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Using side flow jets as a scour countermeasure downstream of a sluice gate

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Abstract

Background: Local scour is one of the main problems affecting the stability and operation of control hydraulic structures. Many techniques were used to control the resulting scour. In the recent study, a new technique was used to control local scour downstream single-gate hydraulic regulator by using side flow jets. This study aimed to demonstrate the effect of side jets at different angles on the local scour parameters (depth, length, and volume) and energy dissipation in the downstream hydraulic regulator.

Results: A physical model was used to represent the open channel, regulator, and the side jets with different angles. Five flow discharges, four jet angles, and three gate openings were applied through the experiment. The experiment results showed that the presence of side jets had a remarkable effect on the parameters of the local scour hole and energy dissipation. They dissipated more energy of hydraulic jump than in the absence of jets, and consequently, scour hole dimensions were significantly reduced. Regression analysis was used to deduce equations that can predict the development of local scour downstream sluice gate considering the inclination angle of side flow jets under different flow conditions.

Conclusions: Side flow jets can be used as scour reducer techniques with the advantages of eliminating the jet clog produced from sediments and suspended solids.

Keywords: Local scour, Energy dissipation, Side flow jets, Sluice gate, Physical model, Free flow

1 Background

The sluice gates are frequently attached to regulators with the function of controlling, measuring flow rate, and regulating water levels in irrigation canals. Various researchers have studied the flow through sluice gates [1–7]. When the flow under the gate acts as an orifice flow forming a flow jet, the high velocity of the jet may cause excessive local shear stress and result in local scour over an erodible bed. Local scour can gradually damage the bed material, which eventually leads to structural failures. Therefore, scour process downstream gates have been extensively investigated [8–16]. Dey and Sarkar [17] studied the scouring process and profiles in non-cohesive

sediment downstream of a sluice gate with submerged horizontal jet. The scour depth was a function of sediment gradation of non-uniform sediments. The equilibrium scour depth increased with the densimetric Froude number. Also, the formula of equilibrium scour of maximum depth has been empirically produced. Negm et al. [18] experimentally investigated the scour patterns due to the gate operation of multi-events regulators under submerged flow conditions. The results concluded that the maximum scour depth is affected by the pattern of bottom velocity, gate operation, type of gates, submergence ratio, and Froude numbers at vena contract. Sarkar and Dey [19], and Aamir and Ahmad [20] presented a comprehensive review of local scour caused by jets. Aamir and Ahmed [21] experimentally measured local scour developed by smooth and rough aprons under wall jets. The study recommended the use of roughness over the apron to reduce scour caused by wall jets. Aamir and

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Ahmed [22] analyzed laboratory data of scour development due to a two-dimensional horizontal jet that moved over rigid rough apron. In addition, the measured depths of scour were compared with those predicted by different equations. Furthermore, Aamir and Ahmed [23] suggested a relationship to determine downstream scour depth for an apron under wall jets. Rostamy et al. [24] used a laser Doppler anemometry (LDA) to report the turbulence characteristics for both rough and smooth surface of wall jets. Their study results concluded that rough surface modified in the inner layer magnitudes and shape of the profiles of Reynolds stress. Kartal and Emiroglu [25] studied a local scour developed under jet of different nozzle diameters with plats. The experimental results proposed scour equations to predict depth of maximum scour, bridge height, and length of scour hole. Karbasi and Azamathulla [26] applied different soft-computing techniques to determine the maximum depth of scour hole downstream of sluice gate and the study provided prediction accuracy for the established scour depth relationships. Aamir and Ahmed [27] used an artificial neural network as well as adaptive neuro-fuzzy interference system models to estimate scour depth due to submerged wall jets.

Specifically, the roughness elements increase flow turbulence through the hydraulic jump and consequently reduce the length of the jump. The main function of energy dissipation is to protect the downstream channel bed from scouring. Appurtenances as end sills, baffle, and chute blocks within the stilling basin are frequently used to dissipate the excess energy in the high velocity, increase turbulence and the hydraulic jump efficiency, control the bed scour, and reduce the stilling basin length [28], and thereby, it may be possible to reduce the cost of protection works. There are several studies available in the literature on energy dissipation and local scour mitigation using such appurtenances [29–34]. Hamidifar et al. [35] used a single bed sill as a countermeasure to investigate the scour reduction downstream of the apron and to assess its effectiveness at different distances from the apron end. The results showed that the maximum scour reduced up to 95% downstream of the apron. It was illustrated also at various locations and heights; the scour profiles were different for the sills. To predict the scour hole profile, a regression-based equation has been proposed. Mesbahi et al. [36] predicted the depth of local scour by applying gene expression programming downstream stilling basins. Abdallah [37] examined the effects of end sills of different shapes and different heights on the scour dip downstream of the apron. The findings showed the sill height was more effective than the shape on the scour hole. Elnikhely [38] has experimentally studied scour hole dimensions downstream of the spillway at

various arrangements, lengths, and diameters of cylinder blocks under different flow conditions. The experimental data were employed to develop simple empirical relations to predict the scour hole parameters downstream of the spillway. Chahartaghi et al. [39] conducted experiments to study the effects of three geometry blocks, including trihedral, semicircle, and trapezoidal shapes using a baffle chute with a 2:1 slope on local scour downstream of spillways. Tuna and Emiroglu [40] studied the dynamics of local scour due to step geometry downstream of stepped chutes. Step heights, chute angles, stilling basin sill heights, and tailwater depths were investigated for different flow conditions. The equilibrium depth of scour was affected by the geometry of the step, decreased with the increase in step height, and increased by the chute angle and discharge.

It is possible to control the hydraulic jump using a jet instead of the usual appurtenances. Using jets as energy dissipators to control a hydraulic jump has been investigated [41–46]. Varol et al. [46] studied the characteristics of hydraulic jump controlled by jet with different flow rates. The length of the jump decreased with increasing the flow rate of the jet. Also, the jump with a water jet resulted in more energy losses compared to the free hydraulic jump. Aboulatta [47] investigated the effect of floor jets on the characteristics of free and submerged jump.

Consequently, the utilization of jets to dissipate energy can be a scour countermeasure to the downstream hydraulic structure. Aboulatta [48] experimentally investigated the impact of the floor jets on scouring development downstream of an apron of a radial stilling basin. For different relative upstream heads, the maximum depth of scour was measured at different time intervals for a flat floor with and without jets. In particular, floor jets significantly reduced the scour depth, length, and volume. The study also proposed equations to predict the depth of scouring developed for both the flat floor and the flat floor with jets. Aboulatta and Kamel [49] studied the protection of the scouring process using different methods including floor jets and riprap bed. The results of the study concluded that the scour depth and volume were severely decreased using floor jets, and at almost the same effects were detected for riprap bed without floor jets. In addition, the study recommended using a riprap protection layer only at Froude numbers less than 4 for structure operation and using floor jets for Froude numbers > 4 .

A lake of knowledge exists about using side wall jets with various inclination angles from the side wall to determine scour development and energy dissipation. Most of the available reviews on controlling scour by jets relate to the study of scour processes caused by floor jets.

Despite this, this paper investigates the effects of using the side flow jets under different angles, and flow conditions to primarily control the scour process downstream sluice gate.

2 Methods

A recirculating flume located within the Channel Maintenance Research Institute, National Water Research Center, was used to conduct the tests. The experiments were performed in a 16.22-m-long, 0.60-m-wide, and 0.42-m-deep channel with a trapezoidal concrete shape and 1:1 side slope. The flume inlet was 4.52 m long, 1.16 m deep, and 1.63 m wide with two vertical walls. And, the outlet part was 0.96 m long, 1.21 m deep, and 1.63 m wide. Two 8-inch pipes were used to collect water from the outlet basin to supply an underground reservoir. A 40-cm-width single sluice gate regulator was constructed vertically with horizontal edge and with three openings. Two side jets of 2.0 cm diameter were installed with positive angles $\theta=150^\circ$, 120° , and 90° (perpendicular to the direction of flow), and one jet was arranged for each side wall (Fig. 1). The side flow jets were fixed to the side walls just upstream the bed

level at a distance of $X_j/X_a=0.41$ downstream the gate, as X_j is distance of jet from the gate and X_a is the length of apron. They worked under the main differences between upstream and downstream gate levels. The soil basin was constructed downstream the regulator with dimensions of 160×60 cm. The basin was filled with the soil in which was leveled to bed level before each run. A drainage system was installed to drain excess water before recording sand levels at the end of each run. The median size of the experiment bed material was $d_{50}=0.50$ mm.

Five discharges were selected during the tests ($Q=32, 34, 36, 38, \text{ and } 40 \text{ L s}^{-1}$), a sluice gate with three openings of $G=6.0, 6.5, \text{ and } 7.0$ cm, resulting in a jet velocity to the velocity upstream the hydraulic jump V_j/V_1 between 0.49 and 0.71. Three jet angles of $\theta=150^\circ, 120^\circ, \text{ and } 90^\circ$ (perpendicular to the flow direction) were tested to examine the effects of side jet angles on the scour hole dimensions and energy loss compared to without jet case. For each run, the resultant scour hole was surveyed and the main scour parameters were determined after 100 min. Table 1 shows the experimental conditions and the ranges of tested parameter.

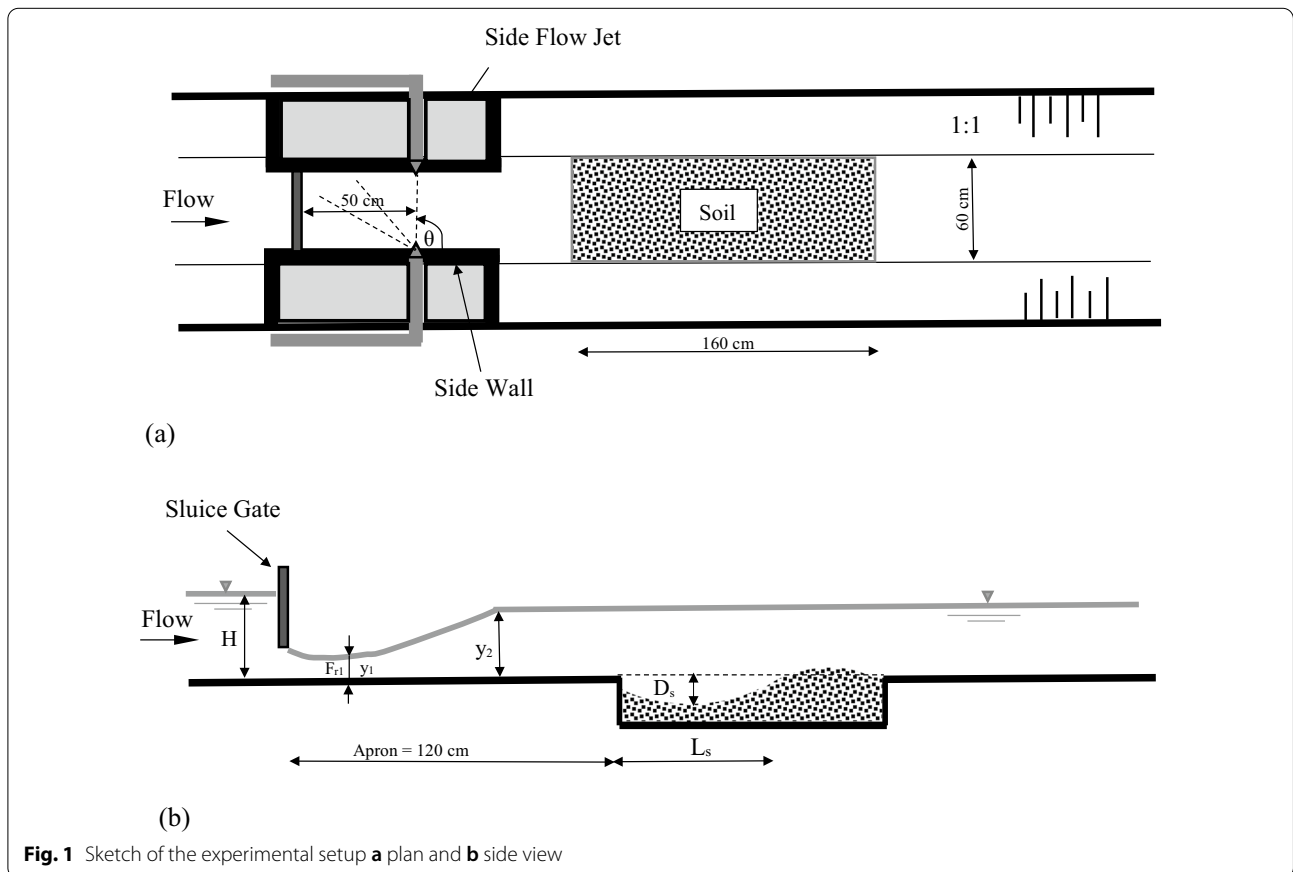


Fig. 1 Sketch of the experimental setup **a** plan and **b** side view

Table 1 Overview of the test conditions and parameter ranges

Parameter	Range
Discharge Q (Ls^{-1})	32, 34, 36, 38, 40
Angle of flow jet from wall θ ($^\circ$)	150, 120, 90, without jet
Sluice gate opening G (cm)	6, 6.5, 7
Froude number upstream of the jump F_{r1}	2.31–3.71
Froude number downstream of the jump F_{r2}	0.31–0.41
Flow depth upstream the sluice gate H (cm)	26.6–37.07
Jet velocity to velocity upstream the jump V_j/V_1	0.49–0.71, without jet
Flow depth upstream of the jump y_1 (cm)	4.2–4.9
Flow depth downstream of the jump y_2 (cm)	17.07–19.54
Maximum scour depth D_s (cm)	5–7.2
Length of scour L_s (cm)	65–113.5
Volume of scour V_s (cm^3)	13,331–38,088

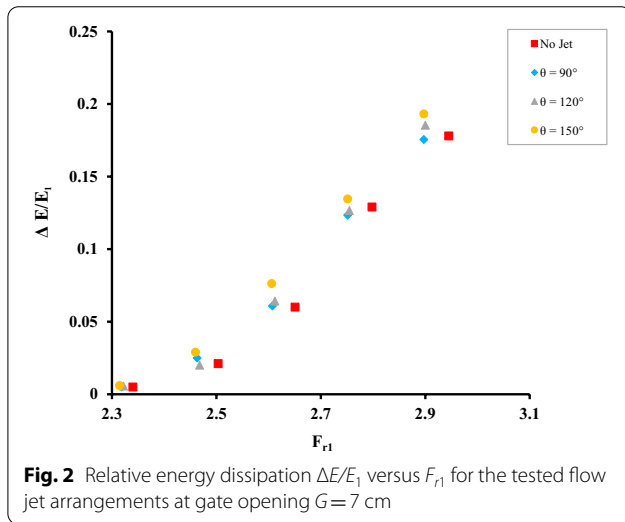


Fig. 2 Relative energy dissipation $\Delta E/E_1$ versus F_{r1} for the tested flow jet arrangements at gate opening $G=7$ cm

3 Results

3.1 Energy dissipation

The variations in the relative energy dissipation $\Delta E/E_1$ with Froude number upstream of the jump F_{r1} for side jet positive angles of $\theta=90^\circ-150^\circ$ and without side jet are shown in Fig. 2. The relative energy dissipation $\Delta E/E_1$ between upstream and downstream the hydraulic jump relative to the upstream energy can be computed using the form:

$$\Delta E = E_1 - E_2 = \left(y_1 + \frac{V_1^2}{2g} \right) - \left(y_2 + \frac{V_2^2}{2g} \right) \quad (1)$$

Then, the relative energy loss is expressed by Eq. 2

$$\frac{\Delta E}{E_1} = \frac{E_1 - E_2}{E_1} \quad (2)$$

where ΔE is the energy dissipation, E_1 , y_1 , and V_1 are the energy head, water depth, and velocity upstream the hydraulic jump, respectively, E_2 , y_2 , and V_2 are the energy head, water depth, and velocity downstream the hydraulic jump, and g is the gravitational acceleration.

3.2 Scour hole dimensions

3.2.1 Effect of side jet angles

The relative terms of D_s/H , L_s/H , and V_s/H^3 were investigated for different side jet positive angles of $\theta=150^\circ, 120^\circ$, and 90° (perpendicular to the flow direction) and without side jet in the range of $F_{r1} \approx 2.90-3.71$ at $G=6$ cm to examine the effect of side jet angles on the scour hole dimensions. The relationship between the relative term of D_s/H and different F_{r1} for the tested jet angles is shown in Fig. 3a with a constant of all other parameters. The relationship between dimensionless term L_s/H and F_{r1} at the tested jet angles is illustrated in Fig. 3b. In Fig. 3b, it is evident that the L_s/H values increase with F_{r1} for all tested angles. Figure 3c demonstrates the effects of jet angles on the scour volume V_s . According to this figure, the angle of jet affects the relative scour volume. As θ increases, the relative term V_s/H^3 decreases in all the tested conditions of flow. Additionally, when F_{r1} reduces, the term V_s/H^3 value increases.

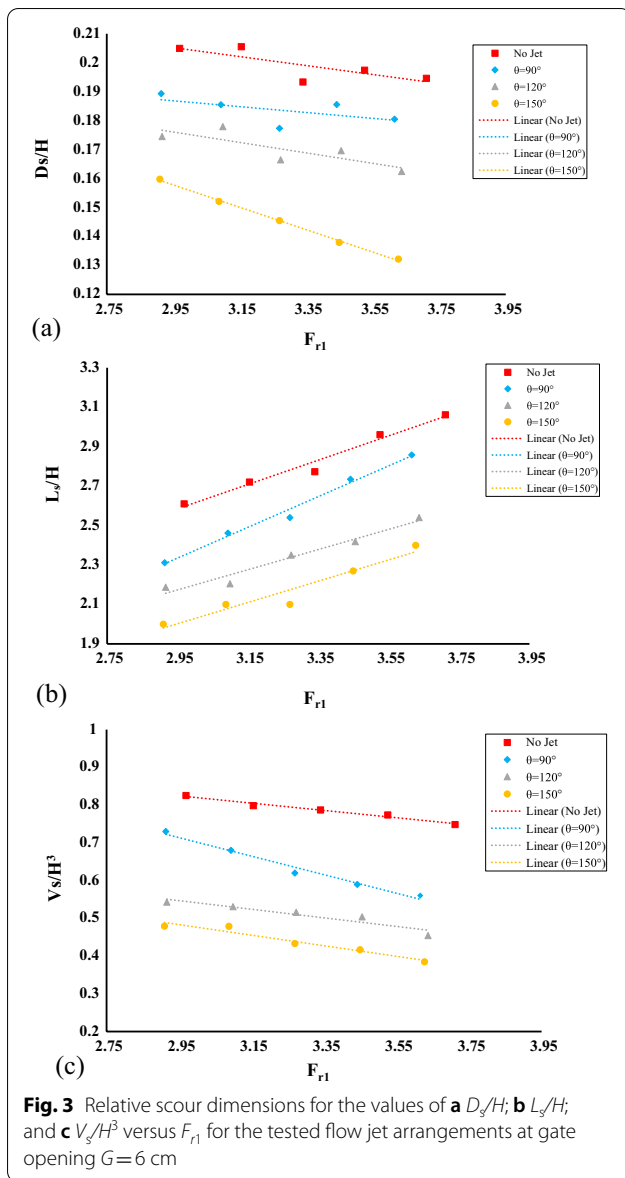
4 Discussion

4.1 Energy dissipation analysis

Figure 2 demonstrates that relative energy dissipation increases with increasing side jet angles. The largest $\Delta E/E_1$ values occur at $\theta=150^\circ$ for a constant Froude number and inclination of angle. Increasing the side jet angle results in more force and resistance against the incoming supercritical flow. Therefore, the use of side jets arrangement can dissipate higher energy for hydraulic jump as compared to the case of without jets and this is consistent with the observations of El Sayed [45]. Figure 2 also displays that $\Delta E/E_1$ increases with increasing F_{r1} at a constant angle.

4.2 Side jet angles analysis

Figure 3a displays the component value of D_s/H decreases with increasing F_{r1} for all test configurations, as maximum scour depth D_s value was less than the value of flow depth upstream the sluice gate H in the term D_s/H during the tests. Therefore, the maximum scour depth parameter D_s increases only with F_{r1} , since a higher energy of F_{r1} results in an increase in scour hole parameters. In addition, increasing θ reduces the D_s/H value for all arrangements indicating



that the maximum scour depth reduces as the jet angles increase. For average Froude numbers, using a jet with $\theta=90^\circ, 120^\circ,$ and 150° decreases the scour depth D_s by approximately 11, 16, and 25%, respectively, compared to without a jet. The presence of side jets can dissipate more energy [45], and hence, the reduction in scour depth occurs. In particular, the flow of side jet against the incoming supercritical flow increases with the jet angle, and hence the energy dissipation increases, which results in reducing the scour hole parameters. In contrast, θ affects the maximum scour depth.

Given the same flow conditions, larger θ results in smaller L_s/H values (Fig. 3b). Hence, the scour length L_s decreases with increasing jet angles. Specifically,

the average scour length reductions are approximately 9, 13, and 15% for jet angles of $\theta=90^\circ, 120^\circ,$ and 150° , respectively, compared to without jet case. Increasing jet angles θ , against the incoming flow under gate, results in more energy dissipation, thus reducing hydraulic jump length, leading to a smaller scour length.

The results show that increasing θ can minimize the relative term V_s/H^3 at all tested flow conditions (Fig. 3c). Specifically, the volume of a scour hole V_s decreases by 19, 31, and 40% compared to the case of no side jet for $\theta=90^\circ, 120^\circ,$ and 150° , respectively. Furthermore, the minimum value of F_{r1} produces the maximum term V_s/H^3 value, as V_s value was less than H^3 value in the term V_s/H^3 , and the maximum volume of scour V_s only occurs with larger F_{r1} for each angle. As previously demonstrated, increasing θ dissipates more flow energy, and hence V_s decreases because the depth and length of scour become smaller downstream of the apron. In summary, it should be noted that the side flow jets can significantly be considered as a scour countermeasure especially with angles against the incoming flow. Furthermore, side jets may have more utility in eliminating the clog of jets that result from suspended solids and sediments, and are also simpler in design compared to floor flow jets.

4.2.1 Design equation for scour hole dimensions

Experimental data with dimensionless terms were employed to propose three equations to predict local scour parameters ($D_s, L_s,$ and V_s) with the presence of side flow jets. With regard to regression analysis, the effective variables on local scour were used and the following equations were deduced:

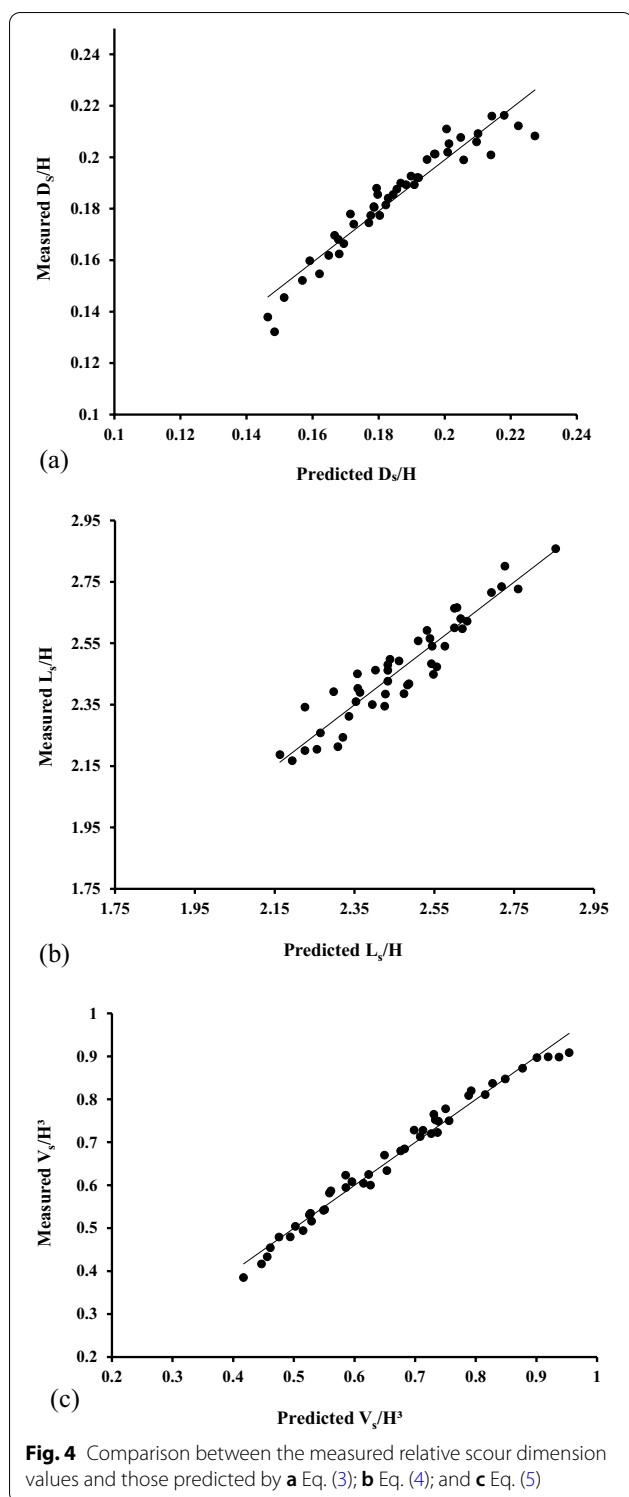
$$\frac{D_s}{H} = 0.026 \cos \theta + 0.047F_{r1} + 0.945\frac{G}{H} - 0.232F_{r2} - 0.061 \tag{3}$$

$$\frac{L_s}{H} = 0.252 \cos \theta + 2.519F_{r2} + 14.740\frac{G}{H} + 1.107F_{r1} + 1.042\frac{V_j}{V_1} - 5.289 \tag{4}$$

$$\frac{V_s}{H^3} = 0.353 \cos \theta + 1.038F_{r2} + 4.094\frac{G}{H} + 0.531\frac{V_j}{V_1} - 0.711 \tag{5}$$

where G =sluice gate opening; H =flow depth upstream the sluice gate; and F_{r2} =Froude number downstream of the jump.

Parameters that affect the scour hole in Eqs. 3–5 have p - values ≤ 0.0001 indicating a significant impacts on the local scour. Theses equations are valid for $90^\circ \leq \theta \leq 150^\circ,$ $0.49 \leq V_j/V_1 \leq 0.71,$ $0.16 \leq G/H \leq 0.26,$ $2.31 \leq F_{r1} \leq 3.71,$



and $0.31 \leq F_{r2} \leq 0.41$. Figure 4 shows the comparison between the values of the measured relative local scour dimensions (D_s/H , L_s/H , V_s/H^3) and the predicted values

by Eqs. 3–5, respectively. These figures illustrate that the predicted values of D_s/H , L_s/H , and V_s/H^3 are consistent with the measured values with $R^2 = 0.92$, 0.89 , and 0.98 , respectively.

5 Conclusions

This paper presents an experimental investigation to allow analysis of side flow jets as scour countermeasure and energy dissipator. Side flow jets were examined for a range of positive angles between 90° and 150° at different flow conditions and compared to the reference case of without jet to define the scour evolution and energy dissipation. The findings imply the following.

- Side flow jets had a notable impact on the local scour hole parameters and energy dissipation. They increased the energy dissipation, thus reducing the depth, length, and volume of scour hole.
- The use of side flow jets reduced the scour hole by approximately 11, 16, and 25% for scour depth, 9, 13, and 15% for scour length, and 19, 31, and 40% for scour volume for jet angles of $\theta = 90^\circ$, 120° , and 150° , respectively, compared to without jet case due to the increased energy dissipation.
- Three empirical equations have been proposed to predict the depth, length, and volume of local scour resulting from the presence of side flow jets.

In fact, side jets may have more advantages about eliminating the jets clog that developed from sediments and suspended solids and are also simpler in design compared to the floor flow jets. For further studies, it is essential to investigate the scour processes downstream multi-gate regulator for different side flow jet positions under various flow conditions. Furthermore, considering the effects on vena contracta could be useful with possible consequences for the performance of the sluice gate discharge coefficients.

Abbreviations

D_s : Depth of maximum scour; d_{50} : Median size of mobile bed; E_1 : Energy head upstream of the hydraulic jump; E_2 : Energy head downstream of the hydraulic jump; F_{r1} : Froude number upstream of the jump; F_{r2} : Froude number downstream of the jump; G : Sluice gate opening; g : Gravitational acceleration; H : Flow depth upstream the sluice gate; L_s : Length of scour; Q : Flow discharge; V_j : Velocity of flow jet; V_s : Volume of scour hole; V_1 : Velocity upstream of the hydraulic jump; V_2 : Velocity downstream of the hydraulic jump; X_s : Length of apron; X_j : Distance of jet from the gate; y_1 : Flow depth upstream of the hydraulic jump; y_2 : Flow depth downstream of the hydraulic jump; θ : Inclination positive angle of flow jet from wall; ΔE : Energy dissipation between upstream and downstream the hydraulic jump.

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Authors' contributions

MSA designed the study and carried out research. MZ wrote manuscript. All authors have read and approved the manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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