Paper 92 - Implications of high availability requirements on the hydraulic design of the Panama Canal Third Set of Locks

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ABSTRACT: The Panama Canal Third Set of Locks has been designed to provide a safe and reliable transit system for Neo-Panamax vessels travelling in both directions between the Pacific and the Atlantic Oceans.

According to the employer's requirements, the single 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 – i.e., unavailable less than 36 hours per year. The lock filling and emptying system – involving multiple-lift lock chambers and water saving basins – is one of the critical systems necessary to meet this requirement. 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 a summary of the main lock operations and lock chamber water level equalization scenarios, considering the chamber configurations, use of lock gates, lockage sequences, turnaround, initial water level conditions and the use of the filling and emptying valves (for the chambers and the water saving basins). In addition to the normal operating scenarios, the system must function acceptably under a variety of different maintenance conditions and unusual operating cases.

1 INTRODUCTION

The Panama Canal Third Set of Locks is being constructed for the Panama Canal Authority (ACP) under a design-build contract awarded in August 2009 to a JV consortium *Grupo Unidos por el Canal* (GUPC). The design is prepared by CICP *Consultores Internacionales*, a design JV led by MWH Global, Inc.

According to the employer's requirements, the single 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.

A lane is considered out of service when maintenance functions take control of the lane and lockages cannot be carried out because some essential component is not available. For this reason, in addition to the normal operating scenarios, the system must function acceptably under a variety of different maintenance conditions and unusual operating cases.

The stringent lane availability required in this project results in a high redundancy of all the critical components of the lock system.

This paper focus on the implications of the lock filling and emptying (F/E) system required redundancy for meeting the required lane availability and how it derives in different particular operating conditions.

The F/E 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.

2 HYDRAULIC SYSTEM FOR THE LOCKAGE OPERATION

2.1 *Lock complexes*

The Third Set of Locks of the Panama Canal consists of two new lock facilities, one at each end of the Canal. These are in addition to the existing two lock 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 will be connected to the existing channel system through new navigational access channels.

Each of the new lock facilities consists of three (3) aligned locks chambers (Upper, Middle, and Lower) separated by a pair of Rolling Gates housed in four (4) Lock Heads, through which vessels move in three steps from sea level to the level of Gatun Lake (~+27m) and back down again. Each complex is completed with the associated buildings, facilities, and other systems required for its operation.

Each chamber will have three (3) lateral water saving basins (WSB) totaling nine (9) basins per lock and eighteen (18) basins all told. The three WSBs (Top, Intermediate, and Bottom) store water when lowering the chamber water level, and supply water when increasing the chamber water level. This procedure allows the reutilization of up to 60% in each cycle reducing the water consumption of the lock system.

As for the existing Panama locks, the chambers, and also the water saving basins will be filled and emptied through a network of culverts, conduits, ports and connections controlled by valves. Filling and emptying is only by gravity and does not use pumps. The rolling gates will hold water unless the levels on both sides of them are equal. , When the water levels either side are equal the rolling gates can be opened enabling the vessels to move from one side to the other.

The required new lock's standard chambers are 458 m (1,500') long, by 55 m (180') wide, and 18.3 m (60') minimum depth, allowing vessel drafts of up to 15.2m (50') in tropical fresh water.

The lock system can operate with or without the 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, successively in time (starting with the bottom WSB); (ii) by receiving water from the target reservoir (chamber or the Lake) through the culverts, untill 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, successively in time; (ii) by sending water to the target reservoir (chamber or the Ocean) through the culverts, untill the two water levels are equalized.

For the operation without WSBs, step (i) is skipped for both uplockage and downlockage.

2.2 *Filling and emptying system*

The main objectives of the Filling and Emptying System are to achieve four main objectives:

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

To achieve these objectives, the F/E system was designed and constructed to be as symmetrical as possible. If possible, depending of the availability of the different components, the F/E system must be 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 must be operated according to particular rules that minimize the impact of non-symmetrical operation.

The F/E system principally consists of the main and secondary culverts, valves, conduits and water saving basins (WSBs). 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 (see Figure 1):

- Intake and Outlet Structures located in the Locks Complex Wingwalls. Each structure incorporates four bays or openings.
- Culvert valves. These valves 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 (2) branches in parallel. Every branch has two (2) culvert valves in series for redundancy;
- One (1) main culvert 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. The near main culvert is the one closest to the WSBs (Island side), while the far main culvert is the one on the opposite side of the chamber (Continental side).
- Four (4) secondary culverts (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 different ports during emptying. The secondary culverts are also connected to the WSB conduits to transfer water between the chamber and the WSB in both directions.
- Ten (10) ports per secondary culvert, connecting the lock chamber through the lock walls for a total of forty (40) 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 (2) chamber conduits per chamber. They connect the secondary culverts from both sides of the chamber with the trifurcations. They convey water between the chamber and each one of the three WSB in both directions.
- Two (2) trifurcation structures per chamber. They connect the chamber conduits with each one of the WSB conduits. Each trifurcation is connected to six (6) conduit valves that regulate the flow of the three conduits that connect with the three WSB. Each WSB conduit is divided in two (2) branches in parallel, each one controlled by only one (1) conduit valve.
- 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. Equalization valves 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 1 shows a general view and details of the F/E system.

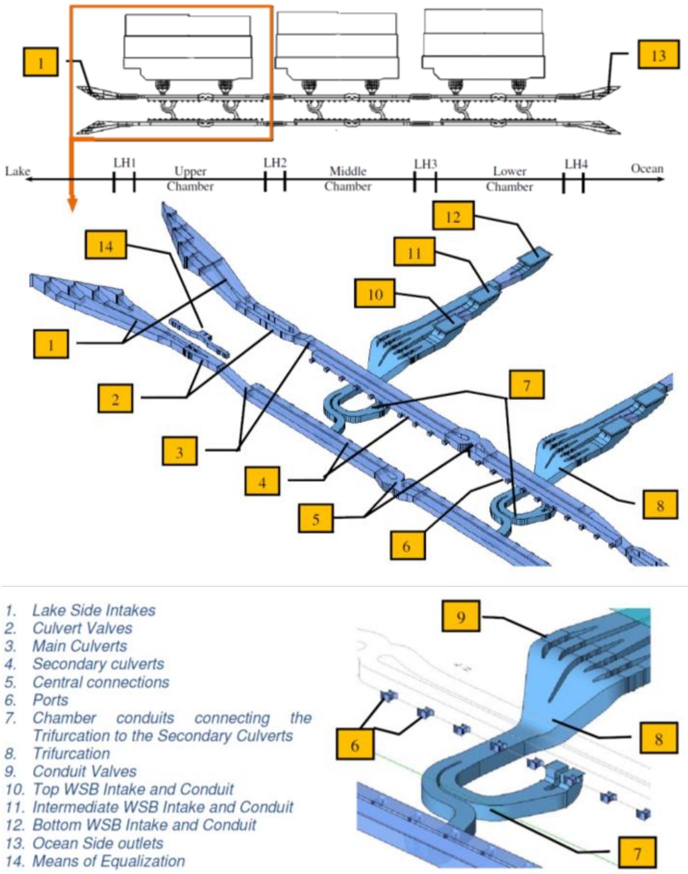

Figure 1 – F/E System Scheme

2.3 *Uplockage and Downlockage operations*

For a transit of a vessel through the lock complexes a series of equalization operations between different water bodies are required.

The operations are controlled by different valves at the Lockheads for the equalization between the chambers, or with the lake or with the oceans, and in the trifurcation structures for the equalizations between the chambers and the WSBs.

Different single operations can be identified. They were studied through physical and numerical models during the design phase of the project. They are:

- *Lake to Lock operation*. The operation fills the Upper Chamber up to the equalization with the Lake elevation. The operation is controlled by the culvert valves in Lockhead 1 (see Figure 2 for Lockheads numbering).
- *Lock to Lock operation*. The operation connects two lock chambers until the two levels are equalized. It could be a filling operation, if the vessel is in the downstream chamber, or an emptying operation, if the vessel is in the upstream chamber. The operation is controlled by the culvert valves in Lockhead 2 for the operations between the Upper and Middle chamber and by the culvert valves in Lockhead 3 for the operations between the Middle and Lower chamber.
- *Lock to Ocean operation*. The operation empties the Lower Chamber up to the equalization with the Oceans elevations. The operation is controlled by the culvert valves in Lockhead 4.
- *WSB to Lock*. The operation fills the chamber up to the equalization of water levels between the chamber and the WSB. It is controlled by the conduit valves.
- *Lock to WSB*. The operation empties the chamber up to the equalization of water levels between the chamber and the WSB. It is controlled by the conduit valves.

During an uplockage operation, the vessel will take part in three chamber filling operations. These operations are two Lock to Lock operations and a Lake to Lock. They are one Lower chamber filled from the Middle chamber (Lock to Lock), one Middle chamber filled from the Upper chamber (Lock to Lock) and one Upper chamber filled from the lake (Lake to Lock). At the beginning of the operation the chamber with the vessel is at its lower level (ocean level) and the rest of the chambers are at their high level, so as to continue with the above described operations. The process can be performed with or without the use of the WSB.

During a downlockage operation, the vessel will take part in three chamber emptying operations. These operations are two Lock to Locks operations and a Lock to Ocean. They are one Upper chamber emptying to the Middle chamber (Lock to Lock), one Middle chamber emptying to the Lower chamber (Lock to Lock) and one Lower chamber emptying to the Ocean (Lock to Ocean). At the beginning of the operation the chamber with the vessel is at its higher elevation and the rest of the chambers are at their lower elevations, so as to continue with the above described operation. The sequence can be performed with or without the WSB.

The total drop (or lift) between the lake and the oceans is between 24-27 m and is divided in three (3) relatively equal pieces per chamber. Taking into account the characteristics of the complexes and of every single operation the average initial heads of these are:

- 8-9 m for Lake to Lock operations without the use of WSBs, and 3.6 m when the WSBs are used.
- 16-18 m for Lock to Lock operations without the use of WSBs, and 7.2 m when the WSBs are used.
- 8-9 m for Lock to Ocean operation without the use of WSBs, and 3.6 m when the WSBs are used.
- 3.6 m for WSB to Lock operations.
- 3.6 m for Lock to WSB operations.

The Third Set of Locks accommodates the transit of Neo-panamax vessels in both directions. The lock system accommodates both uplockage and downlockage of the vessels, with a planned reversal once per day. Between the two operations a reinitialization has to be done in order to allow the change in the direction of the vessels transit. The sequence required is called Turnaround, which is a sequence that permits the change in direction from up to downlockage and another that permits the change from down to uplockage.

The main purpose of the turnaround is to prepare the chambers and WSB water levels to allow a vessel to enter the lock complex and continue the transit by a sequence of equalization operations.

The described redundant systems allow for continued operation of the lock complex to meet the 99.6% availability requirement while also allowing for the planned maintenance over the 100 year life of the project.

3 LOCK CHAMBER CONFIGURATION

3.1 *Safety, chamber length and use of gates*

The use of redundant gates or a single gate at each end of the chamber has an influence on the operating procedures, safety, chamber length, and water consumption.

For safety reasons during the lockage the following guidelines will be applied for the use of the gates:

- A redundant set of gates shall be used, when available, in front of vessels as a safety precaution against the possibility of vessel contact. Whenever gate redundancy is not available in front of the vessel, 2-stage vessel movements shall be used to reduce the risk of collision with the gate. The first step brings the vessel to a full stop at a safe distance from the gate, and the second step moves the vessel, dead slow, to the final position.
- The gates are operated when water levels on either side of the gates are equalized within a permissible head difference.

The numbering of the rolling gates is presented in the scheme shown in Figure 2. The Odd gates (RG1, RG3, RG5 and RG7) are at the upstream side of each Lockhead and the Even gates (RG2, RG4, RG6 and RG8) are located at the downstream side of each Lockhead.

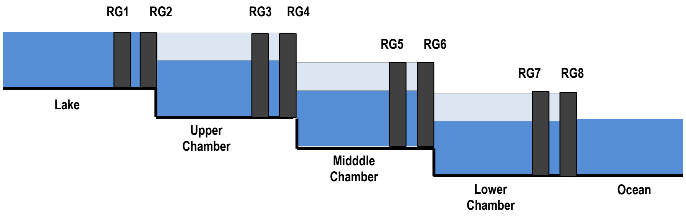

Figure 2 – Numbering of the Rolling gates scheme

Different chamber lengths may be used to lock vessels, depending on the availability of the gates and the size of the vessels. The different chamber length configurations are Short, Standard, and Long, according to the following description:

1. The Short chamber length corresponds to the internal length of 427 m (1,400 feet). It is configured by using inner gates of the chamber at both ends. This is a non-standard or special operating condition.
2. The Standard chamber length corresponds to the internal length of 458 m (1,500 feet). It is configured by using only one outer gate behind the vessel and both inner and outer gates in front of the vessel, for safety reasons. This safety condition requires two different configurations of the chamber, one for every transit direction. This is the standard or normal operating condition.
3. The Long chamber length corresponds to the internal length of 488 m (1,600 feet). It is configured by using only outer gates of the chamber at both ends. This is a non-standard or special operating condition.

For Uplockage, the Standard chamber is configured with the downstream outer gate and the two upstream gates. Figure 3 presents a scheme for the chamber (Lake side is on the left).

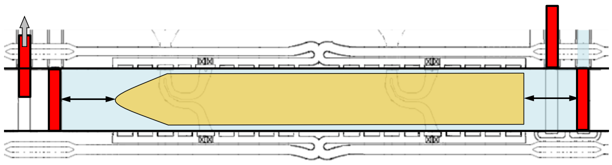

Figure 3 – Scheme for Uplockage Standard Chamber configuration

The inner upstream gate and the outer downstream gate are holding water, taking into account that the seals are at the downstream side of the gate. The outer upstream gate is closed for safety reasons during the vessel movement.

After the vessel is in final position, the redundant gate (the outer upstream) is opened, after which the equalization operation starts. In this condition the upstream part of the gates and their recesses are always flooded at the same elevation as the upstream chambers. This chamber configuration during the equalization process is called Standard Even due to the use of the even gates to configure the chamber.

The design vessel is positioned at the center of the lock chamber configured by the inner upstream gate and the outer downstream gate. In this case, the design vessel is located between the most upstream and most downstream port of the filling and emptying system. At each end of the design vessel there is a distance of 47 m to the gates available for the tug boats used to help guide and position vessels transit the locks complex.

For Downlockage, the Standard chamber is configured with the upstream outer gate and the two downstream gates. Figure 4 presents a scheme for the chamber (Lake side is on the left).

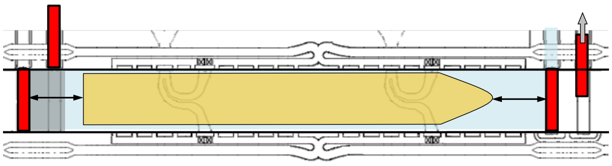

Figure 4 – Scheme for Downlockage Standard Chamber configuration

The outer upstream gate and the inner downstream gate are holding water. The outer downstream gate is closed for safety reasons during the vessel movement. After the vessel is in position, the redundant gate (the outer downstream) is open and then the equalization operation starts. This chamber configuration during the equalization process is called Standard Odd due to the use of the odd gates to configure the chamber.

The design vessel is positioned at the center of the lock chamber configured by the inner downstream gate and the outer upstream gate. At each end of the design vessel there is a distance of 47 m to the gates available for the tugs. With this configuration, the position of the vessel is shifted around 30 m in the upstream direction compared with the previous one. The emptying operation is less critical regarding the hawser forces than the filling operation.

3.2 *Identification of the equalization scenarios*

Because each Lockhead houses two rolling gates, and either one can be in or out of service, the F/E system must equalize different chamber water volumes.

Different chamber configurations exist, depending upon:

- Rolling gates position;
- Rolling gates availability;
- Installation or not of a Recess Closure during a maintenance operation of the gates; and
- The lockage sequence.

Regarding the maintenance scenarios of the Rolling Gates, a chamber that has a gate under maintenance with the Recess Closure installed to isolate the Gate recess from the chamber is designated as "Special". Since there is only one set of Recess Closure in each complex, only one gate at each complex can be isolated for maintenance at the same time. Therefore, only one "Special" chamber can occur in a complex for all possible gate configurations.

The complex can operate with a minimum of one Rolling Gate available in each Lockhead. If there is more than one Rolling gate out of service, it is considered that only one can be repaired in dry dock within its recess, while the others would be located in their wet recesses. If the gate is under maintenance in its recess without the recess closure installed, it does not affect the volumes to be transferred between water bodies.

In order to take into account the volume differences during the equalization, different configurations of the chambers were identified. These chamber configurations give different operational times to arrive at the equalization because the volume to be conveyed through the F/E System is different in each case.

At the four Lockheads, for each of the single operations presented in Section 2.3, different combinations are possible involving 8 different chamber configurations that are presented in the following table.

Chamber Configuration		Description
1	Standard Even	Used as Standard chamber during uplockage operation
2	Standard Odd	Used as Standard chamber during downlockage operation
3	Short	Inner gates holding water.
4	Long	Outer gates holding water.
5	Special Even	Upstream Gate recess of the downstream Lockhead with Recess Closure installed.
6	Special Odd	Downstream Gate recess of the upstream Lockhead with Recess Closure installed.
7	Special Long 1	Downstream Gate recess of the upstream Lockhead with One Recess Closure installed.
8	Special Long 2	Upstream Gate recess of the downstream Lockhead with One Recess Closure installed.

The total number of cases is obtained by combining the possible different chambers configurations presented before.

Regarding the operations between the WSBs and the chambers, each one of all the nine WSB could be connected to each of the 8 different chamber configurations.

3.3 *Lockage sequences*

The lane is considered available if a vessel transit is possible, including non-standard lockages (though slower). A non Standard lockage involves one or more gates, culverts, or valves out-of-service.

The sequence will vary depending on the availability of the gates. The presence of culverts, or valves out-of-service will not introduce changes in the lockage sequence, it only affects the valve schedule operation and therefore the equalization times (See Section 4).

Each one of the gates could be at three different conditions:

- available,
- unavailable; the gate for any reason is out of service and it is positioned in its recess,
- under Maintenance, the gate is isolated in it recess with the Recess Closure installed.

The use of the gates for the chamber configuration under different availability conditions will follow the general criteria:

- During Downlockage operation: if the inner gate in front of the ship (odd gate) is available it will always be used to hold water, and if the outer gate (even gate) is available it will be closed for safety until the ship stops.

- During Uplockage operation: if the inner gate in front of the ship (even gate) is available it will always be used to hold water, and if the outer gate (odd gate) is available it will be closed for safety until the ship stops.

To determine the lock chambers configuration for all scenarios given by the different gates conditions, all possible combinations of the different gate states were considered. For the analysis of the different possibilities, the following two conditions were applied:

- At least one gate available at every Lockhead.

- As a maximum, only one gate isolated under maintenance per case.

Taking into account the previous conditions, all possible scenarios regarding the combinations of the different gates states were developed for uplockage and downlockage. For each case, the chamber configuration to be used for the Upper, Middle and Lower chamber was determined.

The combination of all valid conditions of the gates results in a total amount of 297 different scenarios of chambers configurations for uplockage and 297 scenarios for downlockage. The following examples can be pointed out:

- One of these scenarios corresponds to the Standard case when all the gates are available. This will be the most frequent case. For Uplockage, the three chambers are Even and, for Downlockage, the three chambers are Odd.

- Twenty four (24) cases will use the Even gates in all the Lockheads for uplockage direction when one or more Odd gate is not available.

- Twenty four (24) cases will use the Odd gates in all the Lockheads for downlockage direction when one or more Even gate is not available.

- Two hundred and seventy three (273) cases correspond to all the other different cases for every direction. For example, for uplockage, one case uses a Short Upper Chamber, a Special Long 2 Middle Chamber and a Short Lower Chamber configuration because RG1, RG4 and RG8 are unavailable and RG5 is under maintenance.

3.4 *Particular lockage sequences*

Two additional type of sequence are provided for the operation of the Third Set of Locks using all the chambers Short and using all the chambers Long.

The Short Chamber sequence uses a short configuration at the three chambers, both for uplockage and downlockage. This sequence is the only one that uses at the same time the two gates closed at the intermediate Lockheads to perform the equalization operations. For this particular lockage scenario, six of the eight rolling gates must be available. Also all means of equalization of Lockheads 2 and 3 must be available. RG1 and RG8 and their means of equalization are not required to be available. The combination of all the different gate conditions gives a total of eight (8) additional cases.

The average water consumption for a Short chamber sequence without WSB is about 20,000 m^3 per ship transit less than that used in a standard lockage without WSBs. With the use of the WSBs, the Short chamber lockage saves around 8,000 m^3 of fresh water per ship transit compared to that of a standard lockage with WSBs.

The Long chambers sequence lockage scenario would permit the transit of single vessels with dimensions longer than the design vessel (maximum length of 366 m) or a tandem of vessels that exceeds that length.

For this lockage scenario, six of the eight rolling gates must be available. RG2 and RG7 are not required to be available. Also all means of equalization of Lockheads 2 and 3 must be available. The combination of all the different gate conditions gives a total of eight (8) additional cases.

Taking into account all the combinations of chambers and type of sequences, the total amount of different lockage sequences is 313.

4 F/E SYSTEM OPERATIONS

4.1 *Use of valves*

The valves control the flow inside the culverts and conduits that results from a differential head between two water bodies.

With the opening of the valves between two water bodies, water starts to flow inside the culverts or conduit from the water body with higher head to the water body with the lower head. Flow accelerates from zero to the maximum velocity and then decreases in accordance with the changes of the water levels of the two bodies, the inertia of the flow, the hydraulic head losses and the valve operating schedule. The valve operating schedule controls the variable hydraulic internal head loss which throttles the flow inside the culverts or conduits.

With the closure of the valves, the flow inside the culverts or conduits starts to decelerate by the establishment of a head loss due to 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 first 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 associated time), valves closure is initiated before first equalization.

The flow through the culverts is regulated by the Culvert Valves. They are 4.15 meters wide and 6.50 meters high. Each culvert is divided in two branches with two valves each. The second valve of each branch is provided for redundancy. Each Lockhead structure has four branches with a total of eight valves, totaling 32 culvert valves in each lock complex. The culvert valve configuration is presented in Figure 5.

The flow through the conduits from the lock chamber to the WSB's and vice versa is regulated by the Conduit Valves. They are 4.50 meters wide and 6.00 meters high. Each conduit splits at the trifurcation structure into two branches with a valve for each. Each trifurcation is connected to 6 conduit valves that regulate the flow of the three conduits that connect with the three WSB. There are a total of 12 conduit valves at each chamber giving a total of 36 conduit valves at each complex. No additional redundancy was provided. The conduit valve configuration is presented in Figure 5 and a detail of a trifurcation is presented in Figure 6.

The flow through the means of equalization is regulated by the Equalization Valves. They are 3.00 meters wide and 4.00 meters high. The means of equalization bypass the chambers into the space between the rolling gates. There are two equalization valves in each Lockhead, totaling 8 equalization valves at each complex, one per each rolling gate. One valve controls the flow from upstream to the space between the two gates and the other controls the flow from this space to the downstream side. No redundancy is provided for these valves.

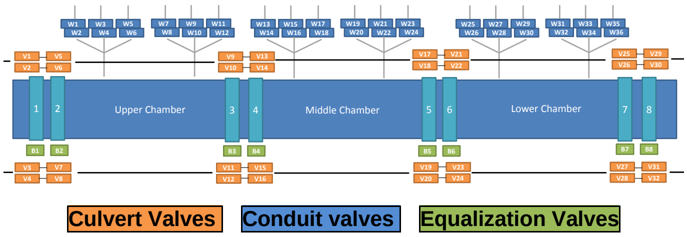

Figure 5 – Valve System Designation

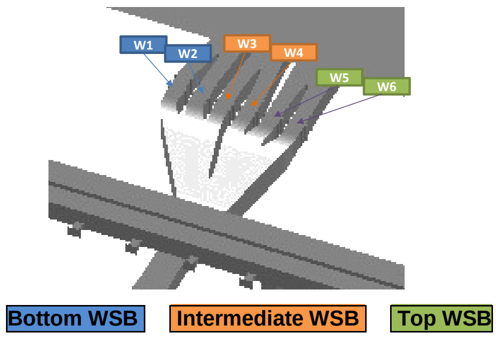

Figure 6 –Conduit Valve numbers for the upstream trifurcation of the Upper Chamber

The sequence of operations of all valves follows the sequence presented in Section 2.3 for each individual equalization operation (i.e. Lake to Lock, Lock to Lock, Lock to Ocean, WSB to Lock or Lock to WSB).

For the operation with the use of WSB, to complete a filling or emptying of a chamber four single operations are required: one equalization operation between the chamber and each of the three WSB using the Conduit Valves and one equalization operation using the Culvert Valves. Figure 7 presents the conceptual schedule of operations for filling a chamber with the use of the WSB and Figure 8 for the emptying of it.

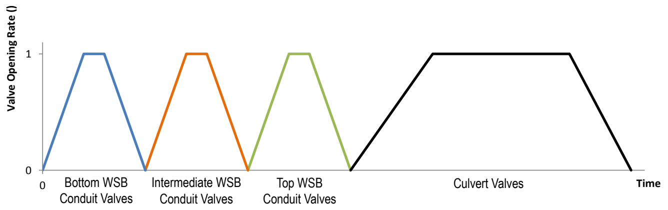

Figure 7 –Valves schedule scheme for a chamber filling

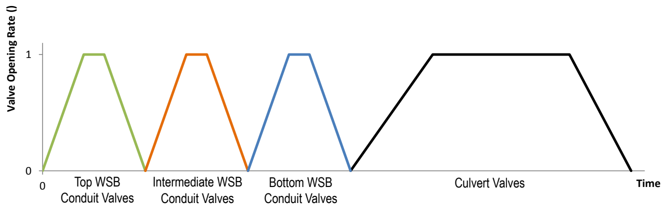

Figure 8 –Valves schedule scheme for a chamber emptying

The valve operating parameters (opening and closing times and cycles) are 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
- Not to exceed Maximum allowed longitudinal and transversal slopes
- Not to exceed Maximum Hawser forces
- No risk of cavitation
- No air entrapment
- No water hammer effects

To achieve these objectives, the F/E system was designed and constructed as symmetrical as possible. Whenever possible, and depending on the availability of the different components, the F/E system will be operated symmetrically to prevent vessel movements causing vessels hitting the wall, gates, tugs or other vessels inside the chamber, or introducing excessive water slopes or hawser forces. If this is not possible due to the lack of certain components, the F/E system will be operated according to the rules that were analyzed for every particular case. The key information for governing the operation of the valves for the 313 different cases is summarized in tables that are used in the Control System.

Numerical models were calibrated 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 the operational tables. 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 can be made during commissioning, after the Tests on Completion and Performance Tests, and during the service life of the complex.

4.2 *Culvert Valves Modes of Operation*

Several possible culvert branch arrangements could be present in one Lockhead to perform one single operation regarding their use or availability. A branch is available when at least one of the two valves in the branch is available and the other is in open position or even it has been removed for extended maintenance (permitting the normal performance of the branch with the use of the available valve).

There are a total of 19 cases grouped among four different modes of operation depending how many and which of the four branches are unavailable or used. These modes are when:

i. all the branches are available;
ii. the operation is performed with two branches, one in each culvert;
iii. the operation is performed with two branches, both available in only one culvert; and
iv. the operation is performed through only one available branch.

The first mode follows the normal operation schedule scheme as described in 4.1 and it is expected to be the most frequent case when all the branches are available. The valves in the other modes follow special operation sequences with steps in the opening schedule and they are expected to be infrequent operations because of the redundancy provided for the mechanical parts of the F/E system.

In the case when only one branch is unavailable, the operation is performed with two branches (one in each culvert) by not using one of the branches in the culvert where both are available. The physical model results using only one branch at each side showed a more efficient way to operate under the condition of one culvert branch out of service. The F/E times and the forces on the vessel are faster and lower than those obtained with the asymmetrical operation using three valves.

4.3 *Conduit Valves Modes of operation*

There are different scenarios for the availability of the conduit branches (a Conduit branch is considered available when the Conduit Valves is available). The possible arrangements of conduit branches total 15 cases grouped in five (5) different modes of operation These modes consider that the two culverts are available, so the flow from or to the WSB is split symmetrically in the flow divider located below the chamber structure (See Figure 9) resulting in a symmetrical flow into or out of the chamber.

These modes are when the operation is performed:

- with all the branches are available
- with three branches
- with two branches, one in each Conduit
- with two branches in the same Conduit
- with only one branch

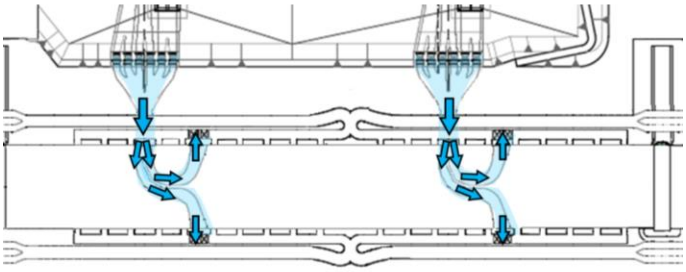

Figure 9 – Scheme showing the flow split symmetrically between the two secondary culverts

The first mode follows the normal operation schedule scheme as described in 4.1 and it is expected to be the most frequent case when all the branches are available. The valves in the other modes follow the special opening schedules.

In the case when a culvert is under maintenance and isolated from the chamber and the conduit (dry culvert), another particular Conduit valves schedule is foreseen. In this situation, the hydraulic performance of the connection between the WSB and the chamber is different because of the performance of the conduit divider under the chamber. It does not split the flow and all the flow is conveyed to the available secondary culvert. A scheme is presented in Figure 10; it shows the water movement during a Filling operation from a WSB with a culvert under maintenance (dry culvert, highlighted in red). This results in an asymmetrical flow inside the chamber.

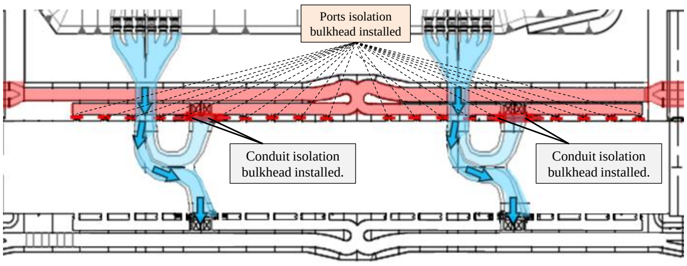

Figure 10 – Scheme for a Special operation with WSBs and with one Culvert in dry condition

5 CONCLUSIONS

The stringent lane availability required in this project results in a high redundancy of all the critical components of the lock system. The redundancy of the Lock Gates results in 313 sequence scenarios. In addition, all the possible scenarios regarding the availability of the Culvert or Conduit valves of the system gives many more different modes of operation that are particular to each one and have to comply with time and safety stringent requirements.

For the Panama Canal Third Set of Locks required lane availability has been achieved by a highly redundant F/E system without reducing the lock transit safety and without incurring excessive additional operating times. The inclusion of redundant systems has resulted in many transit operation scenarios that have been modelled both numerically and physically to demonstrate the required availability and operation requirements (time, safety, etc.) can be met. These operation scenarios have been incorporated into a complex Control System.