AQUA

Water Infrastructure, Ecosystems and Society

 AQUA — Water Infrastructure, Ecosystems and Society Vol 72 No 10, 1906 doi: 10.2166/aqua.2023.269

Upstream vortices of a sluice gate: An experimental and numerical study

Reza Norouzi [a], Parisa Ebadzadeh [a], Veli Sume [b] and Rasoul Daneshfaraz [a,*]

[a] Department of Civil Engineering, Faculty of Engineering, University of Maragheh, Maragheh, Iran
[b] Department of Hydraulics, Civil Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdoğan University, Rize, Türkiye
*Corresponding author. E-mail: daneshfaraz@maragheh.ac.ir

RN, 0000-0002-3756-8746; PE, 0000-0002-9836-8406; VS, 0000-0001-8251-2461; RD, 0000-0003-1012-8342

ABSTRACT

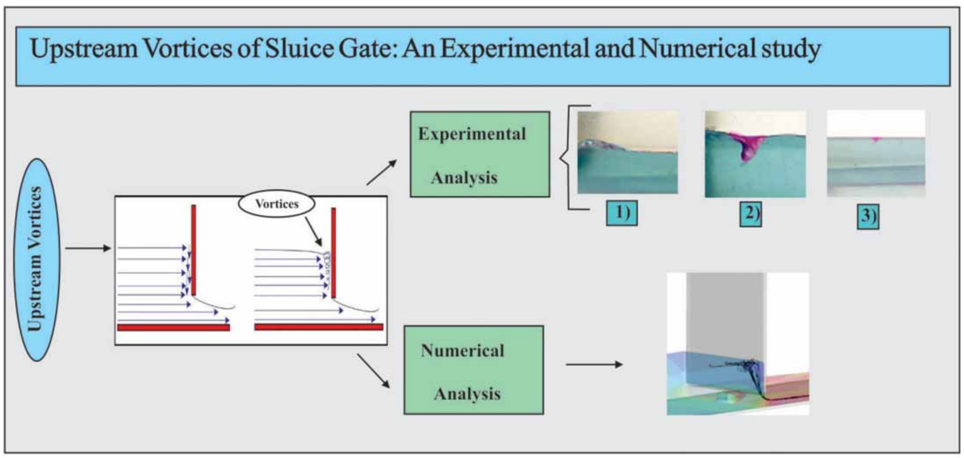
This paper aims to explore the effects of a sill under a standard sluice gate on the development of the intake vortices. In total, 200 experiments were carried out. Sills with different shapes and widths were considered both numerically and experimentally. Results indicated that using a sill changes the flow depth and upstream pressure. Using a silled gate causes a decrease in the amount of air entering the fluid. By increasing the sill width, the vortex intensity reduces and this reduction is further amplified by increasing the approach discharge. The experimental findings are also compared to the results from the numerical model Flow-3D with interesting agreements.

Key words: Flow-3D, free gate flows, intake vortices, pressure, sluice gates, under gate sill

HIGHLIGHTS

- The negative phenomenon of vortices on the flow pattern was investigated experimentally and numerically.
- The sill's width effect on the upstream pressure was investigated numerically.
- The effect of various sill's shapes on vortices was investigated, including semi-cylindrical, cylindrical, pyramidal, and rectangular cube obstructions under the sluice gate.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Examination of the streamline behind the sluice gate indicates that the angular momentum which develops in the vicinity of the gate opening determines the formation of large-diameter vortices. Vortices as a negative factor cause air to enter the flow, which results in vibration of the structure, flow non-uniformity, and asymmetrical patterns upstream of the gate.

The increasing need for water resources control has led designers to adopt new solutions to improve the performance of key hydraulic structures. In controlling water resources, sluice gates have received attention from researchers for ages because of their ease of installation, simplicity of the operation, and the accuracy of the equations controlling their hydraulic performance. When studying the water profiles and flow patterns upstream and downstream of a sluice gate, the coefficient of discharge (C_d) and the energy dissipation downstream of the structure are important aspects to be taken into consideration. Vortices appear as a negative factor upstream of the sluice gate. There have been extensive studies on the hydraulics of this structure. However, the vortices that cause the failure of the structure after the passage of time have been less studied.

An interesting solution to reduce the formation of vortices was proposed by Roth & Hager (1999). In this study, the shock wave height was reduced with a typical reduction of 50% by using elements in upstream. Experimental tests revealed that the change in the cross-sectional geometry (including rectangular, slice-shape, and triangular bottom shapes) did not affect the results. Yousefian (2007) conducted several experiments with sluice gates in a convergent rectangular channel. The sluice gate opening was found as the most important factor affecting the appearance of vortices.

Rajaratnam (1977) carried out further experimental research on sluice gates hydraulic. Based on the results, it was found that the water surface profiles immediately below sluice gates are similar. Moreover, the coefficient of contraction was found larger than the theoretically predicted value and this discrepancy could not be attributed to boundary layer effects alone. Yen *et al.* (2001) investigated various characteristics of a vertical sluice gate in a rectangular flatbed channel. The distinguishing condition was found to be a function of the contraction coefficient, upstream water depth and tailwater depth, and was verified through laboratory experiments. Shammaa *et al.* (2005) analyzed the performance of the different calibration methods. The test program shows that the evaluation of the discharge under sluice gates for free and submerged flows and for the transition between both flows through the methods based on the EM were those that had better results. Belaud *et al.* (2009) studied the contraction coefficient under sluice gates on flatbeds for both free flow and submerged conditions. Results showed that the contraction coefficient may be similar in submerged flow and free flow at small openings but not at large openings. Cassan & Belaud (2012) studied the flow characteristics upstream and downstream of sluice gates with a volume of fluid method. Results showed that the contraction coefficient increases with gate opening at large submergence, which is consistent with the energy-momentum balance. Mohammed & Khaleel (2013) studied the effect of the lower gate lip and gate inclination on the discharge coefficient. The results showed that the discharge coefficient increases when the gate slope increases with flow direction and the lower lip is horizontal. The discharge coefficient decreases when the gate slope increases opposite flow direction and the lower lip is still horizontal.

Karami *et al.* (2020) numerically investigated the effect of rectangular and semicircular sills on the sluice gate discharge coefficient. The authors used Flow-3D software to study the changes in sill height on the discharge coefficient. The results showed that the placement of the sill under the sluice gate always increases the discharge coefficient.

Mohammed (2022) studied the sensitivity of driftwood blocking flow under a sluice gate. It found that a large gate opening and 50% of the maximum upstream head lead to a decreased probability of trapped index and an increasing likelihood of driftwood passage beneath the sluice gate, which causes scour if driftwood is blocked under a sluice gate, so this case must be avoided. Daneshfaraz *et al.* (2022a) investigated the flow pattern and discharge coefficient of a sluice gate with a non-suppressed sill in experimental and numerical conditions. Results showed that the silled gate with a width of 7.5 and 20 cm increased the discharge coefficient by an average of 5.3 and 15.5% in the experimental model and 4.7 and 16% in the numerical simulation. Daneshfaraz *et al.* 2023a numerically studied the labyrinth vertical valve effect on hydraulic parameters. Results indicated that the labyrinth sluice gate increased the discharge coefficient compared to standard gates. Abbaszadeh *et al.* (2023) investigated the effects of gate openings on the sluice gate's energy dissipation and discharge coefficient. Results showed that the relative energy dissipation and the C_d of the sluice gate are larger for all sill widths than without the sill.

Studies on the hydraulics of sluice gates include also the estimation of the shrinkage coefficient. Among these is the study by Lin *et al.* (2002). The shrinkage coefficient of the sluice gate was investigated. They consider different shapes for the gate edge including sharp and circular crests. The shrinkage coefficient was estimated to be 0.59–0.61 for the sharp crest and 0.65–0.75 for the circular one. The kinematic flow field upstream of a sluice gate was investigated experimentally and numerically by Akoz *et al.* (2009). The results showed that the k–ε turbulence model was able to simulate the water–air free surface satisfactorily. Results were also compared with those resulting from the use of the k–ω turbulence model.

One of the topics that has attracted the attention of researchers is the application of machine learning methods in sluice gate hydraulics. Rady (2016) investigated the flow characteristics below vertical and inclined sluice gates for both free and submerged flow conditions, using the artificial neural networks (ANNs) modeling method with backpropagation algorithm. The results indicated that ANNs are powerful tools for modeling flow rates below both types of sluice gates within an accuracy of $\pm 5\%$. Ghorbani *et al.* (2020) used the H_2O machine learning package written in Java to explore the discharge coefficient. The sill geometric sections were selected as being: circular, semicircular, triangular, trapezoidal, and rounded upstream face with a triangular shape in the downstream face. The high performance of the four artificial intelligence methods revealed that the presence of the sill under the vertical gate has a positive effect on the flow characteristics with a significant increase in the discharge coefficient.

Hassanzadeh & Abbaszadeh (2023) investigated the discharge coefficient of a sluice gate with a sill in various positions relative to the gate using support vector machine (SVM) models, the K nearest neighbor (KNN) algorithm, and the ANN method using statistical software.

The above review equally helps to understand the importance of the basic design of hydraulic structures, including sluice gates, it also points out the research gap in the field of the corner vortices upstream of the gate. Vortices appear as a negative factor in the flow profile. The entry of air into the flow by the vortex causes vibration in the structure. Therefore, the main purpose of this study was to design a sill under the sluice gate as an anti-vortex element and, at the same time, able to control the hydraulic parameters. This research shows that the use of the sill under the sluice gate completely removes the vortices from the flow.

2. MATERIALS AND METHODS

2.1. Experimental set-up

The laboratory flume was 5 m long, 0.30 m wide, and 0.45 m high. The flume was equipped with a point gauge of ± 1 mm reading accuracy. The crest shape was of standard geometry: i.e., 2 mm thick with a 45° bevel on the downstream side. Experiments were predominantly performed using a sill under the sluice gate. Sills with semi-cylindrical, cylindrical, pyramidal, and rectangular-cube geometry and different widths of 50, 75, 100, 150, and 200 mm were considered. The sill characteristics are given in Table 1. The gate opening was 40 mm and always free gate flow conditions were guaranteed. The discharges considered in the present study ranged from 8 to 12 L/s. They were measured, with 2% accuracy, through rotameters installed on the inlet pipe. Figure 1 shows the laboratory flume and the polyethylene sills used in this study. Moreover, a definition plot with the main notations is provided, with G gate opening, Z sill height, H approach flow depth, B flume width, b sill width, and A_i partial gate opening area. For the sake of completeness, Table 2 provides the main test conditions for all the experiments conducted in this study.

2.2. Numerical model set-up

In this paper, the results from the experimental study are compared to those from the numerical model Flow-3D, which is a general-purpose Computational Fluid Dynamics (CFD) software for modeling multi-physics flow problems, based on the Finite-Volume Method to solve the Reynolds Averaged Navier-Stokes (RANS) equations. In all the simulations, the six-sided boundary conditions were introduced into Flow-3D according to the specifications in Table 2, where $X_{\min}$ and $X_{\max}$ are the upstream and downstream boundary conditions, $Y_{\min}$ and $Y_{\max}$ are the left and right boundary conditions, and $Z_{\min}$ and $Z_{\max}$ are the bottom and top boundary conditions, respectively.

Various models were tested to select a suitable mesh. According to the performed sensitivity mesh analysis and comparing the upstream flow depths, the 6 mm mesh was used (Table 3).

Table 1 | Geometric characteristics of the sills considered in this study (sizes are in mm)

Sill geometry	Height (*Z*)	Length	Width (*b*)	Gate opening (*G*)
Pyramidal	30	30	50–200	40
Rectangular cube	30	30	50–200	40
Semi-cylindrical	Diameter = 30	30	50–200	40
Cylindrical	Diameter = 30	30	50–200	40

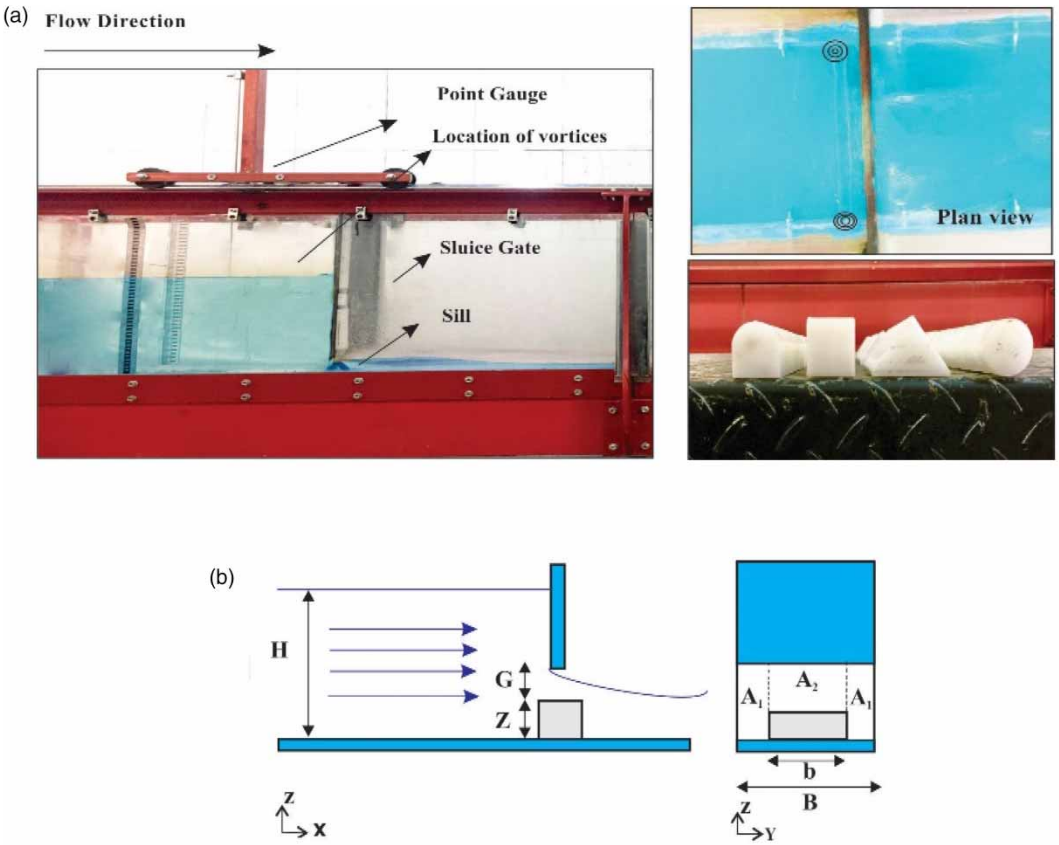


Figure 1 | (a) Lateral and plan views of the flume and view of the sills considered in this study. (b) Definition sketch of the sluice gate and sill with the main notation.

Table 2 | Boundary conditions used for the numerical simulations in this study

X_{min}	X_{max}	Y_{min}	Y_{max}	Z_{min}	Z_{max}
Volume flow rate	Outflow	Wall	Wall	Wall	Symmetry

Table 3 | Sensitivity analysis to select the most suitable mesh

Model#	Cell size (mm)	Total cells	H_{exp} (m)	H_{num} (m)	AE (cm)	RE (%)
1	11	312,579	0.120	0.090	3.0	25.00
2	9	568,788	0.120	0.100	2.0	16.66
3	8	832,580	0.120	0.109	1.1	9.16
4	7	1,228,080	0.120	0.116	0.4	3.30
5*	6	1,939,050	0.120	0.121	0.1	0.83

AE and RE are the absolute error and relative error, respectively.

2.3. Scale effects

In this study, the Reynolds number (Re) was chosen from 26,286 to 38,866. Therefore, the effect of Reynolds number and viscosity were ignored. In order to eliminate the surface tensions, discharges were kept high to minimize the effect of the viscous forces and surface tensions themselves. In constant temperature, Weber (We) and Reynolds number are dependent on each other, so one of the two must be eliminated; therefore, the effect of We was ignored (Daneshfaraz *et al.* 2023b). This study was done in a flume of constant width. So, the results would strictly refer to the flow conditions in this research (Madadi *et al.* 2014; Lauria *et al.* 2020; Daneshfaraz *et al.* 2022b, 2022c) However, the experimental conditions in the present study should be unaffected by scale effects according to the guidelines provided in the study by Roth & Hager (1999), which devotes to scale effects important experimental insights.

3. RESULTS AND DISCUSSION

3.1. Causes and development of the intake vortices

Figure 6 provides a scheme that describes how the streamlines would move toward the gate opening after having impacted the sluice gate. The development of the angular momentum causes the horizontal and vertical flow velocity components to extend in the vicinity of the gate opening. The suction of the gate opening and consequently the presence of downstream currents reduces the pressure in the flow surface layers and leads to the entry of air into the flow. As air enters the flow, the vortex formation intensifies, and the diameter of the vortex increases until the air pressure inside the vortex and the surrounding flow reaches an equilibrium state. Then the vortex that had formed disappears. A recurring period of vortex formation was observed throughout the experiments. Figure 2(d) shows the turbulence created by the collision of the flow with the sluice gate upstream, which leads in the later stages to the entry of air into the vortex fluid (Figure 2(e)) and finally after balancing between the vortex and the fluid gradually disappears (Figure 2(f)). The purple color was used in the photographs to indicate the position and extent of the vortices.

3.2. Effects of the sill under the sluice gate on the intake vortices

In order to explore the sill effect on the development of the intake vortices, sills of different shapes and widths were placed under the sluice gate by lining up their centroid with the crest of the gate. The results showed that the shape of the sill did not significantly affect the characteristics of the resulting intake vortices. Conversely, more significant effects are to be expected when the width of the sill is changed: the increase in the sill width reduces the cross-sectional area of the flow passing under the sluice gate and the results showed that the gate opening is the most important factor in the development of the intake vortices. Therefore, the vortices observed in the present study were divided into four categories according to their features, in turn due to the sill width (Figure 3).

The first group refers to the sluice gate without a sill. In this case, a spatial flow pattern in front of the gate develops although the occurrence of an almost 2D approach flow (Figure 3(a) – Group 1). According to Roth & Hager (1999), for inviscid flows, the vortex intensity is typically 5 (i.e., vortex-pulling air bubbles) and the vortex intensities would decrease with decreasing the relative gate opening G/H. In other words, the increase in the discharge implies an increase of the approach energy head and then the reduction of the ratio G/H. However, in this case, even the increase in discharge cannot wholly remove the vortices from the flow.

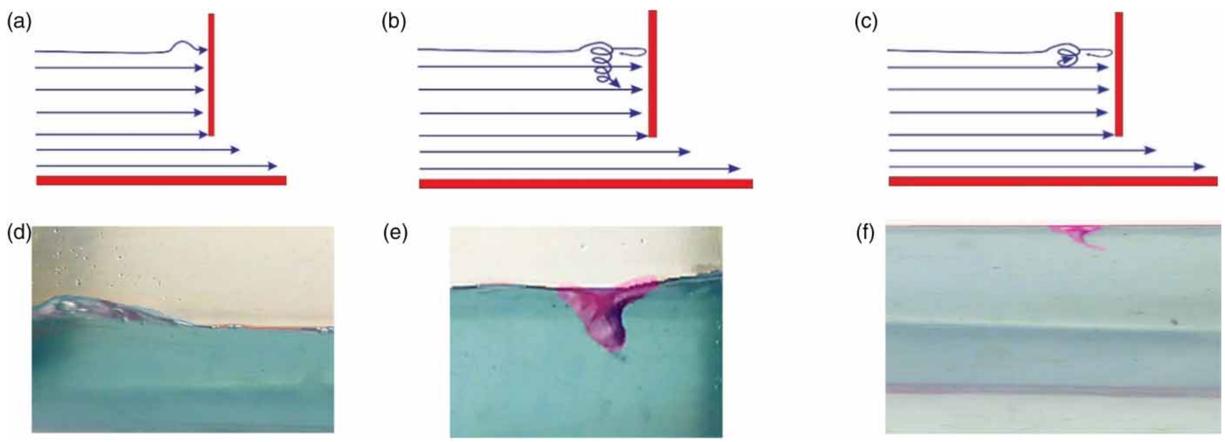


Figure 2 | Illustrations and photographs of vortex flows. Colors are used in the photographs to indicate the position and extent of vortices.

The second category refers to the sills 50 and 75 mm wide. In this case, the presence of the sill would not entail significant changes in the development of the vortices. However, the formation of vortices with large diameters are replaced by smaller vortices almost linear in shape at the end, due to a significant reduction in the amount of air entering the flow. The horizontal component of the velocities dominates in the flow domain and increases especially near the gate opening, thus resulting in a significant deflection of the vortex end toward the opening. Figure 3(b) (Group 2) also shows that the increase in discharge (and then of the approach energy head) leads to the formation of vortices with an ever-smaller diameter.

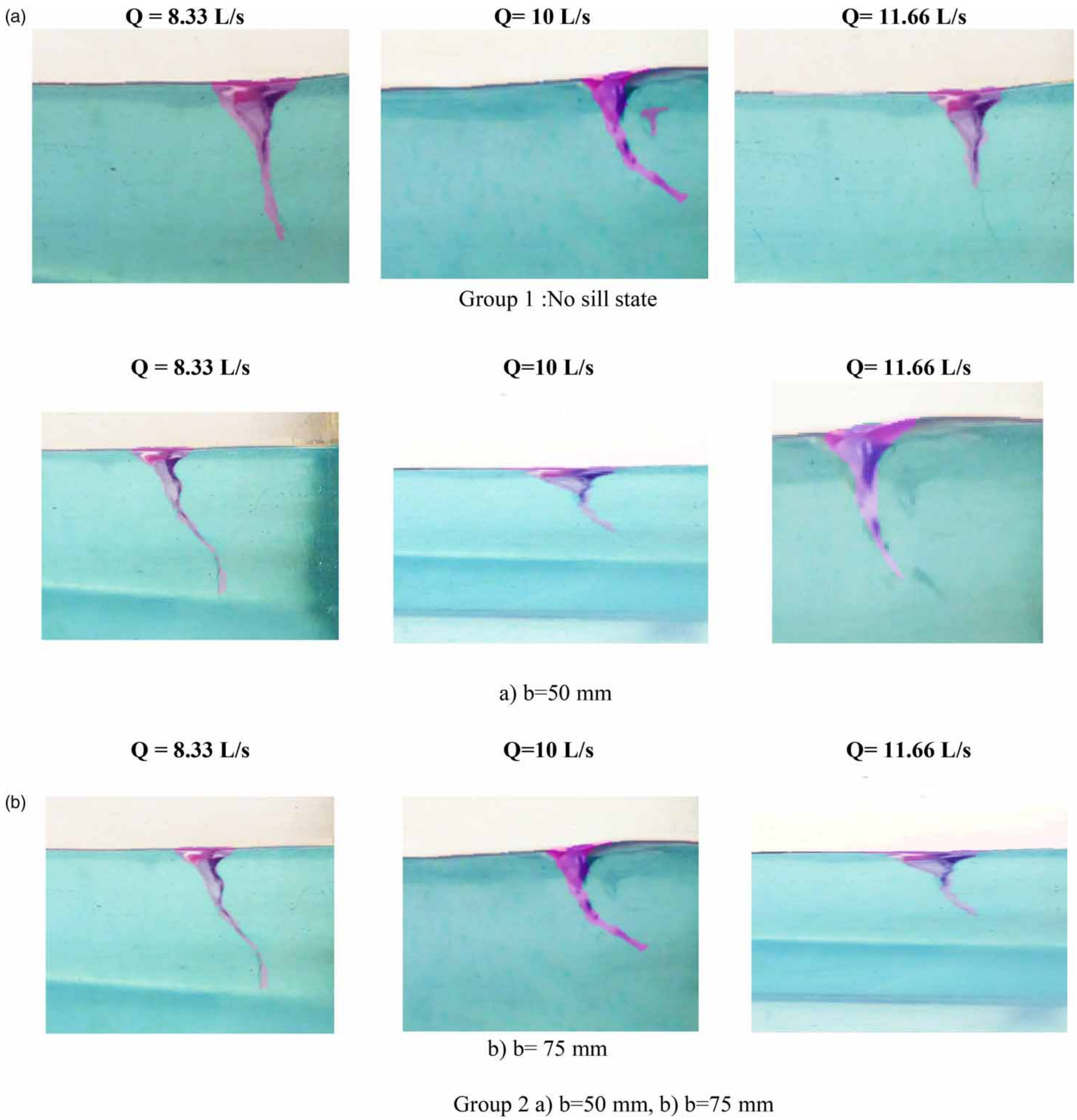


Figure 3 | Characteristics of the intake vortices depending on the sill width and the approach energy head. The purple color is used to highlight the location and extent of the vortices. (a) Group 1: no sill state, (b) group 2: $b = 50$ and $b = 75$ mm, (c) group 3: $b = 100$ and 150 mm, (d) group 4: $b = 200$ mm. (*continued.*).

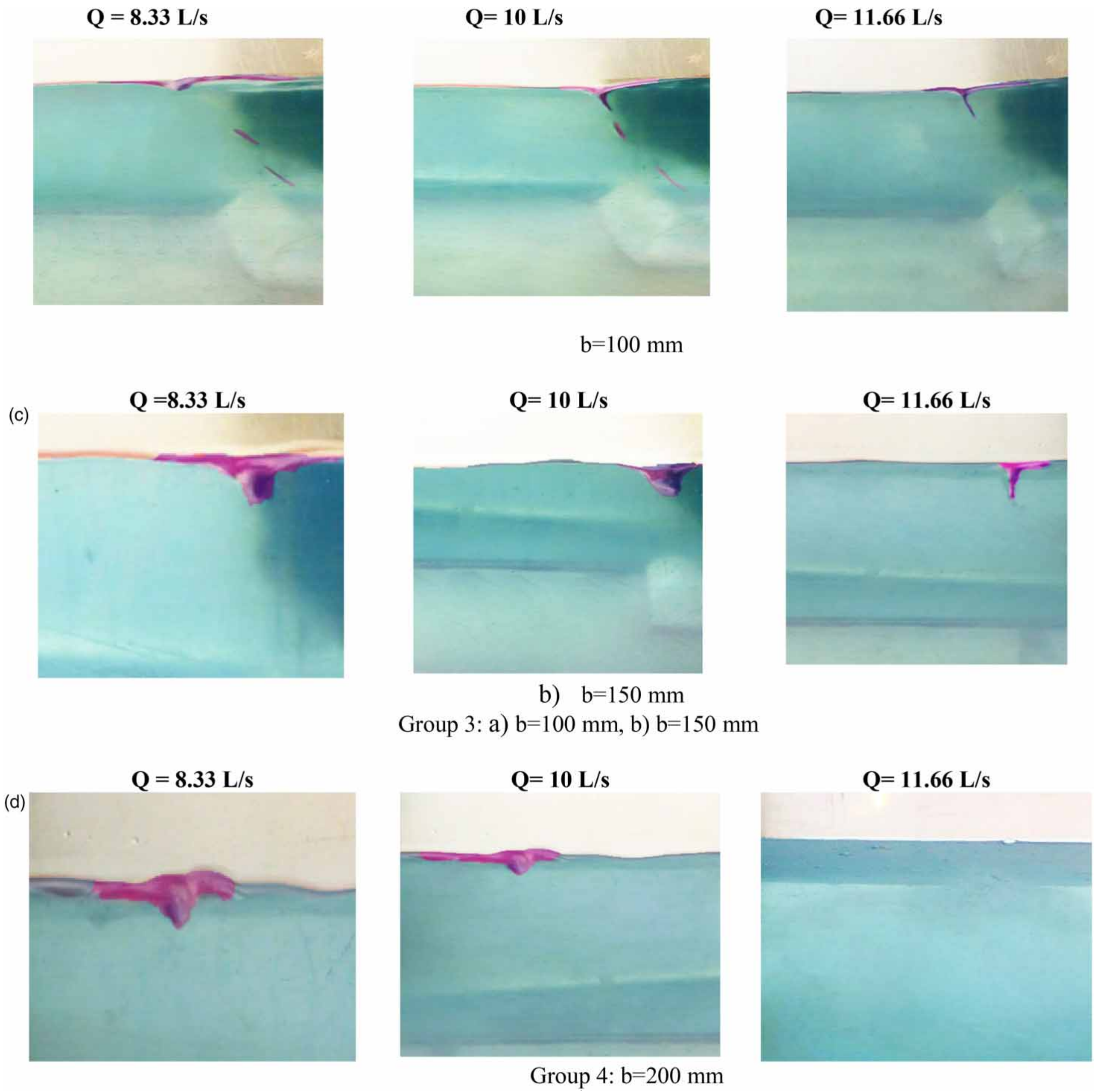


Figure 3 | Continued.

The third group refers to the sills 100 and 150 mm wide. In these conditions, the type of intake vortices observed upstream of the sluice gate was quite different from the previous cases. In particular, by placing the sill 150 mm wide, the rate of air infiltration into the flow decreased due to the increase of the approach energy head and the reduction of suction exerted by the gate opening. Figure 3(c) (Group 3) shows the vortices of the third group that have formed upstream of the sluice gate. The reduction of the vortex strength connected to the increase of the discharge is also observed.

Finally, the fourth group refers to the sill 200 mm wide. This sill significantly increased the velocity of the flow passing through the sluice gate opening due to the reduction in the opening area. The further increase in the approach energy head caused a further decrease in the diameter of the vortices. Flow turbulences were also reduced due to the reduction of the suction effects exerted by the gate opening. Therefore, the formation of vortices decreased until it stopped for the higher values of the discharge (Figure 3(d) – Group 4).

In summary, the results from the experimental tests indicated that using a sluice gate with a sill leads to the reduction (and even to the elimination) of the intake vortices that would form upstream of a standard sluice gate. Increasing the discharge and the sill width is the best way to reduce or even eliminate the intake vortices. This is because increasing the sill width and discharge increases the water depth upstream of the sluice gate. The water intake through a sluice gate with the sill already occurs in the lower layers of the flow; as a result, there is no significant change in the approach flow level, and the flow becomes more stable.

3.3. Comparison of the characteristics of the intake vortices in the present study with those from previous studies

In this section, the experimental observations of the present study are compared with those of Yousefian (2007) and Roth & Hager (1999). Yousefian (2007) examined the vortices that were being developed upstream of a sluice gate in a convergent rectangular channel. Figure 4(a) shows the proposed classification based on visual observations. Groups 1–3 correspond to a progressive increase in the gate opening. The author reduced the formation of the vortices by reducing the sluice gate opening. Vortices of Groups 2 and 3 were characterized by the larger diameters and an almost linear end.

Roth and Hager studied water flows under standard gates. The development of shock waves is intimately connected to the development of the intake vortices. Therefore, to minimize the formation of vortices upstream of a sluice gate, vertical plates (called anti-vortex elements) are installed upstream of the gate. In their study, Roth and Hager have adopted the classification introduced by Hecker (1984) for the definition of the vortex intensity. This classification, including six groups, is re-proposed in Figure 4(b).

In the present study, the development of the vortices in the case of a standard sluice gate (i.e., without sill) was also explored to better understand the effects induced by a sill. As previously mentioned, sills of different shapes and widths were tested. Figure 4(c) shows a schematic classification of the vortices based on the experimental observations arising from the present study. The first, second, third, and fourth groups are respectively related to: (1) no sill, (2) sills: 50 and 75 mm wide, (3) sills: 100 and 150 mm wide, and (4) sills: 200 mm wide. The results imply that the placement of the sill under the sluice gate effectively reduces the intake vortices by reducing the changes in the direction of flow. Indeed, vortices were not observed on the flow surface for the sills with the largest width. Increasing the approach flow depth is another factor in suppressing the formation of vortices. In the standard case, the highest discharge had no significant effect on the complete inhibition of vortices. The increase in discharge allowed the complete suppression of the vortices only when the sill was placed under the sluice gate. Therefore, the fourth group outlined in Figure 4(c) corresponds to the higher discharges and to the wider sills up to the complete inhibition of the vortices from the water surface.

The study by Yousefian (2007) demonstrated the attenuation of the intake vortices by reducing the gate opening; the study by Roth and Hager promoted anti-vortex elements upstream of the sluice gate to reduce the strength of the vortices. The present study would combine these previous results presenting a new solution based on the use of a sill under the sluice gate. By placing the sill, the gate opening is reduced and, therefore, the water depth behind the gate increases. But what is more

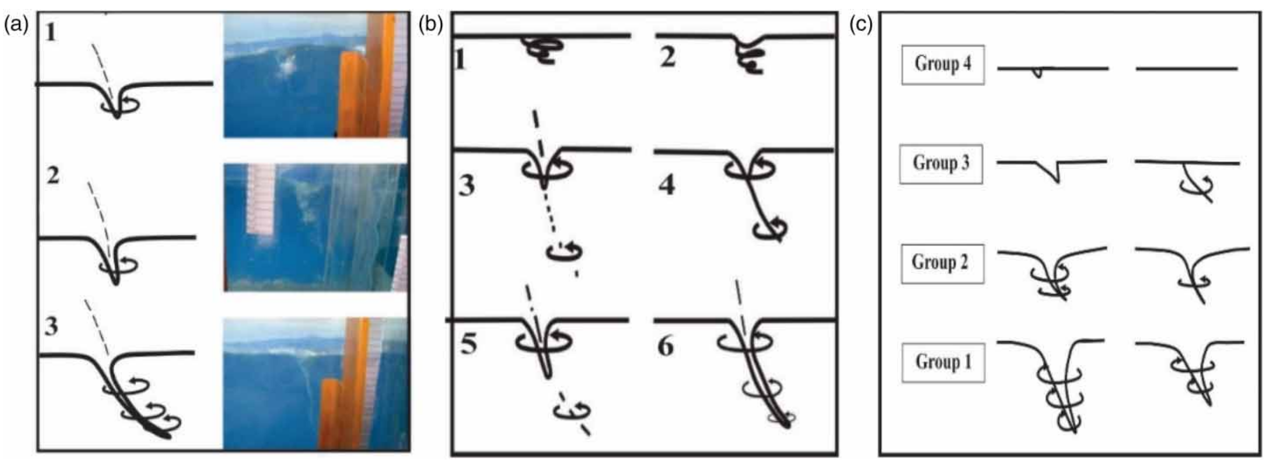


Figure 4 | Comparison of the characteristics of vortices observed in the present study with those from previous studies. (a) Yousefian (2007); (b) Roth & Hager (1999); and (c) present study. Flow direction is from left to right.

important, the sill would involve flow direction changes with sluice gate intake occurring from the lower layers of the flow which also contributes to inhibiting the development of the vortices.

3.4. Results from numerical modeling

In the following, the numerical results obtained from the application of Flow-3D in the case of the sill under the gate are reported.

The use of a sill under the gate causes a change in the hydraulic parameters, including the upstream flow depth, as expected. Figure 5 shows the changes in the water depth upstream of the gate when sills of different widths are placed under the gate. This, for a given flow rate of 11.66 L/s.

The use of a silled gate caused an increase in the upstream water depth. By using sills of width 50, 75, 100, 150, and 200 mm, the upstream water depth increase of 0.017, 0.042, 0.062, 0.100, and 0.153 m in comparison to the reference case of no sill, respectively. An increase in water depth causes an increase in pressure upstream of the gate. The installation of a sill increased the pressure in comparison to the reference case and the pressure values along the centerline vertical Z direction are shown in Figure 6(a). The maximum pressure values in the reference state and in the case of the presence of a sill of width 50, 75, 100, 150, and 200 mm were equal to 1,200, 1,450, 1,600, 1,800, and 2,500 Pa, respectively. In the field of vortices, hydrostatic pressure in the upstream of sluice gate is one of the most important parameters in reducing the extent of the vortices. Using the sill increases the pressure on the upstream of the gate by increasing the water depth. An increase in pressure causes a decrease in the suction of the sluice gate. This reason causes a decrease in the extent of vortices. Figure 6(b) shows the comparison of water depth and pressure in different sills. where the highest pressure and depth of water is related to the sill with the largest width ($b = 200$ mm)

Analogously, the depth-averaged velocities along the centerline flow direction were investigated. The use of a sill causes a change in the flow velocity vectors. Figure 7 shows the depth-averaged velocity changes in the X direction. Position $X = 1$ m is the location of the sluice gate. The flow velocity increases significantly just downstream of the sluice gate with the transition from subcritical to supercritical flow. The maximum depth-averaged velocity was equal to 1.25 m/s for the reference case and 2.20 m/s in the case of sill of maximum width (i.e., $b = 200$ mm).

The results showed that the increase in the width of the sill changes the maximum pressure and depth-averaged velocity (Table 4). The depth-averaged velocity increased from 1.28 to 2.20 m/s. The results of the maximum pressure showed that the maximum pressure increased from 1,152 to 2,635 Pa.

Figure 8(a) and 8(b) shows the streamlines upstream of the sluice gate in control and with sill state, respectively. The results of the investigation of the streamlines showed that vortices with a larger diameter are formed upstream of the sluice gate in without sill state. By placing the sill under the sluice gate, with the increase in depth and water pressure upstream, the extent of the vortices decreased and smaller diameter vortices appeared in the upstream.

In order to investigate upstream vortices of the sluice gate, different widths of sill were installed under the gate. Figure 9 shows the numerical results of the simulation of vortices using Flow-3D software. Results showed that the use of sills in

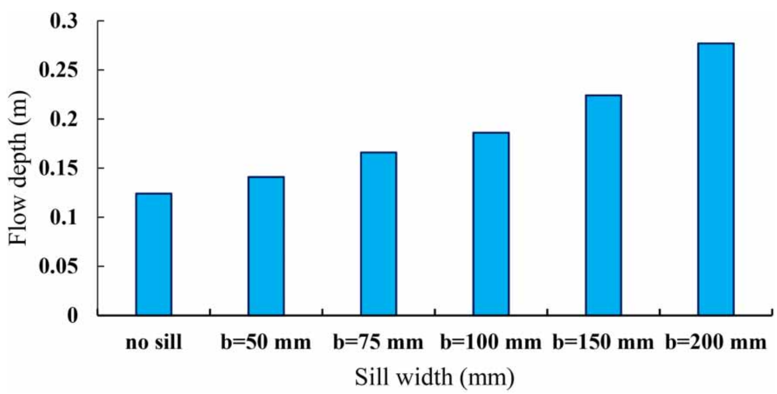


Figure 5 | Simulated upstream flow depths, at given approaching discharge, when sills of different widths are placed under the gate.

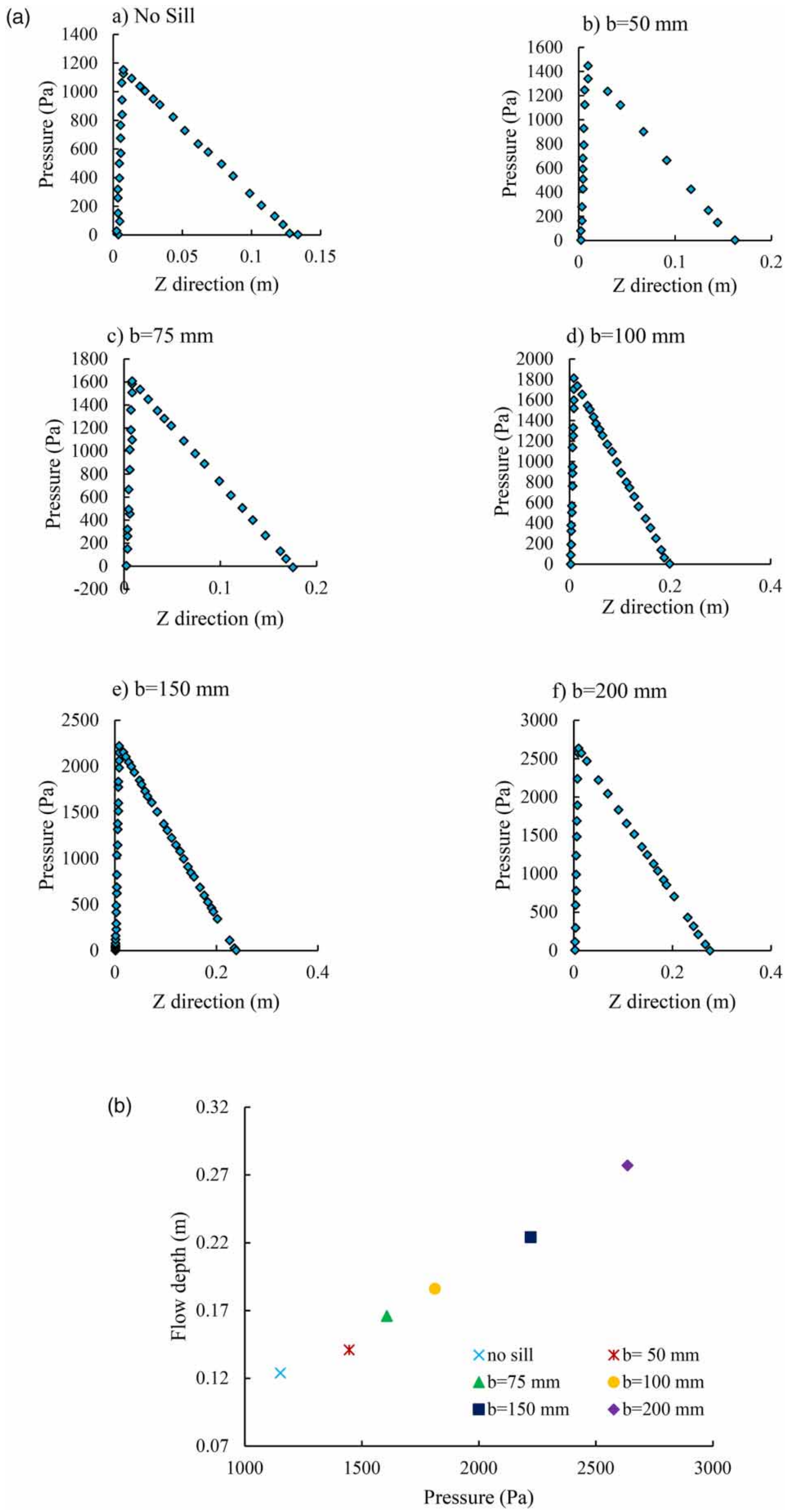


Figure 6 | (a) Pressure along the vertical direction *Z*, at given approaching discharge, when sills of different widths are placed under the gate: (a) no sill, (b) $b = 50$ mm, (c) $b = 75$ mm, (d) $b = 100$ mm, (e) $b = 150$ mm, and (f) 200 mm. (b) Changes in flow depth and pressure of upstream for each sills.

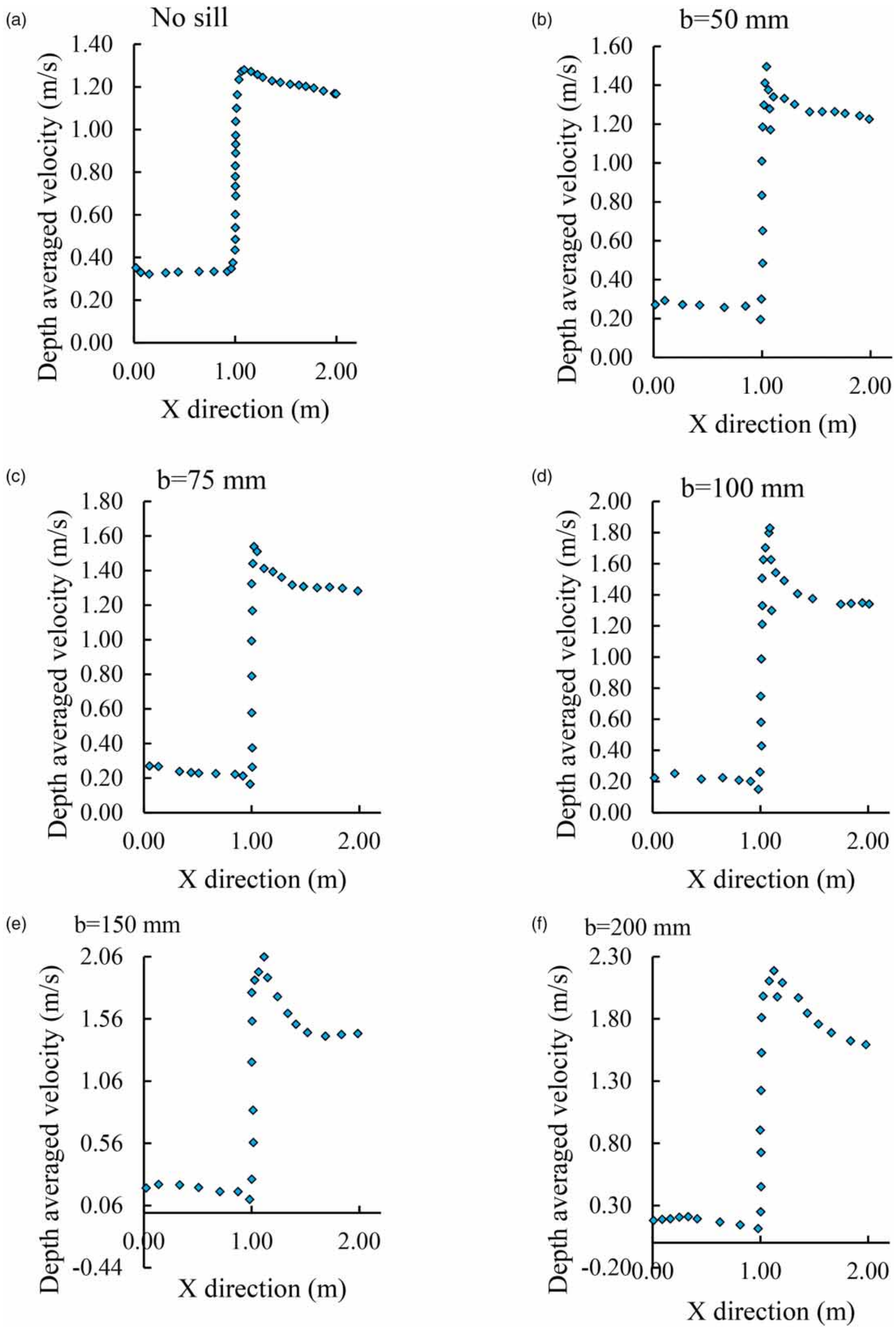


Figure 7 | Depth averaged velocity along the longitudinal direction *X*, at given approaching discharge, when sills of different widths are placed under the gate: (a) no sill, (b) $b = 50$ mm, (c) $b = 75$ mm, (d) $b = 100$ mm, (e) $b = 150$ mm, and (f) 200 mm.

Table 4 | Max of pressure and depth-averaged velocity in this study

	No sill	$b = 50$ mm	$b = 75$ mm	$b = 10$ mm	$b = 150$ mm	$b = 200$ mm
Max pressure (Pa)	1,152	1,446	1,607	1,813	2,222	2,635
Max depth-averaged velocity (m/s)	1.28	1.50	1.6	1.84	2.06	2.20

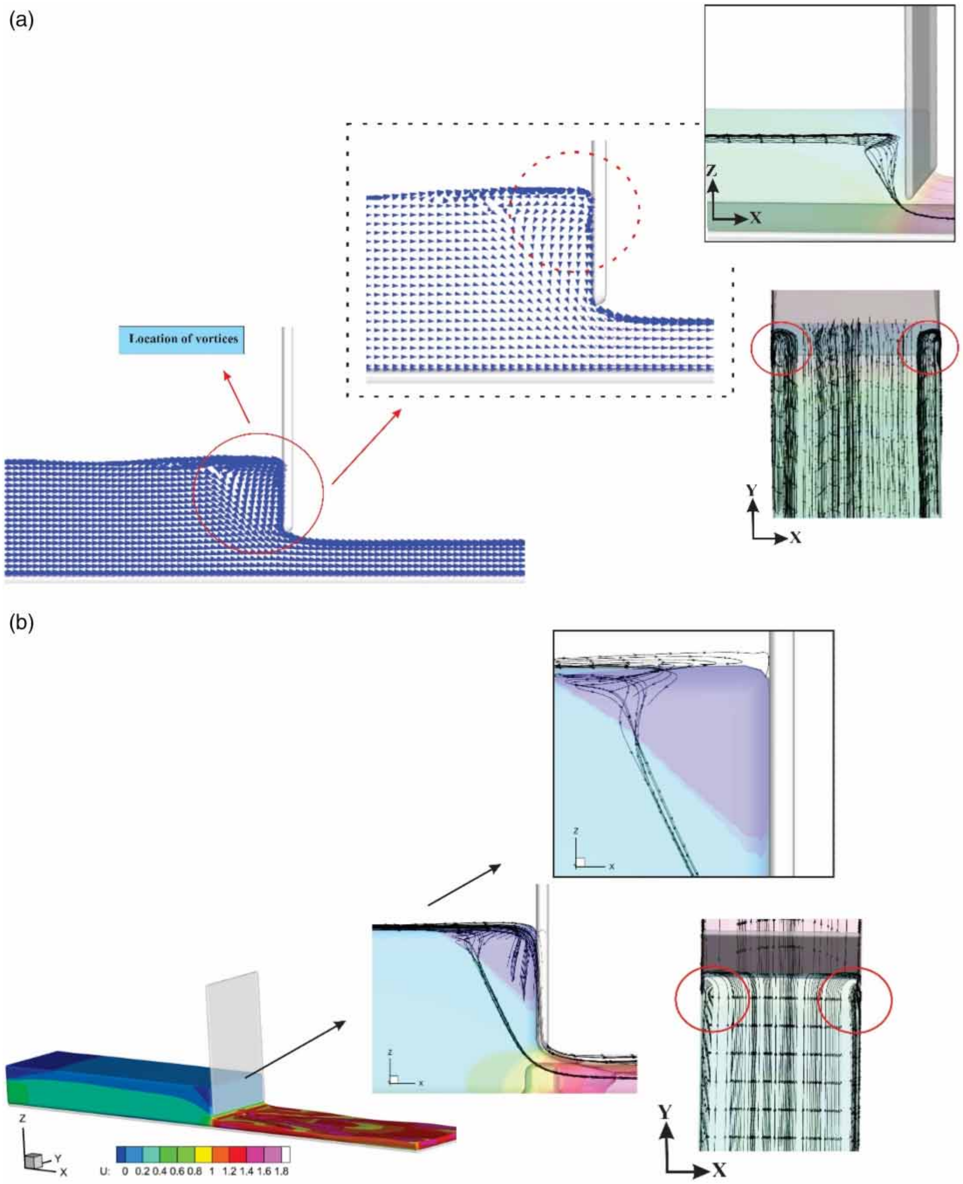


Figure 8 | Simulation of vortices and streamlines for (a) the reference case 'no sill' and (b) with sill for an approaching discharge of 11.66 L/s. The values of the local longitudinal velocities, u, are in m/s.

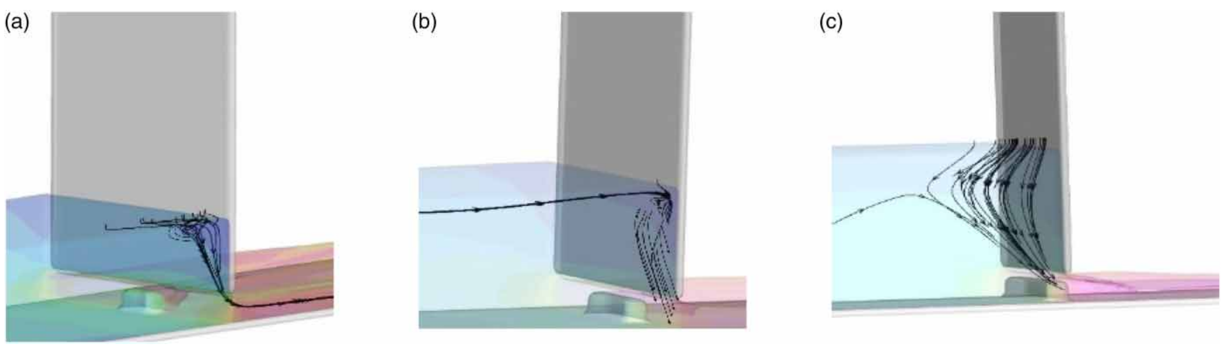


Figure 9 | Comparison between streamlines for the reference case, $b = 50$ mm, $b = 10$ mm, and $b = 200$ mm at a given approaching discharge of 11 L/s.

widths of 50–200 mm has caused a decrease in the extent of the vortices. In the case of placement of the sill with the largest width (200 mm), the vortices were removed from the upstream Figure 9(c).

4. CONCLUSIONS

This study was primarily conducted to explore the vortices that would develop upstream of a sluice gate. Therefore, the effects of sills of different shapes, including cylindrical, semi-cylindrical, pyramidal, and rectangular shapes, as well as different widths from 50 to 200 mm, were investigated experimentally and numerically in order to appreciate their ability to dampen or even suppress the intake vortices. Sluice gate opening and flow rate were identified as the main factors affecting the formation of vortices. Reducing the sluice gate opening by using a sill increased the flow depth upstream of the sluice gate. As a result, vortices tended to vanish or their intensities significantly reduced. Conversely, a decrease in the gate opening tended to generate fully developed air-entraining vortices with a continuous air core. The results also showed that the shape of the sill placed under the sluice gate did not have a significant effect on the vortices. Conversely, the sill width would play an important role so that increasing the sill width would minimize the development of the vortices because of the reduction of the sluice gate opening. When higher discharges occurred, vortices were completely inhibited. The results of this study can be useful for future research, which is given below. Investigating the hydrodynamic force caused by the formation of vortices in the upstream, investigating the effect of different shapes of the sill, and the effect of increasing and decreasing the width of the channel on the extent of the vortices.

AUTHORS' CONTRIBUTIONS

Conceptualization, R.N., P. E., and R.D.; methodology, R.N., P. E., and R.D.; formal analysis, R.N., P. E., and R.D.; investigation, R.N., P. E., V.S. and R.D.; data curation, P. E.; writing, original draft preparation, R.N., P. E., and R.D.; writing, review and editing, R.N., P. E., V.S. and R.D. All authors have read and agreed to the published version of the manuscript.

FUNDING

There is no funding source.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animals performed by any authors.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abbaszadeh, H., Norouzi, R., Sume, V., Kuriqi, A., Daneshfaraz, R. & Abraham, J. 2023 Sill role effect on the flow characteristics (experimental and regression model analytical). *Fluids* **8** (8), 235. https://doi.org/10.3390/fluids8080235.

Akoz, M., Kirkgoz, M. & Oner, A. 2009 Experimental and numerical modeling of a sluice gate flow. *Hydraulic. Research* **47**, 167–176.

Belaud, G., Cassan, L. & Baume, J. P. 2009 Calculation of contraction coefficient under sluice gates and application to discharge measurement. *Journal of Hydraulic Engineering* **135** (12), 1086–1091.

Cassan, L. & Belaud, G. 2012 Experimental and numerical investigation of flow under sluice gates. *Journal of Hydraulic Engineering* **138** (4), 367–373.

Daneshfaraz, R., Norouzi, R. & Ebadzadeh, P. 2022a Experimental and numerical study of sluice gate flow pattern with non-suppressed sill and its effect on discharge coefficient in free-flow conditions. *Journal of Hydraulic Structures* **8** (1), 1–20. https://doi.org/10.22055/jhs.2022.40089.1201.

Daneshfaraz, R., Noruzi, R. & Ebadzadeh, P. 2022b Experimental investigation of non-suppressed sill effect with different geometry on flow pattern and discharge coefficient of sluice. *Journal of Hydraulics* **17** (3), 47–63. doi:10.30482/jhyd.2022.316603.1566.

Daneshfaraz, R., Norouzi, R., Abbaszadeh, H. & Azamathulla, H. M. 2022c Theoretical and experimental analysis of applicability of sill with different widths on the gate discharge coefficients. *Water Supply* **22** (10), 7767–7781. https://doi.org/10.2166/ws.2022.354.

Daneshfaraz, R., Norouzi, R., Ebadzadeh, P. & Kuriqi, A. 2023a Influence of sill integration in labyrinth sluice gate hydraulic performance. *Innovative Infrastructure Solutions.* **8** (4), 118. https://doi.org/10.1007/s41062-023-01083-z.

Daneshfaraz, R., Norouzi, R., Ebadzadeh, P., Di Francesco, S. & Abraham, J. P. 2023b Experimental study of geometric shape and size of sill effects on the hydraulic performance of sluice gates. *Water* **15**, article number 314.

Ghorbani, M. A., Salmasi, F., Saggi, M. K., Bhatia, A. S., Kahya, E. & Norouzi, R. 2020 Deep learning under H_2O framework: A novel approach for quantitative analysis of discharge coefficient in sluice gates. *Hydroinform* **22**, 1603–1619.

Hassanzadeh, Y. & Abbaszadeh, H. 2023 Investigating discharge coefficient of slide gate-sill combination using expert soft computing models. *Journal of Hydraulic Structures* **9** (1), 63–80.

Hecker, G. E. 1984 Scale effects in modelling vortices. In: *Symposium on Scale Effects in Modeling Hydraulic Structures*. International Association for Hydraulic Research, Esslingen am Neckar, Germany.

Karami, S., Heidari, M. M. & Rad, M. H. A. 2020 Investigation of free flow under the sluice gate with the sill using flow-3D model. *Iranian Journal of Science and Technology, Transactions of Civil Engineering* **44**, 317–324.

Lauria, A., Calomino, F., Alfonsi, G. & D'Ippolito, A. 2020 Discharge coefficients for sluice gates set in weirs at different upstream wall inclinations. *Water* **12**, article number 245.

Lin, C. H., Yen, J. F. & Tsai, C. T. 2002 Influence of sluice gate contraction coefficient on distinguishing condition. *Irrigation and Drainage Engineering* **128**, 249–252.

Madadi, M. R., Hosseinzadeh, D. A. & Farsadizadeh, D. 2014 Investigation of flow characteristics above trapezoidal broad-crested weirs. *Flow Measurement and Instrumentation* **38**, 139–148.

Mohammed, A. Y. 2022 Driftwood blocking sensitivity on sluice gate flow. *Open Engineering* **12** (1), 1051–1059.

Mohammed, A. Y. & Khaleel, M. S. 2013 Gate lip hydraulics under sluice gate. *Modern Instrumentation* **2**, 16–19.

Rady, R. A. E. H. 2016 Modeling of flow characteristics beneath vertical and inclined sluice gates using artificial neural networks. *Ain Shams Engineering Journal* **7** (2), 917–924.

Rajaratnam, N. 1977 Free flow immediately below sluice gates. *Hydraulics Division* **103**, 345–351.

Roth, A. & Hager, W. H. 1999 Underflow of standard sluice gate. *Fluids* **27**, 339–350.

Shammaa, Y., Zhu, D. Z. & Rajaratnam, N. 2005 Flow upstream of orifices and sluice gates. *Journal of Hydraulic Engineering* **131** (2), 127–133.

Yen, J. F., Lin, C. H. & Tsai, C. T. 2001 Hydraulic characteristics and discharge control of sluice gates. *Journal of the Chinese Institute of Engineers* **24** (3), 301–310.

Yousefian, M. 2007 *Flow Through the Sluice Gate in Rectangular Channels with Different Widths*. *M.Sc. thesis*, Isfahan University of Technology.

First received 18 July 2023; accepted in revised form 8 September 2023. Available online 21 September 2023