



Local Scour Process in Conduit Aerated Water Jets

M. CIHAT TUNA,¹ RAMAZAN ACAR,² and MUSTAFA TUNÇ¹

Abstract—High-velocity water jets emerging from hydraulic structures cause local scouring in downstream areas, creating significant risks to structural safety. In this study, the effects of natural aeration provided through pressurized pipes on jet-induced scouring were investigated through laboratory experiments. A total of 60 experiments were conducted for different gate openings, flow rates, and downstream water levels; the scour geometries created by aerated and non-aerated jets were compared. The aeration level was defined by the dimensionless air-to-water flow ratio (Q_a/Q_w); maximum scour depth, scour length, scour slope angle, and jet fall distance were considered as basic evaluation parameters. The experimental results showed that increased aeration significantly reduced the maximum scour depth and scour length while moving the point of contact of the jet further upstream. While the scour depth and slope angles reached their highest values in non-aerated jets, shallower and flatter scour profiles were formed in aerated conditions. An empirical relationship predicting the maximum scour depth using experimental data has been developed and found to be in high correlation with the measured values ($R^2 = 0.93$). The findings reveal that channel aeration is an effective method for reducing scouring and demonstrate that this approach can be considered a safe and economical alternative in the design of spillways, wastewater treatment plants, and similar hydraulic systems.

Keywords: Aeration, air/water flow, scour hole, conduit, Froude number.

1. Introduction

High velocity water jets occur downstream of water structures. Due to the large energy of these jets, sediment erosion, called scour, occurs downstream of the structure. The increase in scour over time may result in a hole near the foundation of the structure and overturn the structure into this hole. This

situation may jeopardizes the safety of the water structure and cause both serious economic losses and a dangerous situation for the lives of living creatures living downstream. Aeration, which is widely used in hydraulic engineering, is an effective way to break the energy of the jet. Therefore, the effects of aeration in the scouring process need to be fully demonstrated.

In recent years, the local scouring problem has been addressed in detail not only in the context of spillway and jet-induced flows but also in terms of various engineering applications such as bridge foundations, coastal piles, and underwater structures. Experimental studies have shown that downward currents and vortex systems developing around structures accelerate sediment transport, leading to the formation of scour holes. Studies examining scouring behavior around underwater foundations, particularly using AI-supported experimental channels, emphasize both the mechanical process and predictability of scouring (Wang et al., 2024). Similarly, experimental research evaluating ground improvement applications for scour prevention reveals the failure mechanisms of protective measures, demonstrating that scour is a critical limit condition in engineering design (Wang et al., 2025). Comprehensive reviews on scouring around bridge foundations have evaluated mechanisms, prediction methods, monitoring techniques, and mitigation measures together, clearly stating that scouring is a fundamental problem that directly affects structural safety (Wang et al., 2017a, 2017b). Additionally, experiments conducted around cylindrical shore piles under sloping bottom conditions show that the bottom geometry significantly alters the flow pattern and scour morphology (Barrie et al., 2024). However, most existing studies focus on structure-induced scour under constant flow; the effect of high-velocity jets from pressurized pipes and, in particular, the

¹ Hydraulic Division, Civil Engineering Department, Firat University, Elazığ, Turkey.

² Hydraulic Division, Civil Engineering Department, Munzur University, Tunceli, Turkey. E-mail: ramazanacar@munzur.edu.tr

impact of natural aeration on downstream scour is addressed to a limited extent. Accordingly, the influence of naturally aerated pressurized conduit jets on downstream scour geometry has not yet been sufficiently documented.

In recent years, the use of data-driven approaches in predicting scouring and jet behavior has become increasingly widespread. Artificial intelligence-based models can represent the nonlinear relationships between flow structure, air entrainment, and sediment transport by utilizing experimental data. The literature contains studies where parameters such as submerged jet aeration, scour depth, and oxygen transfer have been successfully predicted using artificial neural networks, ANFIS, and support vector machines (Baylar et al., 2008; Kramer et al., 2016; Lashkar-Ara et al., 2020; Puri et al., 2023). However, most of these approaches focus on developing models based on existing datasets. Studies that directly investigate the physical effects of natural aeration on jet behaviour and downstream scouring through controlled experiments are limited. Therefore, experimental studies are important for improving our understanding of the scouring mechanism and for establishing reliable references for future data-based models.

Several researchers have investigated the erosion caused by various types of jets, including propeller jets (Curulli et al., 2023; Wei et al., 2020), plane jets (Mostaani & Azimi, 2022; Sharafati et al., 2020), free-fall jets (Salmasi & Abraham, 2022; Salmasi et al., 2023), and moving jets (Wang et al., 2021). Vertical jets were preferred over inclined jets because of their uncomplicated equipment and effective silt-scouring performance (Chen et al., 2023; Wang et al., 2017a, 2017b). Many authors have suggested many empirical formulae, both static and dynamic, to predict the scour depth of submerged jets. Recent research has expanded the understanding of scour processes under different jet–bed interaction scenarios. Suljevic and Kesgin (2025) examined twin-propeller scour near various quay wall configurations and showed that propeller spacing, wall geometry, and densimetric Froude number strongly affect maximum scour depth. Kesgin et al. (2025) conducted laboratory experiments on single-propeller scour near vertical and parallel quay walls,

highlighting the influence of propeller speed, gap distance, and wall orientation on scour geometry. Yüksel et al. (2019) investigated scour at the toe of quay walls under propeller wash and proposed empirical equations describing how propeller diameter, rotational speed, and propeller–wall distance govern final scour depth. Yüksel et al. (2018) analyzed propeller-jet-induced scour around piles and showed that scour depth and profile shape depend on densimetric Froude number, pile diameter, and propeller gap, introducing predictive relationships for different sediment conditions. Chen et al. (2022) and Mao et al. (2023) examined how jet diameters, jet angles, exit velocities, and impinging distances affect scouring effects. Tuna (2012), Habib et al. (2016), Aminpour and Farhoudi (2017), Elnikhely (2018), Kazempour Larsari et al. (2019), and Gharibi et al. (2022) conducted experimental studies on local scour downstream of hydraulic structures. It has been proven by many studies that aeration reduces scour. Firstly, Johnson (1967) conducted studies on the scour caused by air–water jet. Martínez-Bazán et al. (2002) performed experiments in which they injected air into the center of a water jet. Xu et al. (2004) measured scour for aerated and non-aerated flow by injecting air into the jet. They found that the most important parameter on scour is air concentration. To do this, the study used a glass channel. This channel is 3 m long, 0.22 m wide and 0.8 m deep. In addition, a rectangular nozzle system made of polymethyl methacrylate tubing was used. It was designed to provide homogeneous aeration by mixing air through small holes into the water coming out of the nozzle. Dey and Sarkar (2007) vertically injected an air–water mixture into a scour hole. The effects of the

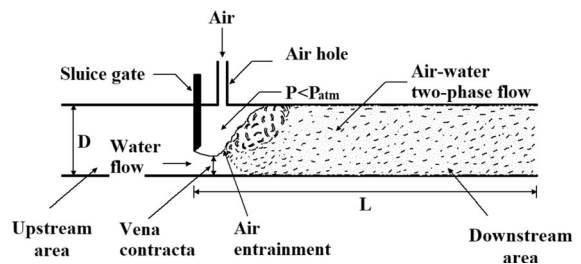


Figure 1
Flow in high head gated circular conduits (Tuna et al., 2014)

Table 1
Range of parameters tested in the experiments

Gate opening (%)	Discharge (L/s)				Hydrostatic level (cm)		
K ₁	Q ₁	Q ₂	Q ₃	Q ₄	h _{t1}	h _{t2}	h _{t3}
K ₂	Q ₁	Q ₂	Q ₃	Q ₄	h _{t1}	h _{t2}	h _{t3}
K ₃	Q ₁	Q ₂	Q ₃	Q ₄	h _{t1}	h _{t2}	h _{t3}
K ₄	Q ₁	Q ₂	Q ₃	Q ₄	h _{t1}	h _{t2}	h _{t3}
K ₅	Q ₁	Q ₂	Q ₃	Q ₄	h _{t1}	h _{t2}	h _{t3}

K₁, Non-Aerated; K₂, 20%; K₃, 30%; K₄, 40%; K₅, 60%; Q₁, 4.5 L/s; Q₂, 6 L/s; Q₃, 6.75L/s; Q₄, 7.5 L/s; h_{t1}, 20 cm; h_{t2}, 30 cm; h_{t3}, 40 cm

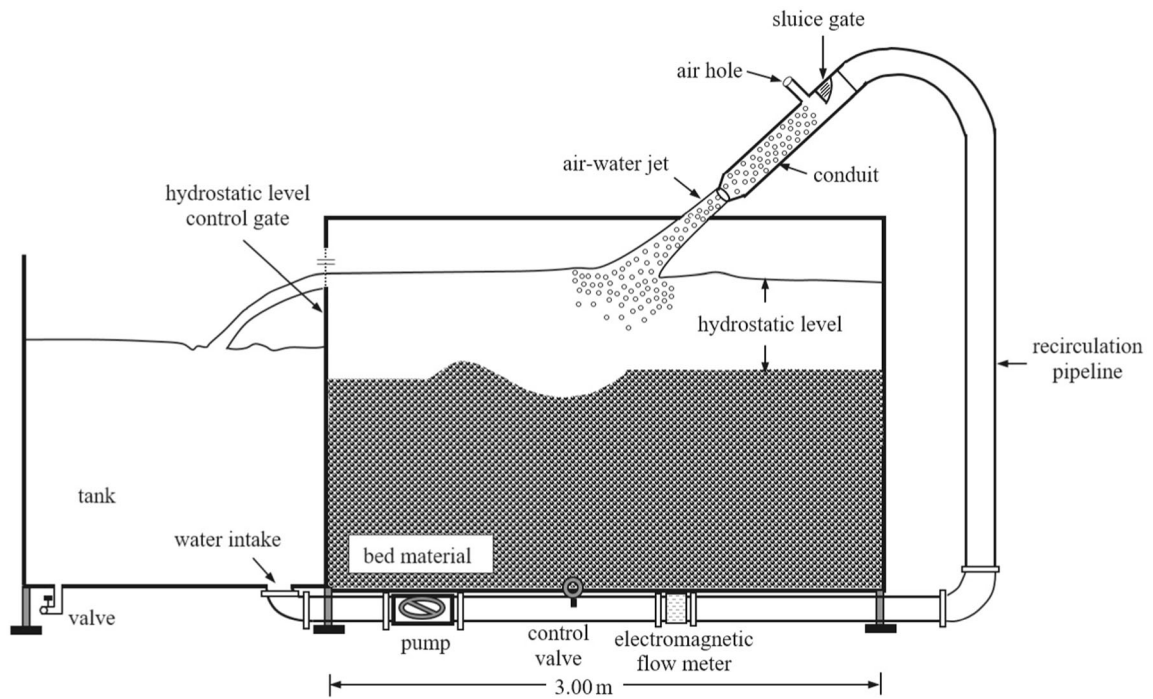
injected mixture velocity on the scour geometry were determined. A channel 10 m long, 0.6 m wide and 0.71 m deep was used for this purpose. The test channel contained a sediment bed 0.3 m deep and 2 m long. Three different types of sediment ($d_{50} = 0.8$ mm, 1.86 mm and 3 mm) were used in the study. Neto et al. (2008) conducted a study to determine the effect of single and multi-hole nozzles on the scour hole. Schmocker et al. (2008) conducted experiments with air injection into plunging jets. They found that air injection has a significant effect on the air concentration in the plunge jet. However, the effect of air injection on scour was not investigated in this study. Mason (1989) investigated how the depth of scour in plunge pools changes with the effect of aeration. This study aims to evaluate the effects of unit flow rate (q), height difference (H), and aeration rate (air entrainment) on scour separately using hydraulic model tests. Bai et al. (2016) is an experimental study that investigates how air concentration and bubble properties change in the downstream flow of an aerator chute. The aim of this study was to investigate the characteristics of the air–water mixture produced by the aerators and the dynamics of this mixture downstream.

Aeration as a method of reducing downstream scour is a very good unique solution. Alternative solutions are expensive and often not efficient. Some hydraulic structure, such as conduits, can increase aeration due to air–water two-phase flow. This structure air is entrained into the flow in the form of a large number of bubbles. Air bubbles greatly increase the surface area available for mass transfer. Conduit aeration is a particular instance of this. If the gate of a high-head outlet conduit is partly opened, a

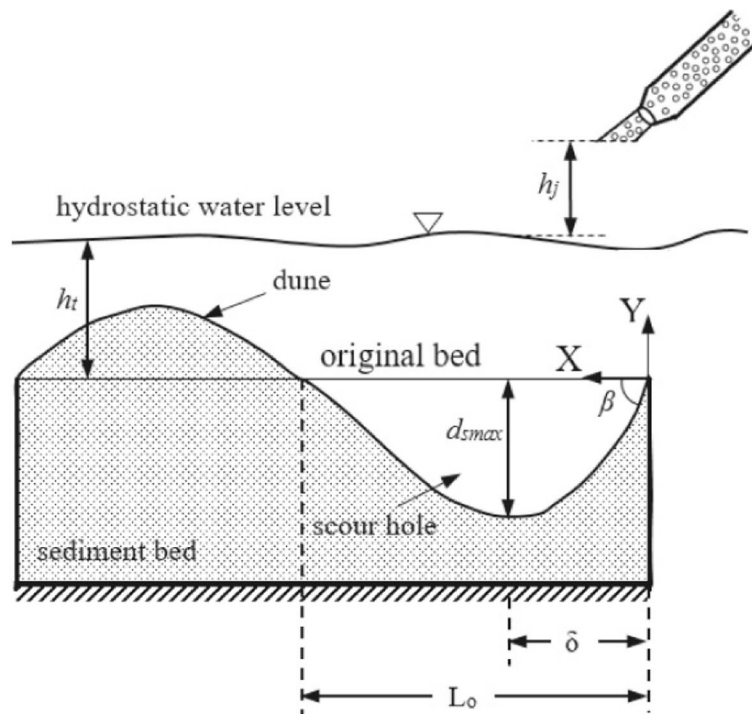
high velocity flow occurs downstream of it resulting in subatmospheric pressure (Fig. 1). This subatmospheric pressure causes air to be drawn through the air vent. Air that is entrained into the water is instantly forced downstream in the form of small air bubbles. The smaller the bubbles, the more air is exposed to the water increasing the efficiency of oxygen being absorbed into the water (Aytac & Tuna, 2023).

Therefore, it is predicted that conduits, which are widely used in water aeration, can significantly reduce scour with their high aeration performance. Conduit systems are widely used in dam bottom outlets, irrigation plants and wastewater plants. Especially the scour caused by the jet coming out of the dam bottom outlets is of critical importance because it is very close to the dam body. It is very important to use conduit as an aerator to prevent scour in such structures and to determine its effect on the scour process. There are many studies to determine the aeration performance of conduits (Aydin et al., 2023; Aytac & Tuna, 2023; Aytac et al., 2024; Baylar et al., 2022; Tuna et al., 2014). However, there is no study in the literature that reveals the effects of this hydraulic structure on downstream scour.

The main aim of this study is to provide a comprehensive examination of the applicability of pressurized conduits with high aeration capacity in water structures with scour problems in the downstream area. A number of experimental studies were carried out to determine the optimum size parameters of the conduits with different physical characteristics designed for this purpose and to determine their effects on the scour hole geometry. In our study we focus on the ability of high-pressure conduits to



(a)



(b)

Figure 2
Experimental setup, **a** stepped-channel chute, **b** definition sketch



Figure 2
continued

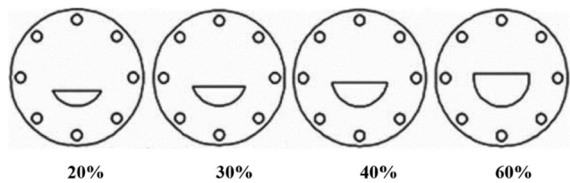


Figure 3
Circular cross-section conduit gates opening ratios

minimize the scour problem by focusing on the ability of high-pressure conduits to increase oxygen transfer efficiency and break the energy of the water jet by adding a large amount of air to downstream water flows. Our study is based on the potential to provide alternatives to improve the overall sustainability of water structures in terms of cost and efficient use and to increase the safety of the structure. When the literature is examined, there is no study on the scour problem caused by jets aerated by high-pressure conduits. In our study, in order to overcome this deficiency, we tried to determine the effects of conduits with different physical characteristics on the scour geometry. In recent years, conduits have been used extensively in wastewater treatment plants, aquaculture facilities, sluice gates, and drinking water installations. Prediction of the scour process downstream of these facilities is directly related to the safety and operational economy of the structure.

2. Dimensional Analysis

In this section, the physical variables affecting the local scour in conduit aerated water jets are discussed. In Fig. 2, the sketch of the experimental setup and the parameters affecting the event are shown schematically.

The local scour process change in the conduit aerated water jets differ according to the impact of physical parameters, including varying gate openings, downstream depths, and flow with distinct Froude numbers, on the aeration performance and scouring process in pressurized conduits. The gate opening of the conduit installed in the channel also have a great effect on the bed topography and the transported sediment discharge. It is known that the equilibrium state has been reached in which the bed geometry changes very little after a certain period of time (Rezaie-Balf, 2019).

In an open channel with a movable bed, the maximum local scour in the conduit aerated water jets (d_{smax}) can be expressed as a function of the parameters in Eq. (1).

$$d_{smax} = f(h_j, K, V_1, \rho, g, \mu, \beta, Q_a, Q_w, h_t, S_o, \sigma, \alpha, d_{50}, t)$$

(1)

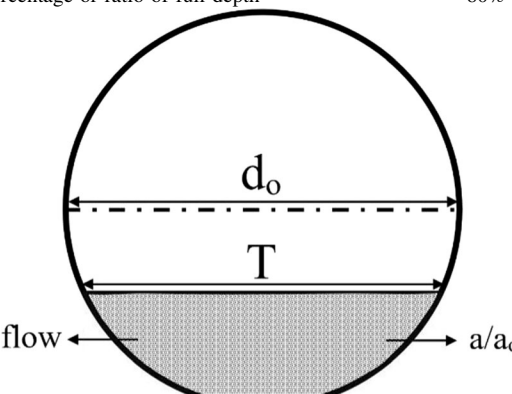
Here, d_{smax} is the maximum scour depth, h_j is the jet drop height, K is the gate opening ratio, V_1 is the water velocity at the gate outlet, ρ is the water density, g gravitational acceleration, μ dynamic

Table 2
The gate opening's dimensions

The ratio of gate openings (φ)	
20%	20.6 mm
30%	27.5 mm
40%	34.1 mm
60%	46.8 mm

Table 3

An example table for calculating the Froude number for full or partially full currents

Inputs		Outputs	
Pipe diameter (d_o)	0.0809 m	Depth of flow	0.0647 m
Manning roughness coefficient (n)	0.012	Flow area	0.004 m ²
Pressure gradient	2.1 (%)	Pipe area (a_o)	0.0051 m ²
Percentage or ratio of full depth	80%	Relative area (a/a_o)	85.76 (%)
		Wetted perimeter	0.1791 m
		Hydraulic radius	0.0246 m
		Upper width (T)	0.0647 m
		Velocity (v)	1.0217 m/s
		Velocity head (h_v)	0.0757 psi
		Froude number (Fr)	1.25
		Average shear stress (τ)	5.0677 N/m ²
		Full flow (Q_o)	0.0046 (m ³ /s)
		Ratio to full flow (Q/Q_o)	97.75 (%)

viscosity, β scour slope angle, Q_a air flow rate, Q_w water flow rate, h_t downstream hydrostatic water level, S_o channel bed slope, σ surface tension, α jet angle parameter, d_{50} average particle diameter, and t test duration. The effect of the channel bed slope (S_o) and surface tension (σ) can be neglected. The apex angle (α) of the conduit tested is constant. The used sediment median grain diameter (d_{50}) is constant. The test time (t) is constant. Equation (2) was obtained after the application of Buckingham Π Theorem Koochak and Bajestan (2016), which is frequently used as the relevant dimensional analysis method.

$$\frac{d_{smax}}{h_j} = f_1 \left(\frac{Q_a}{Q_w}, \frac{h_j}{h_t}, \frac{h_j \cdot g}{V_1^2}, \frac{\mu}{V_1 \cdot h_j \cdot \rho}, K, \beta \right) \quad (2)$$

In order to analyze the hydrodynamics effectively, after the necessary operations, the parameters were divided into each other and the dimensionless parameters in Eq. (3) were obtained. As a result; Eq. (4) is obtained.

$$\frac{d_{smax}}{h_j} = f_2 \left(\frac{Q_a}{Q_w}, \frac{h_j}{h_t}, \frac{h_j \cdot g}{V_1^2}, K, \beta \right) \quad (3)$$

$$\frac{d_{smax}}{h_j} = f \left(\frac{Q_a}{Q_w}, \frac{h_j}{h_t}, Fr, K, \beta \right) \quad (4)$$

in which; d_{smax}/h_j is the dimensionless maximum scour depth in the conduit aerated water jets, Q_a/Q_w is the dimensionless air flow rate, h_j/h_t is the dimensionless drop height, Fr is the Froude number, K is the conduit gate opening ratio and β is the scour hole slope angle.

3. Experimental Setup

The present study aimed to investigate the impact of physical parameters, including varying gate openings, downstream depths, and flow with distinct Froude numbers, on the aeration performance and scouring process in pressurized conduits. All experiments were conducted on experimental setups established in the Hydraulic Laboratory of Firat University Civil Engineering. The experiments were conducted using mains water. No discernible impact of suspended solids, organic matter, or salt, which might influence the efficiency of air intake and oxygen transfer, was observed in the mains water.

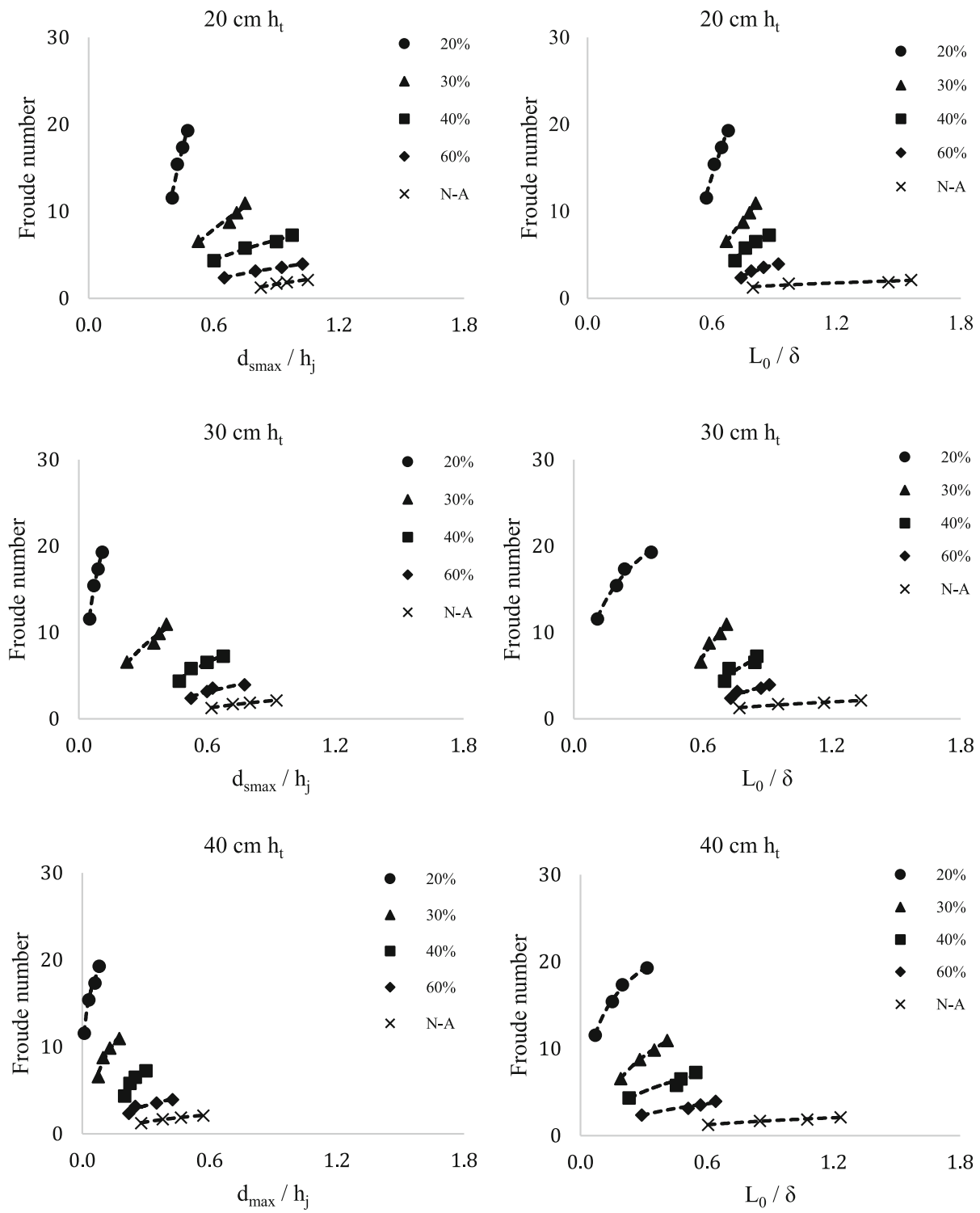


Figure 4

The relationship between the Froude number and the maximum scour parameters at different hydrostatic water levels

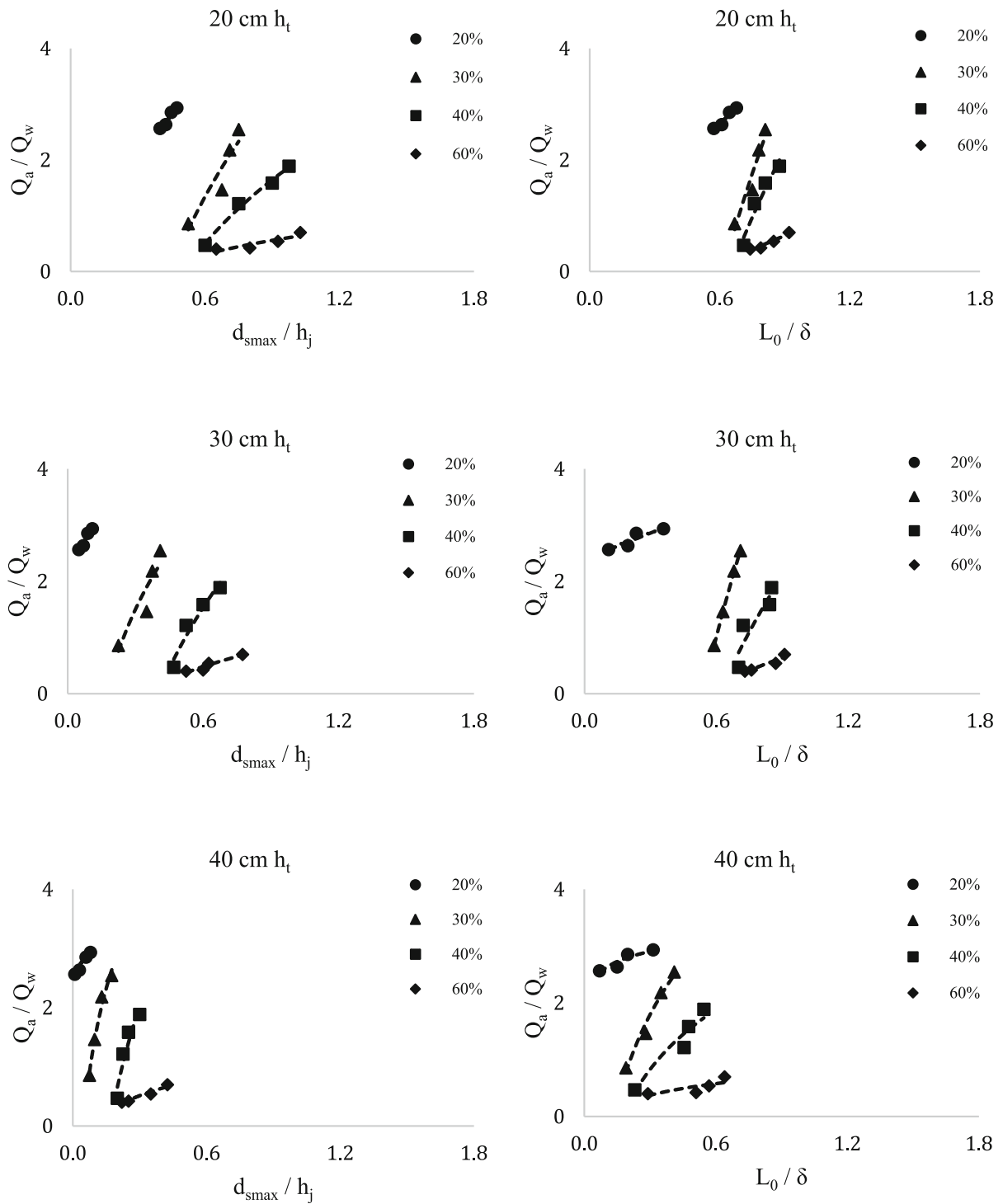


Figure 5

The relationship between the Q_a/Q_w ratio and the maximum scour parameters at different hydrostatic water levels

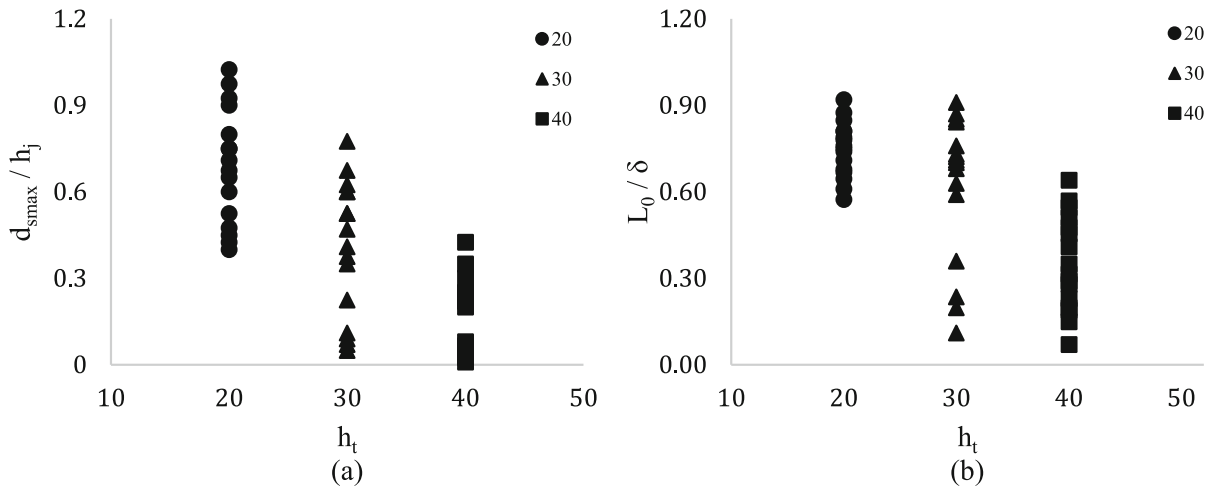


Figure 6

The relationship between the hydrostatic water levels and the maximum scour parameters for all experimental groups

The Fig. 2 illustrates the components used in the experimental setups. Where ' h_t ' is the hydrostatic water level, ' h_j ' is the drop height, ' d_{smax} ' is the maximum scour depth, ' L_0 ' is the length of the scour hole, ' δ ' is the horizontal distance of the jet from the maximum scour depth and ' β ' is the scour hole slope angle. In the course of the experiments, the system was operated in a reverse cycle. A suction hose supplied the water in the $1.5 \times 1.5 \times 3.0$ m tank to the pump (Fig. 2). The pump was utilized to elevate the pressure and subsequently deliver it to the system in a pressurized state. The flow control gate and

Kohne brand electromagnetic flow meter adjusted the water flow rate. The front side of the assembly was manufactured from tempered glass. In order to perform three-dimensional measurements (in the x, y, and z directions) of the scour parameters, a movable measuring stand was incorporated into the set-up, and an electronic limnimeter was placed on it. On the downstream side of the apparatus, a gate was installed that adjusts the hydrostatic level to the desired height and can move vertically.

The conduit used in this study was a circular-cross-section pipe with an internal diameter of

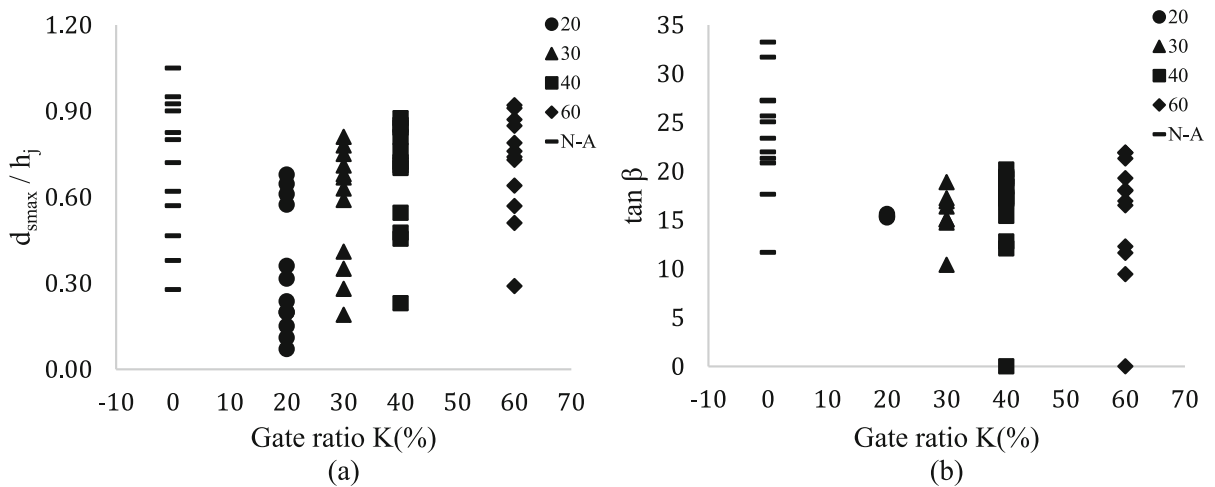


Figure 7

The relationship between the scour parameters of the conduit gate opening and the scour hole slope angles for all experimental groups

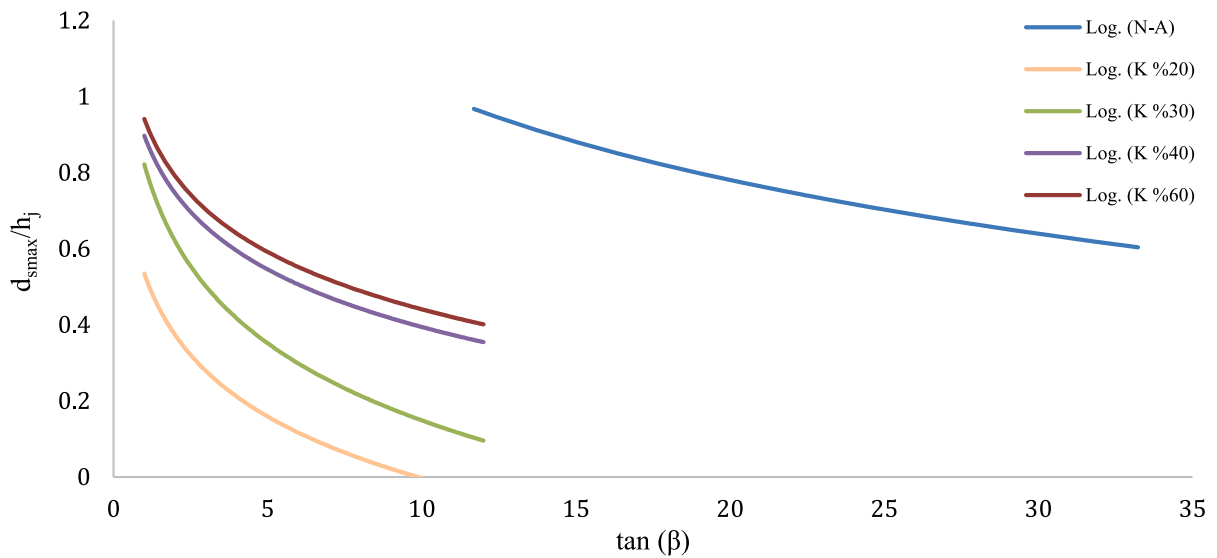


Figure 8
Change in normalized scour angle $\tan(\beta)$ for jets without aeration and with different aeration rates

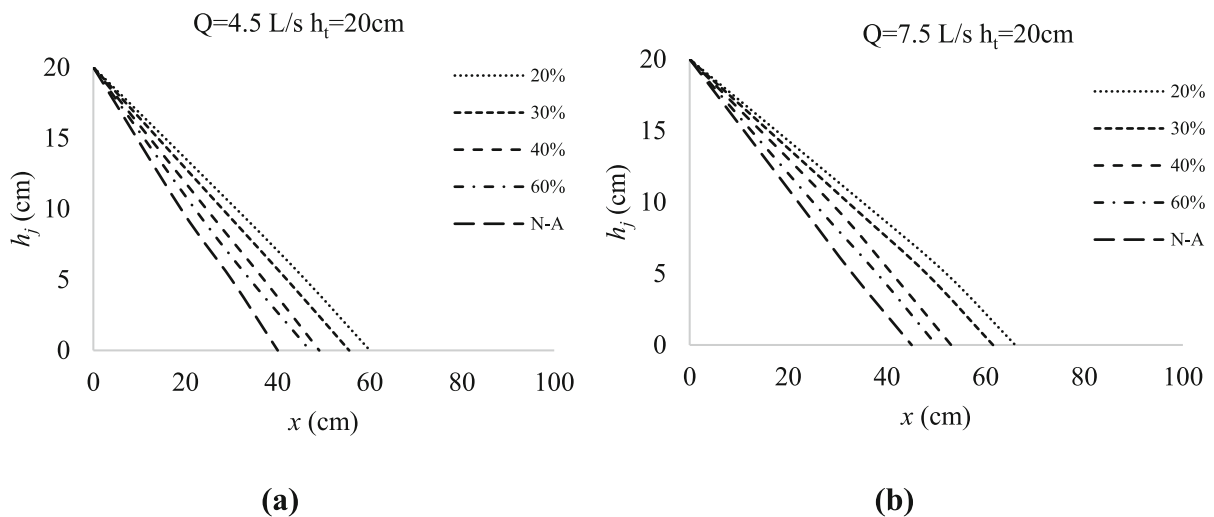


Figure 9
In the cases of aerated and non-aerated flow, a jet's trajectory: **a** for $Q = 4.5$ L/s, $h_t = 20$ cm; **b** $Q = 7.5$ L/s, $h_t = 20$ cm

80.9 mm and a length of 2.0 m. It was positioned at a 45-degree angle (45°) to the horizontal. Aeration was provided by natural suction through an atmospheric air entry pipe located at the cover outlet; no external pressurized air was applied to the system. The jet velocities obtained in the experiments were selected to produce Froude numbers in the range of 2.37–19.28; this range represents high-energy outlet jets. Sediment with a non-cohesive, uniform particle

size distribution was used in all experiments. This ensured that changes in the scour geometry were primarily due to flow conditions and aeration levels. The experimental design was based on Froude similarity, which is commonly used in free-surface jet flows.

The experiments were carried out separately for each gate opening. For each experimental setup, experiments were conducted at the same drop height,

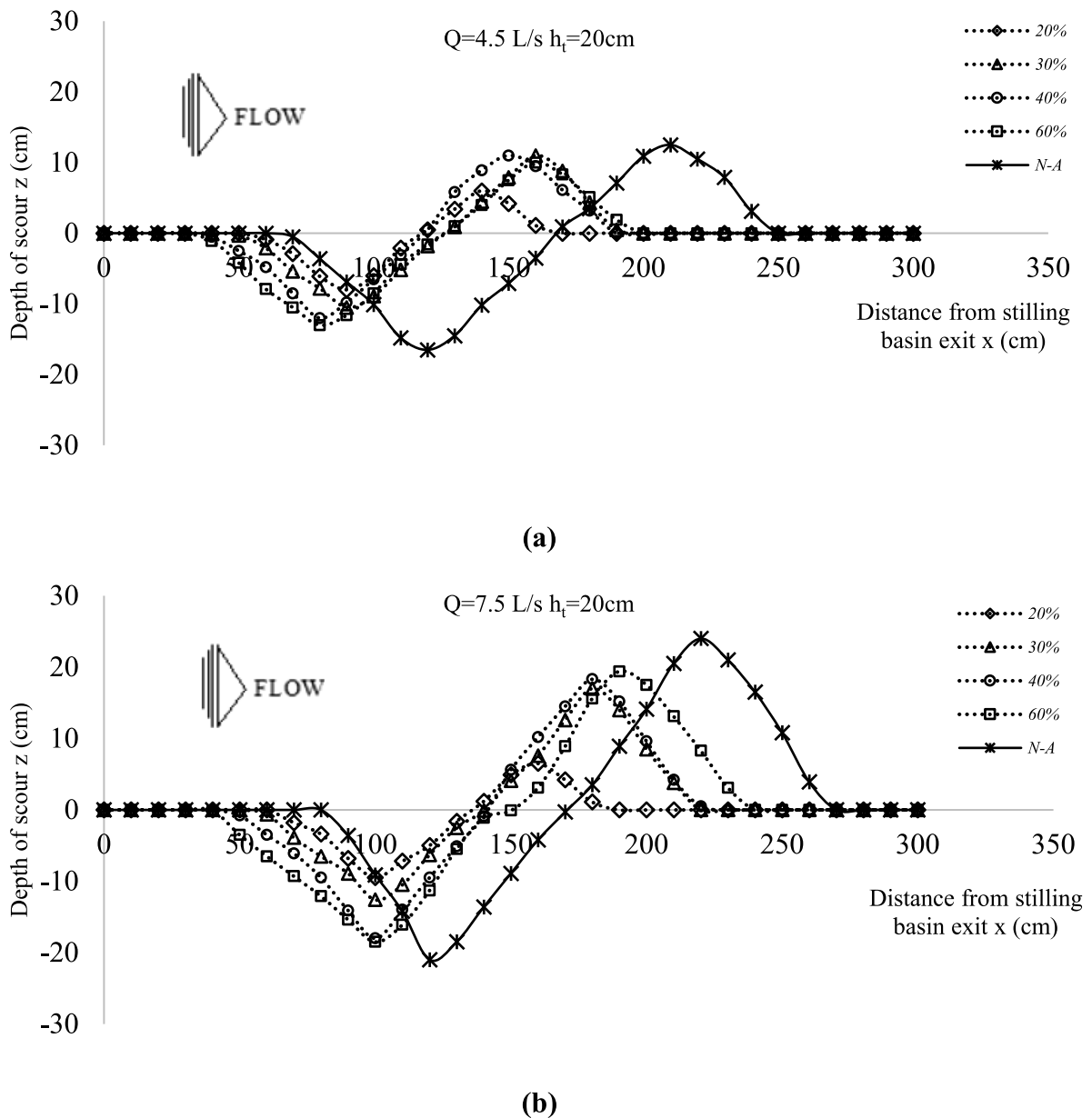


Figure 10

Longitudinal sections from maximum scour depth area: **a** for $Q = 4.5$ L/s, $h_t = 20$ cm; **b** $Q = 7.5$ L/s, $h_t = 20$ cm

three different downstream water levels, and different flow rates. In this context, a total of 60 different experiments were conducted and 60 different scour hole were analyzed. The parameters used in the experiments are given in Table 1. This study is an experimental study based on a clean water scouring technique. Therefore, after the scouring process in the scouring hole formed in each experimental parameter

reached equilibrium, the water flow was stopped and measurements were taken.

The opening ratios for the conduits were selected as 20, 30, 40, and 60 percent (Fig. 3). Table 2 provides the dimensions of the constrictions for each cross-section.

An air inlet pipe was opened just downstream of the gate in order to facilitate the introduction of

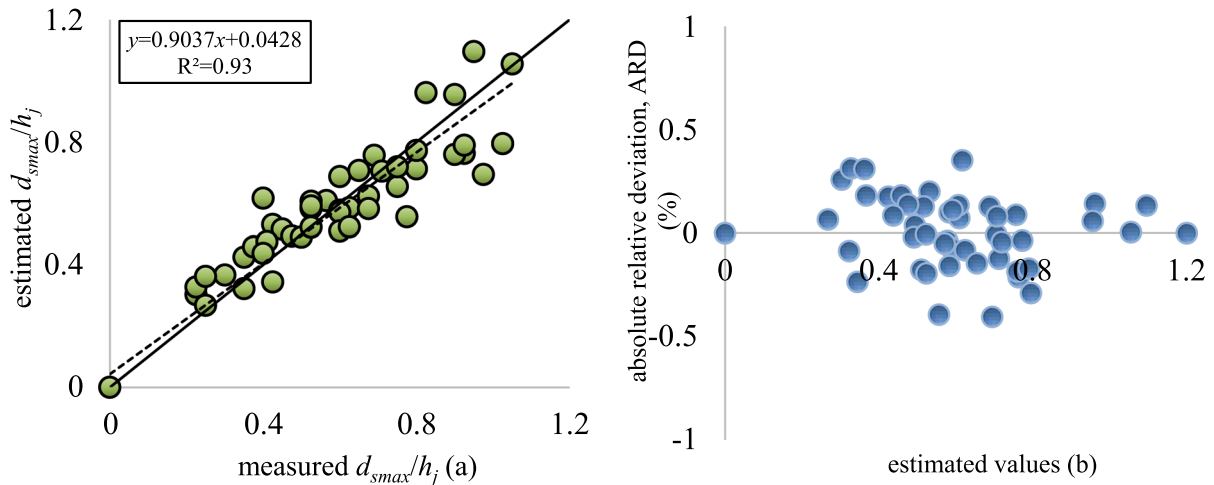


Figure 11

a Comparison of the measured and estimated values of dimensionless discharge of transported sediment; **b** absolute relative deviation (ARD) of the predicted values

atmospheric air into the water. The air inlet pipe consists of a pipe measuring 15 mm in diameter and 200 mm in height. The velocity of the air entering the system was quantified using a Testo 435 anemometer.

A series of experiments were conducted using different flows. Although free surface flow was observed at low flow, pressurized flow was observed at higher flow. The Froude number under the gate was calculated for each flow rate.

Froude numbers (Fr) were between 2.37 and 19.28. The Froude number was calculated by using Eq. (5) using the effective depth (y_e) in the conduit (Table 3).

$$Fr = \frac{V}{\sqrt{g y_e}} \quad (5)$$

where V is water velocity at gate location, g is acceleration of gravity and y_e , effective depth, is water cross-sectional flow area divided by water surface width. In the literature Froude number has often been based on the vena contracta section. Because high-head gated conduits involve high-velocity air–water mixture flow, to avoid the problem of determining flow depths and velocities at the vena

contracta section, in this study the Froude number was based on the effective depth in the conduit. The velocity used in the froude number calculations was measured under the constriction flap and in the area where the air has not yet mixed with the flow (vena contracta).

In the anemometer measurements, the velocity probe was placed in the center of the air inlet pipe. The anemometer measured each air velocity for 60 s, thereby determining its average. The average air velocity measured in the air inlet pipe was multiplied by the area of the air inlet pipe to calculate the air flow rate.

4. Experimental Procedure

The sediment bed was placed in the channel and manually leveled before each run. Flow rate was set using the electromagnetic flowmeter. The downstream water level was adjusted with the tailgate. Air velocity was measured inside the inlet pipe, and air discharge was obtained from these measurements. Experiments were carried out until no further change

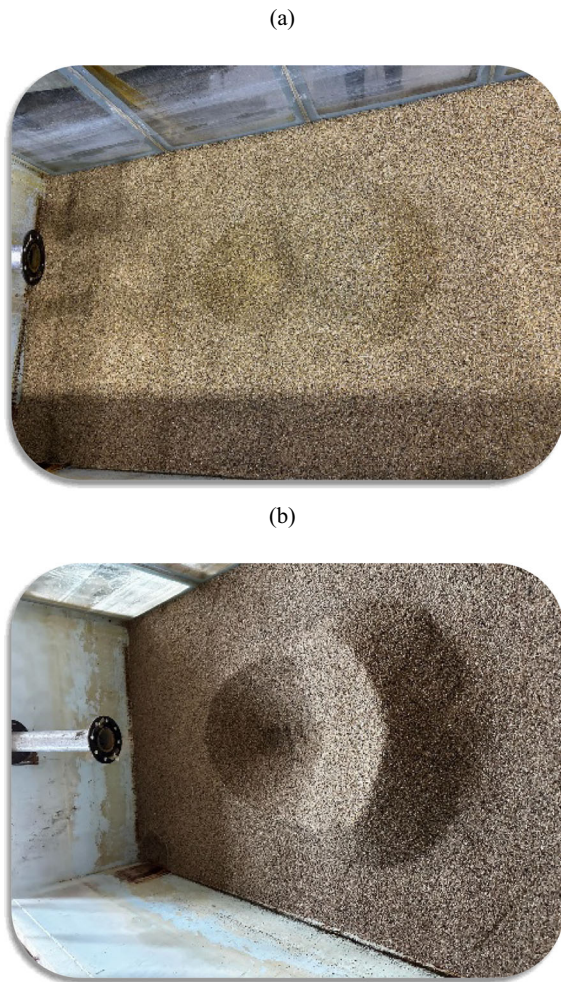


Figure 12

Relationship of control gate height with the scour geometry **a** for $Q = 4.5$ L/s, $h_t = 20$ cm; **b** $Q = 7.5$ L/s, $h_t = 20$ cm

in bed shape was observed. The flow was then stopped. Scour depth and bed geometry were measured using the electronic limnimeter and the movable measuring frame.

5. Uncertainty Analysis

The reliability of the measurements used in this study was evaluated through a basic uncertainty assessment. The electromagnetic flow meter employed for discharge measurements has an accuracy of $\pm 0.5\%$. Air velocity in the inlet pipe was measured with a Testo 435 device with an accuracy

of ± 0.03 m/s. The scour depths were recorded using an electronic limnimeter with a resolution of ± 0.1 mm, and geometric dimensions were checked with a steel ruler (± 0.5 mm).

6. Results and Discussion

Figure 4 is analyzed to examine the d_{smax}/h_j and L_o/δ values of non-aeration jets (N-A, 0%) and aeration jets (20%, 30%, 40% and 60%) with different conduit gate openings in the experimental groups with hydrostatic water depths of $h_t = 20, 30$, and 40 cm. It can be observed that the values of d_{smax}/h_j and L_o/δ are at their maximum in the experimental series where the hydrostatic water level is $h_t = 20$ cm with the same froude number. In contrast, the values of d_{smax}/h_j and L_o/δ are at their minimum when the hydrostatic water level is $h_t = 40$ cm. All experimental groups maximized both parameters in non-aeration jets. The maximum scour hole depth and width for non-aeration jets tend to increase significantly with an increase in the Froude number. In contrast, in aerated jets, the depth and width of the hole have a lower, increasing trend.

Upon examination of Fig. 5, it can be observed that the values of d_{smax}/h_j and L_o/δ are also maximized in the experimental series where the hydrostatic water level is $h_t = 20$ cm with the same Q_a/Q_w values. Conversely, the values of d_{smax}/h_j and L_o/δ are minimized when the hydrostatic water level is $h_t = 40$ cm. The scour depths and widths were minimal at low gate openings where the Q_a/Q_w values were maximized. It has been observed that the scour parameters d_{smax}/h_j and L_o/δ values tend to increase at large conduit gate openings where the Q_a/Q_w values are relatively low. As the conduit gate opening increases, the scour parameters also increase in parallel. Consequently, the scour parameters decline as the aeration quantity of the jet increases. The phenomenon in question can be elucidated as follows: the introduction of air into the water jet results in a reduction in the specific gravity of the jet, accompanied by a corresponding decline in the momentum value. This results in a decrease in the scour parameters' values.

Table 4
Empirical equations in the literature for the estimation of scour depth

References	Equation
Nou et al. (2020)	$\frac{D}{H} = f\left(SN, \frac{Y_i}{H}, \frac{d_{50}}{H}\right)$
Heng et al. (2012)	$D = \frac{7.483g^{1.4652}}{g^{0.7326}Y_i^{1.1978}}$
Muzzammil and Siddiqui (2009a, 2009b)	$\frac{D}{H} = 14.68 \left(\frac{q}{\sqrt{gH^3}}\right)^{1.236} \left(\frac{h}{H}\right)^{-0.269} \times \left(\frac{R_1}{H}\right)^{-0.212} \left(\frac{d}{H}\right)^{0.0658} (\theta)^{0.0911}$
Muzzammil and Siddiqui (2009a, 2009b)	$\frac{d}{h} = 1.40 \left(\frac{h}{H}\right)^{0.72} \sigma_s^{-0.27} F^{0.22}$
Sui et al. (2008)	$\frac{d_{sc}}{H} = 3 \times 10^{-5} \left(\frac{F_0 \left(\frac{B}{d_0}\right)^{0.1}}{\frac{H}{d_0}}\right)^3 - 3.3 \times 10^{-3} \left(\frac{F_0 \left(\frac{B}{d_0}\right)^{0.1}}{\frac{H}{d_0}}\right)^2 + 28.5 \times 10^{-2} \left(\frac{F_0 \left(\frac{B}{d_0}\right)^{0.1}}{\frac{H}{d_0}}\right)$
This study	$\frac{d_{smax}}{h_j} = -0.215 + 0.102 \times K - 0.020 \times Fr + 0.024 \times \beta + 0.088 \times \frac{Q_a}{Q_w} + 0.441 \times \frac{h_j}{h_t}$

As shown in Fig. 5, the relationship between d_{smax}/h_j and Q_a/Q_w is due to changes in air and flow rates, as well as gate opening and jet hydrodynamics. At small gate openings, the rate of air intake increases and the Q_a/Q_w value rises accordingly. Consequently, jet density decreases, energy loss increases, and less momentum is transferred to the bed. Consequently, the scour depth decreases. As the gate opening increases, the air intake rate decreases, and so does the Q_a/Q_w value. Consequently, the jet becomes denser and more energetic. Additionally, the dynamic pressure applied to the bed increases and the scour depth grows. Therefore, it can be concluded that an increase or decrease in the d_{smax}/h_j value is not solely dependent on the aeration rate but is also influenced by changes in jet momentum and gate opening occurring simultaneously.

The reducing effect of aeration on the scour hole can be explained by changes in the jet's hydrodynamic properties. As the amount of air mixed into the jet increases, the effective density of the flow decreases. Consequently, the momentum transferred to the bed also decreases. During the experiments, it was observed that aerated jets made contact with the scour hole at a greater distance. Furthermore, it was observed that the scour angle decreased and the maximum scour depth decreased significantly. This behavior indicates that aeration weakens the dynamic effect of the jet and limits the turbulence intensity in

the bed-jet interaction region. Therefore, under natural aeration conditions, the jet's energy is more effectively dissipated, and the scour geometry becomes shallower.

Figure 6a, b illustrates the impact of hydrostatic water level on d_{smax}/h_j and L_0/δ values at varying flow rates, including non-aerated jet (N-A, 0%) and aerated jet (20%, 30%, 40%, and 60%). In the same way, Fig. 7a, b shows what happens to d_{smax}/h_j and β angle values when the conduit gate opening values change (air intake status) at different flow rates and water levels. Figure 6a, b illustrates a consistent decline in both the d_{smax}/h_j and L_0/δ values across all experimental series as the hydrostatic water level increases. Figure 7a shows that as the conduit gate opening increases, the d_{smax}/h_j values increase in all series of experiments. The data indicates that the highest d_{smax}/h_j value is obtained with the non-aerated jet (N-A). As illustrated in Fig. 7b, the $\tan \beta$ values exhibit an upward trend in all experimental series as the gate opening increases. The data indicates that the highest $\tan \beta$ value is obtained with the non-aerated jet (N-A). In consideration of the aforementioned comments, it can be concluded that when the hydrostatic water level is elevated and the conduit gate opening value is diminished, the quantity of scour on the downstream side is diminished as well. In the case of the comparison of aerated and non-aerated jets, it is observed that the amount of scour is

greater in the downstream portion of the non-aerated jet.

As can be seen from the graph in Fig. 8, there is a direct relationship between the value of the pipe gate opening, the maximum depth of the scour hole, and the value of the slope angle. The non-aeration case showed the largest values for the hole depth and the slope angle. Namely, while the slope angles of the non-aeration jets were up to 35, the slope angles of the aeration jets were observed to be around 7 on average. This clearly indicates a decrease in the scour hole angle of the aerated jets.

It was observed that the Q_a/Q_w value significantly affected the jet trajectory in the experimental groups. Figure 9a, b reveals that an increasing Q_a/Q_w value causes the jet trajectory shifts downstream to more distant points. As the Q_a/Q_w value decreases, the jet approaches upstream. The explanation for this is that while the aeration jets are lighter (water and air) and therefore spread out further, the non-aeration jets are heavier and therefore fall in the immediate vicinity. This allows the scour hole to be moved further away from the body of the hydraulic structure. There are different gate openings ($K = 20\%$, 30% , 40% , 60%) and no-aeration (N-A, $K = 0\%$) in Fig. 9a, b. The jet discharges are 4.5 L/s, 7.5 L/s, and the height is 20 cm. Figures 9a, b examine the impact of non-aeration and varying gate openings on the jet trajectory for a given drop height ($h = 20$ cm) at varying flow rates. The non-aeration (N-A) case showed the closest distance to the jet exit opening upon examination of the findings, while the horizontal distance to the jet exit opening decreased as the gate opening value increased. The increase in rate is calculated as 50% for Fig. 9a and 46.7% for Fig. 9b between the "N-A" case and the 60% gate opening. As can be observed, the standard deviation value between the two cases was calculated to be 6.6%. As the flow rate increases, the horizontal distance between the point where the water jet falls and the gate also increases due to the increasing momentum. The distance between the exit point of the water jet and the point of impact on the downstream pool is calculated to increase by approximately 9.5% on average, with an increase of 66.7% in the flow rate. This demonstrates that the value of flow alters the impact on the jet trajectory. Consequently, as the momentum of the

water jet increases, the angle of impact with the surface of the water decreases. This occurs because the jet falls a greater distance as it accelerates. The aforementioned flow characteristics of the jet exert a significant influence on the scour geometry. Upon examination of Fig. 9b in isolation, it can be observed that the non-aerated jet ($Q_a/Q_w = 0$) falls a distance of 45 cm further downstream of the structure. The experiment alternative with a 20% gate opening ($Q_a/Q_w = 2.93$), which provides the highest aeration at the same flow rate, was observed to fall 66 cm downstream of the structure. This implies that the scour hole transports the aerated jets a greater distance downstream.

In this study, the increase in the jet contact distance downstream is related more to the change in the flow characteristics of aeration than to the jet penetrating more strongly. In aerated jets, the air–water mixture has a lower effective density, causing the jet to advance with a wider spread. In contrast, non-aerated jets exhibit a more compact structure and make contact closer to the exit point on the water surface. In the experiments, it was observed that as the Q_a/Q_w ratio increased, the jet's contact point shifted downstream and the scouring zone moved away from the structure. This indicates that increased aeration weakens the effect of the jet on the bed while increasing the horizontal spread of the flow. Therefore, the observed increase in distance can be explained by the change in the jet's trajectory rather than momentum.

Figure 10a depicts the cross-sections of the scour geometry in the downstream pool for a $Q = 4.5$ L/s and a depth of 20 cm, while Fig. 10b illustrates the cross-sections of the scour geometry in the downstream pool for a $Q = 7.5$ L/s and a depth of 20 cm. In particular, changes to the conduit gate opening have a significant impact on the geometry of the scour hole. It is observed that the maximum value of the scour depth occurs for the non-aerated jet (N-A), while with the decrease in the gate opening ratio, the air rate entering the jet increases and significantly reduces the scour. Furthermore, as the flow rate increases, the volume of the scour hole increases.

An empirical formula for the estimation of the maximum scour depth was developed based on the results of the experimental study. Therefore, the

multiple linear regression method and statistical significance values are presented in the results section along with the ANOVA test and R^2 accuracy analysis. Figure 11 presents the values obtained from the analysis and the values obtained from the experimental observations. The correlation coefficient (R^2) between the obtained results and the observation results is 0.93.

$$\frac{d_{smax}}{h_j} = -0.215 + 0.102 \times K - 0.020 \times Fr + 0.024 \times \beta + 0.088 \times \frac{Q_a}{Q_w} + 0.441 \times \frac{h_j}{h_t} \quad (6)$$

The variables in question are as follows: ' d_{smax} ' represents the maximum scour depth (m), ' Fr ' is the Froude number (-), ' K ' is the conduit gate opening ratio (%), ' β ' is the scour hole slope angle ($^\circ$), ' Q_a ' is the air flow rate (m^3/s), ' Q_w ' is the water flow rate (m^3/s), and ' h_j ' is the drop height (m). Finally, ' h_t ' denotes the hydrostatic water level (m).

Furthermore, the data obtained from the experiments were compared with the data obtained from the model to verify the accuracy and limitations of the developed model. To assess the accuracy of Eq. (6), the absolute relative deviation (ARD) was calculated using Eq. (7) (Mahdaviara et al., 2020).

$$ARD(\%) = \frac{Experimental - Model}{Experimental} \times 100 \quad (7)$$

Figure 11b shows that the absolute relative deviation (ARD) values are mostly distributed around the zero axis. The model developed in this study was found to have high accuracy, with deviation values generally between -0.4% and $+0.4\%$. In addition to the statistical analysis based on the d_{smax}/h_j value, the physical properties of the scour results of the model proposed in the study were also examined through experimental findings. The erosion profiles and base topographies presented in Figs. 10 and 12 show that as the Q_a/Q_w ratio increases, the erosion pits become shallower, the slope angles decrease, and the jet contact point shifts downstream. These situations are consistent with the parameters Q_a/Q_w , β , and h_j/h_t , particularly those in Eq. (6). The flattening of the scour profiles under high aeration conditions reveals that the air mixture reduces the momentum

transferred by the jet to the bed. Therefore, model validation is not limited to maximum scour depth; it is also supported by the temporal and spatial variation of the measured scour geometry, demonstrating that the developed relationship can represent both the scour size and the hydraulic behavior associated with aerated jet–bed interaction.

Following the conclusion of the pertinent experiments, regular measurements were taken with a limnimeter to ascertain the bottom topography. Figure 12a depicts images at the end of the experiment in the downstream pond with a $Q = 4.5$ L/s and a $h_t = 20$ cm. Figure 12b presents the same information for a $Q = 7.5$ L/s and a $h_t = 20$ cm. As shown in Fig. 12a, water spilled from the non-aeration (N-A) conduit created the maximum scour hole approximately 10 cm from the beginning of the scour chamber. It has been observed that the pitting occurs in a symmetrical manner. The maximum scour depth was determined to be approximately 16.5 cm. A sand pile with a maximum height of 12 cm was formed by the material being transported and deposited in this manner. The sand pile was distributed in a crescent shape across the width of the scour chamber. As illustrated in Fig. 12b, the water that spilled from the non-aeration (N-A) conduit created the greatest scour hole, situated approximately 30 cm from the beginning of the scour chamber. It can be observed that the scour hole is approximately symmetrical. The maximum scour depth was determined to be approximately 21 cm. The carved material carried forward, forming a sand pile with a maximum height of 24 cm. The sand pile was distributed in a crescent shape across the width of the scour chamber.

So far, many studies have been carried out on the scour mechanism occurring downstream in many subjects (water jets, ski-jumps, free-fall spillways, etc.) in order to develop a relationship to predict the maximum scour depth. Table 4 shows some of the empirical relationships available in the literature and developed in this regard.

When examining the studies in Table 4, most empirical relationships have been developed based on ski-jump and wall jet experiments, where the effect of aeration is either negligible or quite limited. Sui et al. (2008) particularly highlight jet expansion, downstream water depth, and densimetric Froude number;

Muzzammil and Siddiqui (2009a, 2009b) relate scour depth more to flow power and sediment properties. Nou et al. (2020) examine the behavior of protective structures. A common feature of the studies in Table 4 is that they do not include any term that directly incorporates the reducing effect of aeration on scouring. The empirical equation presented in this study, however, explicitly accounts for the fact that aeration reduces scouring depth by decreasing jet intensity. This makes it both consistent with the general trend in the literature and provides a more suitable explanation for conditions where high aeration is observed. In this respect, the proposed approach is complementary to existing equations and is expected to be applicable to data sets with similar hydraulic structures.

Previous experimental studies have shown that changes in the structure of the jet flow directly affect the scour geometry. In line with this, the current study also found that an increase in air mixing reduces jet density and significantly decreases the dynamic forces transferred to the jet-ground interaction zone. This finding is consistent with the findings of Xu et al. (2004), who showed that aeration reduces jet momentum and thus decreases scour depth. Xu et al. (2004) determined the effect of aeration by comparing the scour holes and profiles caused by aerated and non-aerated jets. In addition, a quantitative relationship between aeration rate and scour depth was to be established. It was stated that the scour pit profile was mainly dependent on the scour depth under the same bed material and tailwater depth conditions and was affected by the air concentration in the test interval.

The findings obtained from this study are also consistent with the mechanisms described in the literature. As the natural air mixture in the conduits increased, the decrease in jet density led to a reduction in the pressure applied by the jet to the bed and, consequently, a decrease in the maximum scour depth. Furthermore, the increased aeration rate caused the point of contact between the jet and the water surface to shift to a more advanced region. This behavior is generally consistent with the

hydrodynamic findings of Chen et al. (2022), which revealed that the jet flow structure affects the scour geometry. The smaller scour slope angles and more limited scour volume observed under aerated conditions are consistent with the findings of Xu et al. (2004), who concluded that air mixing limits scour by weakening the dynamic effect of the jet. In this respect, the present study demonstrates the potential of natural air intake in high-pressure conduits to reduce scour severity and provides evidence that will contribute to the safe design of hydraulic structures.

This study experimentally examines how different Q_a/Q_w levels, governed by the gate opening of a pressurized conduit, influence scour geometry downstream. Unlike previous investigations that primarily focused on free jets or plunge pools, the present work evaluates the conduit gate parameters–aeration–jet trajectory–scour response within a experimental setup. Accordingly, the results provide direct experimental evidence of how the natural aeration level (Q_a/Q_w) affects both the scour depth and geometry. It also provides a practical estimation relationship for d_{smax} in pressurized channel jets.

7. Study Limitations

The results presented here are obtained from laboratory-scale experiments performed under controlled hydraulic conditions. For this reason, the observed scour depths and jet characteristics should be interpreted as representative physical responses rather than direct estimates for field applications. The experimental outcomes mainly describe how natural aeration modifies jet behavior and scour geometry in high-energy tailwater flows. While actual performance may differ in prototype structures due to scale effects and site-specific conditions, the findings help clarify the role of air–water interaction in reducing jet intensity and downstream erosion. From a practical perspective, these results may assist engineers in evaluating aeration-based approaches for energy dissipation and scour mitigation. Further studies considering different sediment sizes, conduit

configurations, and extended hydraulic ranges would help broaden the applicability of the experimental observations.

8. Conclusion

The present study employed a comprehensive experimental investigation to examine the effects of channel parameters on aeration performance and scour processes under varying gate openings, flow rates, and downstream conditions. The results showed that scour hole parameters decreased as the aeration level of the jet increased. Conduit gate opening had a pronounced influence on scour geometry, with the maximum scour depth observed in non-aerated jets (N-A). As the gate opening ratio decreased and the air ratio entering the jet increased, scour depth was significantly reduced. In non-aerated jets, both scour depth and width increased markedly with Froude number, whereas aerated jets exhibited a much lower increasing trend. Non-aerated jets produced scour slope angles as high as 35° , while aerated jets averaged approximately 7° , indicating a substantial reduction in slope under aerated conditions. In addition, the jet impact point was located closest to the outlet in the non-aerated case, whereas increasing gate opening shifted the impact point downstream by approximately 50% on average. An empirical equation for maximum scour depth was obtained from the experimental data, showing strong agreement between measured and predicted values ($R^2 = 0.93$).

The experiments demonstrate that natural air mixing generated under different gate openings affects the scouring process and can be considered during design. Aeration shifts the jet impact point downstream and reduces bed interaction intensity, providing additional safety in the dimensioning of protection structures. The tests were conducted at laboratory scale with specific sediment conditions and limited gate openings; therefore, studies including different particle sizes, conduit geometries, and

wider flow ranges would broaden applicability. Field implementation depends on site-specific sediment properties, hydraulic conditions, and operating regimes, and laboratory results should be interpreted with caution and evaluated individually for each application. In practical design, downstream protection length and tailwater depth should be selected by considering the downstream shift of the jet impact point and its influence on scour slope and scour volume.

Author Contributions M. Cihat TUNA: conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing—original draft, writing—review and editing. Ramazan ACAR: conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing—original draft, writing—review and editing. Mustafa TUNÇ: conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing—original draft, writing—review and editing.

Funding

Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). The authors declare that no funds, grants, or other support was received during the preparation of this manuscript.

Data Availability

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

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

- Aminpour, Y., & Farhoudi, J. (2017). Similarity of local scour profiles downstream of stepped spillways. *International Journal of Civil Engineering*, 15, 763–774.
- Aydin, A., Baylar, A., Ozkan, F., Tuna, M., & Ozturk, M. (2023). Role of closed conduit gate type in the air-demand ratio. Available at SSRN 4470070.
- Aytac, A., Kelestemur, G., & Tuna, M. (2024). An effective aeration system for high performance pond aeration at low energy cost. *Aquaculture International*, 32(5), 6869–6886.
- Aytac, A., & Tuna, M. (2023). Development of a new generation flotation cell and monitoring of air bubbles. *Water Practice and Technology*, 18, 27–39.
- Bai, R., Zhang, F., Liu, S., & Wang, W. (2016). Air concentration and bubble characteristics downstream of a chute aerator. *International Journal of Multiphase Flow*, 87, 156–166.
- Barrie, A., Wang, C., Liang, F., & Qi, W. (2024). Experimental investigation on the mechanism of local scour around a cylindrical coastal pile foundation considering sloping bed conditions. *Ocean Engineering*, 312, Article 119225.
- Baylar, A., Hanbay, D., & Ozpolat, E. (2008). An expert system for predicting aeration performance of weirs by using ANFIS. *Expert Systems with Applications*, 35(3), 1214–1222.
- Baylar, A., Ozkan, F., Yildirim, C., Aydin, A., Tuna, M., & Ozturk, M. (2022). The role of cross-sectional geometry of high-head gated conduit in oxygen transfer efficiency. *Water and Environment Journal*, 36, 372–379.
- Chen, J., Wang, X., Shi, H., & Si, J. (2023). Experimental investigation on flow characteristics of vertical and oblique circular impinging jet. *Physics of Fluids*, 35(5), 055139.
- Chen, J., Zhang, G., Si, J., Shi, H., & Wang, X. (2022). Experimental investigation of scour of sand beds by submerged circular vertical turbulent jets. *Ocean Engineering*, 257, Article 111625.
- Curulli, G., Penna, N., & Gaudio, R. (2023). Improved formulation for the geometric characteristics of the scour hole and deposition mound caused by a rotating propeller jet on a mobile bed. *Ocean Engineering*, 267, Article 113175.
- Dey, S., & Sarkar, A. (2007). Effect of upward seepage on scour and flow downstream of an apron due to submerged jets. *Journal of Hydraulic Engineering*, 133, 59–69.
- Elnikhely, E. (2018). Investigation and analysis of scour downstream of a spillway. *Ain Shams Engineering Journal*, 9, 2275–2282.
- Gharibi, S., Esmaeili Varaki, M., Mahmoudi Kurdistani, S., & Malekpour, A. (2022). Experimental investigation of effect of labyrinth and apron on local scour downstream of stepped weirs. *Irrigation and Drainage Structures Engineering Research*, 22, 1–26.
- Habib, A., Fahmy, M., & Taha, N. (2016). Scour characteristics downstream converging spillways. *The Egyptian International Journal of Engineering Sciences and Technology (EIJEST)*, 19, 258–266.
- Heng, S., Tingsanchali, T., & Suetsugi, T. (2012). Prediction formulas of maximum scour depth and impact location of a local scour hole below a chute spillway with a flip bucket. *WIT Transactions on Ecology and the Environment*, 172, 251–262.
- Johnson, G. (1967). The effect of entrained air on the scouring capacity of water jets. In *Proceedings of the 12th congress of International Association for Hydraulic Research, Fort Collins, Colo Paper C. 26* (pp. 218–226).
- Kazempour Larsari, Z., Esmaeili Varaki, M., & Malekpour, A. (2019). Laboratory study of scour downstream of stepped-Labyrinth weirs. *Iranian Journal of Soil and Water Research*, 49, 1227–1241.
- Kesgin, E., Kuzgun, R., Kesgin, R. İT., & Gezici, K. (2025). Experimental analysis of single propeller scour dynamics near vertical and parallel quay walls. *International Journal of Pure and Applied Sciences*, 11(1), 252–268.
- Koochak, P., & Bajestan, M. S. (2016). The effect of relative surface roughness on scour dimensions at the edge of horizontal apron. *International Journal of Sediment Research*, 31(2), 159–163.
- Kramer, M., Wieprecht, S., & Terheiden, K. (2016). Penetration depth of plunging liquid jets—a data driven modelling approach. *Experimental Thermal and Fluid Science*, 76, 109–117.
- Lashkar-Ara, B., Baharvand, S., & Najafi, L. (2020). The study of the performance of data-driven models to predict the scour depth caused by the aerated vertical jet. *Irrigation Sciences and Engineering*, 43(4), 79–89.
- Mahdaviara, M., Rostami, A., & Shahbazi, K. (2020). State-of-the-art modeling permeability of the heterogeneous carbonate oil reservoirs using robust computational approaches. *Fuel*, 268, Article 117389.
- Mao, J., Si, J., Chen, J., Li, G., & Wang, X. (2023). Experimental investigation on sand bed scour by an oblique planar water jet at varying impinging angles. *Ocean Engineering*, 279, Article 114526.
- Martínez-Bazán, C., Montanes, J., & Lasheras, J. (2002). Statistical description of the bubble cloud resulting from the injection of air into a turbulent water jet. *International Journal of Multiphase Flow*, 28, 597–615.
- Mason, P. J. (1989). Effects of air entrainment on plunge pool scour. *Journal of Hydraulic Engineering*, 115(3), 385–399.
- Mostaani, A., & Azimi, A. (2022). Analytical approach for predicting local scour downstream of submerged sluice gate with an apron. *International Journal of Sediment Research*, 37, 522–537.

- Muzzammil, M., & Siddiqui, N. A. (2009a). A reliability-based assessment of bridge pier scour in non-uniform sediments. *Journal of Hydraulic Research*, 47(3), 372–380.
- Muzzammil, M., & Siddiqui, N. A. (2009b). Reliability analysis of scour downstream of a ski-jump bucket. *Proceedings of the Institution of Civil Engineers-Water Management*, 162(6), 389–398.
- Neto, I., Zhu, D., & Rajaratnam, N. (2008). Air injection in water with different nozzles. *Journal of Environmental Engineering*, 134, 283–294.
- Nou, M. R. G., Moghaddam, M. A., Bajestan, M. S., & Azamathulla, H. M. (2020). Control of bed scour downstream of ski-jump spillway by combination of six-legged concrete elements and riprap. *Ain Shams Engineering Journal*, 11(4), 1047–1059.
- Puri, D., Kumar, R., Sihag, P., Thakur, M., Perveen, K., Alfaisal, F., & Lee, D. (2023). Analytical investigation of the impact of jet geometry on aeration effectiveness using soft computing techniques. *ACS Omega*, 8(35), 31811–31825.
- Rezaie-Balf, M. (2019). Multivariate adaptive regression splines model for prediction of local scour depth downstream of an apron under 2D horizontal jets. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 43(1), 103–115.
- Salmasi, F., & Abraham, J. (2022). Multivariate nonlinear regression for predicting free falling-jet scouring: An experimental study. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 46, 3859–3870.
- Salmasi, F., Sihag, P., Abraham, J., & Nouri, M. (2023). Experimental investigation and prediction of free fall jet scouring using machine learning models. *International Journal of Sediment Research*, 38, 405–420.
- Schmocker, L., Pfister, M., Hager, W., & Minor, H. (2008). Aeration characteristics of ski jump jets. *Journal of Hydraulic Engineering*, 134, 90–97.
- Sharafati, A., Tafarjoruz, A., Shourian, M., & Yaseen, Z. (2020). Simulation of the depth scouring downstream sluice gate: The validation of newly developed data-intelligent models. *Journal of Hydro-Environment Research*, 29, 20–30.
- Sui, J., Faruque, M. A. A., & Balachandar, R. (2008). Influence of channel width and tailwater depth on local scour caused by square jets. *Journal of Hydro-Environment Research*, 2(1), 39–45.
- Suljevic, A., & Kesgin, E. (2025). Twin propeller scour in non-cohesive seabed with different quay wall configurations. *Ocean Engineering*, 322, Article 120554.
- Tuna, M. (2012). Effect of offtake channel base angle of stepped spillway on scour hole. *Iran J Sci Technol Trans Civ Eng.*, 36, 239–251.
- Tuna, M. C., Ozkan, F., & Baylar, A. (2014). Experimental investigations of aeration efficiency in high-head gated circular conduits. *Water Science and Technology*, 69, 1275–1281.
- Wang, B., Van Rhee, C., Nobel, A., & Keetels, G. (2021). Modeling the hydraulic excavation of cohesive soil by a moving vertical jet. *Ocean Engineering*, 227, Article 108796.
- Wang, C., Jin, L., Qian, Y., Wu, Y., & Liang, F. (2025). Investigation of the protection mechanism and failure modes of solidified soil utilized for scour mitigation. *Construction and Building Materials*, 472, Article 140858.
- Wang, C., Wang, X., Shi, W., Lu, W., Tan, S., & Zhou, L. (2017a). Experimental investigation on impingement of a submerged circular water jet at varying impinging angles and Reynolds numbers. *Experimental Thermal and Fluid Science*, 89, 189–198.
- Wang, C., Wu, Q., Liang, J., Liang, F., & Yu, X. B. (2024). Establishment and implementation of an artificial intelligent flume for investigating local scour around underwater foundations. *Transportation Geotechnics*, 49, Article 101433.
- Wang, C., Yu, X., & Liang, F. (2017b). A review of bridge scour: Mechanism, estimation, monitoring and countermeasures. *Natural Hazards*, 87(3), 1881–1906.
- Wei, M., Chiew, Y., & Cheng, N. (2020). Recent advances in understanding propeller jet flow and its impact on scour. *Physics of Fluids*, 32(10), 101303.
- Xu, W., Deng, J., Qu, J., Liu, S., & Wang, W. (2004). Experimental investigation on influence of aeration on plane jet scour. *Journal of Hydraulic Engineering*, 130, 160–164.
- Yuksel, Y., Tan, R. I., & Celikoglu, Y. (2018). Propeller jet flow scour around a pile structure. *Applied Ocean Research*, 79, 160–172.
- Yuksel, Y., Tan, R. I., & Celikoglu, Y. (2019). Determining propeller scour near a quay wall. *Ocean Engineering*, 188, Article 106331.