Investigation of discharge coefficient and energy dissipation in free-flowing Quarter-Circular Gates

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ABSTRACT

This study investigates the hydraulic performance of quarter-circular gates (QCGs) under free-flow conditions, with a focus on the discharge coefficient (Cd) and the energy dissipation rate (EDR). Results demonstrate that the C_d exhibits a logarithmic increase with the ratio of upstream flow depth to gate opening (y_1 / w), rising from approximately 0.9 to 1.1 as y_1 / w varies from 4 to 20, indicating that the gate's efficiency improves with increasing upstream flow depth. Notably, the C_d remains stable even when upstream load increases fivefold, reflecting the robustness of the QCG design. Additionally, the relationship between C_d and the ratio of flow depth to radius (y_1 / R) is nearly linear, with higher curvature and streamline compression resulting in increased C_d due to flow acceleration caused by geometric constraints. Regarding energy dissipation, the EDR ranges from 10% to 55%, growing logarithmically with $y1/w$ and being more pronounced with greater streamline curvature associated with larger y_1 / R ratios. Increased flow curvature causes more energy loss, so larger gate openings that reduce streamline compression consequently lower EDR. The findings reveal that despite increases in downstream loads, the QCG maintains high efficiency, with energy dissipation occurring at a diminishing rate. Compared to traditional sluice gates with sills, which typically have a discharge coefficient between 0.5 and 0.8, the QCG outperforms with coefficients ranging from 0.9 to 1.0. Overall, the results highlight the significance of geometric parameters, including gate opening, flow depth, and radius, in improving hydraulic performance. These insights highlight the potential of QCGs for high-capacity flow regulation, offering predictable and efficient behavior, which is valuable for hydraulic engineering applications.

KEYWORDS
Flow Measurement, Discharge Coefficient, Flow Energy Dissipation, Hydraulic Structures, Streamline Curvature.

1. Introduction

Flow measurement and water level control are crucial components in the design of hydraulic engineering projects, including irrigation and drainage networks, as well as dam construction. Various tools, such as weirs and gates, have been developed to achieve these objectives (1, 2). While weirs are primarily employed for flow measurement, their capacity for controlling water levels is somewhat limited. Corrective measures, such as labyrinthine the crest (1), piercing the lower part of the weir body in the form of gates or orifices (3–5), and utilizing devices like fuse-gates (6) and pivoting weirs (2), have been implemented to mitigate this limitation.

Gates are also extensively used for flow measurement and upstream water level control, with two predominant types: vertical (sluice) gates and radial gates (3). A different type of gate has been recently developed, known as Lopac gates (4–7), which have been extensively studied. Due to their superior performance in dam construction and primary water conveyance channels, where accurate flow control and high discharge measurement are essential, radial gates are generally favored. Over the past decade, numerous studies have investigated the hydraulic properties of radial gates (8,9). For instance, researchers have examined the effect of body slope and various geometric shapes of sills, including pyramidal, semi-cylindrical, cylindrical, and rectangular forms, on the performance of vertical sluice gates (8,9). Findings indicate that the shape and height of the sills significantly influence the discharge coefficient (Cd) of sluice gates, with the use of sills enhancing Cd by approximately 20% and markedly increasing energy dissipation by over 100%. Notably, the semi-cylindrical sill is particularly effective in increasing Cd, while the pyramidal sill enhances energy dissipation(10–13).

In recent years, in addition to laboratory studies, numerical investigations based on computational fluid dynamics (CFD) (12) and soft computing techniques(14)—including Gaussian process regression, generalized regression neural networks, support vector machines, and multi-genetic programming—have been utilized to predict the Cd of both radial and sluice gates (15,16). These studies indicate that soft computing models perform reasonably well compared to empirical formulas.

A literature review reveals that research on radial gates has predominantly focused on determining their Cd and methods for its enhancement, with comparatively less emphasis on energy dissipation. In contrast, quarter-circular gates (QCGs), a novel type of radial gate introduced by Babaei et al. (17), have not received the same level of attention. This study aims to investigate the Cd of these structures and the energy dissipation of the flow passing beneath them.

2. Material and methods

The QCG consists of a quarter-circle arch, as shown in Figure 1, which provides a sketch and its geometric and hydraulic parameters.

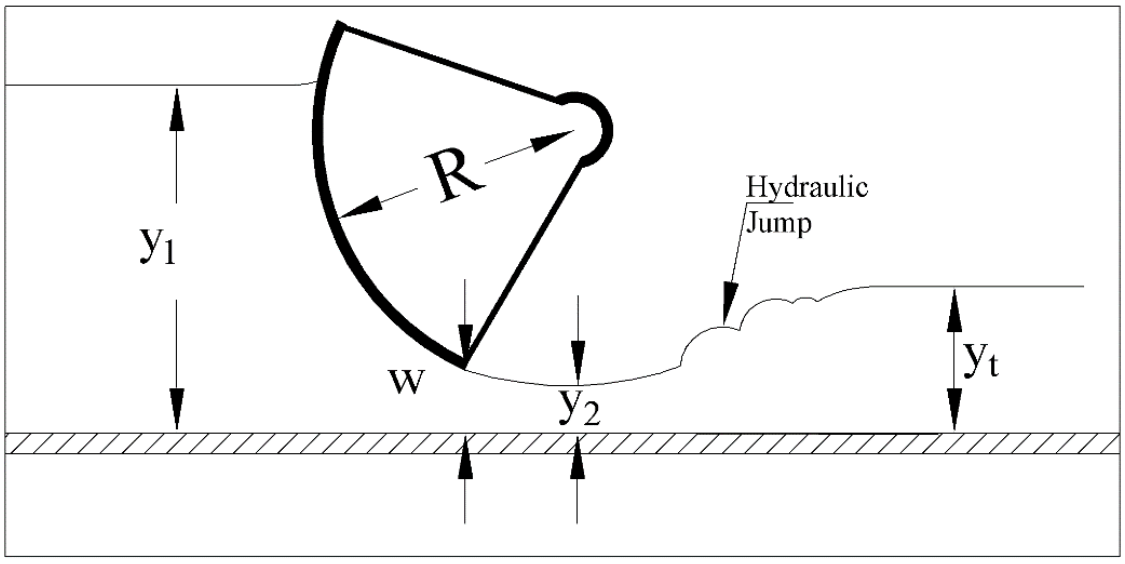


Figure 1. A Sketch of QCG

In Figure 1, R is the gate radius, $y_1$is the upstream flow depth, w is the gate opening, and y_2 is the downstream flow depth. Note that y_t is the tailwater and represents the submergence threshold. Equation (1) estimates the discharge capacity of the gates, which is a function of the upstream flow depth (y_1),C_d, and the gate opening (w)(5).

$$q = c_d w\sqrt{2gy_1} \quad (1)$$

To estimate the discharge capacity, $y_1$and w should be measured. However, for such structures, the $C_d$must be specified in advance. C_d is a function of geometric and hydraulic characteristics (Eq. 2).

$$Cd \text{ and } EDR = \varphi(y_1, y_2, y_t, R, W, g, \rho, \mu, \sigma) \quad (2)$$

Where g is the acceleration due to gravity, and ρ, μ, and σ are the water's density, viscosity, and surface tension, respectively. y_t is the maximum allowable downstream flow depth at which the flow condition is free-flowing. In addition to the C_d, the *EDR* should also be evaluated. Bernoulli's equation is used to calculate the *EDR* for upstream (Eq. 3) and downstream (Eq. 4), and then the *EDR* is computed using Equation (5).

$$H_1 = y_1 + \frac{{V_1}^2}{2g} = y_1 + \frac{q^2}{2g{y_1}^2} \quad (3)$$

$$H_2 = y_2 + \frac{V_2^2}{2g} = y_2 + \frac{q^2}{2g{y_2}^2} \quad (4)$$

$$\text{EDR}(\%) = \left(\frac{H_1 - H_2}{H_1}\right) \times 100 = \frac{\Delta H}{H_1} \times 100 \quad (5)$$

Where H_1 and H_2 represent the total upstream and downstream heads, respectively, the dimensionless parameters involved in $C_d$and *EDR* are obtained using dimensional analysis and are given by Equation (6).

$$Cd \text{ and } EDR = \varphi\left(\frac{y_1}{R}, \frac{y_1}{w}, \frac{y_t}{y_1}, \frac{w}{R}, Fr, Re, We\right) \quad (6)$$

Where Fr, Re, and We are the Froude, Reynolds, and Weber numbers, respectively. Note that y_t/y_1 is used in the submerged flow condition and does not affect the hydraulic properties of QCG in the free flow condition. It is noteworthy that due to the turbulent nature of the flow (Reynolds Number), merit the minimum flow depth in experiment (weber number) and also because the gate is installed in the flow path and the Froude (its range is very limit), these dimensionless number are neglected, To justify the relationship between Cd, EDR, and the independent parameters (y_1 / w, y_1 / R, and w / R), reference was made to the study conducted by Babaei et al. (18). The experiments were performed in a 10 m long, 0.6 m deep, and 0.4 m wide channel. The models were positioned 6 m from the start of the channel, and flow was measured with a volumetric flow meter. Flow depth was measured using a point gauge with a precision of ±1 mm upstream and downstream of the gate. The tailwater depth controlled the submergence threshold. The geometric and hydraulic characteristics of the models tested are detailed in Table 1.

Table 1. Geometrical and hydraulic specifications of the models

Range	W(m)	R(m)	q(m^3/s.m)	y_1	y_t
Min	0.01	0.2, 0.3, 0.5	0.0177	0.09	0.093
Max	0.06		0.124	0.505	0.236

3. Results and discussion

This section presents the results of the analysis and investigation of the $C_d$and *EDR* of the flow passing through the QCG under free-flow conditions. According to Equation 2, $C_d$and *EDR* depend on the ratio of upstream flow depth to gate opening (y_1 / w), the ratio of flow depth to the radius (y_1 / R: indicating the curvature of the streamlines), and the relative gate opening (ratio of opening area to radius of the gate: w/R). The C_d has been calculated (using Eq. 1), and the results are plotted against y_1/w in Figure 2. Examination of this figure shows that in the range of y_1 / w between 4 and 20, the C_d undergoes a logarithmic change, increasing from 0.9 to 1.0. An essential point of this figure is that the C_d does not decrease as the upstream flow depth increases. Figure 2 shows that even if the load behind the QCG is increased by about 5 times, its C_d not only decreases but also increases (even partially).

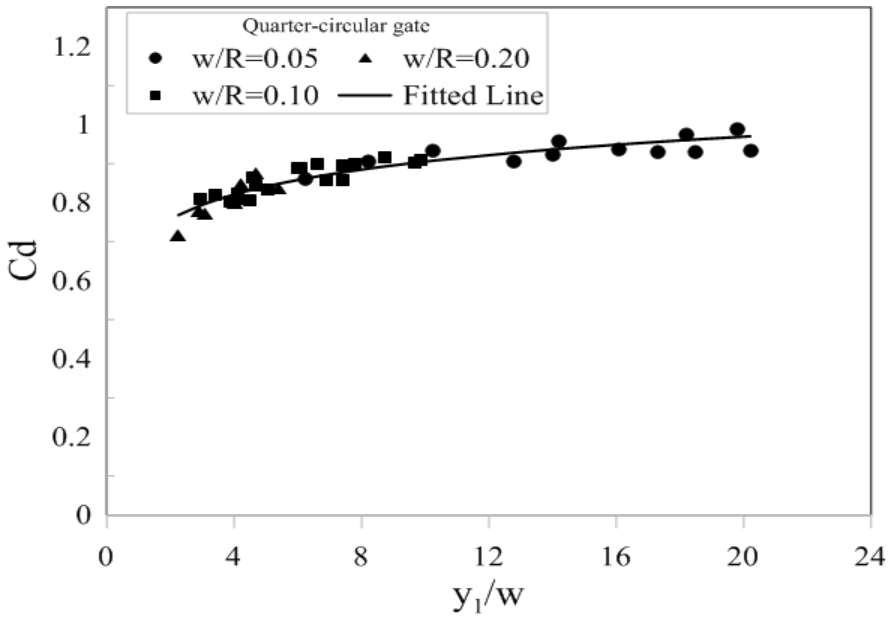


Figure 2. Variations of C_d of QCGs versus y_1/w

The changes in C_d with respect to the parameter y_1 / R are analyzed and presented in Figure 3. The analysis indicates that within the y_1 / R range of 0.25 to 1.5, the relationship between C_d and y_1 / R is almost linear. In other words, as the streamlines become more curved and compressed within the range of y_1 / R, the C_d also increases partially linearly. This is due to the acceleration of the flow caused by the curvature and compression of the streamlines. However, the deviation and curvature of the streamlines result in increased energy loss. In Figure 3, the legend also illustrates the effect of *w/R* on Cd. Examining Figure 3 reveals that at lower upstream flow depths, Cd decreases as *w/R* increases, which is attributed to the reduction in flow acceleration resulting from the curvature of the streamlines. The insignificance of the difference in the curvature and compression of the streamlines hydraulically explains this difference.

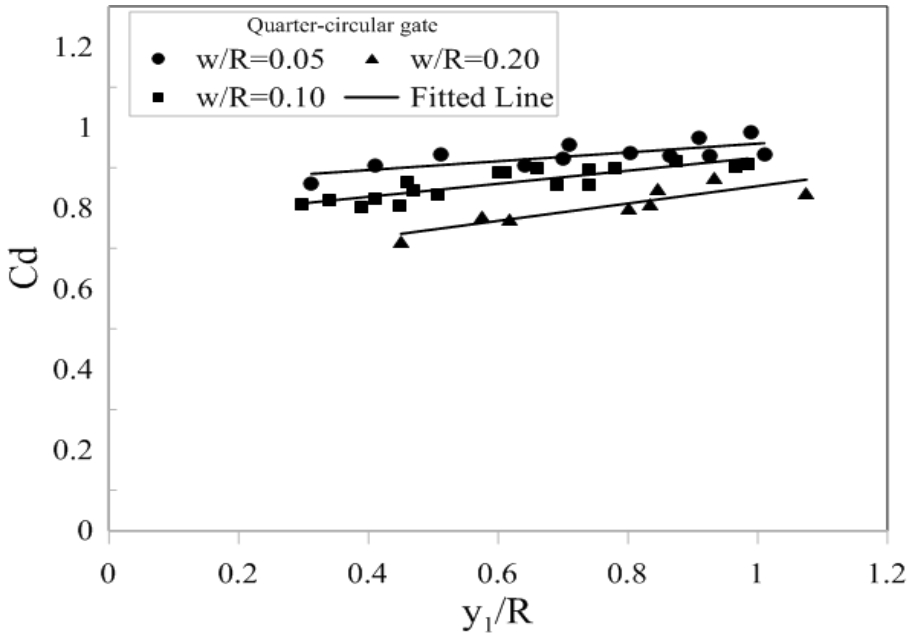


Figure 3. Variations of C_d of QCGs versus y_1/R

The *EDR* of the flow passing under the QCG was calculated using equations 3 to 5, as shown in Figure 4. Figure 4 shows the variation of *EDR* as a function of y_1/w. An essential point in estimating the *EDR* is the consideration of the maximum downstream flow depth (submergence threshold) in the calculation of the *EDR*. However, for values of downstream flow depths less than the submergence threshold, the *EDR* is less than the submergence threshold condition. As shown in Figure 4, the *EDR* varies between 10% and 55% for the same range of y_1 / w. As the value of y_1 / w increases, the EDR increases logarithmically. This is due to increased curvature, deviation, and compression of the streamlines as y_1 / w increases. The noteworthy point in this figure is that if the load behind this structure increases by 5 times, its energy dissipation is increased but much slower, indicating the efficiency of the QCG model.

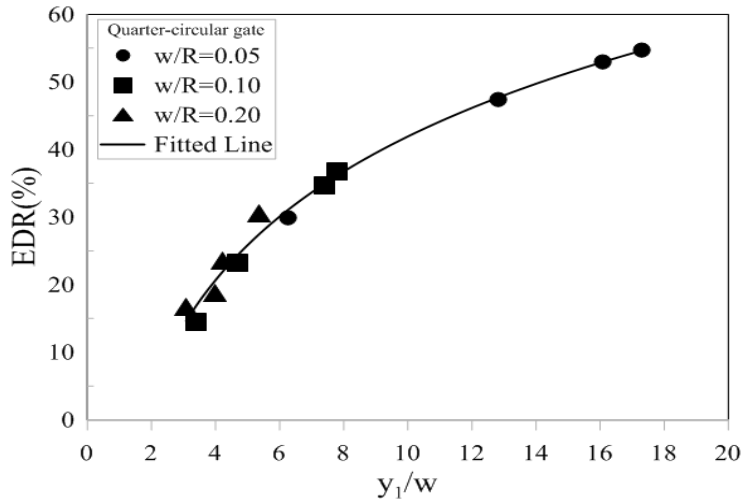


Figure 4. Variations of EDR of QCGs versus y_1/w

The effect of streamlined curvature and their compression on the *EDR* of flow passing under the *QCG* is shown in Figure 5. The graphs in Figure 5 show the relationship between *EDR* and y_1 / R for different values of w / R. It is clear from the graph that the relationship is nearly linear. As y_1 / R increases, the deflected streamlines become more curved and compressed, leading to an expected increase in flow energy loss. For example, when the gate opening was doubled and $y_1 / R \cong 0.6$, the *EDR* decreased by about 75%. Of course, the opposite analysis is correct, i.e., a 50% reduction in gate opening quadruples its energy dissipation. The decrease in EDR with increasing gate opening is logical from a hydraulic point of view. Thus, as the gate opening increases, the streamlines become less curved, resulting in less energy dissipation

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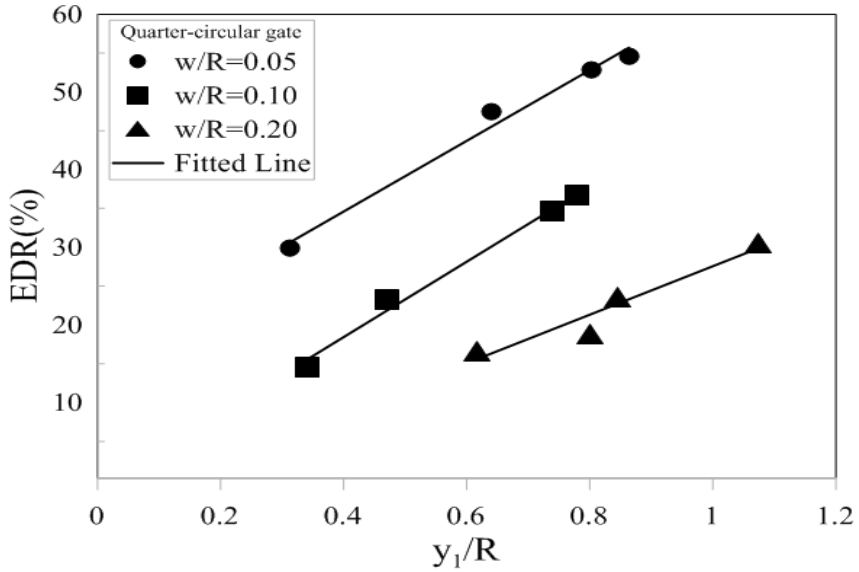


Figure 5. Variations of EDR of QCG versus y_1/R

4. Comparison with Previous Studies

Daneshfaraz et al. (19) investigated the effect of sills on the discharge coefficient of sluice gates. In this regard, they considered cubic sills in different dimensions, including length, height, and width, which ranged from the width of the sills to the width of the channel. They found that the discharge coefficient of sluice gates in the presence of sills ranges from 0.5 to 0.8, considering the range of upstream flow head to the gate opening between 0.1 to 50.

Heidari et al. (12) studied the effect of semicircular and rectangular sills on the discharge coefficient of sluice gates. They found that in rectangular sills, the discharge coefficient varied between 0.53 and 0.62, while the ratio of upstream head to gate opening varied between 2 and 6. In the same range of relative upstream head, the semicircular sill changes the discharge coefficient between 0.6 and 0.7.

Salmasi et al.. (13) studied the effect of different types of sills, such as rectangular and circular, on the discharge coefficient of radial gates. They found that in the presence of all the sills tested, the discharge coefficient varied between 0.55 and 0.75, while the relative upstream head varied between 5 and 30.

In total, through the tested relative upstream head, the discharge coefficient of the sluie and radial gates varies between 0.5 and 0.8. In contrast, the discharge coefficient of QCGs varies between 0.9 and 1.0 (without any sill).

5. Conclusion

This study provides a comprehensive analysis of the discharge coefficient (C_d) and energy dissipation rate (EDR) for flow passing through the quarter-circular gates (QCG) under free-flow conditions. The findings reveal that the C_d exhibits a logarithmic increase for the ratio of upstream flow depth to gate opening (y_1/w), demonstrating resilience to increased upstream loads. Specifically, C_d rose from 0.9 to 1.1 within the range of y_1/w from 4 to 20, indicating that the performance of the QCG improves with greater flow depth. The relationship between C_d and the ratio of flow depth to radius (y_1/R) was found to be approximately linear, suggesting that as flow streamlines become more curved and compressed, C_d also increases. Despite the associated energy losses, this linearity underscores the hydraulic implications of streamline curvature on flow acceleration. Additionally, the EDR analysis revealed that energy dissipation under varying conditions of y_1/w and y_1/R is significant, with EDR values ranging from 10% to 55%. The logarithmic increase in EDR with y_1/w further emphasizes the influence of streamline curvature on energy loss. Notably, the efficiency of the QCG model is highlighted by the observation that while increased downstream loads enhance energy dissipation, this occurs at a diminishing rate. Overall, the results highlight the crucial role of geometric parameters in enhancing the performance of QCGs. Future studies should explore the implications of these findings in practical applications and further investigate the effects of varying flow conditions (submerged flow condition) and gate geometries to refine the understanding of hydraulic efficiency in similar structures.

Notations

c_d	Discharge Coefficient
y_1	Upstream Flow Depth
y_2	Downstream Flow Depth
y_t	Tail Water
QCG	Quarter-Circular Gate
R	Gate Radius
w	Gate Opening
EDR	Energy Dissipation Ratio
g	Acceleration due to Gravity
q	Discharge Per Width
μ	Water Viscosity
ρ	Water Density
σ	Water Surface Tension
H_1	Total Upstream Head
H_2	Total Downstream Head

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Conflict of Interest

The authors declare that they have no conflict of interest.

AI Statement

The authors did not used AI in the context

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Abbas Parsaie. The first draft of the manuscript was written by AmirHamzeh Haghiabi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

1. Parsaie A, Pili-Dezfouli M. Estimating the discharge coefficient of piano key weirs using soft computing models. Applied Researches in Water Engineering. 2025;2(2):239–48.
2. Bijankhan M, Ferro V. Experimental Modeling of Submerged Pivot Weir. J Irrig Drain Eng. 2020 Mar;146(3):04020001.
3. Akan AO, Iyer SS. Open channel hydraulics. Butterworth-Heinemann; 2021.
4. Fathi S, Sajjadi SM, Ahadiyan J, Parsaie A. Investigation of the effect of different submerging on the flow hydraulic parameters in multiple rectangular Lopac gates. Water and Irrigation Management. 2024;14(2):249–61.
5. Mobarak F, Sajjadi SM, Ahadiyan J, Zeynivand M. Numerical modeling of the effect of elliptical elongation on the hydraulic performance of an elliptical Lopac

gate. Water and Irrigation Management. 2022;12(2):263–75.
6. Sajjadi M. Numerical Hydraulic and Hydrodynamic Investigation of the Flow through Multiple Rectangular Lopac Gates with Flow 3D Software. JWSS-Isfahan University of Technology. 2024;28(1):51–64.
7. Taheri Talavari T, Sajjadi SM, Ahadiyan J, Azizi Nadian H. Numerical hydraulic and hydrodynamic investigation of flow passing through multiple elliptic lopac gates with Flow 3D software. Advanced Technologies in Water Efficiency. 2024;4(3):40–60.
8. Salmasi F, Abraham J. Expert System for Determining Discharge Coefficients for Inclined Slide Gates Using Genetic Programming. J Irrig Drain Eng. 2020 Dec;146(12):06020013.
9. Salmasi F, Shadkani S, Abraham J, Malekzadeh F. Experimental Investigation for Determination of Discharge Coefficients for Inclined Slide Gates and Comparison with Data-Driven Models. Iran J Sci Technol Trans Civ Eng. 2022 Jun;46(3):2495–509.
10. Daneshfaraz R, Norouzi R, Ebadzadeh P, Di Francesco S, Abraham JP. Experimental study of geometric shape and size of sill effects on the hydraulic performance of sluice gates. Water. 2023;15(2):314.
11. Daneshfaraz R, Norouzi R, Abbaszadeh H, Kuriqi A, Di Francesco S. Influence of sill on the hydraulic regime in sluice gates: an experimental and numerical analysis. Fluids. 2022;7(7):244.
12. Heidari MM, Karami S, Adibrad MH. Investigation of free flow under the radial gate with the sill. Journal of Civil and Environmental Engineering. 2020;50(100):9–19.
13. Salmasi F, Nouri M, Abraham J. Laboratory study of the effect of sills on radial gate discharge coefficient. KSCE Journal of Civil Engineering. 2019;23(5):2117–25.
14. Parsaie A, Najafian S. Mathematical Expression of Energy Dissipation of Flow over Stepped Spillways Using Genetic Programing. Applied Researches in Water Engineering. 2024;2(1):97–110.
15. Roushangar K, Alirezazadeh Sadaghiani A, Shahnazi S. Novel application of robust GWO-KELM model in predicting discharge coefficient of radial gates: a field data-based analysis. Journal of Hydroinformatics. 2023;25(2):275–99.
16. Salmasi F, Abraham J. Prediction of discharge coefficients for sluice gates equipped with different geometric sills under the gate using multiple non-linear regression (MNLR). Journal of Hydrology. 2021;597:125728.
17. Babaei SS, Mohammadzadeh-Habili J, Zomorodian SM. Experimental and theoretical modeling of a quarter-circular gate flow. 2021;80:101983.
18. Babaei SS, Mohammadzadeh-Habili J, Zomorodian SM. Experimental and theoretical modeling of a quarter-circular gate flow [Internet]. Vol. 80, Flow Measurement and Instrumentation. Elsevier; 2021 [cited 2025 Feb 5]. p. 101983. Available from: https://www.sciencedirect.com/science/article/pii/S0955598621000923
19. Salmasi F, Nouri M, Sihag P, Abraham J. Application of SVM, ANN, GRNN, RF, GP and RT models for predicting discharge coefficients of oblique sluice gates using experimental data. Water Supply. 2021;21(1):232–48.

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