Title: Hydraulic modelling of a mixed water level control hydro-mechanical gate

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Abstract:

The article describes the hydraulic functioning of a mixed water level control hydro-mechanical gate present in several irrigation canals. According to the flow conditions, this automatic gate maintains the upstream level close to a target value for low flow, then it controls the downstream level close to a target, and switches back to control the upstream level to avoid overflow. Such a complex behaviour is obtained via a series of side tanks linked by orifices and weirs. We analyze this behaviour and propose a mathematical model for its functioning, assuming the system is at equilibrium. The proposed model is analyzed and evaluated on real data collected in the field, showing the ability of the model to reproduce the functioning of this complex hydro-mechanical system.

Introduction

Irrigation canals have been managed for millenniums with static devices (spillways, proportional diversions) or manually operated moving structures (gates). Automatic hydro-mechanical gates have been developed in the 20th century in order to better control the water levels, and ensure a better water distribution. The first automatic gates developed at an industrialized scale have been, to our knowledge, the so-called AMIL gates. These gates are hydro-mechanical gates using a float and two counter weights in order to control the water level upstream of the gate close to a target level. These gates have been designed in the 1930s by a French company named Neyrpic (latter on called Neyrtec, then Alsthom Fluide and now belonging to the Gec-Alstom Group). Other hydro-mechanical gates have been designed using alternative approaches and technologies for the same objective of controlling an upstream water level: the Begemann and Vlugter gates, designed by Dutch engineers (Vlugter, 1940; Burt et al., 2003; Litrico et al., 2005; Belaud et al., 2007). All these gates are adapted to the classical way of controlling irrigation canals called upstream control (Malaterre et al. 1998). This type of control is compatible with a water distribution to users according to a fixed rotation schedule. This strategy is easy to implement for the canal manages but rigid for the users and is the source of possible important water losses. Neyrpic company then developed hydro-mechanical gates for the control of downstream water levels. These gates named AVIS and AVIO have the important advantage of being adapted for a type of canal regulation called downstream control (Malaterre et al. 1998). This type of control allows on-demand water distribution to users as opposed to fixed rotation schedule. To our knowledge, the AVIS and AVIO gates are the only hydro-mechanical gates designed for downstream control of irrigation canals. In some cases, the upper reaches of large irrigation canals are managed by an upstream control strategy, while the lower reaches are managed by a downstream control strategy. This prevents frequent head discharge changes in the upstream part, while adapting the release to water demand in the downstream reaches. These two approaches can cooperate only if some intermediate storage volume is available and used along the canals in the intermediate reaches. This task can be managed by a third type of gates named mixed gates, also developed by Neyrpic. These gates are the only example of such advanced automatic operated gates using only hydro-mechanical principals.

All these hydro-mechanical gates are very interesting compared to electronically motorized gates since they do not require power or any electronic component. They just need regular maintenance (painting and grease). They are very well suited for difficult environments such as those prevailing in developing countries or in remote locations. Their properties are all the more interesting in a context of increasing energy cost or possible power cuts. Several successful examples of irrigation canal using such gates exist in the world such as the Tadla canal in Morocco where original gates installed in the 1950s are still very well maintained. Due to their performances and robustness properties, they are still installed on new irrigation canals (PHLC canal in Pakistan, Atbarra canal in Sudan) even though the electronically controlled and motorized gates are increasing their market shares. All these gates have then been built in several countries such as France, Algeria, Morocco, Spain, Portugal, Brazil, USA, cf. www.canari.free.fr/control/co_avis.htm and have been installed on hundreds of irrigation canals.

The purpose of this paper is to describe such gates and to model their complex functioning. The paper is organized as follows: first we provide a physical description of the gate and detail its general functioning. Then we develop a model of the gate, taking into account the various hydraulic devices. Subsequently, we use the model to study its sensitivity to various parameters. Finally, we compare the model results to experimental measurements from an operating gate installed in a real channel network.

Gate design and behaviour

The mixed gate is a regulation hydraulic structure which is designed to manage a difference between a discharge Q_p provided into the network by pumping or derivation and a demanded discharge Q_d corresponding to water abstraction.

If $Q_p > Q_d$ the upstream reach will be used as a storage and the upstream level will increase. If this difference persists or if the discharge variation is too fast, the gate will open completely to avoid overflow.

If $Q_p < Q_d$ then the mixed gate allows the system to fulfil the demand as the discharge through the gate equals Q_d, until the upstream level reaches a minimum value. If this difference persists or if the discharge variation is too fast, the gate closes completely, therefore maintaining the level in the upstream reach but no longer fulfilling the demand.

The overall functioning of the gate can be described by the theoretical relation between the upstream level Z_u and the downstream level Z_d as depicted in Figure 1. This curve shows that the mixed gate is similar to a constant downstream level gate (AVIS) with two security modes. These modes for low and high value of downstream level allow respectively to avoid the complete emptying and the overflow of the upstream reach.

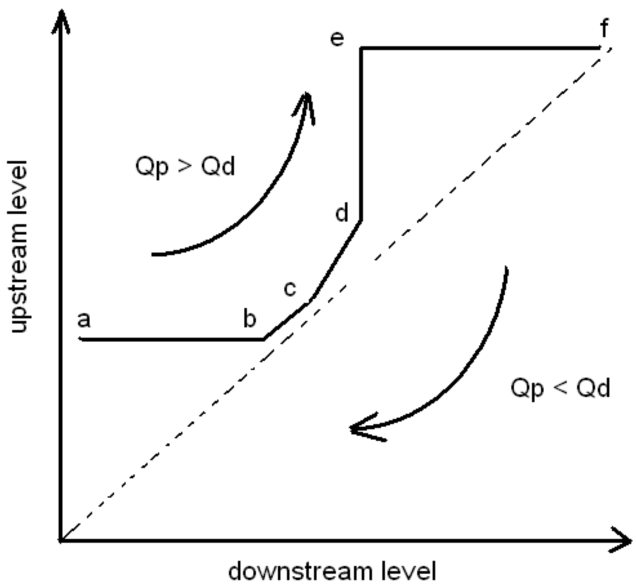

Figure 1: Theoretical curve of the upstream level as a function of the downstream level.

Physical description of the mixed gate

A mixed gate consists of three main parts: a gate leaf, a set of side tanks and floats (Fig. 2 and Fig. 3). The gate leaf has a cylindrical trapezoidal section and is placed across the channel to regulate the flow of the canal. The second part is an auxiliary circuit composed of side tanks connected by spillways and orifices. Figure 3 and 4 shows the pattern of tanks and their connections.

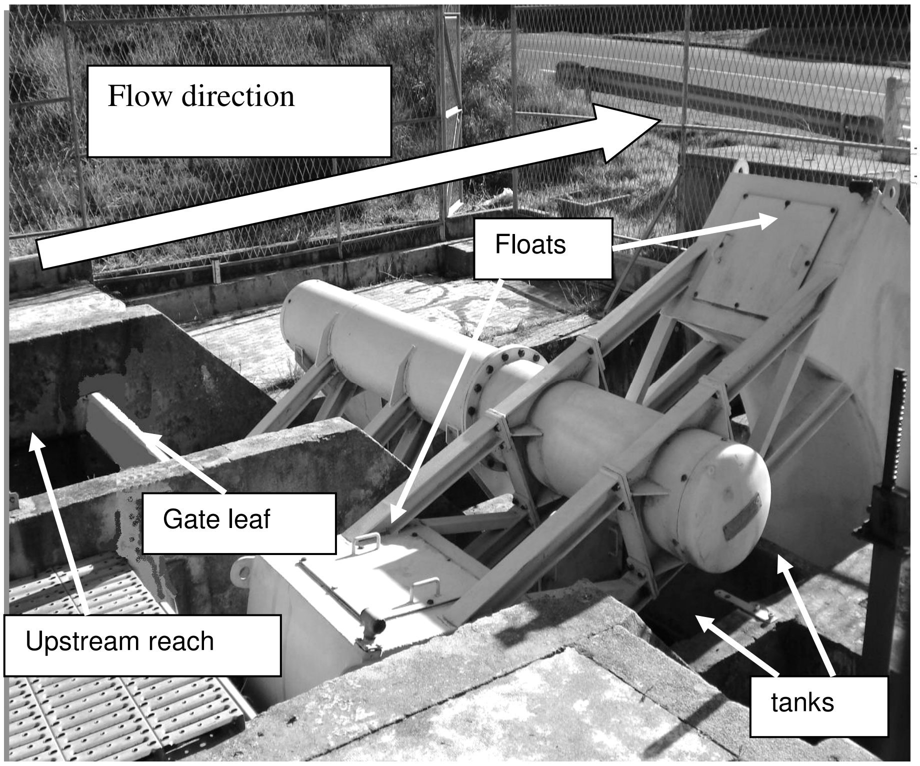

Figure 2: Photography of a mixed gate

The inlet tank is connected to the upstream reach of the channel via a circular orifice O_1. Part of the flow goes through this orifice to be diverted into the side tanks. Water can flow into the upstream regulation tank through a submerged orifice O_3, or above the spillway S_{10} if the flow depth is sufficient. Water is evacuated by three different orifices depending on the water depth:

- the orifice O_4 is always submerged, it connects the upstream tank to the downstream tank,
- the grid G_7 has a specific form, with a decreasing width as the water level rises,
- the orifice O_9 flows directly into the downstream reach.

The downstream tank has a spillway S_5 to maintain a minimum level. It is connected to the downstream reach through the orifice O_6. Similarly a mid-tank is linked through the orifice O_8 with the downstream reach.

The third part is composed of a sector float fixed to the gate leaf thanks to a metal frame. The set can revolve around a rotational axis. The floats are weighted so that the gate leaf and the floats are in indifferent equilibrium for the whole set of possible openings. This means that, without water in the tanks, the torque on the axis of rotation due to the weight of the gate leaf is exactly compensated by the torque due to the ballast (Fig. 4). Therefore, the opening or closing of the gate will be only due to the difference in water levels between the upstream and downstream tanks.

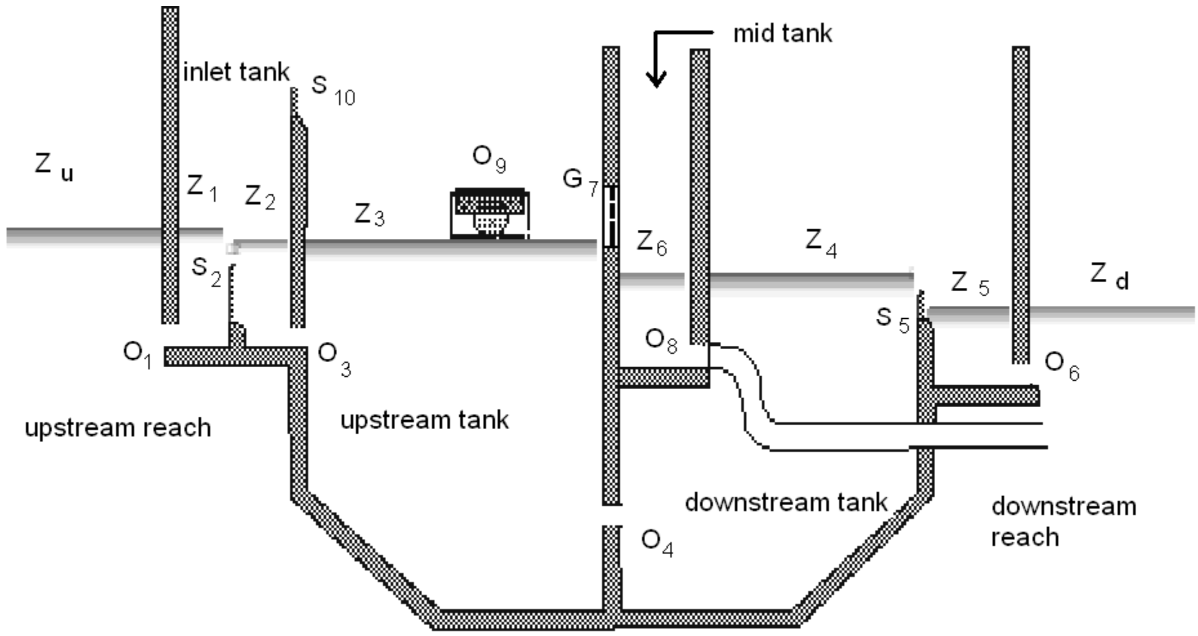

Figure 3: Hydraulic structures and position of side tanks

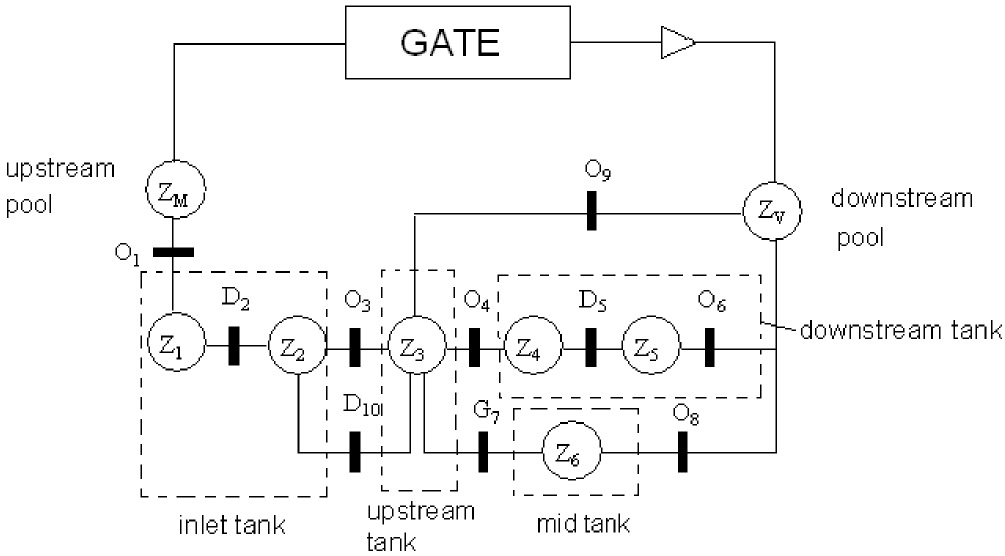

Figure 4: Flow chart of the mixed gate

Operation mode

Five different modes can be distinguished in the relationship between the upstream and the downstream levels as depicted in Fig. 1. These five modes can be linked to the flow patterns between the tanks.

Mode 1, corresponding to the line between points a and b in Figure 1, ensures a regulation of the upstream level Z_u. This mode occurs when a free flow is observed on the spillway S_5. In that case there is no influence of the downstream level Z_d on the levels in the upstream and downstream tanks.

Mode 2, corresponding to the line between points b and c in Figure 1, imposes a constant gap between the upstream and downstream tanks. In this case the gate opens or closes to maintain a constant head loss and discharge in O_4 by acting on the water depth (Z_u and Z_d) in the main channel. As the flow through O_4 is also passing through the orifices O_1, O_3, and O_6, the head losses Z_u-Z_1, Z_2-Z_3, and Z_5-Z_d are constant. As a consequence the water depth difference between the upstream and downstream levels is also constant. This mode occurs when the height Z_3 is lower than the height of the grid G_7.

Mode 3, corresponding to the line between points c and d in Figure 1, imposes a linear relationship between Z_u and Z_d because a part of the inflow does not flow through O_4. Consequently the gap between Z_u and Z_3 will be higher than the gap between Z_4 and Z_d when the discharge in the side tanks increases. The shape of G_7 ensures that the discharge through O_3 is proportional to the discharge through O_4 when Z_3 increases.

Mode 4, corresponding to the line between points d and e in Figure 1, begins when a flow occurs through the orifice O_9. It provides a constant level downstream regulation. Z_3 only depends on the downstream level since the overflow from the increase in Z_u will be dumped entirely by O_9 and G_7. Z_d will not be strictly constant since the head losses in O_9 and G_7 are not zero. We will have a functioning similar to mode 3, but for which the head loss between upstream and downstream reaches will be higher and adjustable through the shutter of O_9.

Mode 5, corresponding to the line between points e and f in Figure 1, occurs when there is flow above the spillway S_{10}. The principle is identical to mode 4 but here Z_u will be maintained almost constant thanks to the spillway S_{10}.

Gate equilibrium design

The torque due to floats on the axis of the gate is a function of the gap *D* between the upstream and downstream tanks water depths. This torque is expressed by:

$$C_0 = \frac{\rho . g . L_f . D \left(r_1^2 - r_2^2 \right)}{2g} \tag{1}$$

where L_f is the width of floats and r_1 and r_2 are the outer and inner radius of the floats, respectively. ρ is the water density and *g* is the gravitational acceleration.

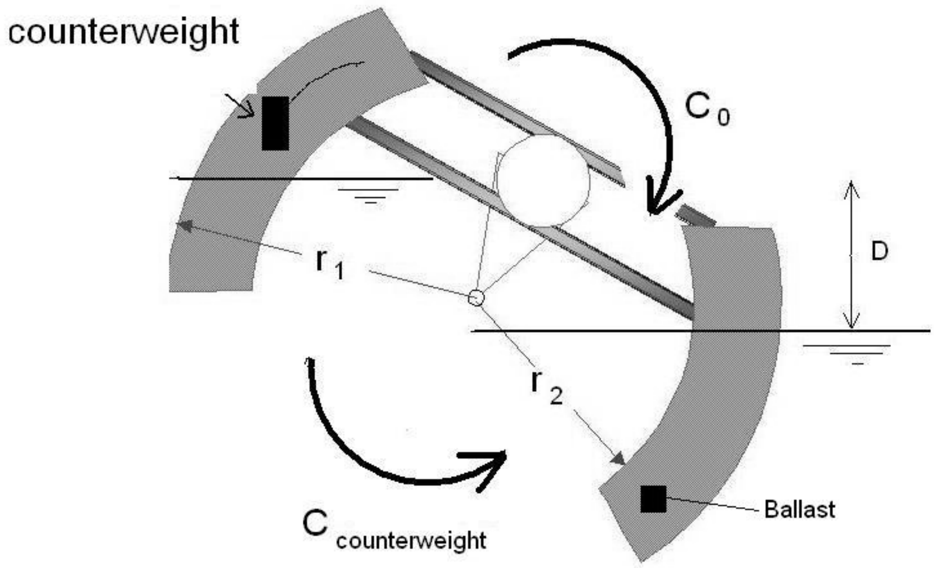

Figure 5: Description of torques acting on gate and the counterweight system

To maintain the gate at equilibrium for any opened position (with water in tanks), a counterweight is placed in the upstream float in order to produce an opposite torque, exactly compensating C_0. This ensures that, for any value of the discharge, there is a constant gap *D* between the upstream level and the downstream level. Indeed, if the difference in upstream and downstream level diminishes, the counterweight will tend to close the gate and conversely if this difference increases, the counterweight will tend to open the gate. Flows in side tanks will evolve to changing water levels in order to establish a new equilibrium state. This state only depends on the water levels in the upstream and downstream reaches, so the relationship between water levels in the upstream and downstream tanks is independent of the discharge in the main channel.

Modelling of the mixed gate

We develop in the following a mathematical model of the mixed gate, enabling its implementation into a software solving open-channel flow equations. The proposed model assumes that the gate is at the equilibrium for any given upstream Z_u and downstream Z_d water levels in adjacent reaches. Therefore transient dynamic effects of the gate are neglected which is justified by a shorter time for transfer between tanks than for the evolution of Z_u and Z_d during the storage and removal (Ramirez Luna 1997). We end up with a formal relationship between upstream and downstream levels, according to the different physical devices included in the mixed gate. Such a model could be included in a classical hydraulic simulation model solving Saint-Venant equations (*e.g.* SIC, the model developed by Cemagref (Cemagref 2004).

The hydraulic behaviour of the gate has been modelled to replicate a curve $Z_u = f\,(Z_d)$ that reflects the actual water levels in the tanks.

We recall below the discharge equations that will be used to compute the flow through the hydraulic structures present in the mixed gate. For a given hydraulic structure, we denote by h_1 the upstream head, h_2 the downstream head, w the orifice opening, L the equivalent width, C_d the discharge coefficient, D_O the orifice diameter and Q the discharge. Then, the discharge laws used are:

For a free flow spillway ($h_2 < 2/3.h_1$ and $h_1 < kD_O$):

$$Q = C_{dS} L \sqrt{2g} (h_1)^{3/2} \tag{2}$$

For a submerged spillway ($h_2 \geq 2/3.h_1$ and $h_1 < kD_O$):

$$Q = C_{dS} \frac{3\sqrt{3}}{2} L h_2 \sqrt{2g(h_1 - h_2)} \tag{3}$$

For a free flow orifice ($h_1 \geq kD_O$ and $h_2 < 2/3.h_1$):

$$Q = C_{dO} \frac{2}{3\sqrt{3}} L \sqrt{2g} \left(h_1^{3/2} - (h_1 - kD_O)^{3/2} \right) \tag{4}$$

For a partially submerged orifice ($h_1 \geq kD_O$ and $h_2 < 2/3.h_1 + kD_O/3$):

$$Q = C_{dO} L h_2 \sqrt{2g} \left(h_2 \sqrt{(h_1 - h_2)} - \frac{2}{3\sqrt{3}} (h_1 - kD_O)^{3/2} \right) \tag{5}$$

For a completely submerged circular orifice ($h_1 \geq kD_O$ and $h_2 \geq 2/3.h_1 + kD_O/3$):

$$Q = C_{dO} L k D_O \sqrt{2g(h_1 - h_2)} \tag{6}$$

$$k = \frac{w}{D_O} \tag{7}$$

where $k \in [0\ 1]$ is a coefficient giving the relative orifice opening.

In order to ensure a flow continuity across the orifice and to take into account the contraction for orifice flow ($C_{dO} = 0.6$ (Bos 1978)), a continuous evolution of C_d with the non-dimensional distance between upstream water level (h_1) and orifice opening (w) is proposed as follows:

$$C_d = \frac{(C_{dO}+C_{dS})}{2} + \frac{(C_{dO}-C_{dS})}{\pi}\arctan\left(\beta\frac{h_1-w}{w}\right) \quad (8)$$

where C_{dO} is equal to 0.6 and C_{dS} is equal to 0.4 and β a parameter. β is equal to 10 to have a monotonic evolution of Q as a function of h_1.

According to Figure 4, the flow network in a mixed gate requires to write ten hydraulic structures equations. We further assume that the difference between the water level in the upstream tank and the water level in the downstream tank is constant:

$$Z_3 - Z_4 = D \quad (9)$$

This is provided by the correct balancing of the gate as explained in the previous part (§ gate equilibrium design).
The calculation is done sequentially from the downstream condition.

- The first step is to calculate the levels Z_5, Z_4 and Z_3 from discharge conservation (Q_4) in O_4, S_5 and O_6. So we have a system of 4 nonlinear equations and 4 unknowns that is solved by dichotomy.
- The second step is the calculation of the flow through the grid G_7. The two equations of discharge in G_7 and O_6 generate Z_6 and the flow in mid-tank (Q_7).
- In the third stage, the flow Q_9 into the orifice O_9 is calculated from the level Z_3 and the downstream level.
- Finally, water depth Z_2, Z_1 and Z_u are determined from the equations of discharge through hydraulic structures (S_2, S_{10}, O_1 and O_3) and the discharge balance in the upstream tank (Eq. (10)).

$$Q_3 + Q_{10} = Q_4 + Q_9 + Q_7 \quad (10)$$

For a circular orifice, we use the following formula to determine the equivalent width of a rectangular one:

$$L = \frac{D_O^2(\theta - \sin\theta\cos\theta)}{4w} \quad (11)$$

where w is the opening of the orifice and θ is the angle defined in Figure 7.

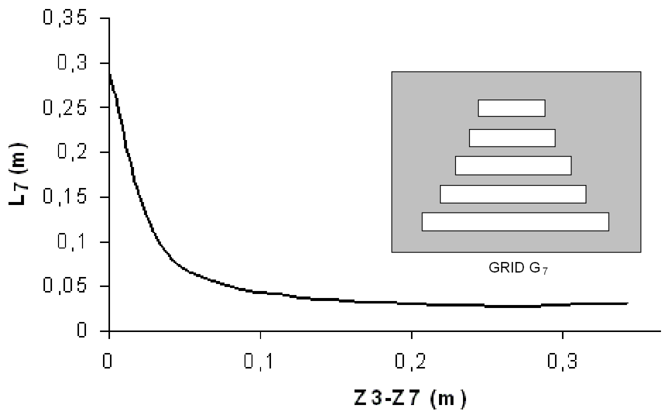

Figure 6: Equivalent width for grid G_7 with a maximal opening (0.27 m)

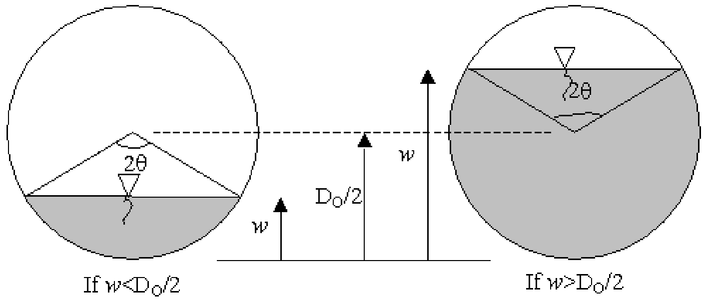

Figure 7: Definition of opening for circular orifice

The grid G_7 has a specific form that imposes a given relation between Z_3 and the discharge through the grid. This grid is made of several horizontal openings, whose widths decrease with the elevation. Therefore the discharge flowing through this grid will vary as a complex function of the hydraulic head. To simplify, we computed an equivalent width, denoted L_7. This equivalent width of the grid G_7 is calculated from the wet surface which depends on the difference between Z_3 and Z_7 (Fig. 6). Given Z_3, Z_7 and L_7, the flow through the grid is described by Eq. (2)-(6), according to the flow conditions.

Sensitivity analysis

Before testing the model on experimental data, a sensitivity analysis was performed to ensure that our model can reproduce the theoretical curve of a mixed gate.

Figure 10 shows that all modes of operation can be simulated and the transition between modes can be almost identified with the geometric characteristics of the gate. In this case it is assumed that $Z_u = Z_1$, $Z_d = Z_4$ and Z_d is constant for the mode 4. Then the change of modes occurs when flow begins through or over the associated device (see operation modes). Compared with the curve based on previous method, it is observed that the downstream level is not strictly constant in mode 4. The difference between both curves can be significant around the transition between mode 3 and 4. This shows an advantage of using a complete model, which enables us to more accurately predict the upstream level. In addition, the water level transitions do not exactly correspond to the heights of structures because they also depend on flows. Thus the upstream water level is often higher than the corresponding height of the device.

The mixed gate has orifices with adjustable openings that can modify the shape of the curve. We performed a sensitivity analysis of the theoretical curve by varying the values of the orifice opening where shutters are settled.

N°	type	height (m)	C_{dS}	C_{dO}	L or diameter (m)
1	orifice	0.7	0.4	0.6	0.2
2	spillway	1.1	0.4	/	0.8
3	orifice	0.7	0.4	0.6	0.1
4	orifice	0	0.4	0.6	0.05
5	spillway	0.9	0.4	/	1.2
6	orifice	0.5	0.4	0.6	0.1
7	orifice	1.4	0.4	0.6	computed
8	orifice	0.6	0.4	0.6	0.1
9	orifice	1.6	0.4	0.6	0.15
10	spillway	2.6	0.4	/	1.2

Table 1: Building characteristic of the modelled gate

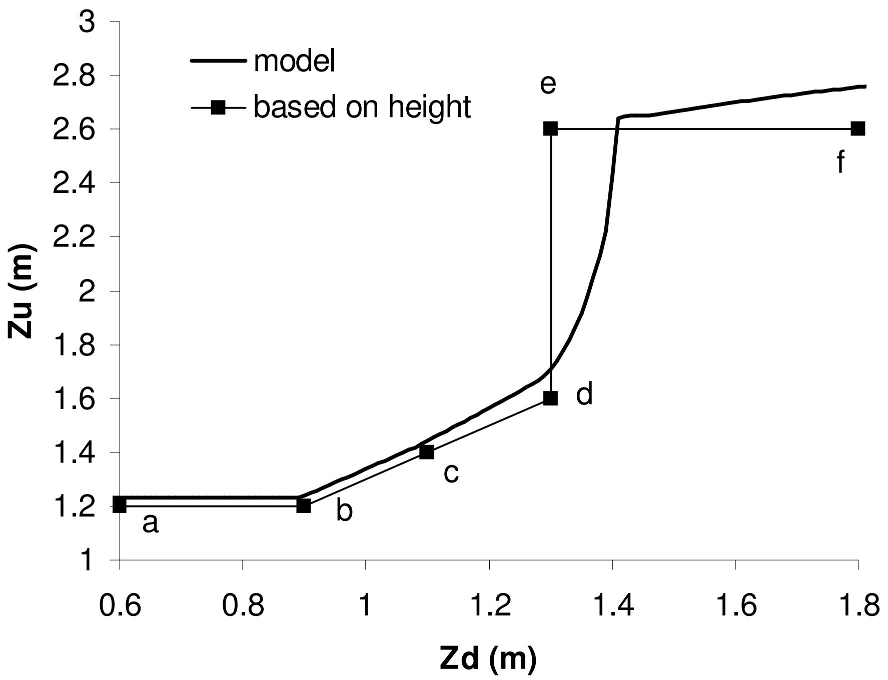

Figure 8: relationship between upstream and downstream water levels from model calculation and height of hydraulic device. Letter labels refer to figure 1 and mode analysis.

The upstream level Z_u is mostly sensitive to the drop *D* settled by the floats (Fig. 9). On figure 10, it is shown that the opening of orifices can either increase or decrease Z_u. It can be noticed that mode 4 is mainly conditioned by the opening coefficients of O_3 and O_9 while changing other openings influences all modes. Thus a desired curve may be obtained by adjusting the settings of the various orifices of the mixed gate.

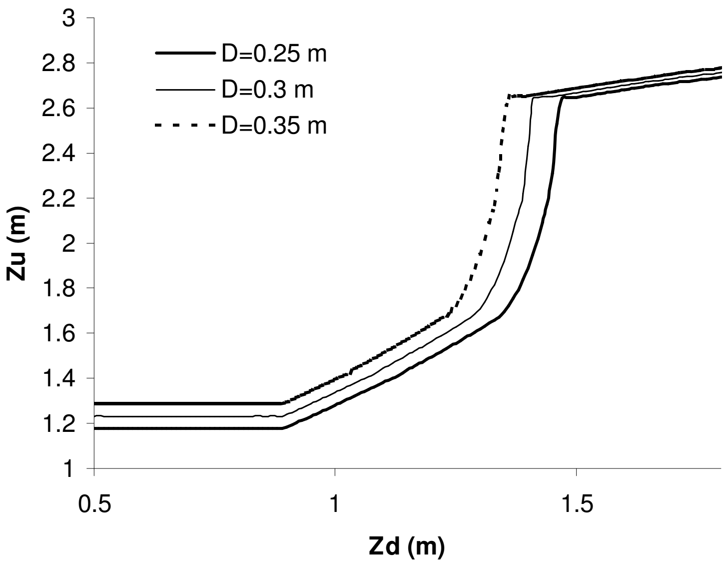

Figure 9: Relationship between upstream level Z_u and downstream level Z_d for various values of parameter *D*. Discharge coefficient of orifice are given by Eq. (8) (0.6 for orifice and 0.4 for spillway).

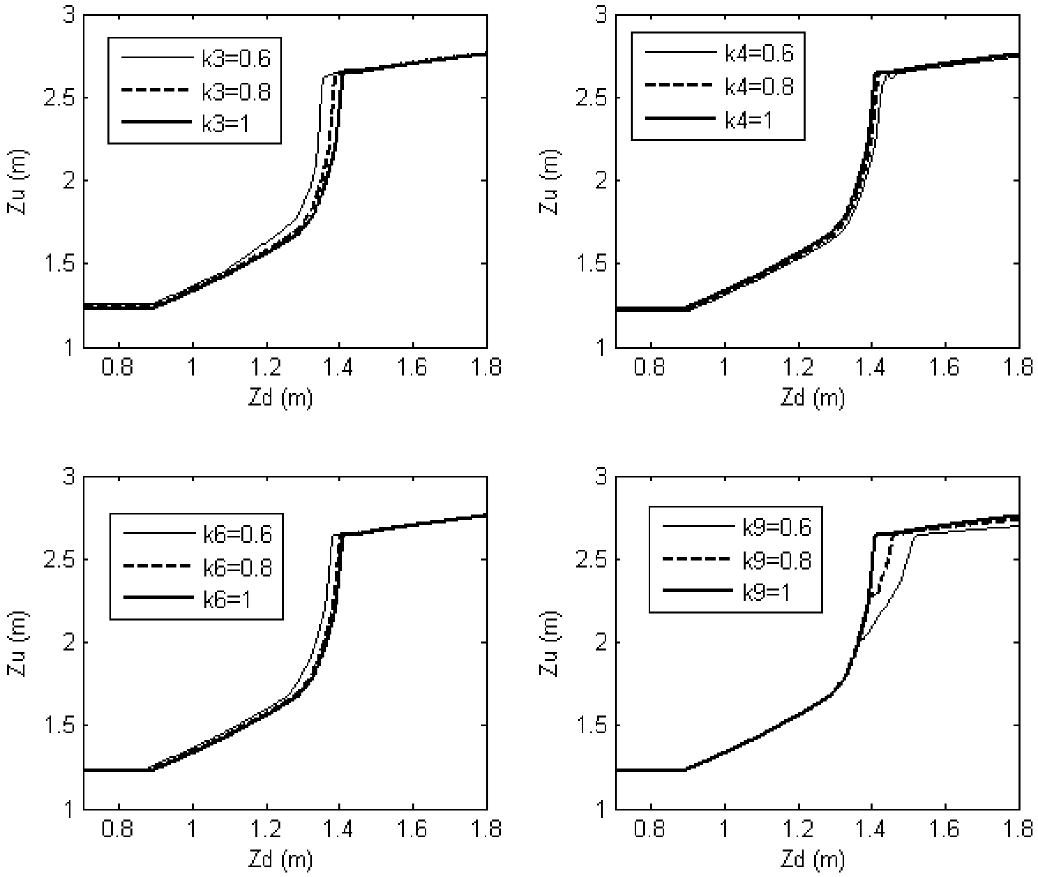

Figure 10: Curves of Z_u as a function of Z_d for various opening orifice coefficients (*D*=0.3). Discharge coefficients of orifices are given by Eq. (8) (0.6 for orifice and 0.4 for spillway).

Let us now summarize the effects of a change in the openings on the hydraulic behaviour of the gate. The modification of the orifice O_3 entails moving water levels mainly for modes 3, 4, and 5. In this case Z_4 is approximately equal to Z_d because the flow in O_4 and head losses in O_6 and S_5 are small compared to those in the upstream part. Therefore Z_3 does not vary whatever k_i is. To modify Z_u for a given Z_d, we have just to change the difference between Z_u and Z_3 which is directly dependent on the inflow across O_3 . As flow through O_4 is fixed by *D*, the inflow Q_3 can be modified by head losses through O_9 (k_9) or through O_3 (k_3) (see equation 10).

Z_u is less sensitive to k_4 and k_6 which influence the discharge in the downstream part and then imposes the difference Z_4-Z_d. The adjustment of O_4 involves the same kind of evolution as the one linked to the adjustment of *D*. Indeed, these two parameters act in the same way on controlling the flow and the head loss in O_4. The coefficient k_6 is insensitive as the head loss in O_6 is small enough to ensure that Z_d is approximately equal to Z_4.

The most useful mode for the downstream regulation is mode 4, and the curve for this mode can be easily adjusted by reducing the flow in the downstream part by acting on the openings of O_4 ,O_3 and O_9 as described before. However it must be noticed that this adjustment could increase the transitional time necessary to reach a steady state. It may therefore disturb the normal functioning of the gate. For instance if Z_4 decreases, the gate will open because the difference between Z_3 and Z_4 will be greater than *D*. If Z_3 is not rapidly adjusted by the flow through orifices (emptying of upstream tank) to get a head loss equal to *D*, the gate will deliver a larger discharge during a long time. This transitional aspect is not taken into account in our steady state model, but imposes additional conditions for the adjustment of the orifices openings.

Experimental Results and Discussions

To test our model on experimental data, we equipped a mixed gate located on the Bas-Rhône Languedoc canal in Southern France with a set of sensors automatically recording water levels and gate opening. The characteristics of this gate are provided in Table 2. Four sensors measure the water level Z_1, Z_3, Z_4 and Z_6. The sensors are settled into the side tanks in order to protect them and because it had been observed that Z_4 is equal to Z_d and Z_1 is near to Z_u. A position sensor measures the distance from a float to the ground. This measurement is then converted to get the value of the opening angle α. The sampling rate is 3 minutes and the measurements were made continuously over 2 months. During this period three significant flow changes were observed, corresponding to a decrease in the flow which caused a decrease in the upstream water level.

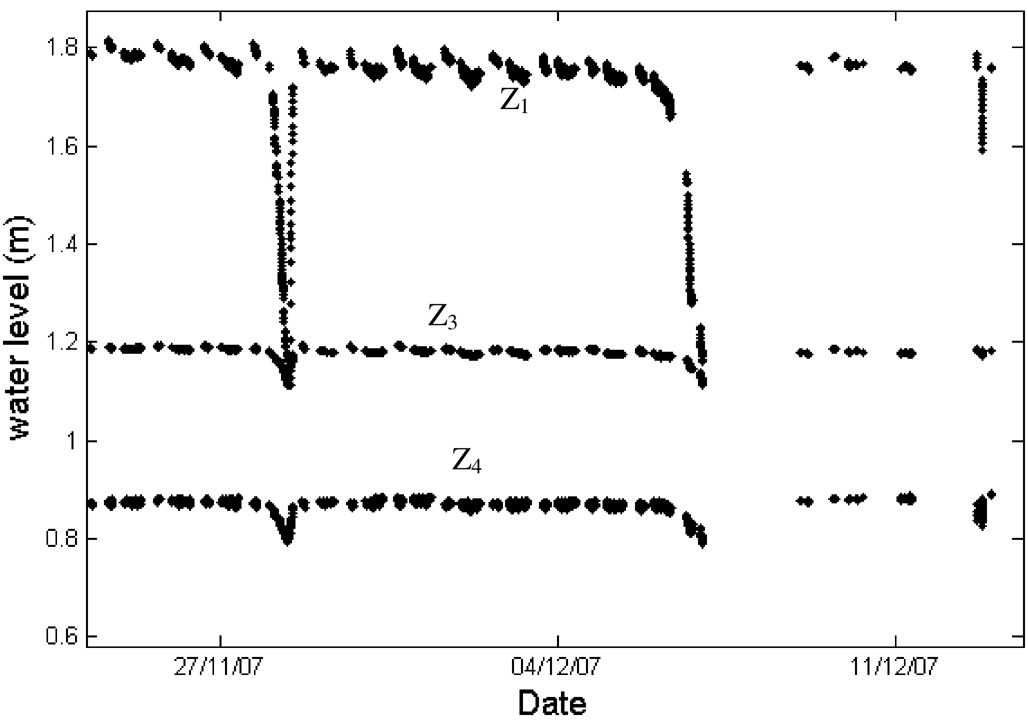

Figure 11: Recorded and selected data of the experimental gate during the 2 weeks

Figure 11 shows data recorded for a period of 2 weeks. This data are averaged by a sliding mean method with a windows of 15 min. Then the noise due to sensors or transitional flows are filtered. Most of the time the upstream and downstream water levels present the same oscillations with two periodicities. The first period is about 3 hours and could be due to waves in the channel and the second one is about 1 day corresponding to changes in water uses. When the water level decreases, the gate opens to maintain a constant discharge. The mixed gate is efficient and regulates the water depths and flow in the channel.

When the provided discharge is stopped (Q_p=0) the upstream water level decreases and the gate opens to ensure the required discharge. This situation ends after few hours because the storage in the upstream reach is not sufficient. The mode of regulation change and the downstream water level decreases too.

The data corresponding to small gate openings (α<1.5 deg) were not considered in the analysis. Indeed in this case we observed that the parameter D evolved linearly with Z_3 instead of being constant. This behaviour can not be explained by a default of the counterweight mechanism which must maintain a constant distance from the rotational axis. At small opening a torque seems to act which could come from friction against the asperities of gate bay. The model cannot accommodate this torque because the calculation of the opening angle does not affect the theoretical curve between upstream and downstream levels. So this kind of data has not been used for the analysis.

The fact that angle opening is always small even during the irrigation period, shows that the channel is clearly oversized.

Given the number of adjustable parameters, optimization of these factors would have little meaning because we can not verify and accurately measure the openings of the hydraulic structures inside the tanks. Moreover not enough data are available to get the setting of each orifice. To fit the model to experiments, the opening orifice coefficients k_3, k_9 and the discharge coefficient C_{dS7} are adjusted. Firstly D is fixed by the relationship between Z_3 and Z_4 (Fig. 13). Secondly the flow balance in the mid tank allows to fit the model to the experimental water level (Z_3, Z_4 and Z_6) by adjusting C_{dS7}, independently of other openings coefficients (Fig. 13). Thirdly the opening coefficients are adjusted to reproduce the theoretical curve (Fig. 12). As shown on figure 10, k_3, k_9 act on an opposite way on the curve and are limited to 1, then a only one solution is possible to fit curves for all modes (k_3 =0.88, k_9 =0.78).

N°	type	Height (m)	C_{dS}	C_{dO}	L or diameter (m)
1	orifice	0.588	0. 4	0.6	0.2
2	spillway	0.996	0.4	/	0.8
3	orifice	0.588	0.4	0.6	0.0875
4	orifice	0	0.4	0.6	0.04
5	spillway	0.9	0.4	/	1.2
6	orifice	0.653	0.4	0.6	0.1
7	orifice	1.055	0.2	0.6	computed
8	orifice	0.533	0.4	0.6	0.7
9	orifice	1.067	0.4	0.6	0.14
10	spillway	2.208	0.4	/	1.2

Table 2: Description of the experimental mixed gate

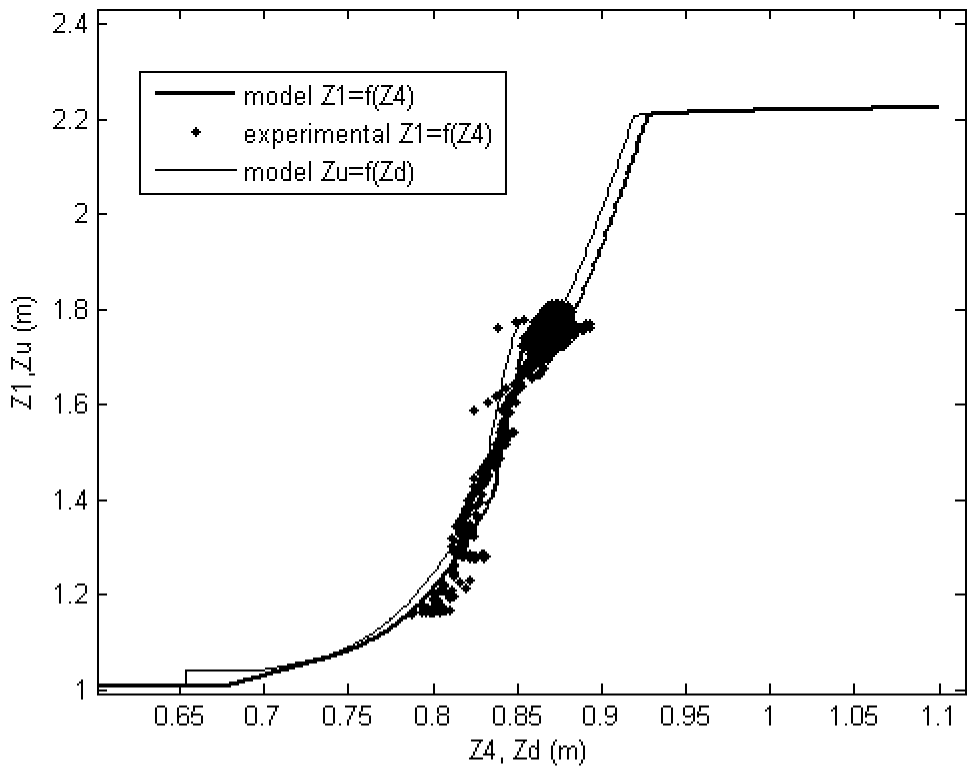

Figure 12: Comparison between modelled curve (-) and measured data (.) (D=0.31, C_{dO}=0.6 , C_{dS}=0.4, C_{dS7}=0.2, k_9=0.78, k_3=0.88). The modelled curve of Z_d as a function of Z_u is added.

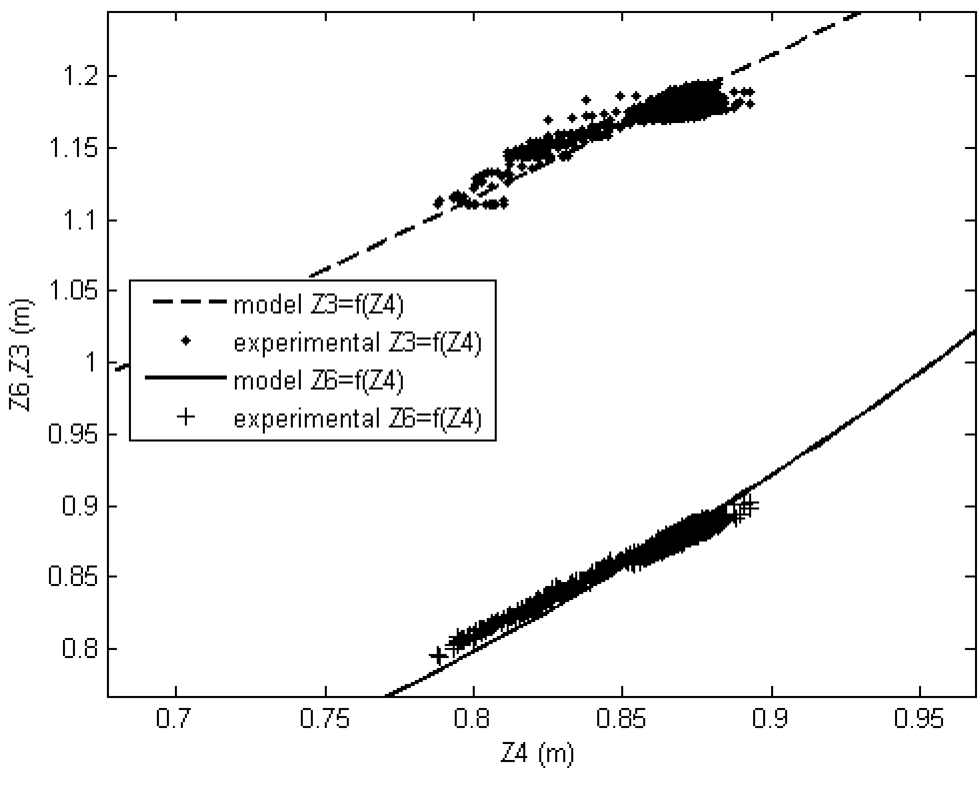

Figure 13: Comparison between modelled curve (line) and measured data (sign) (D=0.31, C_{dO}=0.6, C_{dS}=0.4, C_{dS7}=0.2, k_9=0.78, k_3=0.88).

Figure 12 shows that the model can satisfactorily reproduce the relationship between Z_1 and Z_4. On the same graph the curve giving Z_u as a function of Z_d is depicted. As expected the both curves are similar since experimental observation showed that Z_u is almost equal to Z_1 and Z_u is almost equal to Z_4.

Note that even if the experimental curve is similar to the theoretical curve (Fig. 1), only the modes 4 and 5 are possible. Indeed for modes 1, 2 and 3, the difference between the spillway height S_5 and S_2 is not sufficient to permit flow in tanks ensuring the opening of the gate. Furthermore, the difference of height between the bottom of the orifice O_9 and the spillway S_5, is lower than D. Then it can be observed a flow both through O_9 and free flow over S_5. The regulation of low-level is provided by a mixed mode between modes 1 and 4.

The model also reproduces correctly the temporal evolution of the upstream level from experimental downstream level after opening setting (Fig. 14). The steady assumption is valid even during a large change of discharge.

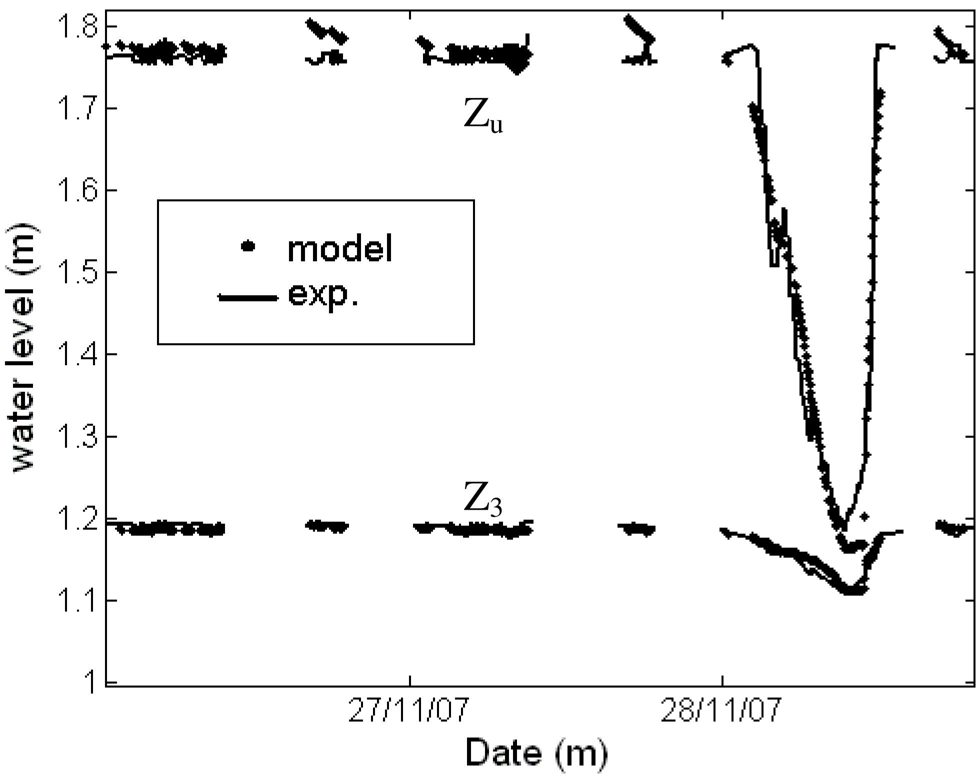

Figure 14: Comparison between modelled curve (-) and measured data (.) (D=0.31, C_{dO}=0.6, C_{dS}=0.4, $k_9=0.8$, $k_3=0.88$)

Conclusion

Although mixed gates have been built and used for several decades, their functioning has not been analyzed and modelled. This paper explains how a hydro-mechanical system can achieve the regulation role in a mixed gate. A set of side tanks can be designed so that the mixed gate can both fix a downstream level and store water in an upstream reach. The mixed gate can be used without human operator thanks to two security modes which prevent overflow and drying of reaches. Between these modes the relationship between upstream and downstream levels depends on the flow in a series of orifices and weirs in the side tanks. We have proposed a model for this complex hydro-mechanical gate, and a numerical algorithm enabling to compute the relation between the flow and the water levels in the tanks. We have obtained a univocal relation depending on flow and building characteristics. With this model, we have analyzed the influence of openings to understand the theoretical curve evolution.

Comparison between model and experiment has been done on an operating gate. Even if we could not act on the discharge, a good agreement was observed between model and data for different functioning points.

This study allows to well understand the theoretical relation between upstream and downstream level around a mixed gate and to implement it in a one-dimensional hydraulic simulation model. Then, it can demonstrate the advantage of this kind of autonomous regulation system for large channel.

Notation

C_0 = torque due to floats (N.m)
$C_{counterweight}$ = torque due to counterweight (N.m)
C_{dOi} = discharge coefficient of the orifice i
C_{dSi} = discharge coefficient of the spillway i
D = water level gap between upstream side tank and downstream side tank (m)
D_O = orifice diameter (m)
g = gravitational acceleration (m/s^2)
h_1 = upstream device water head (m)
h_2 = downstream device water head (m)
k_i = opening orifice coefficient of the orifice O_i
L = equivalent width of device (m)
L_7 = equivalent width of the grid G_7 (m)
L_f = width of float (m)
O_i = name of orifice i
Q = discharge (m^3/s)
Q_i = discharge through or over the device i (m^3/s)
Q_d = required discharge (m^3/s)
Q_p = provided discharge (m^3/s)
r_1 = outer radius of floats (m)
r_2 = inner radius of floats (m)
w = orifice opening (m)
Z_1 = water level in the inlet tank at the D_2 upstream (m)
Z_2 = water level in the inlet tank at the D_2 downstream (m)
Z_3 = water level in the upstream tank (m)
Z_4 = water level in the downstream tank (m) at the D_5 upstream (m)
Z_5 = water level in the downstream tank (m) at the D_5 downstream (m)
Z_6 = water level in the mid tank (m)
Z_7 = height of the grid bottom (m)
Z_u = water level in the upstream reach (m)
Z_d = water level in the downstream reach (m)
α = opening angle of the gate leaf (*degree*)
β = parameter of the discharge coefficient law for orifice
ρ = water density (kg/m^3)
θ = angle of the orifice water level (rad)

References

Belaud, G., Litrico, X., De Graaf, B., and Baume, J.-P. (2008). "Hydraulic modeling of an automatic upstream water-level control gate for submerged conditions." *J. of Irrigation and Drainage Engineering*, 134(3):315–326.

Bos M.G. (1978). "Discharge Measurement Structures." *International Institute for Land Reclamation and Improvement*. Wageningen, The Netherlands.

Burt, C., Angold, R., Lehmkuhl, M., and Styles, S. (2001)." Flap gate design for automatic upstream canal water level control." *J. of Irrigation and Drainage Engineering*, 127(2):84–91.

Brouwer, R. (1987). "Design and application of automatic check gate for tertiary turnouts." *In13th ICID Congress*, pages 671–683, Rabat, Morroco.

Cemagref. (2004). *Simulation of Irrigation Canals (SIC) version 4.30: User's guide and theoretical concepts*, Cemagref, France.

Litrico, X., Belaud, G., Baume, J.-P., and Ribot-Bruno, J. (2005). "Hydraulic modeling of an automatic upstream water-level control gate." J. *of Irrigation and Drainage Engineering*, 131(2):176–189.

Malaterre, P.-O., Rogers, D.C. and Schuurmans, J. (1998). "Classification of canal control algorithms." *J. of Irrigation and Drainage Engineering*, 124(1):3-10.

Ramirez Luna, J.J., (1997). "Modélisation des ouvrages frontaux et latéraux dans les canaux d'irrigation". PhD thesis, Engref, Paris, France.

Sepulveda,C., Gomez, M., Rodellar, J., (2009). "Benchmark of Discharge Calibration Methods for Submerged Sluice". *J. of Irrigation and Drainage Engineering* , 135(5):676–682.

Vlugter, H. (1940). Over zelfwerkende peilregelaars bij den waterstaat in nederlandsch-indie. De ingenieur in Nederlandsch-Indie, (6):84–93. (in Dutch).