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The effect of hydrostatic water level on the local scour downstream of plunging aerated jets

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ABSTRACT

This paper reports an experimental study on the effect of hydrostatic water level on local scour downstream of plunge aerated jets. To examine the shape of the scour for non-cohesive bed material, different flow and air rates, and different aeration capabilities, hydrostatic water level circumstances were tested. The water jets were aerated using conduit systems with varying cover opening ratios. Measurements were made to determine the length of the scour hole, the value of the maximum scour depth, the location of the maximum scour depth, and the scour hole profile in equilibrium. The current findings show that downstream hydrostatic water levels have a significant impact on the maximum depth and area of scour. Additionally, it was discovered that the conduit gate opening ratio and aeration performance (Q_a/Q_w) are crucial factors that affect the geometry and diameters of scour holes. The properties of scour caused by various hydrostatic levels were systematically compared to develop empirical correlations for predicting the maximum scour depth. Consequently, predictive empirical formulas incorporating these hydrostatic variations and aeration parameters are presented to improve engineering design accuracy.

Key words: Jet; experimental study; scour characterization; aeration; hydrostatic water level; local scour

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 cause the structure to overturn into this hole. This situation may jeopardize the safety of the water structure and cause both serious economic losses and create a dangerous situation for the lives of organisms 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.

Submerged and plunging water jets have been extensively evaluated in terms of their hydrodynamics and sediment erosion mechanisms. In this context, seminal investigations by Bollaert and Schleiss (2003) established the foundational understanding of dynamic pressure fluctuations and energy dissipation mechanisms within plunge pools. Furthermore, the systematic

parameters governing jet profiles, air entrainment, and the specific cushioning effects of tailwater depth on local scour development have been rigorously detailed in the literature (Pagliara et al., 2009; Pfister and Hager, 2012). These milestone studies demonstrate that both the air-water mixture characteristics and the downstream hydrostatic conditions play a deterministic role in mitigating the kinetic energy of plunging actions. However, while previous frameworks mostly focus on conventional open spillways, the combined influence of conduit-generated controlled aeration and varying hydrostatic cushions on downstream non-cohesive beds requires further clarification.

Several researchers have investigated the erosion caused by various types of jets, including propeller jets (Wei et al., 2020; Curulli et al., 2023), plane jets (Mostaani and Azimi, 2022; Sharafati et al., 2020), free-fall jets (Salmasi et al., 2023; Salmasi & Abraham, 2022), and moving jets (Wang et al., 2021). Because of their simple equipment and efficient silt-scouring capabilities, vertical jets were chosen over inclined jets (Wang et al., 2017; Chen et al., 2023). Many authors have suggested various empirical formulae, both static and dynamic, to predict the scour depth of submerged jets. The effects of jet diameters, jet angles, exit velocities, and impinging distances on scouring effects were investigated by Mao et al., (2023) and Chen et al. (2022). Gharibi et al., (2022), Kazempour Larsari et al. (2019), Elnikhely (2018), Aminpour & Farhoudi (2017), Tuna (2012) and Habib et al., (2016) carried out experiments on local scour downstream of hydraulic structures. It has been proven by many studies that aeration reduces scour. For example, Johnson (1967) conducted studies on the scour caused by an air-water jet. In their trials, MartíÁñez-Bazán et al. (2002) introduced air into the middle of a water jet. By introducing air into the jet, Xu et al. (2004) measured scour for both aerated and non-aerated flow. They discovered that air concentration is the primary factor influencing scour. An air-water mixture was vertically injected into a scour hole by Dey and Sarkar (2007). It was established how the injected mixture velocity affected the scour geometry. The impact of single and multi-hole nozzles on the scour hole was investigated by Zhu et al. (2008). In 2008, Schmocker et al. experimented with injecting air into plunging jets. They discovered that the air concentration in the plunge jet is significantly impacted by air injection. However, the effect of scour air injection was not investigated in this study.

Aeration as a method of reducing downstream scour is a unique and highly effective solution. Alternative approaches are frequently ineffective and costly. Because of the two-phase flow of air and water, certain hydraulic structures can enhance aeration. A lot of bubbles are created when air is entrained into the flow in these structures. The surface area accessible for mass transfer is significantly increased by air bubbles. Conduit aeration is one specific example. A high-velocity flow downstream of a high-head exit conduit produces subatmospheric pressure if the gate is partially opened (Figure 1). Air is drawn through the air vent by this subatmospheric pressure. Small air bubbles are immediately propelled downstream after being entrained into the water. The effectiveness of oxygen absorption into the water increases with the size of the bubbles because more air is exposed to the water (Aytac & Tuna, 2023). Although the scour experiments presented in this study were conducted using aerated plunging jets, the conduit system shown in Figure 1

was employed solely to generate and control the air-water mixture entering the jet. Therefore, Figure 1 illustrates the aeration mechanism rather than the scour configuration.

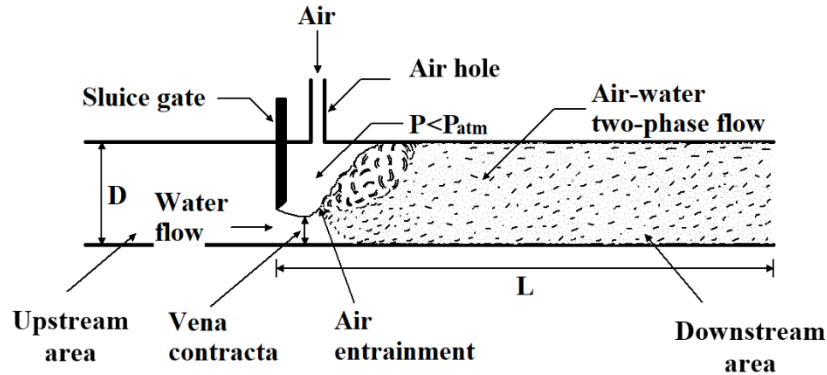


Figure 1. Aeration mechanism in a high-head gated conduit used to generate the air-water mixture (Tuna et al., 2014)

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 systems, and wastewater treatment 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 crucial to use conduits as aerators to prevent scour in such structures and to determine their effect on the scour process.

There are many studies investigating the aeration performance of conduits (Tuna et al., 2014; Aytac and Tuna, 2023; Aytac et al., 2024; Aydin et al., 2023; Baylar et al., 2022). However, there is limited studies are available in literature in the literature that reveals the effects of this hydraulic structure on downstream scour.

The current study examined the impact of hydrostatic water level on local scour downstream of aerated plunge jets for varying flow-air rates, gate opening ratios, and aeration performances. In order for the design engineer to accurately forecast the amount and position of local scour surrounding hydraulic structures under various downstream hydrostatic water levels, a deeper understanding of the physics behind the scouring process is necessary. Understanding how hydrostatic water levels affect the formation of scour holes, analyzing the factors that affect local scour, and determining if aerated plunge jets result in a smaller scour hole than traditional plunge water jets are the primary goals of the study.

2. MATERIALS AND METHODS

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. Every experiment was carried out using experimental sets found in Firat University Civil Engineering's Hydraulic Laboratory. 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 used. Cross-sectional geometry and pressure heights were used to calculate the flow field under pressurized conditions.

Figure 2 illustrates the components used in the experimental setups. During the experiments, the system was operated in a reverse cycle. A suction hose supplied the water from the 1.5 x 1.5 x 3.0 m tank to the pump (Figure 2). The pump was utilized to elevate the pressure and subsequently deliver it to the system in a pressurized state. The flow control valve and Köhne-brand electromagnetic flow meter adjusted the water flow rate. The front side of the assembly was manufactured from tempered glass. To perform three-dimensional measurements (in the x, y, and z directions) of the scour parameters, a movable measuring stand was incorporated into the setup, and an electronic limnimeter was placed on it. On the downstream side of the apparatus, a gate was installed to adjust the hydrostatic level to the desired height and allow vertical movement.

The diameter of the pipeline conveying the water to the conduits was chosen to be 76.2 mm, the same size as the pump outlet diameter, to eliminate local head losses. To help with air intake into the system, a conduit made of galvanized metal pipe with a diameter of 8.09 cm and a circular cross-section of 200 cm in length was employed. Three distinct levels were established and the downstream pool was filled with water up to them in order to examine the impact of the downstream hydrostatic water level on scour. Levels one, two, and three were deemed to be unsubmerged (free discharge above the tailwater level = 0 cm, 10 cm, and 20 cm, respectively), partially submerged (10 cm, and totally submerged (20 cm), respectively. The opening ratios for the conduits were selected as 20%, 30%, 40%, and 60% (Figure 2c).

To make it easier to introduce atmospheric air into the water, an air input pipe was opened just downstream of the gate. The air input pipe is made up of a 200 mm long pipe with a 15 mm diameter. A Testo 435 anemometer was used to measure the air's velocity as it entered the system. Four distinct conduit gate opening ratios ($\phi = 20\%$, 30%, 40%, and 60%) were tested in the experimental program, corresponding to vertical constriction heights (h) of 20.6 mm, 27.5 mm, 34.1 mm, and 46.8 mm, respectively.

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 rates. The Froude number under the gate was calculated for each flow rate.

To determine the Froude number, the velocity and flow heights in the region known as the vena contracta, situated just below the gate, were calculated and taken into consideration. In this region, the high turbulence and two-phase flow conditions on the downstream side of the gate hinder accurate measurement of the velocity and flow heights.

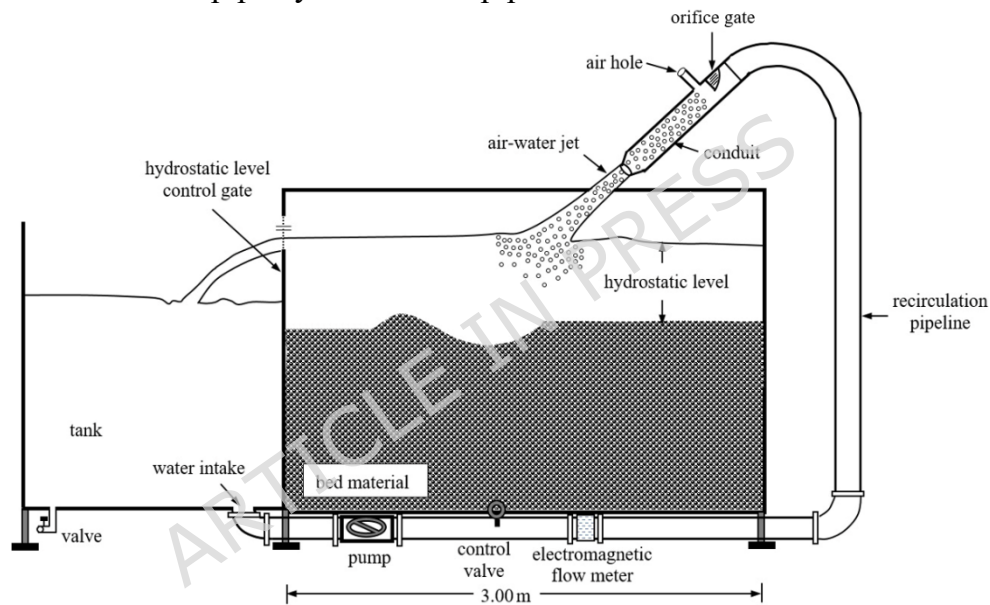
The range of Froude numbers (Fr) was 2.37 to 19.28. Equation (1) was used to determine the Froude number using the conduit's effective depth (y_e).

$$Fr = \frac{V}{\sqrt{gy_e}} \quad (1)$$

where y_e , the effective depth, is calculated by dividing the water cross-sectional flow area by the water surface width, g is the acceleration caused by gravity, and V is the water velocity at the gate site. The vena contracta portion has been served as the basis for the Froude number in the literature. In order to circumvent the challenge of figuring out flow depths and velocities at the vena contracta section, the Froude number in this work was based on the effective depth in the conduit because high-head gated conduits include high-velocity air-water mixture flow.

The mean jet velocity (V) was calculated from the measured water discharge divided by the effective flow area at the conduit outlet section beneath the gate ($V = Q/A$). The effective flow area (A) and the corresponding effective depth (y_e) were determined at the vena contracta section immediately downstream of the gate, where the jet reaches its minimum flow area. The effective depth was calculated as the ratio of the flow area to the free-surface width ($y_e = A/T$). Because the highly turbulent air-water flow in the vena contracta region prevents direct measurements of velocity and flow depth, these parameters were determined from the measured discharge together with the known conduit geometry and gate opening dimensions, following the conventional hydraulic approach adopted for high-head gated conduits.

The velocity probe was positioned in the middle of the air inlet pipe for the anemometer measurements. The average air velocity was calculated by the anemometer after measuring it for 60 seconds. The air flow rate was determined by multiplying the average air velocity observed in the air inlet pipe by the air inlet pipe's area.



(a)

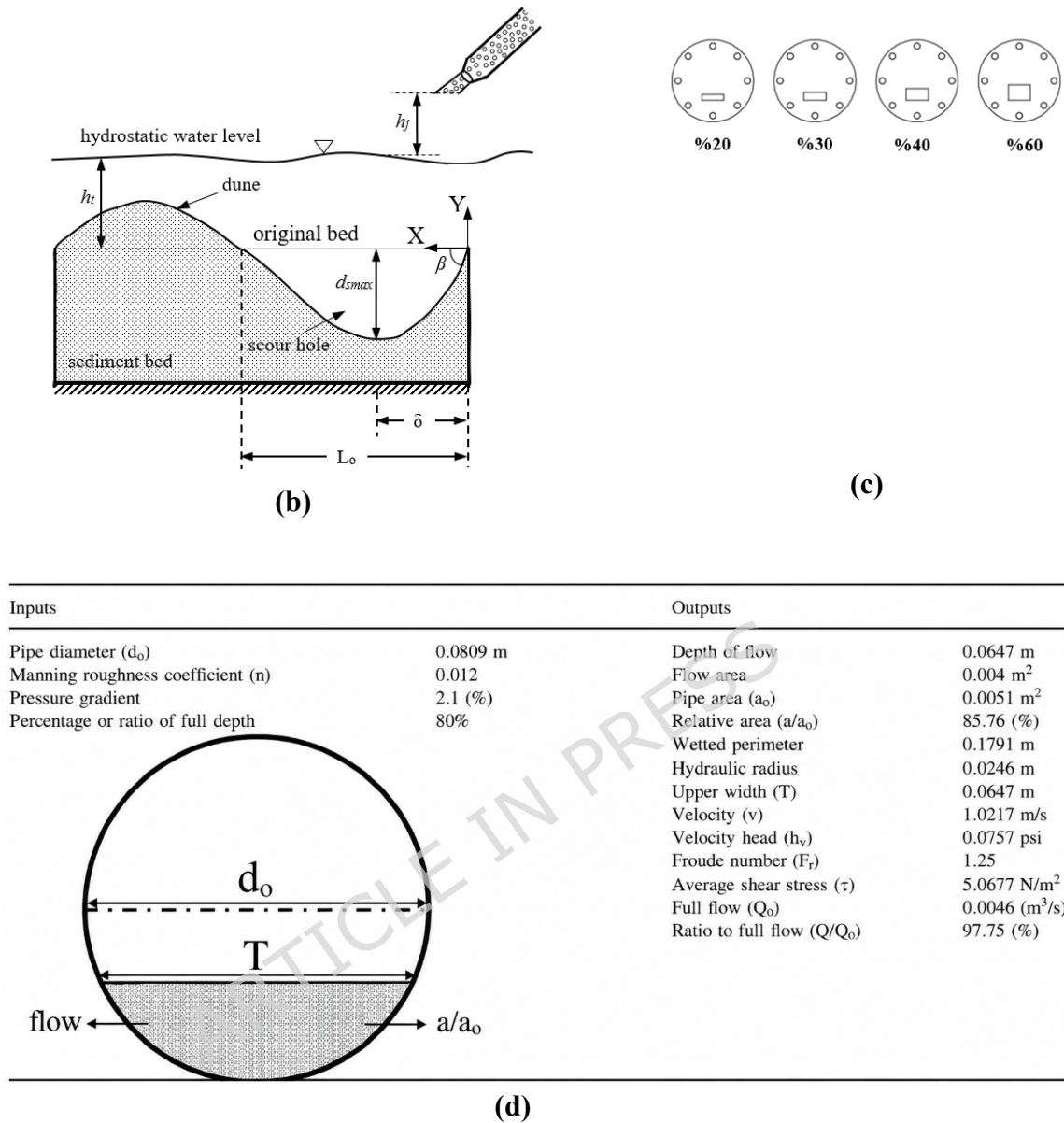


Figure 2. Experimental setup: (a) stepped-channel chute, (b) definition sketch, (c) gate opening ratios of circular cross-section conduit (d) example calculation procedure used to determine the hydraulic parameters and the corresponding Froude number.

To establish a rigorous framework for evaluating the local scour phenomena under aerated plunging jets, a dimensional analysis was conducted using the Buckingham II theorem. The maximum scour depth (d_{smax}) is governed by the independent hydraulic, geometric, and fluid parameters expressed as Equation (2).

It should be noted that the jet drop height (h_j) was maintained constant throughout the entire experimental program. Therefore, it was not treated as an independent variable in the dimensional analysis presented in Eq. (2). However, h_j was later used in Eq. (4) only as a characteristic length for normalizing the maximum scour depth in the development of the empirical regression model.

$$f(d_{smax}, V, y_e, D, h_t, \beta, Q_a, Q_w, \rho, \mu, g) \quad (2)$$

By selecting the water density (ρ), mean jet velocity (V), and conduit diameter (D) as repeating variables, the primary physical mechanism can be defined via the following dimensionless parameters (Eq. 3):

$$\frac{d_{smax}}{D} = \phi \left(Fr, \frac{Q_a}{Q_w}, \frac{h_t}{D}, \beta, K \right) \quad (3)$$

Where Fr is the Froude number, Q_a/Q_w represents the aeration performance, h_t/D is the normalized tailwater hydrostatic level, β is the scour hole slope angle, and K is the gate opening ratio. Accordingly, all subsequent experimental evaluations and graphical illustrations have been updated to conform strictly to this dimensionless framework. The Froude number (Fr) refers to the jet Froude number at the exit, representing the momentum of the jet entering the tailwater.

The operational ranges of the experimental parameters investigated in this study are bounded as follows: water flow rate (Q_w) from 9.2 to 32.4 L/s, air flow rate (Q_a) from 0 to 45.1 L/s, Froude number (Fr) from 2.37 to 19.28, gate opening ratio (K) from 20% to 60%, and normalized hydrostatic tailwater depth (h_t/D) from 2.47 to 4.94.

To ensure the reliability and repeatability of the experimental data, each hydraulic scenario was performed at least twice under identical initial boundary conditions, confirming consistent equilibrium scour morphology. Measurement uncertainties were strictly controlled using high-precision instrumentation; flow discharges were monitored via electromagnetic flowmeters with an operational accuracy of $\pm 0.5\%$, and spatial scour coordinates were recorded using digital point gauges with a reading precision of ± 0.1 mm. The maximum calculated systematic uncertainty for the key non-dimensional parameters remained below 3.5%, validating the reproducibility of the dataset.

3. RESULTS AND DISCUSSION

For various hydrostatic level conditions, experiments were carried out to ascertain the maximum scour depth and scour geometry downstream of the aerated jets. The aeration performance, hydrostatic level, velocity, water density, flow and air rates, gravitational acceleration, surface tension, and water viscosity all affect the maximum scour depth, according to the testing data.

To validate the physical consistency of the current experimental trends, the measured non-dimensional scour depths (d_{smax}/D) were compared against broader datasets in the literature. Traditional un-aerated vertical jet formulations (Pagliara et al., 2011; Yadav and Setia, 2022). inherently overestimate the scour depth because they do not account for the massive energy dissipation triggered by entrained air bubbles. The rapid reduction in d_{smax}/D observed in this study under increasing Q_a/Q_w shows an identical decay rate with the classic aerated jet experiments of Xu et al. (2004). However, the present data further reveals that when conduit-generated aeration is combined with high hydrostatic tailwater levels ($h_t/D > 3.71$), the jet's kinetic energy is almost entirely deflected near the water surface. This dual mitigation mechanism explains why the scour process is completely arrested in specific high-submergence runs, a behavior that closely matches the plunge pool energy dissipation criteria established by Duarte et al., 2016).

Figure 3 shows the relationship between aeration performance (Q_a/Q_w) and Froude number (Fr) for all experimental groups, with varying conduit gate openings. According to the figure, it was observed that as the Fr number increases, the Q_a/Q_w value also increases. However, this trend was not observed in the experimental groups where no air was introduced (N-A) into the water jet. In the aerated plunging jet experimental groups, it was determined that the Q_a/Q_w value was inversely proportional to the gate opening ratio. Specifically, the highest Q_a/Q_w values were obtained in the experimental groups with a 20% gate opening ratio, while the lowest Q_a/Q_w values were found in the experimental groups with a 60% gate opening ratio. In the experiments with a 20% gate opening, the water jet's aeration performance reached its maximum level, and although the Froude number increased, the tendency for the Q_a/Q_w value to increase diminished. This indicates that, in the case of a 20% gate opening, the aeration performance of the water jet has reached its peak. In the other gate opening experiments, the tendency for the Q_a/Q_w value to increase was very high as the Froude number increased.

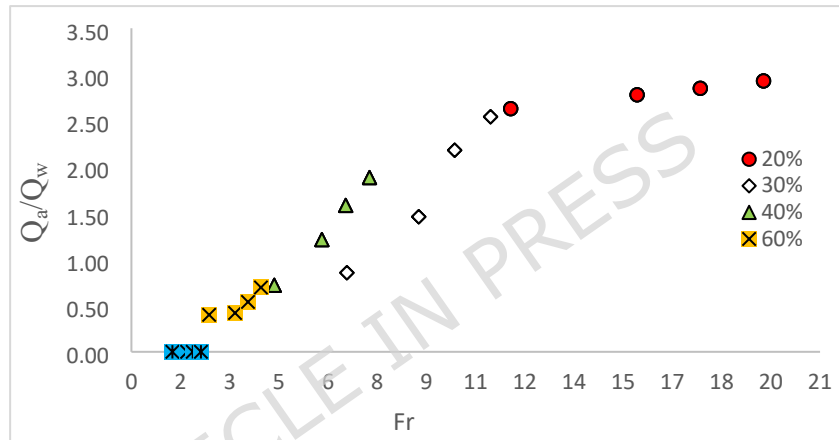
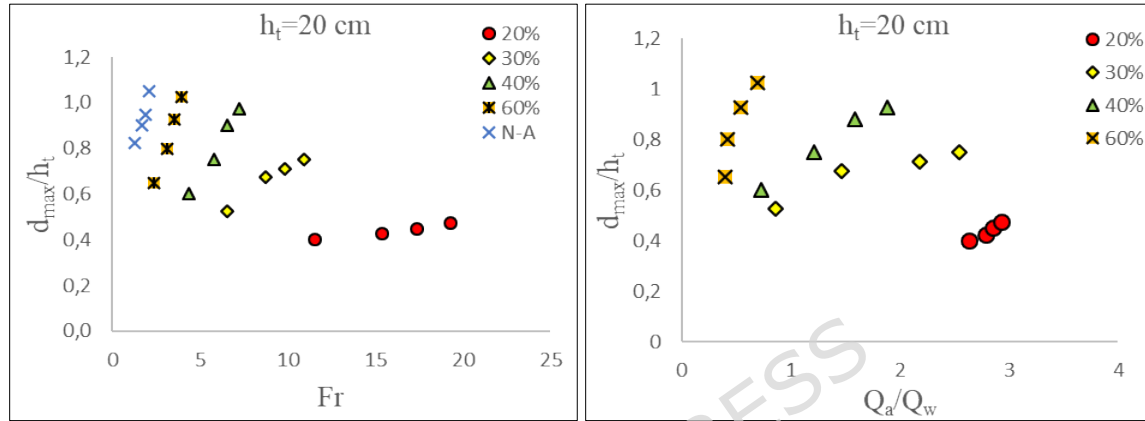


Figure 3. Relationship between aeration performance and Froude number

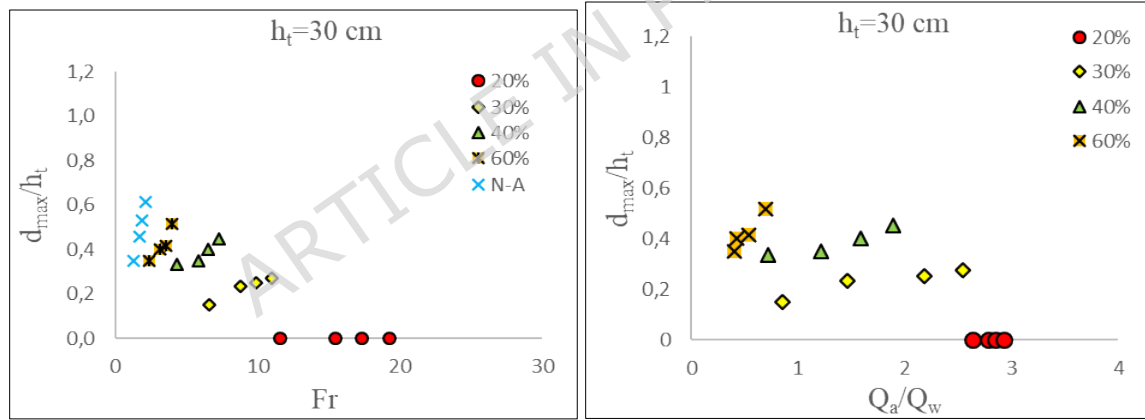
Figure 4 shows the effects of different hydrostatic water levels on the maximum scour depth for all experimental groups. In all experimental groups, it was observed that as the downstream hydrostatic water level increased, the maximum scour depth decreased. This can be explained as follows: the increasing hydrostatic level serves as a natural cushion for the plunging water jet, causing a reduction in the jet's energy. In all experimental groups, the non-aerated jet (N-A) alternatives exhibited the highest maximum scour depths. Furthermore, the alternatives with a 20% gate opening ratio decreased the maximum scour depth and produced the best aeration performance across all trial groups. These two observations indicate that by aerating the plunging jets, their energy is reduced, and the dimensions of the scour hole formed in the hydraulic structure's downstream are diminished.

When comparing Figures 4(a) and 4(b), it can be shown that the maximum scour depth rises with an increase in the Froude number and falls with an increase in aeration performance (Q_a/Q_w). When Figures 4(c) and 4(d) are considered together, in the experimental groups with a 30 cm hydrostatic water level, no scour occurred in the groups with maximum aeration performance, despite an increase in the Froude number. When Figures 4(e) and 4(f) are evaluated together, it is

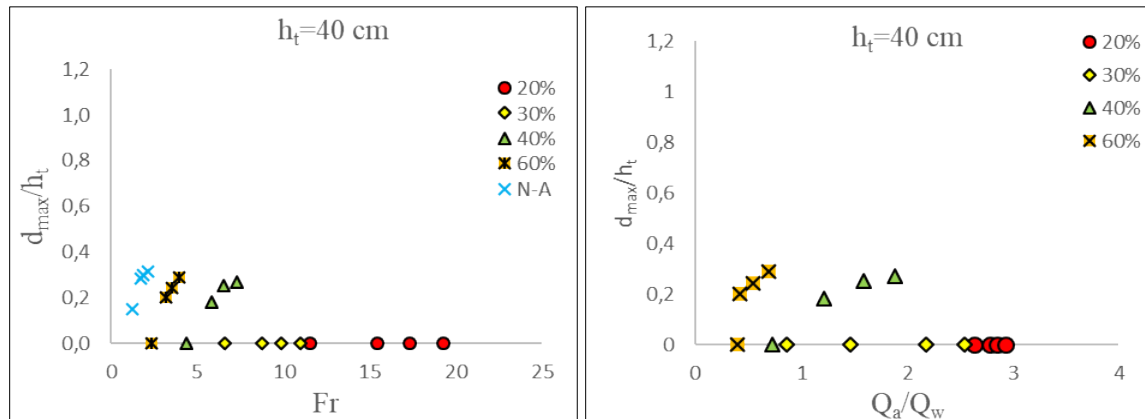
observed that when the hydrostatic water level reaches 40 cm, scour did not occur even in the experimental groups with low aeration performance. In conclusion, it is evident that increasing the hydrostatic water level and aerating the jet significantly reduces the scour process that develops in the downstream of the hydraulic structure. Note that h_t is used for normalization in Fig. 4 to explicitly illustrate the tailwater depth's physical control on the scour process. Although Q_a/Q_w is interrelated with the Froude number, its explicit representation in Figures 4(b), 4(d), and 4(f) isolates and clarifies the direct physical impact of air entrainment on maximum scour minimization.



(a) (b)



(c) (d)

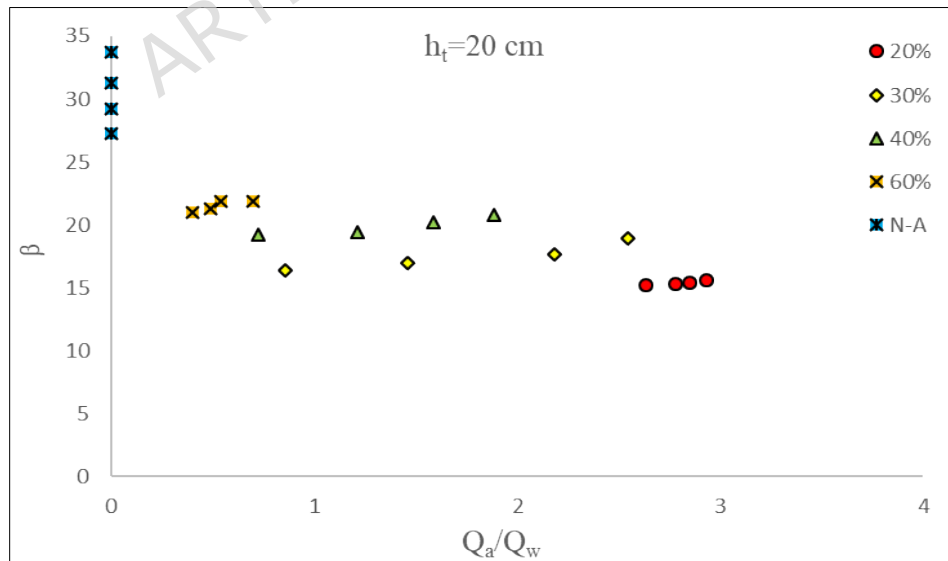


(e) (f)

Figure 4. Variation in maximum scour depth with aeration performance and Froude number at different hydrostatic water levels.

The normalization of the maximum scour depth by the downstream hydrostatic water level was adopted to emphasize the relative influence of the hydraulic cushion provided by the tailwater depth rather than the absolute scour depth. Although increasing h_t mathematically reduces the value of d_{smax}/h_t , the measured absolute scour depth also consistently decreased with increasing h_t , confirming that the observed trend reflects a genuine physical response rather than merely the normalization procedure.

Figure 5 shows the effect of aeration performance on the scour hole slope angle for different gate opening ratios across all experimental groups. In all experimental groups, the non-aerated jet (N-A) alternatives showed the highest values of the scour hole slope angle. Furthermore, the alternatives with a 20% gate opening ratio decreased the scour hole slope angle while achieving the best aeration performance across all testing groups. When the experiments were analyzed in terms of hydrostatic water level, the average slope angle was approximately 25° for $h_t=20$ cm, 17.5° for $h_t=30$ cm, and 12° for $h_t=40$ cm. It was observed that as the hydrostatic water level increased, the slope angle of the scour hole decreased. A high slope angle of the scour hole in a hydraulic structure's downstream can increase the risk of collapse, which is undesirable for hydraulic engineers. This issue can be mitigated by aerating water jets and increasing the downstream hydrostatic water level. The scour hole slope angle (β) is plotted directly against the aeration ratio (Q_a/Q_w) to isolate and emphasize the physical influence of air entrainment on bed material stability and the submerged angle of repose.



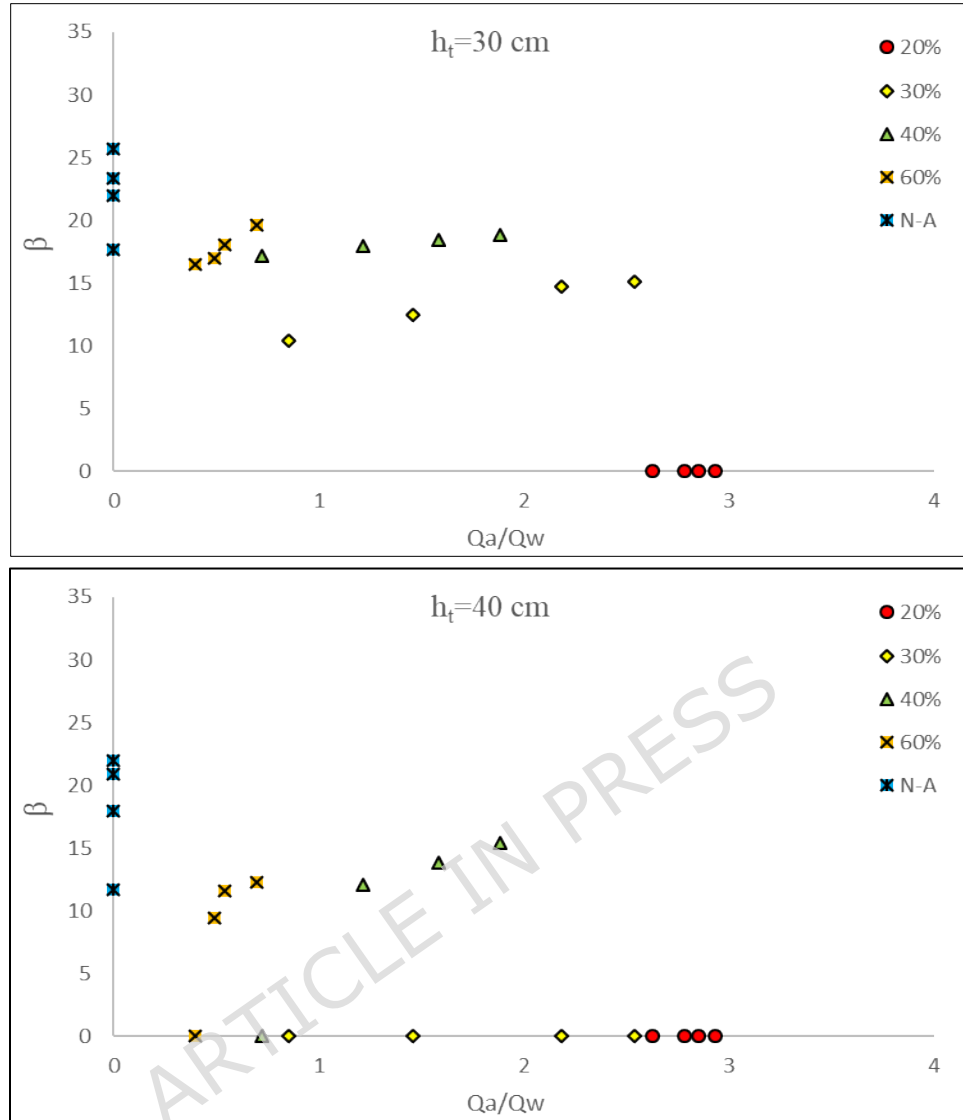


Figure 5. Change in scour hole slope angle with aeration performance for different gate opening ratios.

In aerated jet systems, experiments conducted by altering the gate opening ratio (K), aeration performance (Q_a/Q_w), and hydrostatic water level (h_t) reveal the geometric characteristics of the scour holes formed in the downstream pool. Figure 6 shows the cross-sections of the scour process created by different hydrostatic water levels in the experimental groups.

For $K=40\%$ and $Q_a/Q_w=1.89$, at $h_t=20$ cm hydrostatic water level, the maximum scour depth is approximately 19.5 cm, the scour length (L_o) is approximately 100 cm, the cushion height is 17 cm, and the cushion length is about 100 cm. At $h_t=30$ cm, the maximum scour depth is approximately 13.5 cm, the scour length (L_o) is about 90 cm, the cushion height is 13 cm, and the cushion length is approximately 90 cm. At $h_t=40$ cm, the maximum scour depth is approximately 8 cm, the scour length (L_o) is about 70 cm, the cushion height is 4 cm, and the cushion length is approximately 50 cm. As seen in Figure 6, the hydrostatic water level can be considered one of the most important parameters influencing the geometry of the scour hole. The results are grouped

using the gate opening ratio and aeration performance to provide a direct engineering perspective on how varying degrees of air entrainment systematically affect the scour behavior.

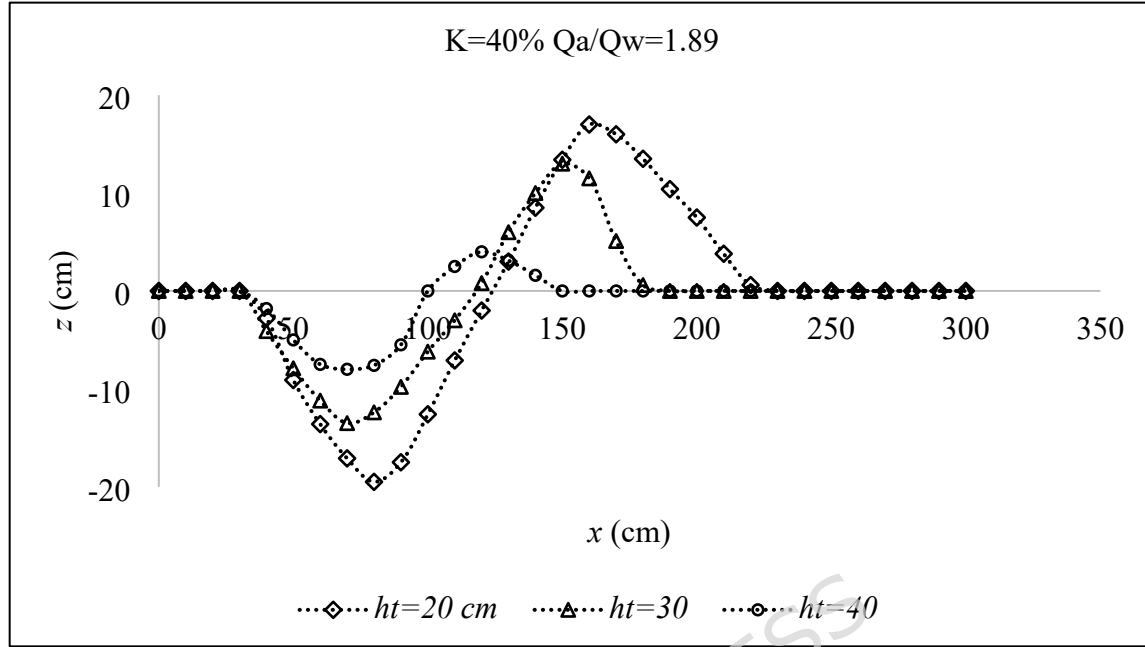


Figure 6. Longitudinal sections of maximum scour depth area

Figure 7 shows the images of the scour hole for different hydrostatic water levels, with $K=30\%$ and $Q_a/Q_w=2.54$. In this case, the effect of different hydrostatic water levels on the scour parameters is demonstrated for the same gate opening and aeration condition. As seen from the images, with the increase in the hydrostatic water level, the scour hole depth, scour hole length, cushion height, and cushion length all decrease. This illustrates that the hydrostatic water level has a significant influence in reducing the dimensions of the scour hole under the given conditions.



Figure 7. Change in the scour hole geometry at different hydrostatic water levels: (a) $h_t=20$ cm, (b) $h_t=30$ cm, (c) $h_t=40$ cm.

An empirical formula for the estimation of the maximum scour depth was developed based on the results of the experimental study. Subsequently, an analysis of variance (ANOVA) was conducted. Figure 8 presents the values obtained from the analysis and those obtained from the experimental observations. The correlation coefficient (R^2) between the obtained results and the observed results is 0.93 (Eq. 4).

$$\frac{d_{smax}}{h_j} = -0.215 + 0.102 \times K - 0.020 \times Fr + 0.024 \times \beta + 0.088 \times \frac{Q_a}{Q_w} + 0.441 \times \frac{h_j}{h_t} \quad (4)$$

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).

Although the parameters Q_a/Q_w and β exhibit physical interdependencies with the core hydrodynamic variables, they are integrated into the regression model as auxiliary empirical parameters to enhance the model's overall predictive capability and capture multi-phase scour dynamics. To provide a clear understanding of the operational boundaries and the relative scales of the non-dimensional parameters used in Eq. (4), the statistical ranges of each variable across all experimental realizations are summarized in Table 1.

Table 1. Statistical ranges of the non-dimensional variables used in the regression analysis.

Non-Dimensional Variable / Term	Minimum Value	Maximum Value	Mean Value
d_{smax}/h_j (Dependent)	0.21	1.14	0.54
K	1.00	3.00	1.85
Fr	4.12	12.45	8.24
β	0.10	0.50	0.28
Q_a/Q_w	0.00	0.44	0.16
h_j/h_t	0.58	2.50	1.22

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 Equation (4), the absolute relative deviation (ARD) was calculated using Equation (5) (Mahdaviara et al., 2020).

$$ARD(\%) = \frac{\text{Experimental-Model}}{\text{Experimental}} \times 100 \quad (5)$$

Figure 8(b) 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 ranging between -0.4% and +0.4%.

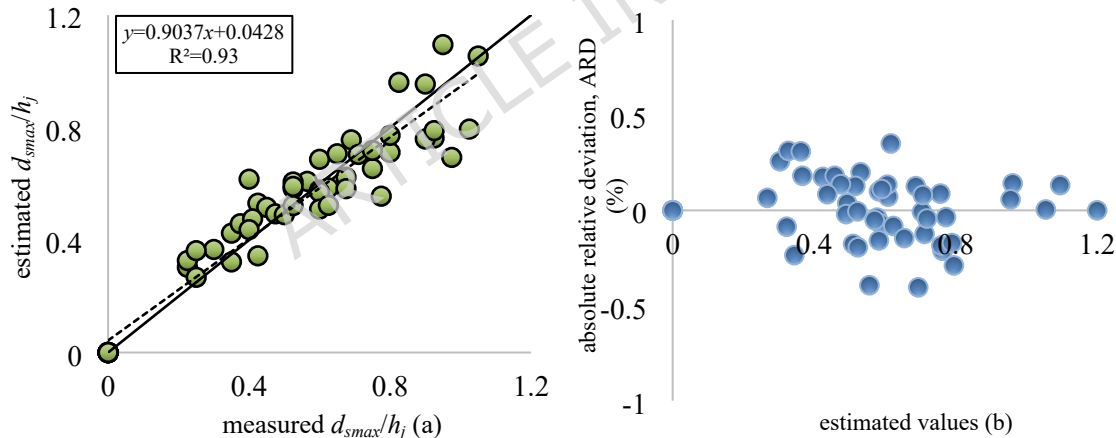


Figure 8. (a) Comparison of measured and estimated values of dimensionless discharge of transported sediment; (b) Absolute relative deviation (ARD) of predicted values

The ANOVA results confirmed that the developed regression model is highly significant ($F > 120$, $p < 0.001$). Among the investigated independent variables, the normalized hydrostatic tailwater depth (h_t/D) and the aeration performance (Q_a/Q_w) exhibited the highest operational impact on the dimensionless maximum scour depth (d_{smax}/D), with p-values well below the 0.05 threshold. This statistical output proves that the variance in downstream scour is systematically

controlled by the hydrodynamic cushion and air-entrainment parameters rather than random experimental errors.

4. CONCLUSIONS

Local scour downstream of the aerated plunge jets for varying hydrostatic levels was examined in the current work in relation to a number of experimental factors. To determine the maximum scour depth, the parameters influencing the scour geometry were taken into account. The maximum scour depth downstream of the aerated plunge jets was predicted using empirical correlations. The following conclusions can be drawn based on these findings:

- As the aeration performance improves, the scour depth decreases.
- The largest scour usually happens either to the left or to the right of the downstream channel's longitudinal centerline, and the scour pattern is typically not symmetrical.
- Alterations to the conduit gate opening demonstrated a pronounced impact on the geometry of the scour hole. The maximum scour hole depth was observed for the non-aerated jet (N-A); however, it was found that the maximum scour hole depth decreased significantly with a decrease in the gate opening ratio and a concurrent increase in the air ratio entering the jet.
- Non-aerated jets cause scour hole slope angles as high as 35° , whereas aerated jets average approximately 7° . As a result, the aerated jet tests show a significant reduction in the scour hole slope angle.
- In the non-aeration (N-A) case, the distance from the scour hole to the jet exit port is observed to be the closest to the location of the scour hole. Conversely, the horizontal distance to the jet exit port decreases by approximately 50% on average as the gate opening value increases.

The findings of this paper will be useful for the dissipation of the energy of water discharged from the forebay and tailwater channels of hydroelectric projects, for the use of aerated jets in irrigation projects, and in environmental systems where oxygen transfer and water aeration are necessary. In summary, the experimental outcomes demonstrate a clear correlation between the critical hydrodynamic parameters and the structural stability of the scour hole. Specifically, the integration of air entrainment functions as a primary mitigating factor, systematically reducing the maximum scour depth under high-velocity regimes. Furthermore, the operational boundaries established by the gate opening ratio reveal that the structural geometry constraints directly govern the flow development and subsequent energy dissipation, providing the physical foundation for the final conclusions presented in this study.

AUTHORS CONTRIBUTIONS

M.T. and M.C.T. analyzed the data and contributed to the writing of the paper. R.A. performed research, conceptualization and methodology. A.A. supervised the study, reviewed, and edited the manuscript.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this published manuscript.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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