PARALLEL JETS EMERGING FROM TWO PARALLEL GATES: DISTINGUISHING FLOW CONDITION

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Abstract: *From the practical point of view, it is usual to install two or more gates in parallel in wide channels. Although it is a very common circumstance in the irrigation networks, there are very few studies to investigate the flow through parallel gates. In this study, two gates installed in parallel were considered. Experiments were then performed to investigate the flow regimes at the downstream of the structure. It was found that for the parallel jets with different discharges as differential opening increased, the gates would be more sensitive to be submerged. This pointed out the role of the interaction between jets, involving momentum exchange and modifications of roller structure. Highly non-uniform velocity distribution was observed by the ADV measurements at the downstream of the parallel gates with a closed side. Also, it was experimentally indicated that when one of the gates was kept closed the tailwater depth value associated with the submergence threshold would depend on the tailwater measuring location from the gate significantly.*

Keywords: *parallel gates, free flow, submerged flow, distinguishing curve.*

1. INTRODUCTION

Gates are usually used in irrigation canals to adjust the upstream water level or to measure the discharge through the canal. In this regard, a suitable head discharge formula is required. Also, according to the tailwater depth value, gates may work under either free or submerged flow conditions. When possible, irrigation structures should be designed to operate in free flow in order to facilitate flow control. Consequently, the necessity of defining suitable criteria to distinguish the flow condition would be highlighted in order to estimate accurately the head discharge formula.

For the free flow case a classical hydraulic jump occurs downstream of the gate. The so called Belanger (1841)'s formula relates the conjugate depths across the jump:

$$\frac{y_2}{y_1}=\frac{1}{2}\left(\sqrt{1+8Fr_1^2}-1\right) \tag{1}$$

where y_1 and y_2 are the supercritical and subcritical conjugate depths respectively, and $Fr_1(=V_1/(gy_1)^{0.5})$, is the Froude number of the supercritical jet, V_1 is the average flow velocity of the jet, and g is the acceleration due to gravity. For a sluice gate having the same width as the channel width, which is called in this paper as single gate, any tailwater depth being greater than y_2 would result in a submerged flow condition provided that $y_1=(C_cw)$ is considered at the vena contracta (Lin *et al*. 2002). Note that C_c and w are the contraction coefficient and gate opening respectively. Consequently, Eq. (1) is usually used as distinguishing curve to determine the flow condition of a single sluice gate, using C_c equal to 0.61.

In the irrigation canals it is very common to see more than one gate installed in parallel (Figure 1). From the practical point of view for the gates installed in parallel two operation types would be feasible; 1- gates with different openings; and 2- some gates are in operation and others are closed. Also, the case for which the gate openings are the same is less practical because it is inherently very difficult to set all gates exactly at the same opening sizes (Clemmens 2004).

Clemmens et al. (2003) indicated that for the submerged flow condition the head discharge formulation associated with the gates installed in a channel expansion would be affected significantly.

In this regard, they proposed energy and momentum equations to calibrate the gates from free to submerged flow regimes continuously through the transition zone. Saudia (2014) conducted a large series of experiments considering both symmetric and asymmetric configurations to calibrate submerged parallel gates. Higher expansion ratios and asymmetric operation were found as important parameters for the gates installed in parallel. More recently, based on the momentum principles, Bijankhan and Kouchakzadeh (2015) developed a formula to predict the required tailwater depth establishing free flow condition due to two parallel gates with different openings.

Figure 1. Two parallel sluice gates (Omidieh irrigation network located at south of Iran)

Most of the current studies assume that the gate width is the same as the channel width (Belaud et al. 2009, Sepulveda et al. 2009, Castro Orgaz et al. 2010, Castro Orgaz et al. 2013). Also, for the case of two gates in parallel, the closed gate condition is not considered in the previous studies. The objective is to investigate the distinguishing curves, and to analyze what differs from the case of single gates. Experiments were done to identify the free hydraulic jump occurred downstream of two gates with different openings and also the extreme condition for which one gate would be fully closed. The result section first shows the limitations of the classical jump approach applied to each gate separately. The experimental results provided an insight on the flow structure, suggesting adaptation to classical jump approach. Then, taking account of the ratio between gate openings, a criterion was derived to distinguish the flow conditions through two parallel gates..

2. EXPERIMENTAL SETUP

The experiments were performed at the hydraulic laboratory of the University of Tehran and Montpellier Agricultural University.

A 1.179 m wide, 1 m high and 7 m long Plexiglas flume located at the hydraulic laboratory of the Irrigation and Reclamation Engineering Department, University of Tehran was used to investigate the flow through two gate installed in parallel having different gate openings. The flume was supplied by an elevated constant head tank and an electromagnetic flow-meter was installed on the feeding pipe to measure the flow rate. Point gages with the accuracy of 0.1 mm were used to measure the water depths. The tail water depth, y_2, was adjusted using a tail gate installed at the downstream end. Two sluice gates, with equal widths of 58.5 cm were installed at 2 meters downstream the inlet section. In order to accurately adjust the gates openings, prefabricated elements of a specified height were slid below the gates, and removed after the gate was positioned. This procedure was found to be accurate compared to the opening measurement of a positioned gate (Roth and Hager 1999). Three different set of gates openings, i.e. w_s=24.7, w_L=46.5, w_s=24.7, w_L=35, and w_s=20.3, w_L=68.3 mm were considered. Consequently, in all experiments the tailwater depth was increased incrementally to observe all possible flow conditions. First, for a given flow rate, by adjusting the flume tailgate, the hydraulic jump was located so that the gate of smaller opening remained at the submergence threshold condition. It has been noted that smaller gate opening approached the threshold condition prior to the other gate, in all tests. Further increasing of the tailwater depth caused one gate to be submerged but the other was free flowing. The submergence threshold of the second gate was distinguished visually for which the jump toe started touching the second gate lip. The associated tailwater and upstream depths were then recorded.

In order to investigate the distinguishing curve associated with the parallel gates having one closed gate the experiments were carried out at the hydraulic laboratory of SupAgro, Montpellier, France. The flume is 30 cm wide, 50 cm high and 8 m long, composed of glass walls and a steel bottom. Two gates with equal widths were positioned at 2 meters downstream of the flume inlet. The gates were made of metal with sharp edges of 1 mm thickness and the widths of 15 cm. One gate was fully closed and another one was 6.5 cm opened. At the upstream side of the gates a wall with the length of 56 cm separated the gates. However, no jet separating wall was considered at the downstream pool. Discharge was adjusted by a valve on the inlet pipe feeding the flume; it was measured on the inlet pipe by an ultrasonic flow-meter. The tail depth was fixed by an adjustable weir at the downstream end of the flume. For a given discharge the tailwater level was fixed by the downstream end weir. Using a 2D side looking ADV the velocity profiles were recorded in flow direction at the distances of x=126, 186, 246, and 306 cm from the downstream face of the gate. For each section, the velocity profiles were recorded at five section located at y=4.5, 9.5, 14.5, 19, and 24.5 cm from the channel wall. It should be mentioned that the ADV probe was able to record the velocities with the rate of 50Hz. Also based on the preliminary tests for each node the collecting data time of 45 seconds was considered. For a given velocity time series, It was observed that 45 seconds would be enough to obtain the average velocity accurately.

It should be mentioned that in both experimental setup the gates' lips had 2 mm thick with a 45 degree bevel on the downstream side. Consequently in both cases the emerging jet dimension was independent of the gate lip shape. However, further experimental work should be carried out to study the effect of the closed gate on the jet contraction.

3. RESULTS AND DISCUSSIONS

3.1. Classical hydraulic jump limitations

The principle of the classical hydraulic jump is usually used to distinguish the flow condition of the single gate (Lin *et al*. 2002). Consequently, for the multiple gates installation, one may question the applicability of using the classical hydraulic jump for each gate individually to distinguish the flow condition. In this regard two gates installed in parallel were considered. For a given flow depth upstream the gates, y_0, and defining the gate openings as w_L and w_s for the larger and smaller gate openings respectively, it would be possible to obtain the distinguishing condition curve of the gates using the classical hydraulic jump formula. Accordingly for each gate the tailwater depth associated with the submergence threshold, y_2, was obtained separately based on the definition of a single gate condition. Then the observed submergence threshold values of y_2 and y_0 normalized with the associated gate openings were plotted in Figure 2 along with the classical hydraulic jump definition. Figures 2a and 2b are plotted for the case with different gate openings while Figure 2c is for the case with a closed gate.

According to the figure, considering two gates with different openings, for the gate with the smaller opening (Figure 2a), the classical hydraulic jump slightly underestimates the submergence threshold while for the gate with larger opening (Figure 2b) it is overestimated especially for the higher values of w_L/w_s. Also as an extreme condition, when one gate is closed the classical hydraulic jump overestimated the submergence threshold significantly (Figure 2c). This can be attributed to the fact that when there are two jets in parallel, the momentum exchange between the jets resulting in higher friction forces cannot be neglected. As a consequence of the jet interactions, Bijankhan and Kouchakzadeh (2015) indicated that the effect of the highly non-uniform velocity distribution at the tailwater section should not be neglected. Also, further tailwater increasing made the gate with the smaller opening to be completely submerged but the gate with the larger opening was free flowing. Then, the lateral flow due to the first gate submergence made the second gate to be drowned. This is clearly visible in Figure 2b, where the observed submergence threshold of the gate with larger opening is significantly underestimated compared to the single gate condition. Consequently the classical hydraulic jump concept which considers each gate individually and neglects the interaction between the jets is useless to distinguish the flow condition through multiple gates.

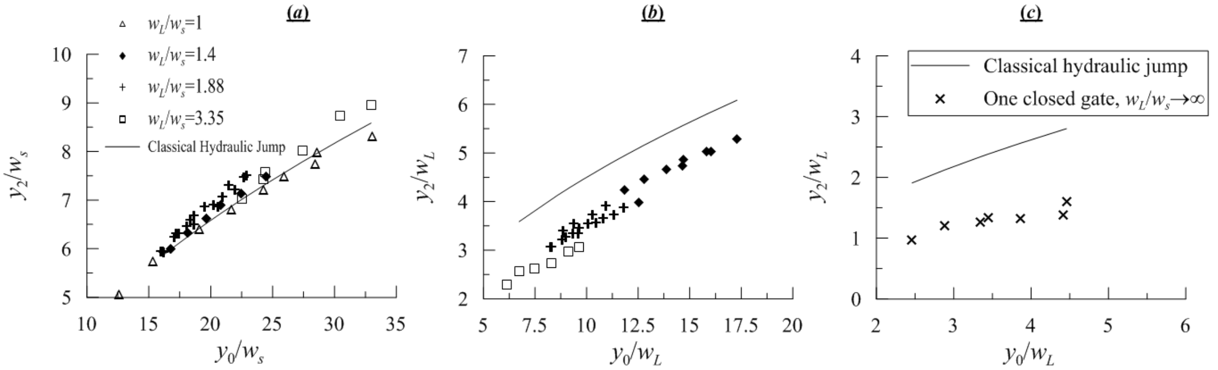

Figure 2. Submergence threshold conditions (*a*) Two gates in parallel with different openings; the gate with the smaller opening (b) Two gates in parallel with different openings; the gate with larger opening (c) Two gates in parallel for which the one gate is closed

3.2. Hydraulic jump features due to multiple gates

In order to distinguish the flow condition of the multiple gates installed in parallel, the free hydraulic jump must be characterized. As indicated in Figure 3, the free hydraulic jump downstream multiple gates is significantly affected by the gate configurations. Figure 3a shows the free hydraulic jump downstream multiple gates with different gate openings. For such a condition two different roller zones were observed for which the gate with the smaller opening tends to be submerged prior to that with larger opening. However, the free hydraulic jump, associated with the parallel gates with one closed gate, consists of an oblique shaped jump with a strong reverse flow toward the closed gate (Figure 3b). Due to the significant discrepancy between the free hydraulic jumps associated with these two practical conditions, the associated distinguishing condition curves should be investigated to explore the differences.

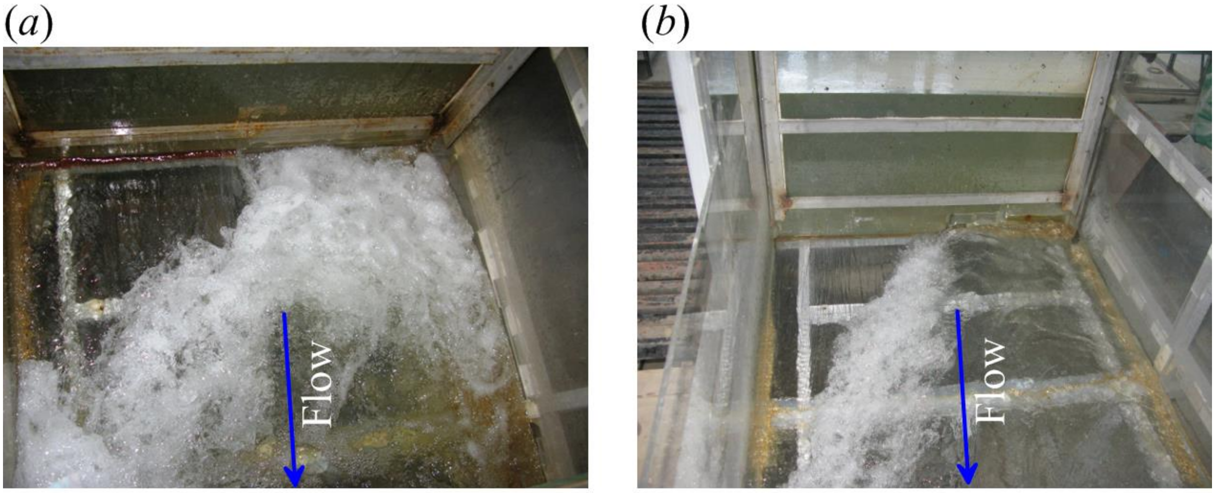

Figure 3. (*a*) Free hydraulic jump downstream multiple gates with different gate openings (*b*) Free hydraulic jump downstream parallel gates with one closed gate (Experimental flume located at the University of Tehran)

In the drought seasons, in order to manage the water level upstream of the multiple gates, it is probable to see one gate closed. In such a case the flow characteristics is completely different from the configurations where both gates are under operation. According to the experimental observations, two kinds of free hydraulic jumps were identified in the downstream pool: semi classical hydraulic jump and oblique hydraulic jump.

Since the supercritical jet width was smaller than the channel width it would tend to expand across the channel width (Figure 4*a*). Consequently, if the tailgate was lowered enough and the supercritical jet could be completely expanded across the channel width, then the semi classical hydraulic jump was formed. It was observed that a distance of about x/w_L=7.7 would be required for the jet to be completely expanded. Consequently, the jump was formed far downstream the gate and the tailwater depth value associated with this kind of jump cannot be considered as a benchmark to properly distinguish the flow conditions.

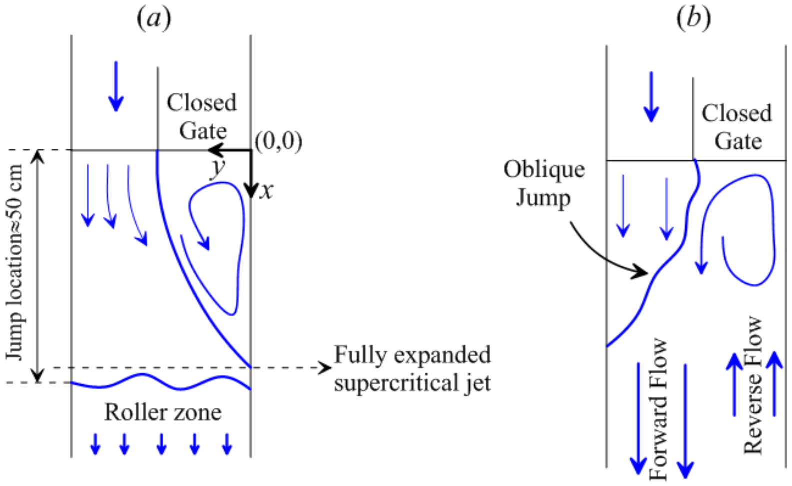

Figure 4. Schematic plan view of (*a*) semi classical and (*b*) oblique hydraulic jumps through the multiple gates with a closed side

Increasing the tailwater depth makes the jump to be oblique and start touching the emerging jet (Figure 4*b*). Consequently, the properties of this kind of jump can be considered as the submergence threshold. The condition for which this situation appears therefore needs to be characterized. It also suggests that a one-dimensional approach, as used in the Belanger's formula, should be modified in order to take account of non-uniform velocity and non-horizontal water levels at the cross sections upstream and upstream of the jump.

In order to quantify the momentum corrections when a gate is closed, the velocity profiles through *x* and *y* directions were measured using 2D-ADV (*x* and *y* axes are shown in Figure 5).

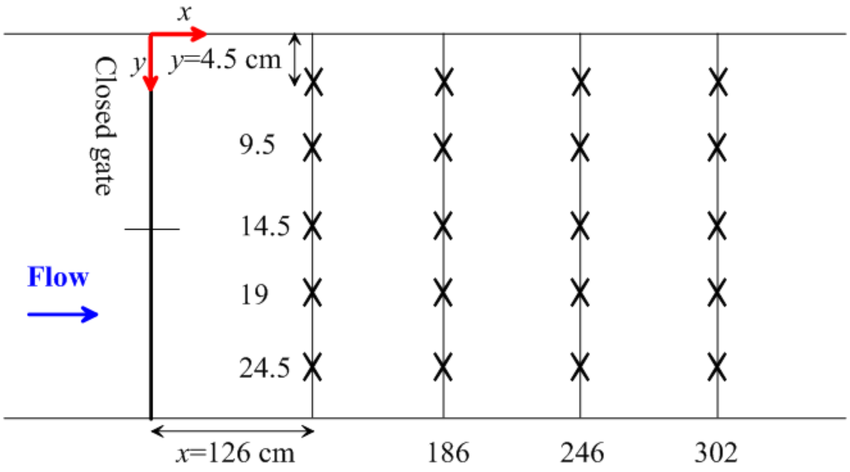

Figure 5. Schematic plan view of the velocity measuring locations

For Q= 12.8 l/s and y_0=289.7 mm the velocity profiles were plotted in Figure 6. As indicated, for x=126 and 186 cm, reverse flow was formed at the left side of the channel, i.e. y=4.5 cm, and a zone of high forward velocity was observed at the right side of the channel, i.e. y=24.5 cm. Also as x increases the flow tends to be more uniform across the channel width. The momentum correction factors associated with the velocity fields were then calculated numerically. It was revealed that the Boussinesq coefficients were decreased from about 2.4 for x=126 cm to 1 for x=302 cm. This would highlight the effect of non-uniform velocity distribution at the tailwater section.

The flow depths values, y, related to the submergence threshold condition were then plotted versus x/w_L in Figure 7. As it is shown, the water level increases through the flow direction and consequently, specifying a downstream section associated with the submergence threshold condition would be a challenging task as it is also a function of x/w. Moreover, water level fluctuations due to the presence of some standing waves would make it very difficult to measure the flow depth accurately very close to the gates. For a specific discharge value and a given distance from the gate, the tailwater depth being greater than that of plotted in Figure 7, would make the gate to be submerged. However, in order to present a general distinguishing condition curve formula more configurations should be explored.

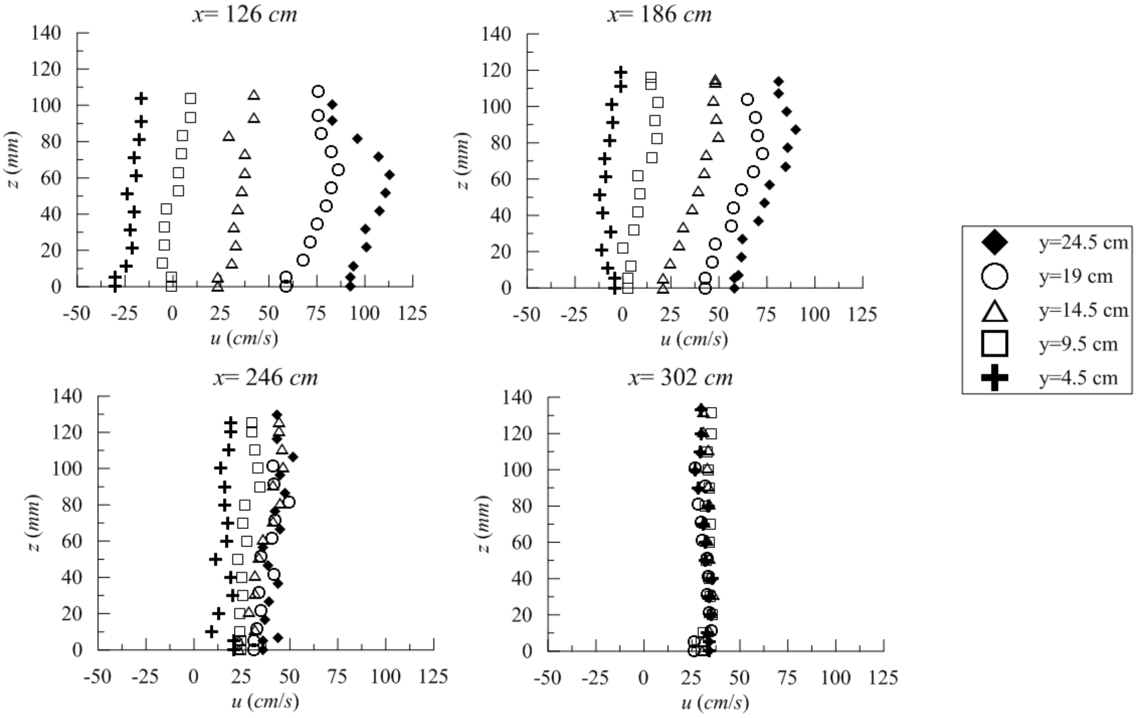

Figure 6. Velocity profiles across the channel width for Q= 12.8 l/s and y_0=289.7 mm

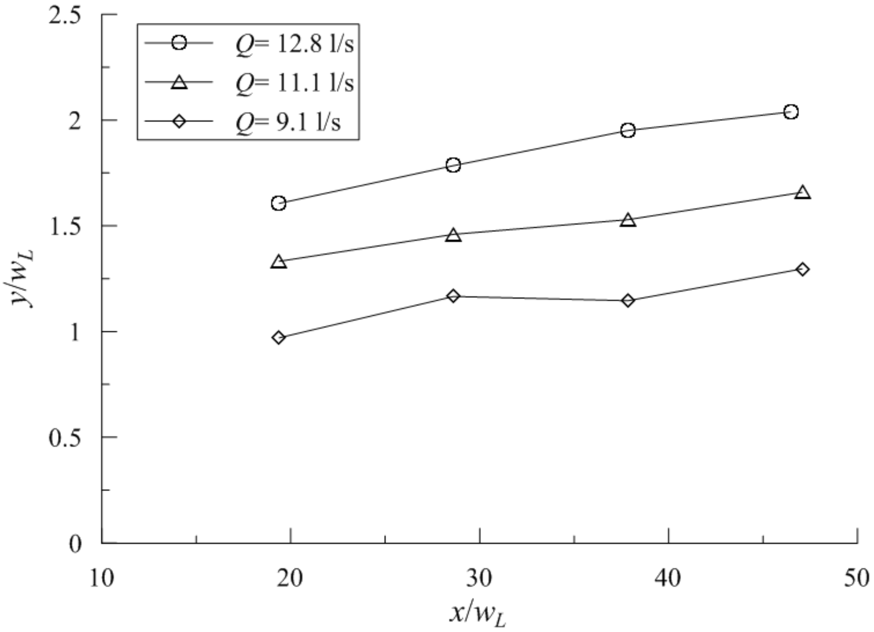

Figure 7. y/w_L versus x/w_L for w_L=6.5 cm and different flow rates

3.3. Deriving the distinguishing condition curve

Due to the interaction between the jets, it might be preferable, for a two-gate configuration, not to consider the momentum balance for each gate individually, but the total momentum balance instead. To do so, it requires taking account of non-uniform velocity at the tail section (see 3.2). The momentum balance between the supercritical jet and tailwater sections yields:

$$\frac{Q_s^{\ 2}}{gA_{1,s}}+\frac{Q_L^{\ 2}}{gA_{1,L}}+\frac{b_s y_{1,s}^2}{2}+\frac{b_L y_{1,L}^2}{2}=\beta_2\frac{Q^{\ 2}}{gA_2}+\frac{By_2^2}{2} \tag{2}$$

Where the subscribes *s* and *L* indicates the smaller and larger gate openings, $y_{1,s}=C_c w_s$, and $y_{1,L}=C_c w_L$, C_c(=0.616) is the contraction coefficient, $A_{1,s}=b_L y_{1,s}$, $A_{1,L}=b_R y_{1,L}$, *B* is the channel width, *b*(=*B*/2) is the gate width, β_2 is the velocity correction factor, Q_s *and* Q_L are the discharges through the gates with smaller and larger openings under free flow condition respectively, and $Q(=Q_L+Q_s)$ is the total discharge.

Based on extensive experimental observations Bijankhan and Kouchakzadeh (2015) indicated that the discharge through the gates installed in parallel can be described by a unique formula. Applying the energy formula between the upstream and vena contracta sections and considering the approaching velocity and head-loss to be negligible Eq. (3) can be used to determine the discharge through each gate:

$$Q_{s(L)}=by_{1,s(L)}\sqrt{2g\,(y_0-y_{1,s(L)})} \tag{3}$$

For which, y_0 is the upstream water depth, and y_1 is the flow depth at the vena contracta ($=C_c w_{s \text{ or } L}$). Considering $w_L=w(1+\xi)$ and $w_s=w(1-\xi)$ the ratio Q_L/Q_s takes the following form:

$$\frac{Q_L}{Q_s}=\frac{1+\xi}{1-\xi}\sqrt{\frac{y_0/(\mathrm{C_c W})-(1+\xi)}{y_0/(\mathrm{C_c W})-(1-\xi)}} \tag{4}$$

Note that *w* is $(w_L+w_s)/2$ and ξ-values $(=[w_L-w_s]/[w_L+w_s])$ are always between 0 (for single gate installation) and 1 (One gate closed). According to the experimental data it was found that the ratio $\sqrt{[y_0/(\mathrm{C_c W})-(1+\xi)]/[y_0/(\mathrm{C_c W})-(1-\xi)]}$ is very close to unity and therefore can be neglected. Considering the second order values of ξ to be negligible, i.e. $\xi^2=0$, and $\beta_2=1$, and $Q=Q_s+Q_L$, combining Eqs. (4) and (2), the distinguishing condition curve takes the following form:

$$\frac{y_2}{y_1'}=\frac{1}{2}\left(\sqrt{1+8Fr_1^{\ 2}}-1\right) \tag{5}$$

Where, y_1' is $C_c w$, and *J* is a calibration coefficient to compensate the effect of neglected values of ξ^2 and β_2. This coefficient is expected to be unity for the gates equally opened ($\xi=0$). Eq. (5) is therefore similar to the Belanger's jump equation, with $Fr_1^{\ 2}=2(\frac{y_0}{y_1'}-1)$, but modified due to the effect of the different gate openings thanks to the ratio ξ. Note that the first-order approximation also gives the total discharge, i.e. Q_s+Q_L, for free flow,

$$Q\approx 2bC_cW\sqrt{2g\left(y_0-C_cW\right)} \tag{6}$$

Indicating that the first order approximation of the discharge of two gates is similar to a single gate of opening *w*.

In order to consider the effect of the second order values of ξ and non-uniform velocity distribution at the tailwater section a calibration coefficient, J, was considered in Eq. (4) as follows:

$$\frac{y_2}{y_1'}=\frac{J}{2}\left(\sqrt{1+8Fr_1^{\ 2}}-1\right) \tag{7}$$

Employing the experimental data, for a given value of ξ, y_2/y_1' was plotted versus y_0/y_1' (Figure 8) and Eq. (7) was then calibrated. The calculated *J*-values were depicted versus ξ in Figure 9 for which the following formula can be used for $0\le\xi\le0.54$:

$$J=1-0.29\xi-0.42\xi^2 \tag{8}$$

The tailwater depth values being less than that of obtained by Eq. (7) result in a flow condition for which both gates are free flowing (Figure 8). Note that, Eq. (8) is only valid for $0\le\xi\le0.54$ associated with two parallel gate having equal widths. For $\xi=1$, i.e. considering one gate closed, *J* equates 0.7. No significant difference was observed between $\xi=0.54$ and $\xi=1$. However, more experimental investigation should be carried out for $0.54<\xi<1$. It should also be mentioned that the tailwater depth, y_2, should be measured just after the jump where there is no release of bubbles. Also, for a single gate, i.e. $\xi=0$, we verify that *J* equates to unity and Eq. (7) reduces to the well-known classical jump equation.

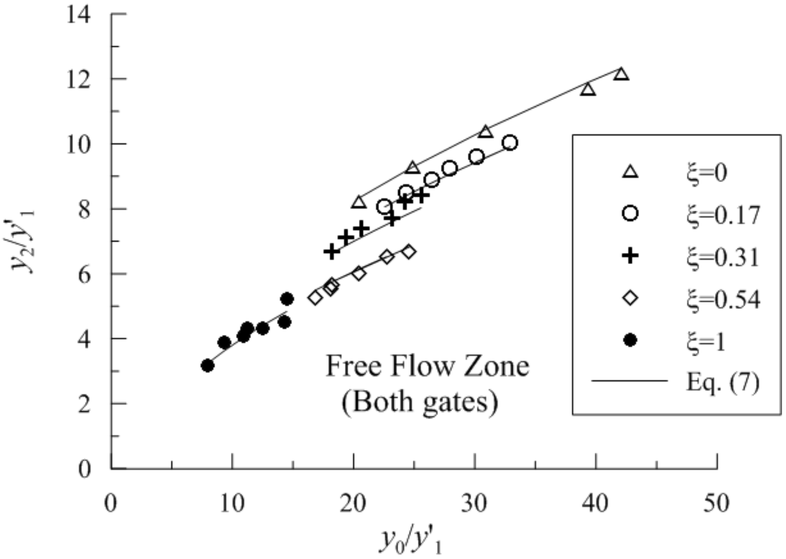

Figure 8. y_2/y'_1 versus y_0/y'_1

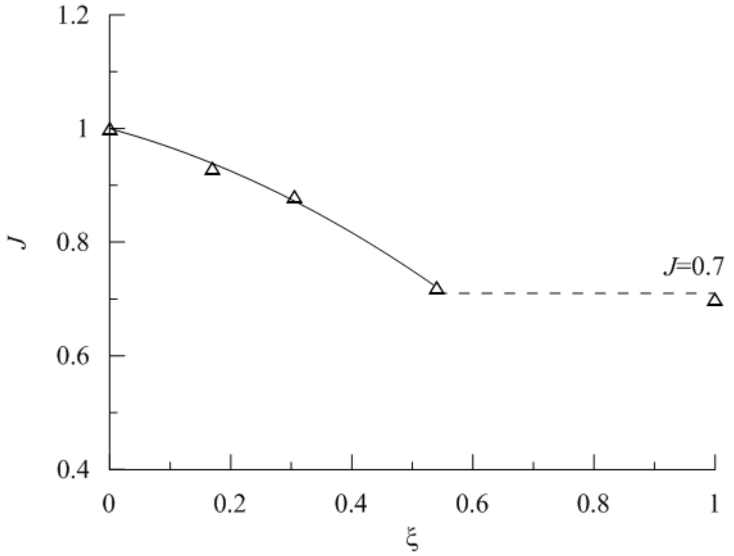

Figure 9. calibrated *J*-values in terms of ξ

For a given upstream flow depth and considering two gates with different openings, increasing the tailwater depth beyond the value obtained by Eq. (7) would make the gate with the smaller opening submerged and another free flowing. It was experimentally observed that the gate with the larger opening would tend to be submerged with higher tailwater depths values. The associated downstream water depths for which the second gate became submerged, i.e. y_{2t}, were observed experimentally. Then for a given gates' configuration the average values of y_{2t}/y_2 were plotted against ξ in Figure 10. As indicated in the Figure, for the higher ξ-values, higher values of y_{2t}/y_2 should be provided to make the second gate submerged. In other words, the gate with larger opening is less susceptible to be submerged. Also as ξ tends to zero, i.e. single gate condition, y_{2t}/y_2 tends to unity and consequently the gates would be submerged simultaneously for smaller ξ-values. In order to distinguish the submergence threshold associated with the gate having the larger opening Eq. (9) was then proposed empirically for $0 \le \xi \le 0.54$ based on the observed experimental data:

$$\frac{y_{2t}}{y_2} = 0.341\xi^2 - 0.0447\xi + 1 \qquad (9)$$

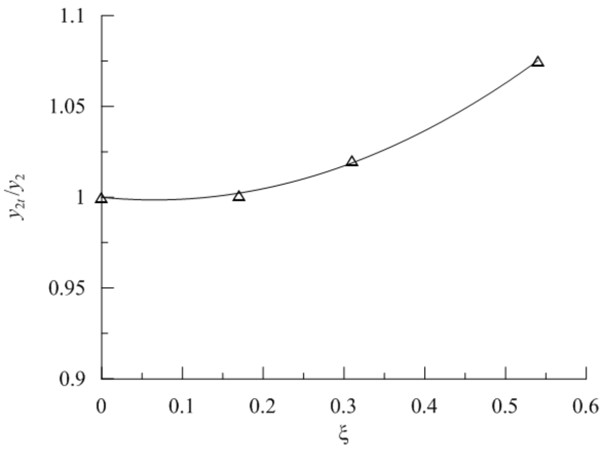

Figure 10. Average values of y_{2t}/y_2 in terms of ξ

4. CONCLUSIONS

In this study two parallel gates were considered. Experiments were then performed to investigate the distinguishing condition curves, i.e. the threshold between free and submerged flow conditions. We showed basically that the conditions for free flowing are affected by the interaction between the jets. According to the gates' configurations different kinds of hydraulic jumps were observed. For the case of two parallel gates with different gate openings, a roller zone was observed downstream of each gate. The gate with the smaller opening tended to be submerged prior to that of with larger opening. A highly non-uniform flow condition was observed when one of the gates was kept closed. Also it was indicated experimentally that the submergence threshold would depend significantly on the tailwater measuring location when one of the gates is closed.

However, the momentum formula could adapted in order to develop a suitable definition of the conjugated depths values, giving the distinguishing curve between free and partially submerged flow conditions for two gates in parallel, as a function of opening ratio. Large differences in openings produce strongly 2D-horizontal flow structures, as well as non-horizontal water profiles at the sections we usually consider for discharge measurement. This issue is the subject of ongoing research.

5. ACKNOWLEDGMENTS

The first and second authors gratefully acknowledge the research facility provided by the Center of Excellence for Evaluation and Rehabilitation of Irrigation and Drainage networks, University of Tehran. Also the first author gratefully acknowledges the experimental facilities provided by the Center for Higher Education in Agricultural Sciences, SupAgro, Montpellier, France.

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