both levels equalize. In order to stop the flow and avoid the oscillation of the levels and the associated extended operational time, valves closure is initiated in advance.

Numerical models were calibrated and a simplified 1D numerical model was specially developed using all the data collected during the physical model tests and also taking into account the scale effects in order to predict the expected final performance of the prototype. All possible initial head ranges of operation, all possible modes of operation regarding the availability of the valves, and all the different scenarios regarding the chambers configurations were simulated to complete operational tables that include the data required to operate the valves of the system (Badano & Re, 2015). With these tables, the operation of the valves for all the foreseen scenarios can be accomplished safely and in compliance with operating requirements. Final adjustments of the valves operation were performed during commissioning, after the Tests on Completion and Test after Completion, and could be performed during the service life of the complex.

4 TESTING AND COMMISSIONING

4.1 Test on completion

A prototype measurement plan was developed as part of the commissioning activities of the new facilities in order to demonstrate compliance with all of the stringent Employer's Requirements for system performance. The requirements included maximum allowable filling and emptying times, maximum allowable water surface slopes in the locks, maximum allowable flow velocities in the conduits, and a required minimum water saving rate. Other limiting hydraulic parameters included no cavitation, no air entrapment, no water hammer, and limited currents in the lock approach channels.

To demonstrate the fulfillment of all the requirements, instruments to measure pressures, flows, water levels and surface velocities were installed at both sites, in addition to the permanent process measuring devises of the locks. Figure 8 presents a plan view of the type and position of the installed instruments.

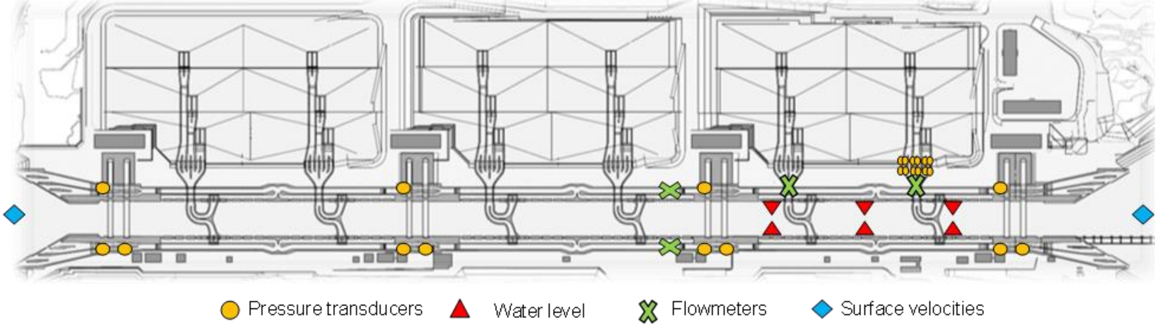

Figure 8. Prototype measuring plan devises location

During Start-up and Performance Tests of the F-E System, measurements were performed. The initial tests were used to calibrate the simplified 1D model developed to reproduce the main variables of the F-E system. Figure 9 shows the chambers water levels, the flow through the culverts and the culvert valves schedule compared to the calibrated simplified 1D model. It was used to calculate the required valve operational schedules for all identified possible scenarios. With the collected data, the valve operations were defined, optimizing the operational times and fulfilling all the stringent Employer's Requirements. The final Performance Tests were carried out at the end of May 2016 where all variables involved were measured and presented for validation of the F-E system performance.

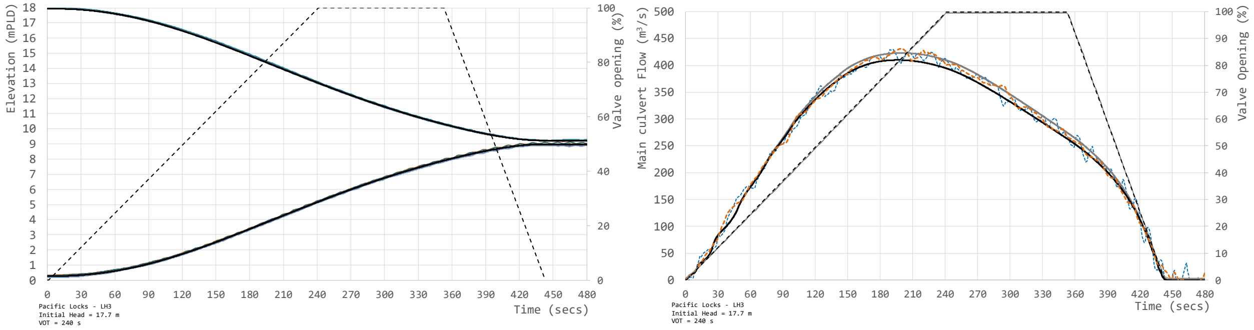

Figure 9. Middle and Lower chamber water level and culverts flows - Calibration of the 1D Model

Each performance test consists of three consecutive runs. Each of the three runs in each performance test implies the filling or emptying all three lock chambers and where applicable WSB's simulating a full lockage. For each performance test for each of the 8 test cases, the measured operating time is the average of the three runs.

The commissioning process demonstrated that the performance of the system complied with the Employer's Requirements. The observed F-E times were faster than expected. Velocities in the system were as expected, not exceeding 8 m/s. No air entrapment was observed during operation at Culvert and WSBs Intakes and the design sill elevations of the valves structures were appropriate. In addition, expected approach channels surface velocity were measured, the water saving rates were as expected and the measured longitudinal water slopes met the employer's requirements for different types of operations.

The main finding related to the F-E system performance was related to F-E times. The locks performed with lower head losses, resulting in shorter operational times than the expected from the Design phase, even with the scale effects correction developed with the interaction of the physical and numerical models. During the tests, the observed F-E times were approximately 10% to 15% shorter than the observed during the 1:30 scale Physical Model studies. In addition, they were approximately 5% smaller than the expected after the scale effects correction using numerical modelling.

The Employer's Requirements stated maximum allowable times for the F-E system operations, considering the addition of the hydraulics times of the involved operations in one transit as a function of the total lift between the Lake and the Ocean called "Not-to-Exceed Times" (NTETs). These times were defined for each site, for the two transit directions and with and without the use of WSBs. Severe penalties would have been applied for not meeting the specified values.

Results of two of the eight contractual cases that correspond to the NTETs for an Uplockage in the Pacific Locks with the use of WSBs (Case 1) and without the use of WSBs (Case 5) are shown in Figure 10. The figures present the Employer's Requirements NTETs, the times based on Physical model measurements, the expected times after scale effects corrections with numerical modelling, and the values measured during the Performance test on site. It is noticeable that the system performed slightly faster than the expected during the Tests on Completion.

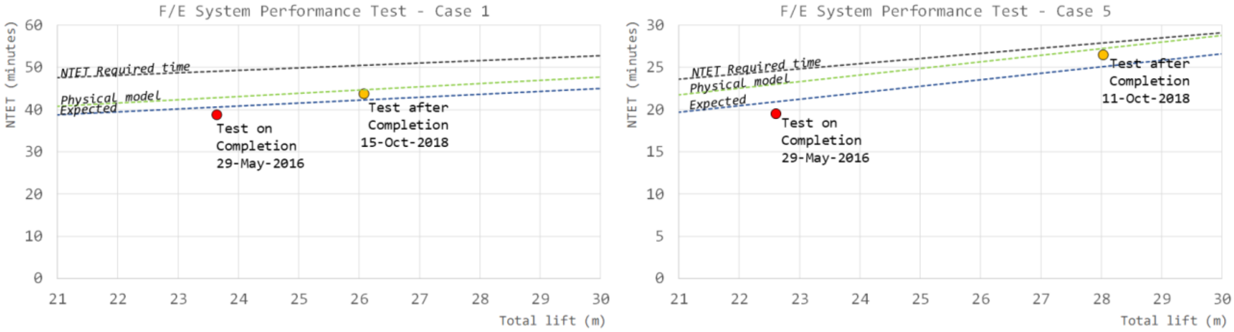

Figure 10. Not-to-Exceed Times for Uplockage in Cocoli Locks with the use of WSBs (Case 1) and without the use of WSBs (Case 5)

Water surface measurements were carried out during Performance tests for the evaluation of the expected hawser forces, using the six water level sensors installed in both locks complex as shown in Figure 11. Measured longitudinal water slopes met the employer's requirements for different types of operations fulfilling maximum allowable longitudinal slopes of 0.14 $^{o}/_{oo}$.

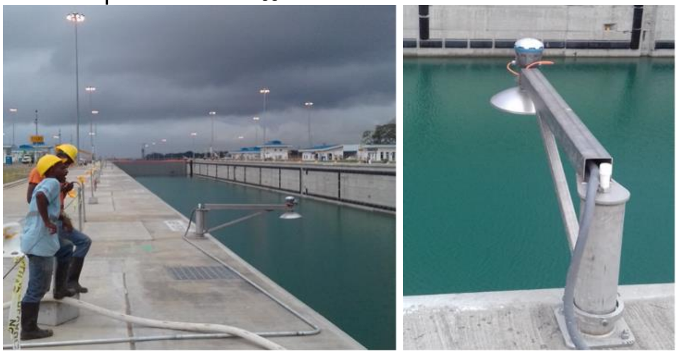

Figure 11. Water level measurement installed devises for water slopes measurement

The measurements were difficult to perform because the small magnitudes to measure were affected by uncontrollable environmental factors and chamber conditions created by different salinity content, residual oscillations and density currents from recent rolling gates operations. Due to uncertainty in the measurements, the transversal slopes results were inconclusive.

In all cases, the order of magnitude of the maximum observed longitudinal slopes was as expected by previous numerical and physical model results. However, the pattern of the water surface slope oscillations was not in complete coincidence. The differences in salinity between the inflow and chamber water resulted in surface slopes that did not accurately represent the difference in hydrostatic forces between the two ends of the chamber. The actual water surface slopes patterns in the lock chambers were different than the Physical model tests that were performed using only fresh water. Figure 12 presents a series of F-E system operations where the longitudinal water slopes at the Lower Chamber were measured. It can be seen a sequence of three chamber emptyings and two fillings and the measured slopes which do not exceed the required 0.14 $^{o}/_{oo}$ despite the interference between the operations.

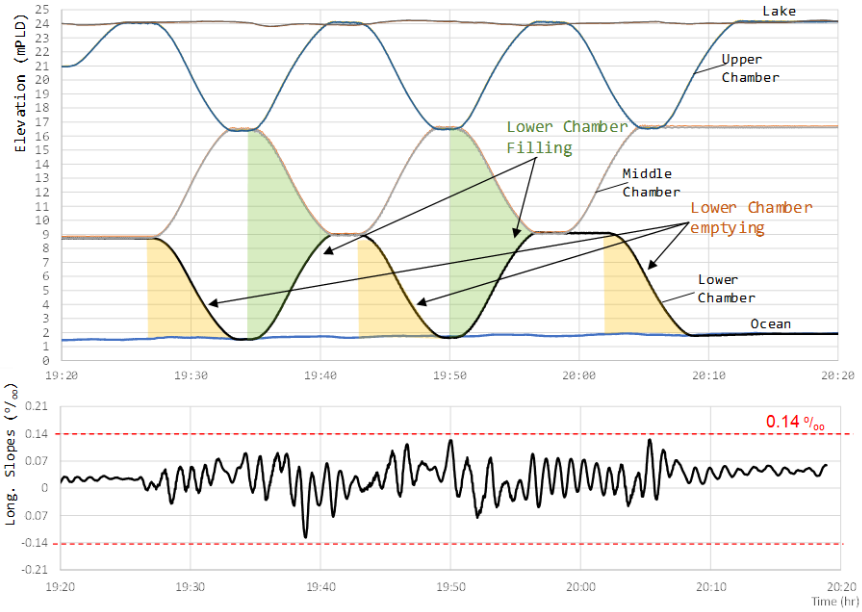

Figure 12. Water surface longitudinal slopes for a series of consecutive tests

Figure 13 presents a detail of the measured longitudinal water surface slope of the first emptying operation presented in Figure 12 compared to a similar test carried out in the physical model during the design process. In this particular test, because site conditions related to previous operations, the salinity content of the Lower Chamber was minor, and the dynamics of the water surface slopes tend to be similar to those observed in the Physical Model studies.

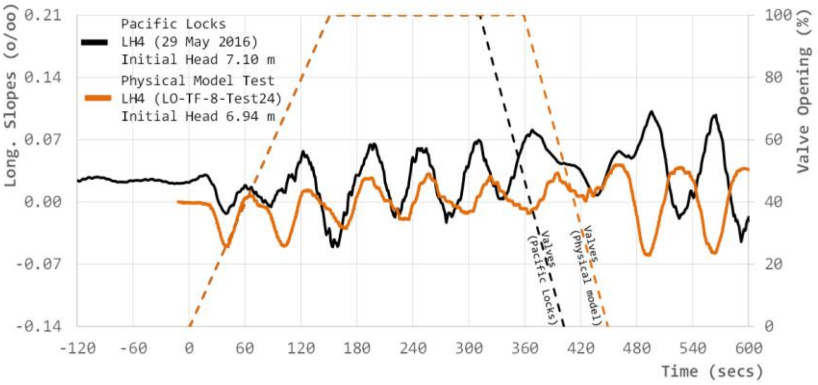

Figure 13. Slopes measurements comparison – Lower Chamber emptying

All performance tests data and specially the water slopes measurements results were presented to ACP prior to the start of the navigational tests of a Neopanamax vessel in the Atlantic Locks June 9, 2016. The overall results validated the design process and performance values for the safe operation of the locks and commercial operations of the new locks started on June 26, 2016.

4.1 Test after completion

According the design and construction contract, after two years of operations some of the hydraulic performance tests had to be repeated. The tests were conducted between 1st and 16th October 2018 and were focused on the hydraulic operational times. All the cases were performed by ACP using the fully Automatic sequence of the Lock Machinery Control System (LMCS). Most of the cases were performed without vessels transit and two of the cases were performed with transiting Neopanamax vessels.

Again, the tests demonstrated that the performance of the system complied with the Employer's Requirements besides the observed F-E times were longer than previous measurements as it can be seen in previous Figure 10. The Filling and Emptying system faced a process were the hydraulic surfaces changed from a new concrete finished to "service" surface. This process was a continuous increase of the hydraulic roughness due to the expansion of different kinds of marine growth.

The evolution of the marine growth through the hydraulic system could be observed indirectly by the hydraulic operational times that increased accordingly. The simplified 1D numerical model used for the determination of the valves operation was run again to adjust their schedules. As the calibration parameter was the hydraulic roughness, the evolution of the culverts and conduits roughness actual condition was estimated every time. Then, this back-calculation can show the relative evolution of the roughness compared to the estimated initial roughness condition according the bibliography since the start-up of the system. This evolution was noticed at both sites (Cocoli and Agua Clara Locks) under similar timeframe and similar change in the order of magnitude of the hydraulic roughness. Also, some site inspections and observations showed the presence of marine growth in the system and the magnitude of the fouling is similar to the estimated hydraulic roughness height. Figure 14 shows pictures of a culvert valve that was retired for maintenance where marine growth (mainly barnacles) can be observed in the downstream part.

Figure 14. Maintenance operation of a Culvert valve in Cocoli Locks - Marine growth observed in downstream side (March 2017)

Figure 15 presents the evolution of the estimated hydraulic roughness for different parts of system representative of the different equalization operations using the culverts. It can be seen, that the evolution of the marine growth lasted approximately one year after the roughness magnitude tends to stabilize after an exponential increase. The evolution responded to a typical “S” curve. The magnitude of the roughness changed from the typical roughness of new smooth concrete finishing (0.025 mm) up to approximately 10 mm in the lower part of the system (in contact to ocean waters) and to approximately 2 mm where the system is in contact to mixed fresh and salt waters.

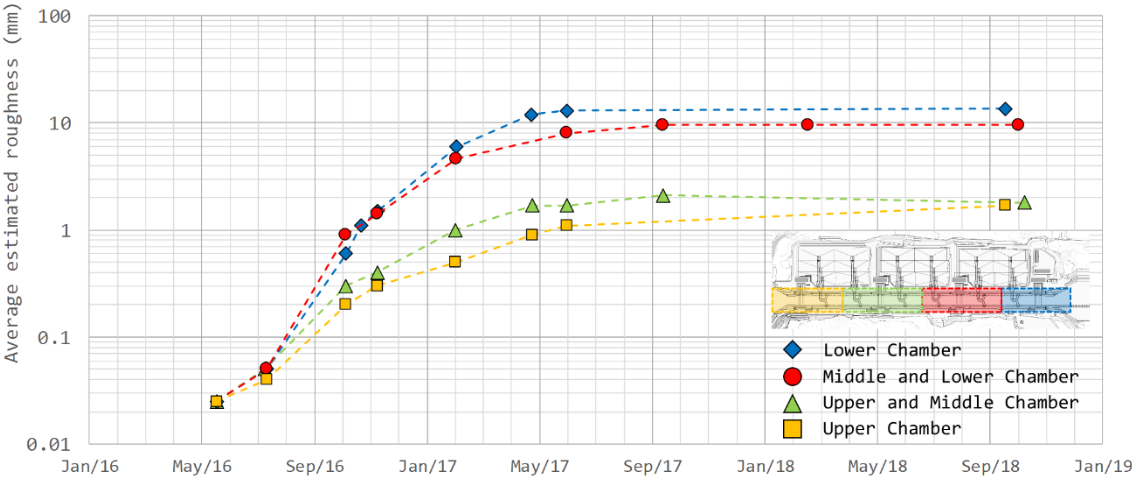

Figure 15. Estimated hydraulic roughness evolution - Cocoli Locks

5 CONCLUSIONS

A robust and comprehensive design methodology was developed and implemented to deliver a Filling and Emptying system design under stringent Employer’s Requirements and tight schedule under a Design-Built contract. The methodology comprised numerical models of different complexities, physical hydraulic modeling and a prototype measurement plan for commissioning activities and to demonstrate performance compliance.

The overall results showed that the Filling and Emptying System of the Panama Canal Third Set of Locks performs as designed and complies with the Employer’s Requirements. This experience validates the followed design process. Commercial operations of the new locks started June 26, 2016. To date, more than six thousand Neopanamax transits have been completed in the new locks.

ACKNOWLEDGEMENTS

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