REENGINEERING VALVE OPENING LAW TO OPTIMISE LOCK LEVELLING: SOME CASE STUDIES

by

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ABSTRACT

When designing a new lock, detailed hydraulic studies are usually executed to fix the layout of the filling and emptying system in order to achieve safe and efficient levelling conditions. During the lifetime of the lock, the concrete works and the culvert layout remain usually stable. On the other hand, it is often observed that the valve opening schedule evolves, as a consequence of successive maintenance or replacement. This results in a lock working in non-optimal conditions. This paper presents case studies illustrating how an abnormal working process can become standard operation, and how reengineering can restore lock performances. It highlights the benefits of a reengineering of the valve schedule, with the input of field measurements.

1. INTRODUCTION

The hydraulic design of a lock levelling has to fulfil several criteria like: (1) short levelling duration; (2) acceptable mooring forces; (3) limited levelling wave amplitude. Usually, reducing the levelling time increases the forces acting on the vessels. In some cases, modifying the design of the levelling culverts enables shorter levelling time, through e.g. longitudinally distributed or even through equal distribution filling systems. This increased culvert complexity may nevertheless impact the building cost of the lock (PIANC, 2015).

The hydraulic design usually results in an optimised design of the levelling culverts and a proposed schedule for opening the valves. During lock commissioning, the valve opening laws are implemented, tested and validated. Then, during the lifetime of the lock, it is often observed that the valve opening schedule evolves. During maintenance or replacement of electro-mechanical parts, performances and settings are not always perfectly replicated. Some technicians may adapt or tune the schedule, without refereeing to the hydraulic design team. In some cases, the reports from the original design are forgotten or even lost. As a result, the lock does not work anymore optimally.

In the last years, the Hydraulic Research Laboratory of the Service Public de Wallonie has been involved in some reengineering studies for such locks on the Walloon waterways network, Belgium. The report from these case studies illustrates how an abnormal working process can become standard operation, and how reengineering can restore lock performances. Field measurement can also provide relevant information in the absence of extensive documentation.

This paper will first present the methodology behind the case studies: flow modelling for valve schedule efficiency assessment; field measurement for data collection; and design criteria. Then, several case studies will be developed, highlighting methodological aspects and results: Lock of Havré on the Canal du Centre; Locks of Pommeroeul and Hensies on the Canal Pommeroeul-Condé (Bousmar & Libert, 2016); and three old locks (Leers-Nord, Estaimpuis, Warcoing) on the Canal de l'Espierres (Bousmar & Libert, 2017). Table 1 summarizes the main characteristics of these locks.

Lock	Dimensions	Drop	Levelling system
Havré	124 m x 12.5 m	10 m	Trough the floor
Pommeroeul	151.7 m x 12.5 m	13.5 m	Trough the floor
Hensies	149 m x 12.5 m	4.6 m	Filling: short culverts with dissipation chamber / Emptying: sluice valves in gates
Leers-Nord, Estaimpuis, Warcoing	38.5 m x 5.15 m	1.8, 2.7, 2.5 m	Sluice / grid valves in gates

Table 1: Lock dimensions and levelling systems

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2. METHODOLOGY

2.1 Modelling of the levelling process

For the sake of simplicity, the levelling process has been modelled in a non-coupled way. Discharge and head losses are first estimated in the culvert system, using a one-dimensional pipe model and assuming a horizontal water level in the lock chamber. The water surface evolution in the lock chamber is then estimated from a one-dimensional or a two-dimensional free surface model, using the discharge hydrogramme as an inlet condition.

The flow in each levelling culvert section *i* can be modelled using an unsteady pipe flow equation:

$$\frac{L_i}{gA_i}\frac{\partial Q_i}{\partial t} + H_{i,downstr.} - H_{i,upstr.} + \frac{\zeta_i Q_i^2}{2gA_i^2} = 0 \tag{1}$$

where Q_i is the discharge in the culvert section; L_i and A_i are the length and wetted area or the culvert; $H_{i,upstr.}$ and $H_{i,downstr.}$ are the head values at both ends of the section; and ζ_i is the head loss coefficient for the section. At each junction between culvert sections, the discharges have to comply with the continuity equation:

$$\sum Q_i = 0 \qquad (2).$$

A pipe equation (1) and a discharge value Q_i are set for each culvert section; and a continuity equation (2) and a head value $H_{i,upstr./downstr.}$ are set for each junction. The number of equations equals thus the number of unknown.

This non-linear equation system is solved in an implicit way, using the following discretization with time and linearization (UCL, 2013):

$$\frac{L_i}{gA_i}\frac{Q_i^{t+\Delta t} - Q_i^t}{\Delta t} + H_{i,downstr.}^{t+\Delta t} - H_{i,upstr.}^{t+\Delta t} + \frac{\zeta_i Q_i^{t+\Delta t}\left|Q_i^t\right|}{2gA_i^2} = 0 \qquad (3),$$

$$\sum Q_i^{t+\Delta t} = 0 \qquad (4).$$

For symmetrical parts of the levelling system, only one side is modelled and the discharges are counted twice.

At the beginning of the simulation, all discharges Q_i are set equal to zero. For a filling simulation, the initial head values at junctions are set equal to either the head in the upstream reach $H_{upstr.}$ or in the lock chamber H_{lock}, depending on the location of the junction with regard to the closed valve. For emptying simulation, the initial head values are similarly set equal to the head in the lock chamber H_{lock} or in the downstream reach $H_{downstr.}$.

During the simulation, the head in the upstream, resp. downstream, reach are kept constant. In the lock chamber, the water level is adapted after each time step, as a function of the total incoming (positive) or exiting (negative) discharge Q_{tot}:

$$H_{lock}^{t+\Delta t} = H_{lock}^t + \frac{Q_{tot}^t \cdot \Delta t}{S} \tag{5}$$

where S is the lock chamber horizontal surface.

The head loss coefficients ζ_i were estimated a priori from tables (Idel'cik 1969) for friction and for singularities like contractions, expansions, bifurcations, confluences, trash racks, outlets, etc. These coefficients were kept constant during all the simulations, assuming a large Reynolds number.

Variable head loss coefficients were used only for the valves. The head loss coefficient values were dependent on the actual valve position at the given time, according to the valve opening schedule:

- Havré and Pommeroeul locks are equipped with butterfly valves Pratt-Hanrez 1B, for which a original head loss diagram from the manufacturer could be recovered;
- Hensies lock is filled through vertical lift cylinder valves. Data could be recovered from an old scale modelling study on a similar valve (LRH, 1954). Emptying is operated through flat sluice valves. The head loss coefficient for the latter was estimated as for an orifice flow;

- The 3 locks on the Canal de l'Espierres are equipped with flat sluice valves and grid valves. The head loss coefficients were estimated a priori for an orifice flow; and then fitted on field measurements (see paragraph 6).

2.2 Field measurements

As only limited data could be recovered from original design studies, field measurements were planned on each lock, excepted Hensies which is currently out of service. Measurement objectives were twofold: (1) confirming the existing valve opening schedule; and (2) recording the current filling and emptying hydrogrammes, for numerical model calibration and validation purpose.

The valve opening schedules were recorded using either a cable-actuated distance sensor fixed temporarily on the valve hydraulic jack; either a stopwatch and a measuring tape. On the Canal de l'Espierres, video recording was used to support stopwatch measurements. Water levels in the lock chamber were recorded with a temporary pressure sensor "Diver" with integrated data logger. The sensor was fixed either on a lock ladder, either on a concrete block immerged in the water. Details on such measurement methods can be found in Bousmar et al. (2017).

2.3 Design criteria

As quoted above, a proper hydraulic design of a lock filling/emptying has to fulfil several criteria (PIANC 2015): levelling duration; maximum discharge; forces exerted on vessels; cavitation risk. The levelling duration has to be limited. In the present case studies, it is wanted that the levelling duration remains identical or decreases after reengineering. Target values are listed in Table 2. The maximum discharge should also be limited, to reduce levelling wave amplitude in the adjacent reach. Target values were set according to field measurements of wave propagation (Swartenbroekx et al., 2014); or to estimations of waves amplitude, based on actual discharge values and consideration on reach lengths. The lower maximum filling discharge at Havré lock is due to the presence of Strépy ship lift at the other end of the upstream reach. The water level in the mobile chambers of the ship lift has to be kept in a limited range, to keep the balance with the counter weight. Accordingly, it is necessary to reduce levelling waves amplitude in this reach.

Forces acting on vessels during the levelling process can be estimated by different approaches: actual forces in mooring lines; total hydrodynamic forces; total hydrostatic forces; or estimation based on water surface slope (PIANC 2015). In the present case studies, the forces were estimated from the water surface slope, computed without vessel in the lock chamber. For Havré, Pommeroeul and Hensies locks, the target vessel is a CEMT Class Va vessel. Recommended maximal forces are fixed to 0.85 to 1.15 ‰ of the weight of the water displacement of the vessel, depending of the presence of floating or fixed bollards (PIANC 2015). To account for the modelling simplification, the criteria was fixed to a maximum water slope S_w = 0.50 ‰ (see Table 2). For the Canal de l'Espierres locks, the recommended maximal forces for a CEMT Class I vessel would be in the range 1.50 .. 2.00 ‰. Accordingly, a criteria was fixed for the global water slope $S_{w,glo}$ computed on the whole lock length (end to end). However, these locks are mainly used by smaller recreational boats. For these, the admissible force can raise up to 3 ‰ (PIANC 2015). This criteria is applied to a local water slope $S_{w,loc}$ computed on a length of 10 m, considering the maximum local value along the lock length.

Lock	**Duration**		**Max. discharge**		**Max. water slope**
	Filling	**Emptying**	**Filling**	**Emptying**	
Havré	10 min	9 min	40 m³/s	60 m³/s	0.5 ‰
Pommeroeul	9 min	9 min	75 m³/s	75 m³/s	0.5 ‰
Hensies	9 min	9 min	30 m³/s	30 m³/s	0.5 ‰
Leers-Nord, Estaimpuis, Warcoing	8 min (6 min)	8 min (6 min)	4.5 m³/s (3.0 m³/s)	4.5 m³/s (3.0 m³/s)	Glob.: 1.5 ‰ (1.0 ‰) Loc.: 3.0 ‰ (2.0 ‰)

Table 2: Design criteria. Optimal target values in parenthesis.

Cavitation risk is only to be considered at the valves of Havré and Pommeroeul locks, who present the largest total head. Cavitation risk is estimated through a cavitation number *C* (Savary & Libert, 2013):

$$C = \frac{H_2 - H_{vap}}{\Delta H_{1-2} + v_2^2 / 2g} \tag{6}$$

where H_2 and v_2 are the head and the mean velocity in the section downstream the valve; $H_{vap} \approx 0.30$ m is the vapour tension of water; and $\Delta H_{1\text{-}2}$ is the head loss at the valve. $C < 2.5$ means cavitation inception; and $C < 1$ means developed cavitation with damage inception.

A last design constraint is the compatibility of the recommended valve schedule with the electromechanical equipment characteristics. For Havré, Pommeroeul and Hensies locks, the electromechanical parts will be replaced. Valve schedules can therefore be fixed more easily. Valves are operated by hydraulic jacks. Constant opening rates will be preferred. Different successive opening rates can also be considered if required. At the locks on the Canal de l'Espierres, no replacement of the electromechanical equipment is foreseen. As the hydraulic jacks have a very short stroke and operate too fast, the valve schedule will be discontinuous with stepwise openings. Such an opening schedule is however known to generate significant waves in the lock chamber and is not to be preferred when possible (PIANC 2015).

3. LOCK OF HAVRÉ

3.1 Available data

Figure 1 shows the lock of Havré. The chamber is 124 m long and 12.5 m wide. An intermediate gate enables locking in a half chamber, to save water. The levelling is operated through a distribution system located in the lock floor. Figure 2 shows the central culvert and a floor diffuser. This system is supplied through longitudinal culverts in the lock walls. Due to the intermediate gate, the distribution system is actually split in an upstream and in a downstream part. Discharge is controlled through 6 butterfly valves of diameter 3 m, symmetrically located in the upstream, intermediate and downstream heads.

Although this lock dates from the early 1970ies, no original design report could be recovered. Only the original valve opening schedule was recovered in the as-built files. This schedule is plotted in red on Figure 3. It is a complex multispeed schedule. It starts with a fast opening till 45°, followed by two lower speed phases. The last 10° are eventually operated at the fast initial speed.

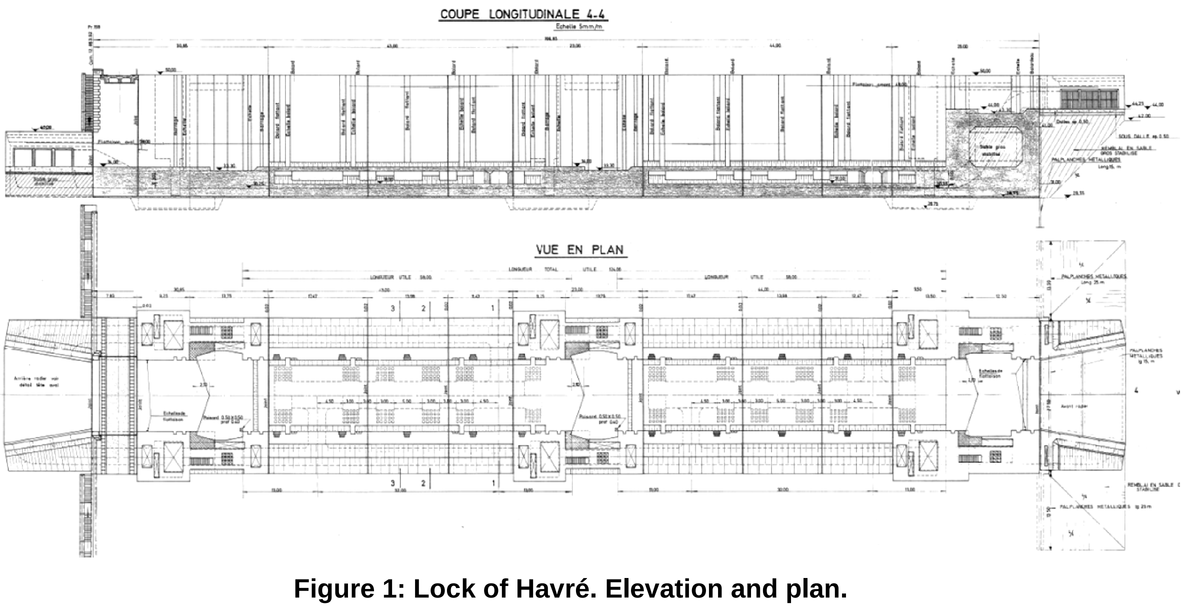

Figure 1: Lock of Havré. Elevation and plan.

Figure 2: Lock of Havré. Views from inside the central diffusion culvert.

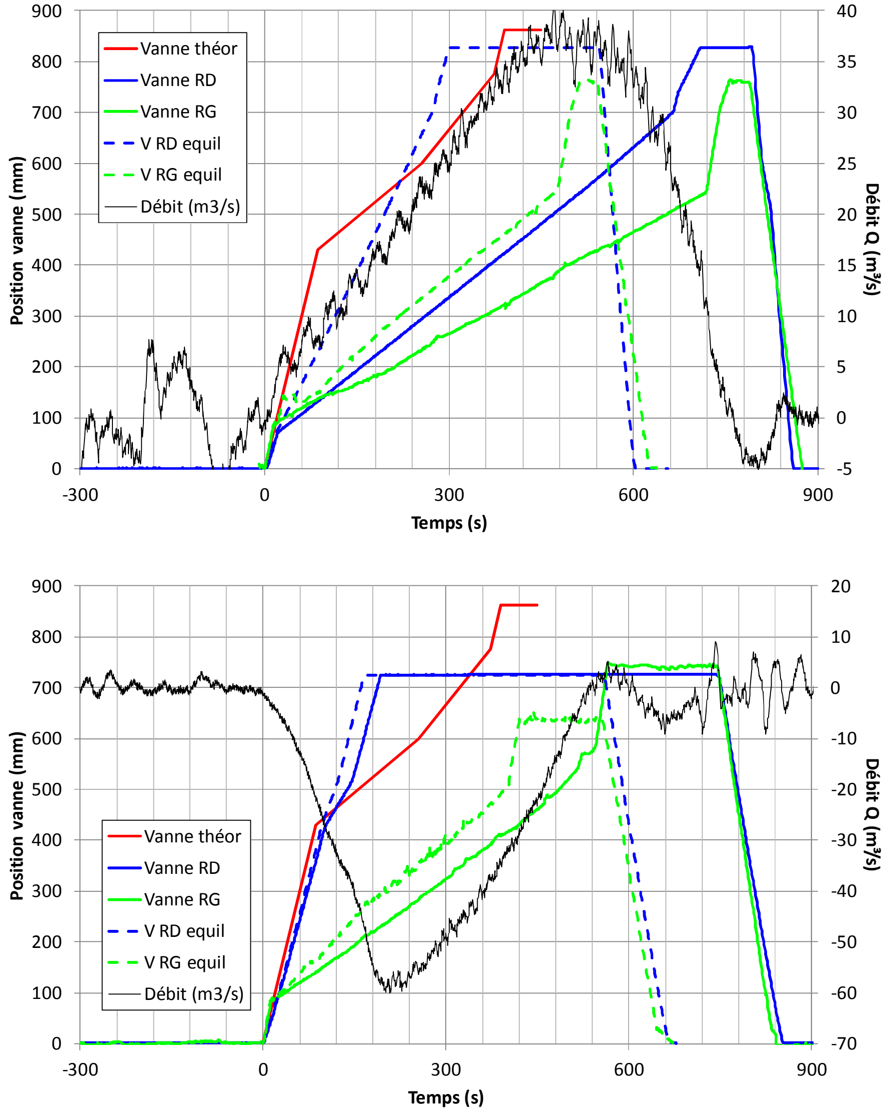

Figure 3: Lock of Havré. (a) Filling; and (b) emptying. Measured hydrogramme in black. Valve opening schedule (given as hydraulic jack position): theoretical curve (red), measured for right (RD-blue) and left (RG-green) valves. Plain curve is during levelling, while dashed curve is measured at equilibrium with no head on the valve.

Field measurements were organised to collect the actual valve opening schedule and the levelling hydrogrammes for both filling and emptying. Those data are also plotted on Figure 3. It clearly appears that the actual valve schedule differs significantly from the original one found in as-built files. Significant discrepancies even appear between left and right side valves. The only similarities between the actual and the theoretical schedules are their multispeed aspect and, up to a certain extent, the fast and low speeds of the different phases. Surprisingly, it was also observed that the valves operated faster when the lock chamber was at equilibrium (thus with no head and discharge) than during actual levelling. As the hydraulic jacks are operated at a constant speed, fixed by a constant oil discharge, no explanation was found for this last observation.

3.2 Modelling of the lock levelling

In a first stage, the culverts of the levelling system were schematized as a succession of prismatic culverts and singularities. Head loss coefficients were estimated for each part, as depicted in § 2.1. Before going through the actual culvert flow modelling by solving the pipe equations system, a simplified analysis of the lock filling was done. This analysis was done for an estimated maximum discharge of 60 m³/s with the valve fully opened and assuming a uniform distribution of the flow through the 24 floor diffusers. Figure 4 shows the head loss estimated in each culvert part for these idealised discharge values.

The culvert system looks like a longitudinally distributed filling system similar to the ones depicted in the literature (PIANC, 1986; 2009). From this simplified analysis, it appears that the system is not equilibrated: (1) the head loss in the longitudinal culvert from inlet to junction with the central culvert is lower for the first half chamber than for the second half chamber; (2) the head loss from the inlet to this junction is lower in the right side culvert; and (3) the head loss in the floor diffusers is much lower than in the longitudinal culverts. As a result, the discharge will be unevenly distributed between the central culverts; and, as the head loss is not large enough in the diffusers, no discharge control can be anticipated at this level.

A last observation from this simplified analysis is that the total head loss at peak discharge with the valves fully opened is lower than 2 m; whereas the total drop of the lock is 10 m. If the valves are opened too fast, the actual discharge resulting from this high drop will be much higher than 60 m³/s. In other words, the valves seem oversized.

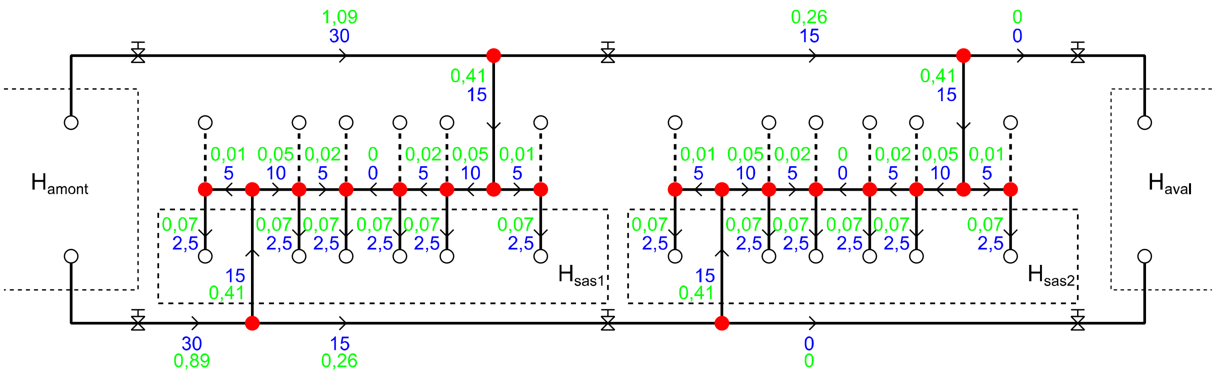

Figure 4: Lock of Havré. Simplified estimation of head losses (in green) and discharges (in blue). Dashed lines in the culvert system are symmetrical parts. White nodes are connected with boundary levels; red nodes are internal junctions.

A detailed numerical modelling was accordingly necessary for a deeper analysis. Figure 5 shows the hydrogramme obtained with the actual valve schedule ("Q insituV"). This hydrogramme is very close to the measured one. This validates the modelling done and the setting of the head loss coefficients. Figure 6 shows the actual discharges from each floor diffuser, also computed for the actual valve schedule. As anticipated from the simplified analysis, the distribution is uneven, with more discharge in the first half chamber, and also with different discharges between diffusers in the same half chamber. This uneven discharge distribution generates waves in the lock chamber. The water surface slope, computed on the total lock length is shown on Figure 7. The maximum values are in the range 0.15 ‰. Such values are acceptable with regard to the design criteria.

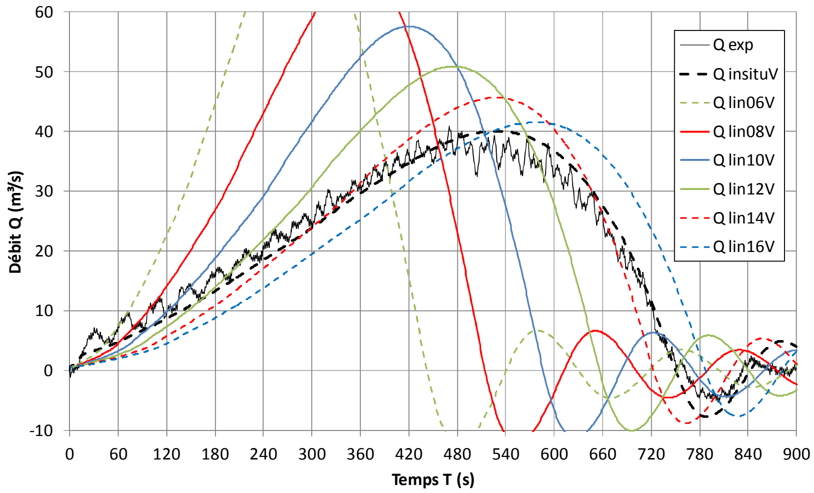

Figure 5: Lock of Havré. Filling hydrogramme, computed for the actual valve opening schedule ("Q insituV") and for linear valve openings ("Q linXXV") in XX minutes.

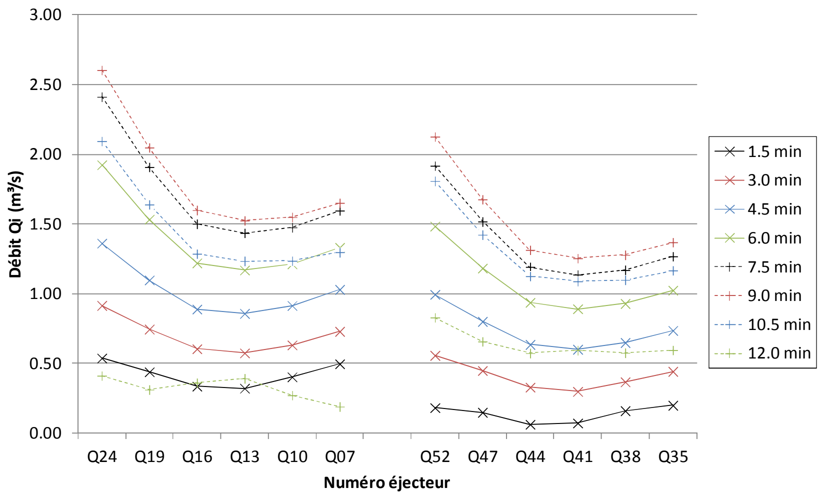

Figure 6: Lock of Havré. Discharge distribution between floor diffusers. Filling computed with the actual valve opening schedule.

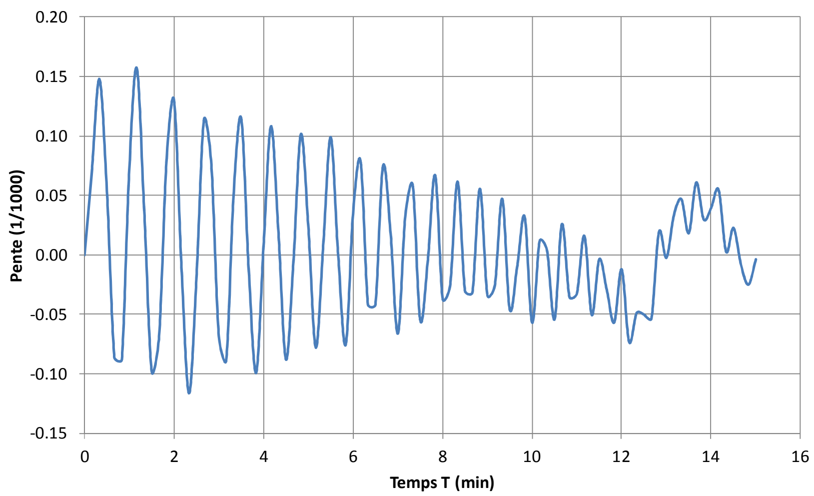

Figure 7: Lock of Havré. Water surface slope in the lock chamber. Filling computed with the actual valve opening schedule.

Using this validated numerical model, different valve opening schedules were then tested for the lock filling. At first, for the sake of simplicity, linear openings were tested, operated at a constant speed. Figure 5 shows the results obtained with a total opening duration varying from 6 to 16 minutes. For the fastest valve opening (6 minutes), the maximum discharge is significantly larger than the admissible discharge as listed in Table 2. This confirms that the total head losses in the filling system are too low and that the valve is probably oversized. The maximum discharge remains too high up to a linear valve opening in 14 minutes. A linear opening is 16 minutes results in an acceptable maximum discharge. But, with such a valve schedule, the levelling duration equals 13 minutes, which is too long. Additionally, the valve movement continues for 3 minutes after the levelling is completed. This again confirms that the valve is oversized. From a technical point of view, such a schedule is also not acceptable, as the hydraulic group that operates the jacks of the valves has to be available as soon as the levelling is finished, to operate the lock gate jacks.

As no optimal solution could be found with a unique valve opening speed, further tests were performed with a bilinear valve schedule, starting with an opening at high speed, followed by a second step at lower speed. With such schedules, no filling time is lost during the first opening step, as the valve is operated fast at the angles were the opening is too low to be efficient. The opening rate is then reduced to avoid too large discharge at a more efficient opening angle. Figure 8 shows the optimized hydrogramme (“Q opti4”) compared to the existing one. The filling duration is reduced by more than 2 minutes. The corresponding valve schedule is shown on Figure 9: the valve is opened at 0.30°/s till an angle of 36°. The opening rate is then divided by 5 to 0.06°/s. As the valve opening duration is again longer than the filling time, a third opening step at high velocity is introduced to open the last 30° at the high speed (0.30°/s, “Q opti4f”).

With this optimized valve schedule, the computed water surface slope remains below S_w = 0.17 ‰. The minimum value of the cavitation number computed with (6) is C = 1.63. C remains below 2.5 during 204 s indicating possible cavitation, but with limited risk of damage.

A similar optimized valve schedule could be found for lock emptying, with a longer first opening step till an angle of 54°, as the maximum allowed discharge is larger than for filling.

The analysis of the levelling process for the lock of Havré resulted in complex valve opening schedules presenting three speed steps. These schedules present a shape similar to the schedule found in the as-built files but they were re-optimized for the actual design criteria. Notably, the lower maximum discharge during filling imposes a shorter first opening step compared to emptying. The analysis also highlighted that these complex schedules probably result from oversized levelling valves.

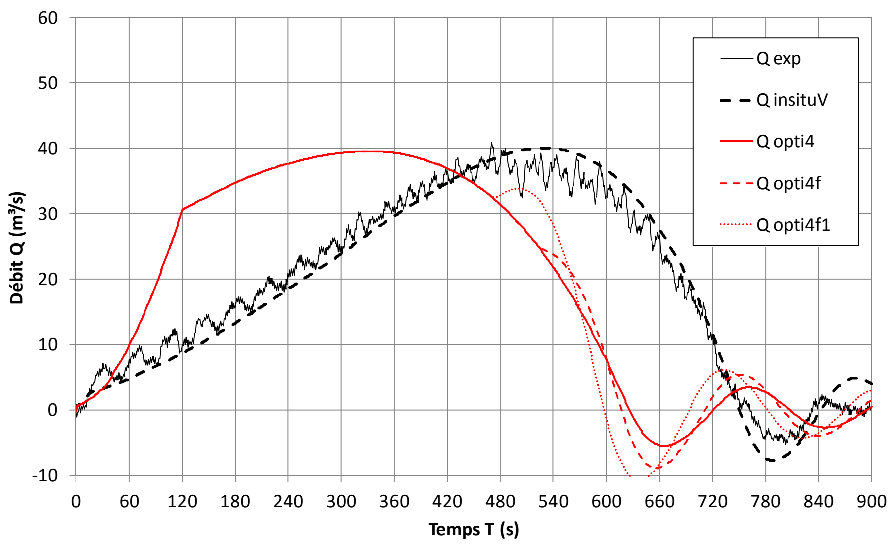

Figure 8: Lock of Havré. Filling hydrogramme, computed with the optimized valve opening schedule (“Q opti4”).

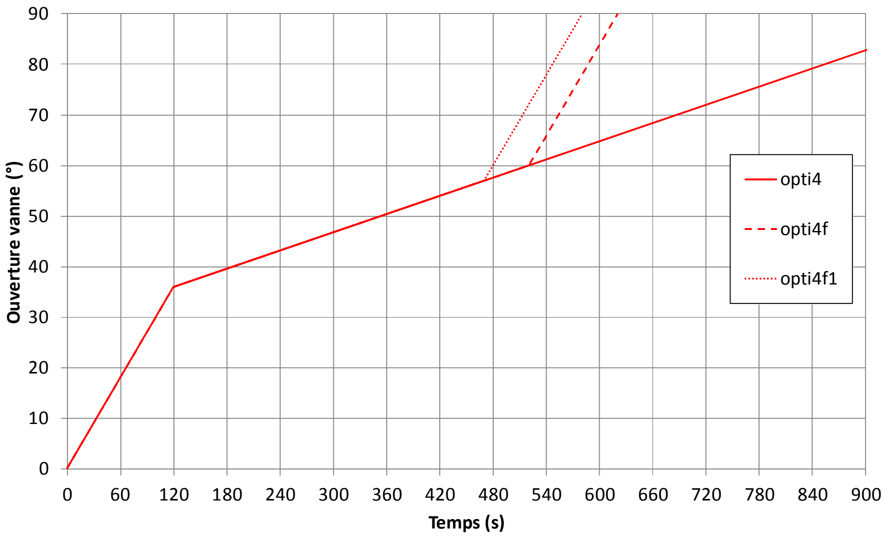

Figure 9: Lock of Havré. Optimized valve opening schedule for filling hydrogramme.

3.3 Robustness of the valve schedule

Field measurement of the current valve opening schedule showed that this schedule had been significantly altered since the lock commissioning. Specific control procedures will have to be implemented in the planning of the maintenance operations to ensure that the proposed schedule won't be affected similarly. Additionally, a sensitivity analysis was performed to check whether small tuning errors could affect the levelling hydrogramme. Two parameters were tested for the first opening step: (1) the duration was increased or decreased by 10 s, resulting in a 3° angle error; and (2) the opening speed was increased or decreased by 10 %. The error on the opening step duration was the most significant, with an impact of up to 5 m³/s on the maximum discharge; and of 30 s on the levelling duration. These results should provide guidance on the acceptable tolerances of the electro-mechanical system tuning.

The hydrogramme was also computed for several special levelling cases, to further check its robustness: (1) operation with one valve out of order; (2) operation on a half-chamber, using the intermediate gate and valves; and (3) emergency stop. When levelling with only one valve, the levelling duration is logically found longer, but the maximum discharge and water slope remain compliant with the acceptance criteria. When operating a half chamber, it was found that the intermediate gates should be operated with the same schedule than the upstream valves. Using the schedule of the downstream valves results in a too large maximum discharge.

An emergency stop may be requested if for example one vessel line is blocked on a fixed bollard. The valves should then be closed at their maximum speed (here 1.5°/s) to minimize the residual water level rise in the lock chamber. The resulting discharge gradient will cause large wave and water surface slope in the chamber. Two cases were tested for an emergency stop during lock filling: at the end of the first opening step (36°), to maximum the discharge gradient, and at the peak discharge, to maximise the residual level rise. Both cases were investigated at maximum closing speed (1.5°/s), and at half closing speed (0.75°/s).

The largest residual level rises were observed when stopping at the peak discharge: 0.28 m at the maximum closing speed, and 0.54 m at half speed. Figure 10 shows the resulting water surface slope. The sudden discharge gradient causes significant waves, notably for a closing at maximum speed starting at 36° ("opti4Ur"). The maximum slope S_w = 1.5 ‰ is 3 times larger than the acceptance criteria. Closing at half speed reduces this maximum slope to S_w = 0.9 ‰. However, regarding the residual level rise, such a slope was found acceptable for an exceptional situation like an emergency stop.

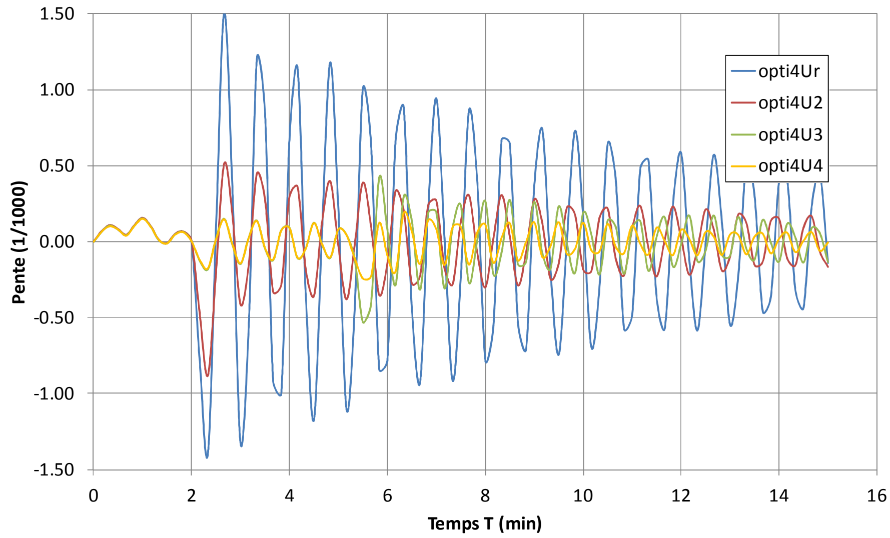

Figure 10: Lock of Havré. Water surface slope in the lock chamber. Emergency stop during filling (Ur, U2: at 36°; U3, U4: at 48°; closing speed: Ur, U3: 1.5°/s, U2, U4: 0.75°/s).

4. LOCK OF POMMEROEUL

The lock of Pommeroeul is 151.75 m long and 12.5 m wide (Figure 11). An intermediate gate enables locking in two half chamber, of non-equal length. As in Havré, the levelling is operated through a distribution system located in the lock floor. Discharge is controlled through 4 butterfly valves of diameter 3 m. The central culvert is separated in two parts. It is connected to the right side longitudinal culvert in the upstream half lock; and to the left side longitudinal culvert in the downstream half lock. Accordingly, the levelling in a half chamber is obtained by operating only one valve, and no intermediate valve is needed.

As for Havré, only the valve opening schedule could be recovered from the original studies. It is a 4 steps multispeed schedule. Field measurements highlighted that this schedule has also been significantly altered with time.

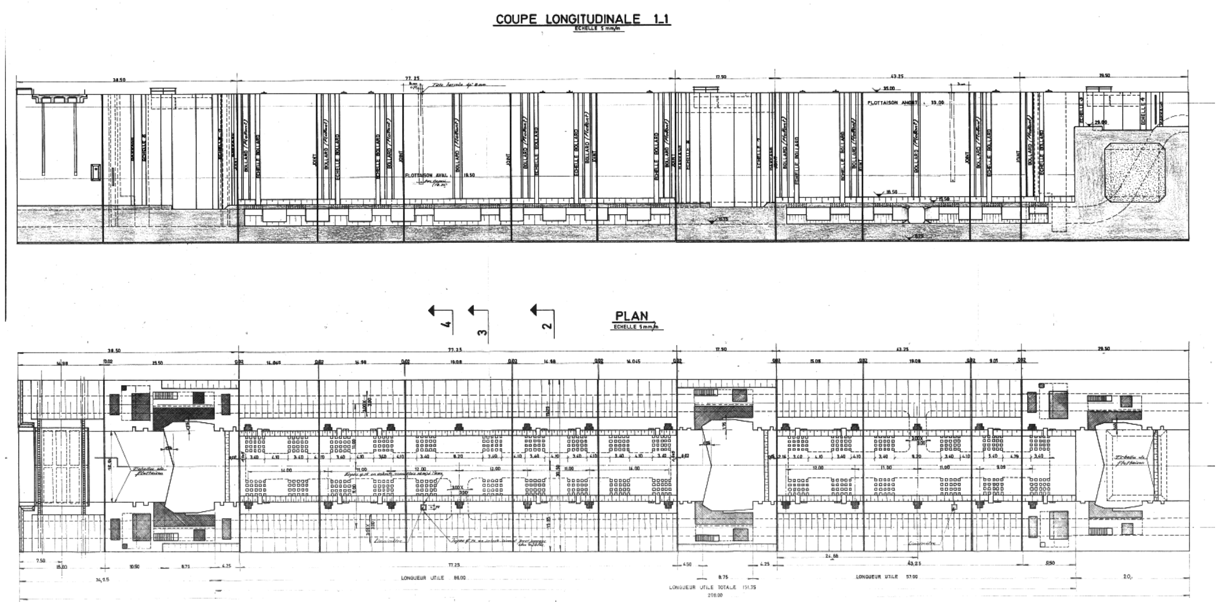

Figure 11: Lock of Pommeroeul. Elevation and plan.

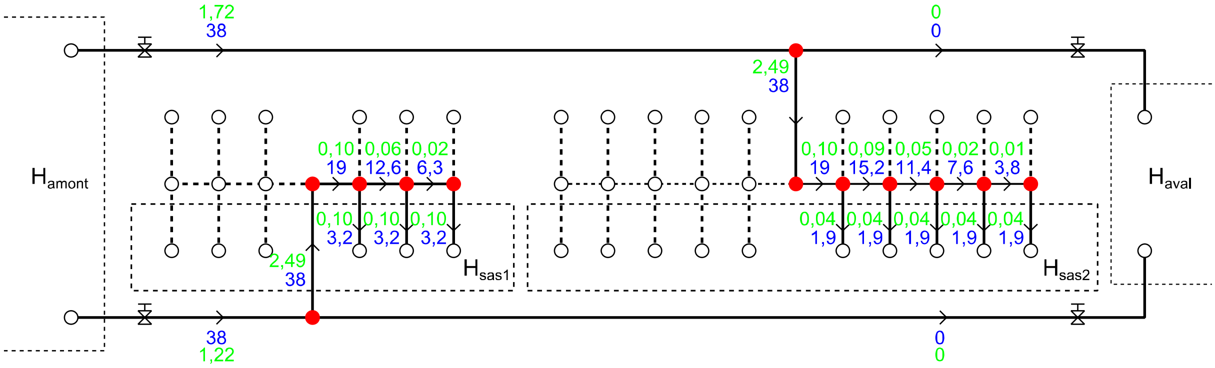

Figure 12: Lock of Pommeroeul. Simplified estimation of head losses (in green) and discharges (in blue). Dashed lines in the culvert system are symmetrical parts. White nodes are connected with boundary levels; red nodes are internal junctions.

Figure 12 shows the results of the preliminary estimation of head losses in the levelling system. In this simplified modelling of the lock filling, a peak discharge Q = 76 m³/s is equally distributed between both longitudinal culverts and the upstream valves are fully open. As for Havré lock, it appears that the system is not equilibrated: (1) due to the different lengths of both half-chambers, the discharge distribution between different number of diffusers won't be equilibrated; (2) the head loss from the inlet to the junction with the central culvert is lower in the right side culvert; and (3) the head loss in the floor diffusers is much lower than in the longitudinal culverts. No uniform discharge distribution can be expected from such a layout. Additionally, the total head loss at peak discharge with the valves fully opened is lower than 4.5 m, for a total drop of the lock equal to 13.5 m. Again, the valves seem oversized.

As for Havré lock, a more comprehensive analysis was performed through numerical modelling. First simulations were run for the existing valve opening schedule. Some limited tuning of a head loss coefficient was necessary to optimise the quality of the results compared to field measurements: on the transverse culvert that links the longitudinal and central culverts, the local head loss coefficient was reduced from ζ = 2.55 to ζ = 1.55 for both filling and emptying.

Figure 13 shows the distribution of discharge between the floor diffusers during a filling simulation. Obviously, the upstream diffusers contribution is larger than the contribution from downstream diffusers in the beginning of the filling; while the trends invert during the filling. As a result, significant waves are observed in the lock chamber.

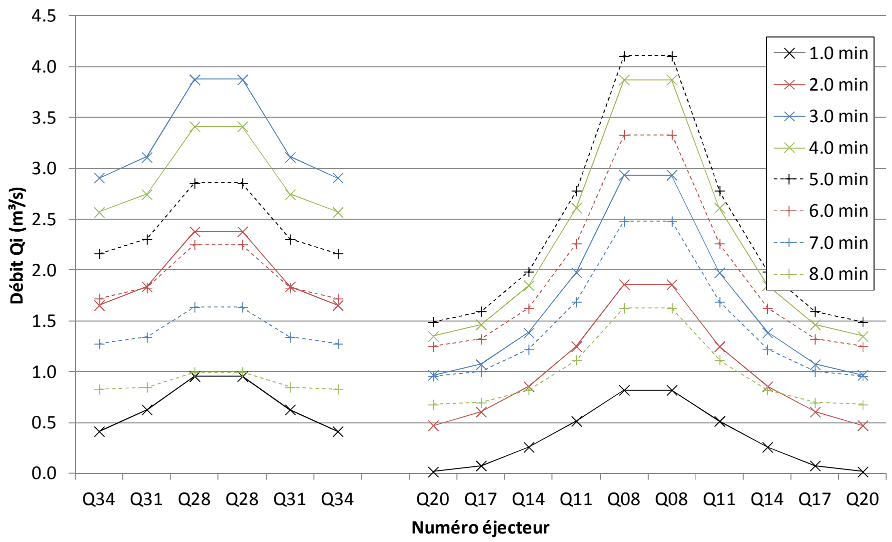

Figure 13: Lock of Pommeroeul. Discharge distribution between floor diffusers. Filling computed with the actual valve opening schedule.

The calibrated and validated numerical model was then used to define an optimized valve opening schedule. Due to the valve oversizing, linear opening turned out to be inefficient, resulting either in a too large discharge, either in a too long levelling duration. A complex schedule with 3 steps similar to Havré was eventually adopted: high opening speed in the beginning (180 s at 0.30°/s, till 54°); lower speed to control the peak discharge (280 s at 0.075°/s, till 75°); high speed to conclude the valve opening within the levelling duration (50 s at 0.30°/s). Compared to Havré, the transition between high and low speed occurs later: the total head loss is indeed higher; and the admissible peak discharge is also higher. The valve opening schedule for emptying is similar to the one for filling, as the admissible peak discharges are equal.

The robustness of the valve opening schedule was also tested. Sensibility analysis leads to results quite similar to Havré. As could be expected from the levelling system layout, asymmetric filling with only one valve leads to non-uniform discharge distribution. Thanks to the reduced total discharge, resulting water slopes remain below S_w = 0.30 ‰. Good results are also obtained when levelling on a half-chamber. Due to its shorter size, the upstream half-chamber is filled faster than the downstream half-chamber.

In case of emergency stop, the residual level rise is 0.49 m at maximum valve closing speed, and 0.93 m at half closing speed. These values are higher than at Havré, due to the larger peak discharge. On the other hand, maximum water slope at maximum speed is S_w = 0.67 ‰. This value remains admissible in such an exceptional case.

5. LOCK OF HENSIES

The lock of Hensies differs from Havré and Pommeroeul by its lower drop of 4.6 m and by the simpler layout of its through-the-head levelling system (Figure 14). The filling is operated through short culverts and a dissipation chamber located under the head floor. The filling discharge is controlled by a lifting cylindrical valve. The intermediate and downstream mitre gates are fitted with sluice valves. This lock is out of service since the mid 1990ies. It was therefore not possible to measure in-situ the valve opening schedule. Only the theoretical schedule for downstream sluice valve could be recovered in the as-built files. This schedule includes 3 phases operated at 3 different opening speeds.

An accurate modelling of the levelling requires a good knowledge of the head loss at the cylindrical valve and in the dissipation chamber. The variation of the head loss coefficient of the valve with its opening was estimated from scale model measurements done on a similar valve for Marchienne lock as depicted on Figure 15 (LRH, 1954). The loss coefficient for the dissipation chamber was set to ζ = 10, according to scale model measurements done on a similar geometry (UCL, 2013).

Linear valve opening at constant speed are tested in a first stage. Figure 16 shows the filling curves and hydrogrammes for openings in 120, 180, 240, 300 and 360 s. The “theor” curve corresponds roughly to the opening schedule of the downstream sluice valve found in the records. Increasing the duration of the valve opening has an impact on the peak discharge. When the opening duration is longer or equal to 180 s, the peak discharge is below the maximum admissible discharge. On the other hand the opening duration has only a limited impact on the filling duration: +95 s, when opening in 360 s instead of 120 s. This shows that the head losses are mainly controlled by the culverts and not by the valve.

As Hensies lock is filled through the head, longitudinal waves will be more important and the water slope criteria will be more significant. Discharge gradients should be avoided to reduce wave amplitude (PIANC, 2015). Figure 17 clearly shows that the speed step at 75 s in the “theor” opening schedule generate large waves in the lock chamber. With the linear opening schedule, the larger waves are observed at the beginning of the filling process. For a valve opening in 120 s, the peak water slope S_w = 0.64 ‰ is larger than the admissible criteria. When the valve is opened in 180 s, the peak water slope reduces to S_w = 0.42 ‰. Accordingly, a linear valve opening in 180 s is an optimal solution.

A similar analysis showed that an optimal emptying can be obtained with a linear opening of the sluice valves in 360 s.

The robustness of these two valve schedules was also tested. As the opening is operated at a constant speed, and as the culvert head losses control the filling process, the sensitivity to the schedule setting is very low. Asymmetrical filling was also less sensitive as the levelling is operated through the head. For an emergency stop, the residual rise is 0.40 m, with a maximal slope S_w = 1.32 ‰.

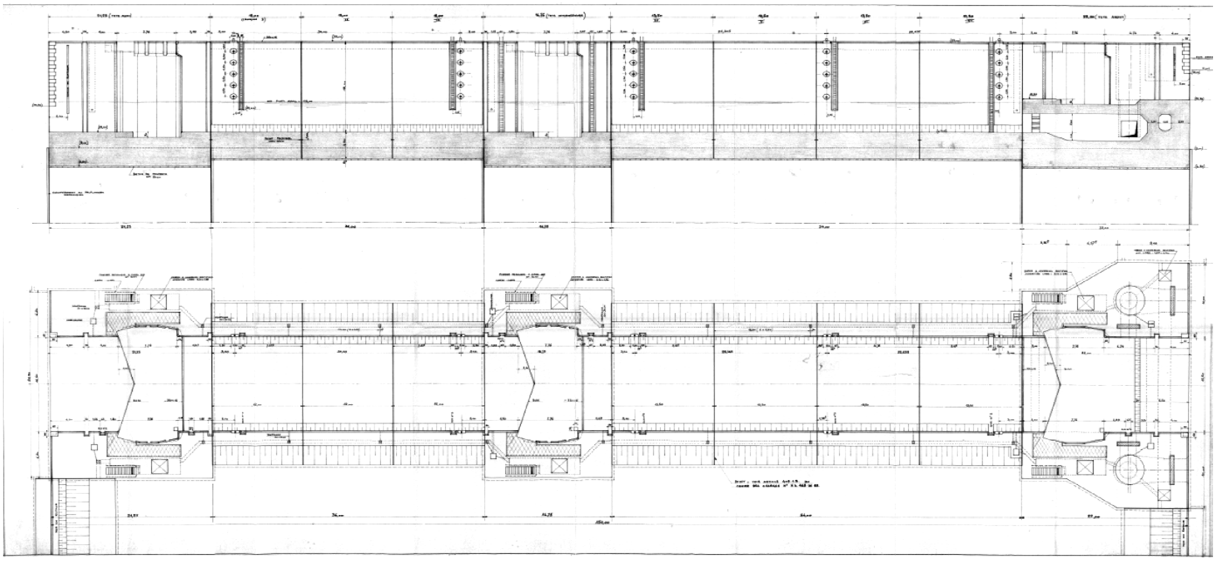

Figure 14: Lock of Hensies. Elevation and plan.

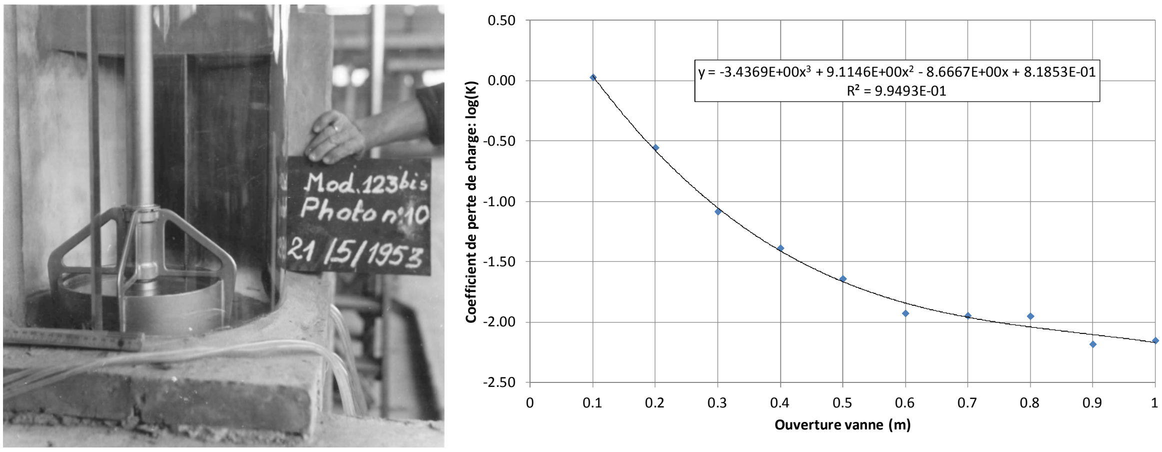

Figure 15: Scale modelling of Marchienne lock cylindrical valve. (a) Model (LRH, 1954); and (b) measured head loss parameter $K = \zeta/2gA$.

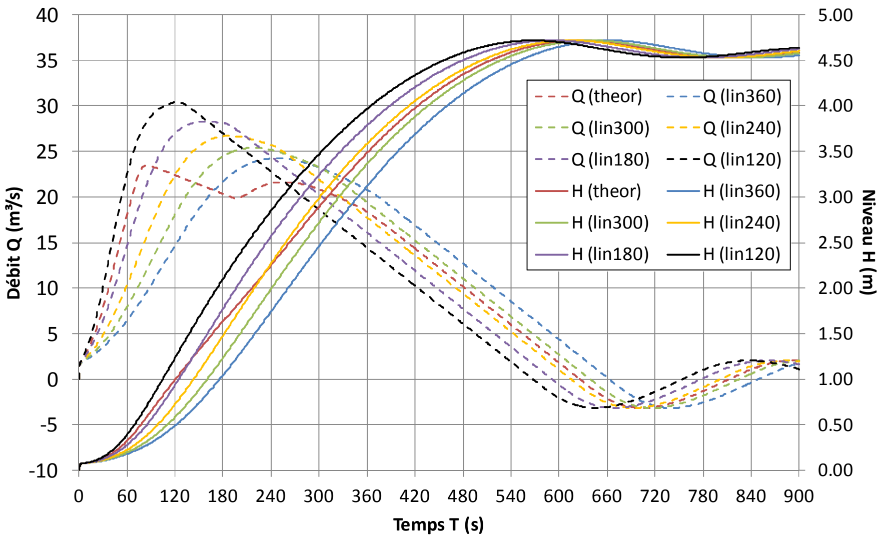

Figure 16: Lock of Hensies. Filling curves and hydrogrammes, computed for linear valve openings (“Q linXXX”) in XXX seconds.

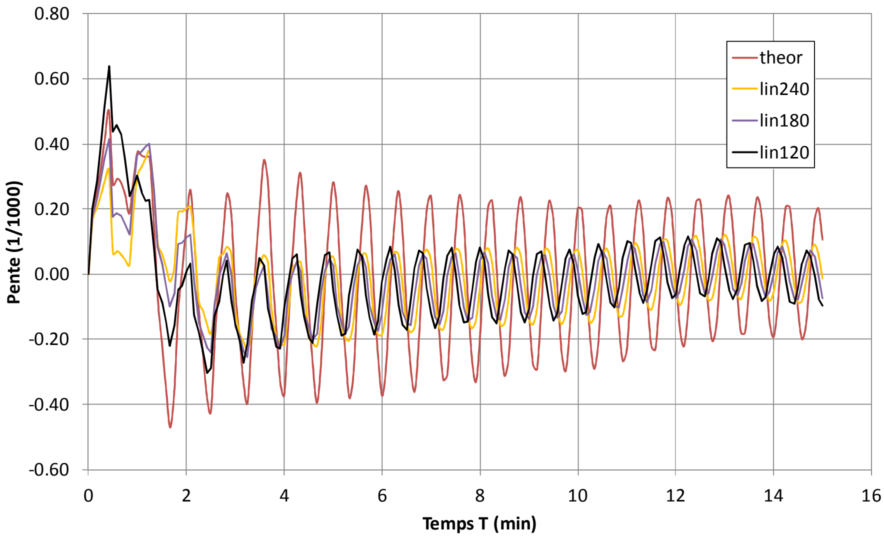

Figure 17: Lock of Hensies. Water surface slope in the lock chamber, computed for linear valve openings.

6. LOCKS ON THE CANAL DE L'ESPIERRE

The last case study covers three old locks (38.5m x 5.15m x H 1.8 .. 2.7m) on the Canal de l'Espierres (Figure 18a). These lock dates from the 19th century. They are equipped with either grid valves with a very short stroke of 150mm (Figure 18b), either with sluice valve with a stroke of 450mm, both located in mitre gates. Twelve years ago, the manual gears system actuating the valves was replaced by hydraulic jacks. According to as-built files, the opening speed of these jacks is 25 mm/s. Position is controlled by automate. The jack is operated in successive steps, with opening phases duration fixed in seconds, and stand-by phases duration fixed in minutes.

Local staff complained about poor levelling conditions: too long valve opening schedule during filling, and too large water movement in the lock chamber during emptying. These complaints were quite inaccurate and possibly subjective. This justified field measurements to obtain a reliable diagnosis before further analysis and reengineering.

Figure 18: Lock of Leers-Nord: (a) General view; and (b) grid valve in the upstream gate

Figure 19 shows the recording of a filling and an emptying sequence at Warcoing lock, operated in automatic mode (450 mm high sluice valves in the upstream gate, and 3 x 150 mm high grid valves in the downstream gate). The upstream valves open in 4 steps. It is nevertheless observed that the 2 last steps occur after the filling is completed. The filling lasts 8'18''; while the valve opening sequence lasts 14'15". The emptying lasts only 3'21". Significant waves were visually observed in the lock chamber. Due to technical problems (end of travel sensor not closed, valve blocked in partially opened position), it was not possible to record fully automated sequences at Leers-Nord and Estaimpuis. Similar observations could nevertheless be collected on valve schedules and filling curves.

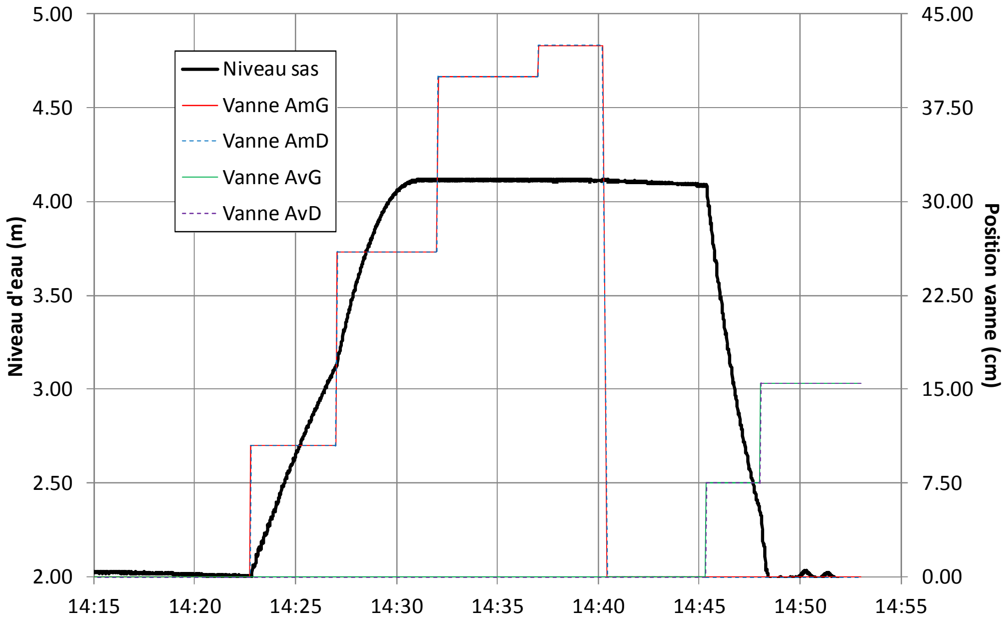

Figure 19: Lock of Warcoing: filling and emptying curve, and valves position.

For the modelling of the lock levelling, the flow equation (1) reduces to a single equation and the inertia term is almost negligible. All the head losses are concentrated at the valves modelled as orifices. According to Idel'cik (1969), the head loss coefficient for an orifice similar to the sluice valve could be in the range $\zeta = 2.7$ .. 2.9. The grid valve in fully opened position could be assimilated to a rack with cylindrical bars and $\zeta = 1$.

From the levelling measurements, it was possible to identify the values of the head loss coefficients that give the best fit between recorded and modelled levelling curves. Figure 20 shows an example of such a fitting for the downstream grid valves at Estaimpuis. The best fit is obtained with a value of $\zeta = 4.17$ at an opening of 90 mm, and $\zeta = 1.31$ at full opening. Similar fitting were obtained for all measurements, leading to a range of ζ values. Additionally, uncertainties up to 20 mm have to be considered on the initial valve position, and accordingly on all valve positions. This results in uncertainty on the ζ value. Figure 21 summarizes the observed values of the head loss parameter $K = \zeta/2gA$, as a function of the valve position, compared to values computed with different values of the head loss coefficient ζ. Eventually, it has been assumed that ζ varies linearly with the valve position, from $\zeta = 4$ for a closed valve to $\zeta = 1$ for a fully opened valve. Similar fittings were obtained for the sluice valves, with a head loss coefficient varying linearly in the range $\zeta = 2.85$ .. 4.00.

With the so-computed levelling hydrogrammes, it was possible to compute water movements in the lock chamber. Figure 22 shows the global and local maximum water slopes recorded during Warcoing lock emptying. These results confirm the visual observation of large waves occurring in the lock chamber. Local slopes up to $S_{w,loc}$ = 8 ‰ are observed. A first peak corresponds to the first valve opening step that generates a first discharge burst. A second peak is observed at the second opening step.

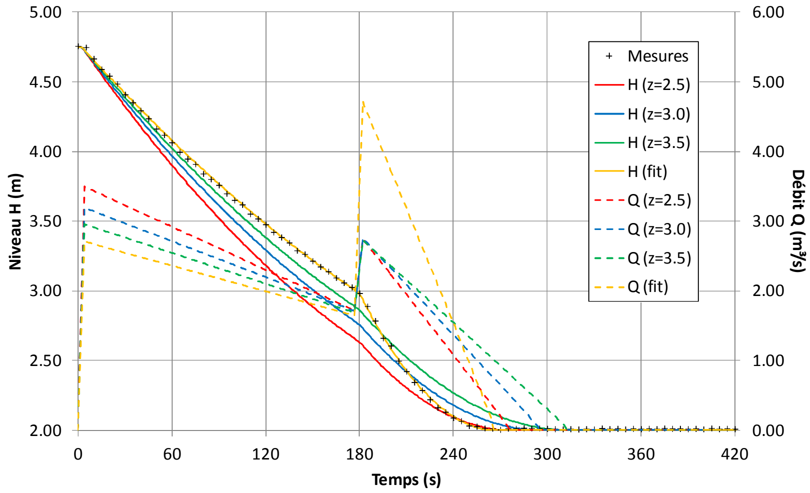

Figure 20: Lock of Estaimpuis: emptying curve, measured and computed for different values of ζ (noted z on the graph legend).

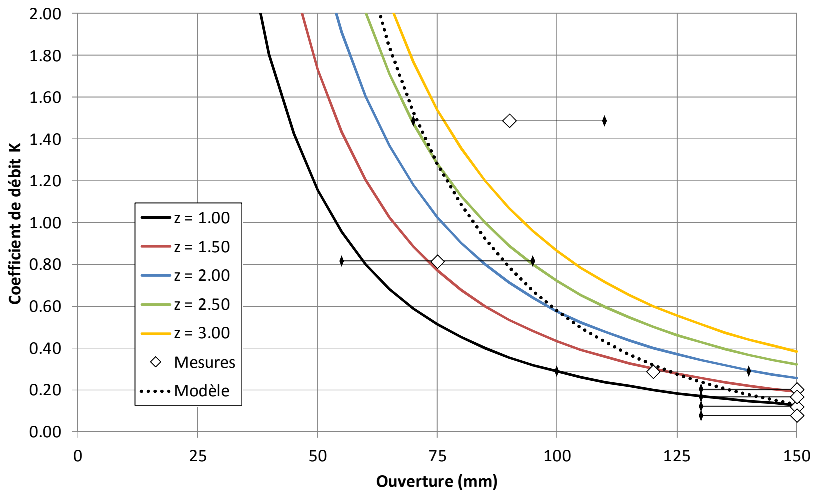

Figure 21: Grid valves on Canal de l'Espierre locks. Best fit head loss parameter *K* = ζ/2*gA*, and associated values of ζ (noted z on the graph legend).

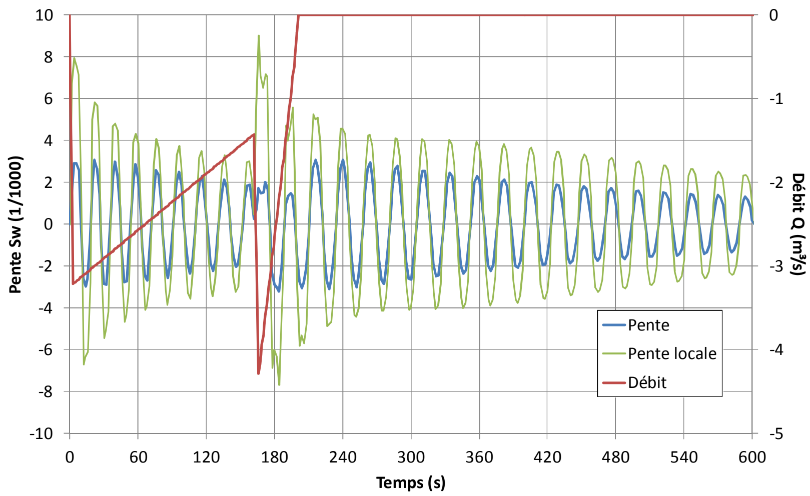

Figure 22: Lock of Warcoing. Global and local water surface slope in the lock chamber during emptying, computed for current valve schedule.

The measurements also roughly confirmed that the hydraulic jacks operate at a speed of 25 mm/s. Due to this high speed, an accurate setting of valve position is difficult, mainly for the grid valves: the full stroke is covered in only 6 s. An inaccuracy of 1 s on the step control results in a 15% error on the valve position. The number of possible step sequences is also limited accordingly: one step of 6 s; two of 3 s; three of 2 s or six of 1 s (see Figure 23). Only a few more schedules are possible for the sluice valves with a total travel time of 18 s.

Figures 24 and 25 show typical results obtained for the filling of Estaimpuis lock, through 450 mm sluice valves. Modelling were done for different steps opening schedules, and for an idealized linear opening, taken as reference. The levelling duration slightly varies with the total duration of the opening sequence. Large local and global water slopes are observed in all cases, except the linear opening. The largest slopes are logically observed for the longer opening steps (9 s) that generate the higher discharge bursts. For longer opening steps, the ratio between local and global slopes decrease, as the wave length is longer compared to the lock length. In any case, the less bad results were obtained for the shortest opening steps: with six steps of 3 s, separated by a 1 min stand-by, the filling duration is 6’02”, the maximum global slope equals $S_{w,glo}$ = 1.4 ‰, and the maximum local slope $S_{w,loc}$ = 3.8 ‰.

The only way to improve results and to reduce local slope is to decrease the valve opening speed. Figure 26 shows that dividing the jack speed by two reduces the maximum local slope to $S_{w,loc}$ = 2.3 ‰, while the maximum global slope and levelling duration remain almost unchanged. With a speed divided by 4, the maximum local slope is almost equal to the maximum global slope.

Quite similar results were obtained with the grid valves, with a preferred schedule in six steps of 1 s. These results are not detailed here for conciseness. From this analysis, it was concluded that the existing situation could be improved by reducing the valve travel at each step and by multiplying the steps. This improvement can be obtained by a simple change in the control automated parameters. Further improvement could be obtained by reducing the valve opening speed, but this will imply a mechanical intervention on the hydraulic system.

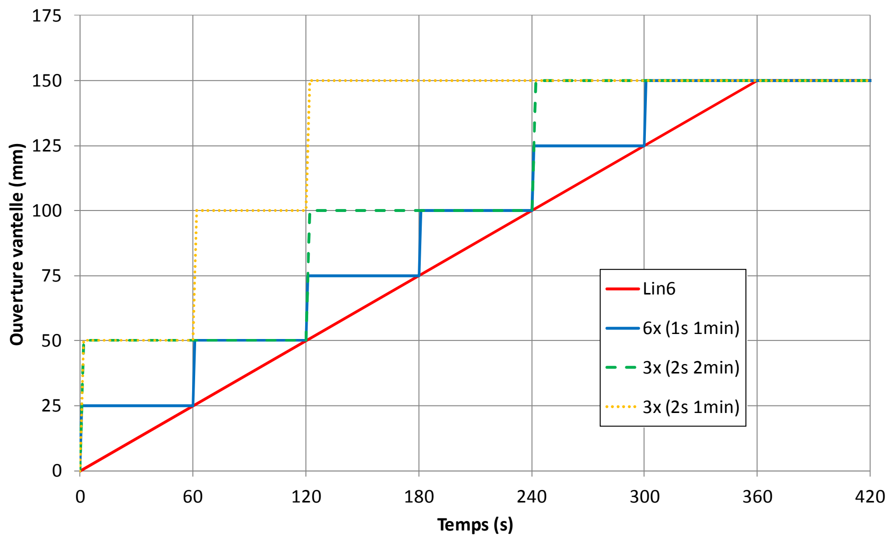

Figure 23: Grid valve on Canal de l’Espierre locks. Technically admissible opening schedules.

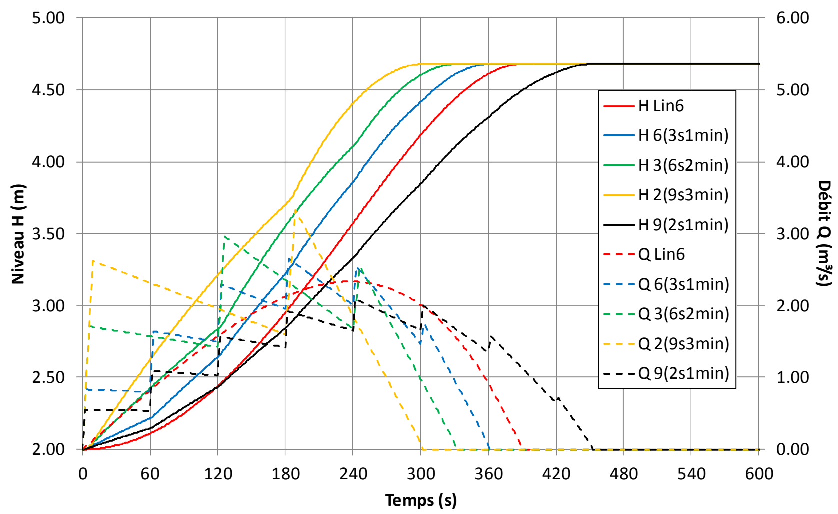

Figure 24: Estaimpuis lock: filling curve and hydrogramme, for different valve opening schedules.

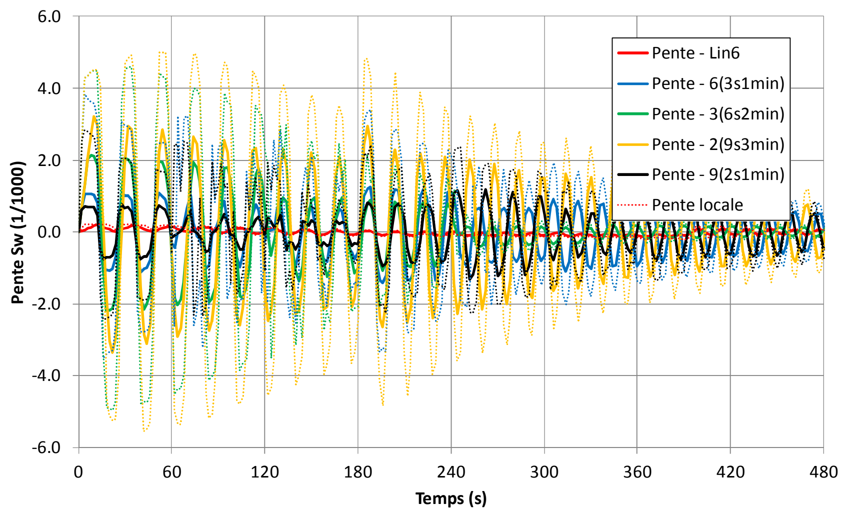

Figure 25: Estaimpuis lock: water surface slope, for different valve opening schedules.

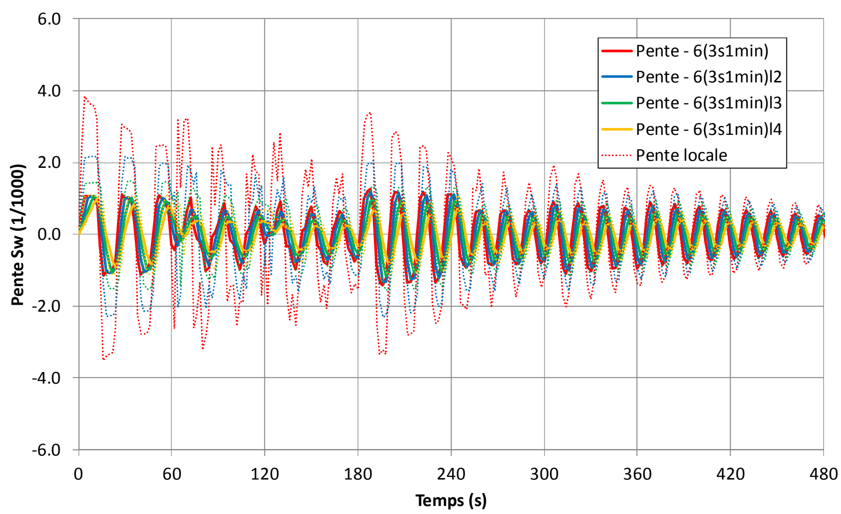

Figure 26: Estaimpuis lock: water surface slope, influence of the valve opening speed.

7. CONCLUSIONS: LESSONS LEARNT

Four case studies of lock levelling systems reengineering were presented, focusing on the adaptation of the valve opening schedule. In three cases, the electro-mechanical equipment is to be fully replaced. This let some freedom for the levelling design. In the last case, the electro-mechanical equipment is on site and severely constrains the possible valve schedules.

For all cases, only limited documentation was available. No hydraulic studies for the levelling could be recovered. The objectives and design criteria of the engineers who designed those locks levelling are therefore unknown. With a new regard and with new modelling tools, some of their choices seem questionable now:

- At Havré and Pommeroeul, a very complex system of levelling culverts was developed. This system looks like a fully equilibrated levelling system, but is not. Also, the butterfly valves seem definitively oversized.
- At the Canal de l’Espierres, the electro-mechanical system has been designed to open the valve, apparently as fast as possible, without consideration for the wave generation in the lock chamber.

These observations confirm the need to consider all flow processes and to perform a careful hydraulic design of any lock. As highlighted by PIANC (2015), all stakeholders should be aware of the possible consequences of their interventions on the vessel safety during levelling.

PIANC (2015) also highlighted the risk of an uncontrolled long term evolution of the valve opening schedules. Field measurements at Havré and Pommeroeul confirmed this risk. Hopefully, on the Canal de l’Espierres, electro-mechanical engineers in charge of the project requested a hydraulic study prior to any modification of the valve schedules. Again, one should conclude by highlighting the need for contacts between people in charge of the design and of the maintenance; and for appropriate maintenance and control procedures, in order to ensure the lasting quality of an optimal lock operation.

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