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The Analytical Approach for Estimating the Hydraulic Characteristics of Sluice Gates

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ABSTRACT

Sluice gates are hydraulic structures used to control the discharge in channels or to direct flow from main channels to secondary channels. These gates can also be utilized in dams to control the amount of water released from the dam. Sluice gates can be installed in different positions; some are vertical, while others are inclined depending on the specific purpose for which the gate is designed. In this paper the hydraulic characteristics of flow upstream and downstream of a vertical sluice gate are studied experimentally and numerically. This study aims to determine an analytical equation to estimate the discharge under the vertical sluice gates with different cases of gate opening. Consequently, experimental investigations were performed on models constructed by dimensional analysis for the parameters influencing the discharge coefficient under sluice gates in an open channel. Four gate openings for the vertical sluice gate were considered: 1, 2, 3, and 4 cm with ten discharges Q were passed for each gate opening, ranging from 1000 l/hr to 5200 l/hr. The results show that increasing the amount of discharge would lead to an increase in the discharge coefficient value; also, increasing the gate opening will reduce the discharge coefficient to pass the same amount of water through the sluice gate. Finally, an empirical equation was derived linking the discharge values passing under the vertical sliding gates for various openings and conditions using the non-linear regression analysis. Additionally, the statistical indices (R^2) and Nash–Sutcliffe efficiency (NSE) were used to test the reliability of this equation, and their results were 0.996 and 0.962, respectively. The analytical approach for estimating the flow under the vertical sluice gates showed a great fitting with experimental findings.

1. INTRODUCTION

Water is a fundamental element for sustaining life and ensuring its continuity. Based on this principle, hydraulic structures have been widely and rapidly developed to serve multiple functions, including water storage and flow regulation. In open channels, sluice gates are devices used to control and regulate water flow in addition to their role in storing water. Also, these gates are used to raise the water level upstream of the main canals, facilitating the flow of water through the secondary channels, as well as, they can serve as instruments for quantifying the discharge flowing through the canal [1]. There are various types of sluice gates, each with its advantages and disadvantages. The appropriate type is selected based on the specific application requirements. Modern sluice gates are frequently constructed from corrosion-resistant materials for endurance; however, they are usually made of wood or metal. They are essential for managing water resources, reducing the danger of floods, and assisting agricultural irrigation systems by delivering water to the right places when needed [2]. Instead of being positioned vertically, an inclined sluice gate is angled, and the discharge and velocity of water flowing beneath the sluice gate are directly influenced by the gate's inclination [3]. Sluice gates are frequently seen in flood control systems, irrigation systems, and dams. They regulate the flow of water in rivers, canals, or channels; an adjustable sliding or lifting door allows for precise control of water flow through a predetermined aperture, allowing for precise regulation of both water level and discharge rate [4].

A theoretical background about open channel flows and the upstream effect of a sluice gate was presented in several research from laboratory tests and theoretical techniques that have been carried out to determine the discharge coefficient [5]. The discharge coefficient (C_d) is a dimensionless metric used to quantify the effectiveness of fluid flow via sluice gates, orifices, nozzles, or other devices; it shows the ratio between the theoretical and actual discharges [6].

An early study addressed the hydraulic characteristics of flow through a gate by solving the Ordinary Differential Equations (ODE) and determining the values of contraction and discharge coefficients (C_c, C_d) and their impact on establishing a water surface profile upstream and downstream of the gate [7]. Also, the Boundary Integral Equation Method (BIEM) was utilized to determine the contraction and discharge coefficients and develop a water surface profile diagram for both the sluice gate and the spillway [8]. In fact, the hydraulic study of flow-exiting gates was conducted mathematically in several studies using the finite element approach and implemented through computational software. The results of these studies showed a great ability to mimic the water surface, velocity, and pressure profiles, along with the calculation of the contraction and discharge coefficients [9-13]. Another experimental work was performed in a rectangular channel to investigate the flow under a gate. The finding showed that the discharge coefficient decreases with an increase in the ratio of gate opening to the upstream flow depth (a/H_1) [14]. This finding was confirmed by another study that showed a strong agreement between experimental and theoretical values. This study obtained the discharge coefficient of vertical sluice gates using Mathematica model software [15].

Furthermore, the impact of the inclination of the sluice gate on the discharge coefficient was addressed in several research works. For instance, the performance of the inclined sluice gates was investigated experimentally. The experimental work was implemented in a rectangular laboratory flume, and it was observed that the value of the discharge coefficient increases as the sluice gate inclination aligns with the flow direction and decreases as the inclination opposes the flow direction [16]. Also, the influence of flow vortex generation upstream of an inclined sluice gate was investigated to check their impact on the discharge coefficient. It was shown that the discharge coefficient of the opposite flow direction sluice gate dropped between 8-12% in comparison to the vertical gate [17].

Another study looked at how the discharge coefficient (C_d) was affected by the sluice gate's vertical, inclined upstream, inclined downstream, and oblique positions, and the research employs a numerical modeling methodology utilizing FLOW-3D software for simulating free-surface flows. The study highlights the significance of strategically placing sluice gates to maximize the effectiveness of water management [18]. An experimental study was attempted to examine how well five models perform in identifying flow regime conditions, calculating the discharge coefficient (C_d), and calculating the flow rate. A numerical model supported the work to investigate all parts of the study strategy for evaluating sluice gate performance under steady-state flow through a sluice gate under varying flow rates, gate openings, and upstream and downstream circumstances [19]. In fact, an Artificial Neural Networks (ANN) modeling approach with a backpropagation algorithm was applied to analyze the flow characteristics below vertical and inclined sluice gates [20]. The results obtained showed that artificial neural networks (ANNs) are effective tools for accurately simulating flow rates below both kinds of sluice gates with an accuracy of ±5% [3]. Also, experimental data and Artificial Intelligence (AI) models were used to investigate (C_d) of oblique and inclined sluice gates. It was concluded that increasing the gate inclination angle resulted in higher discharge coefficients due to greater flow line convergence under the gate for free flow conditions [21]. The characteristics of free flow were studied beneath a vertical sluice gate by analyzing the water surface profile around the gate using a physical model. The results presented several graphs illustrating the relationship between flow depth with discharge, specific energy, and gate opening. It was also concluded that, among the variables considered, discharge and gate opening are the most influential factors affecting the water surface profile beneath the sluice gate [22].

By reviewing the previous scientific literature, it was noted that the discharge coefficient has been studied under different conditions of flow patterns. However, this study aims to support the previous concepts of the discharge coefficient as long as the hydraulics characteristics of flow under another operational condition for sluice gates, which shows how different cases of gate opening could influence the amount of discharge value.

2. COEFFICIENT OF DISCHARGE

The discharge coefficient is considered one of the most important parameters of flow characteristics. In open channels and in general, the discharge coefficient can be defined as the ratio between the actual discharge (Q_{actual}) measured in the field and the theoretical (calculated) discharge ($Q_{theoretical}$).

$$C_d = \frac{Q_{actual}}{Q_{theoretical}} \tag{1}$$

The discharge can be expressed and determined in terms of the discharge coefficient for vertical sluice gates, as shown in Figure 1, using Eq. (2) [23].

$$Q = C_d\, b\, h\, \sqrt{2g\, y_1} \tag{2}$$

where, (Q) is the discharge, (C_d) is the discharge coefficient, (b) is the sluice gate width, (h) is the opening of the sluice gate, (g) is the gravity acceleration, and (y_1) is the depth of flow at the upstream of the sluice gate.

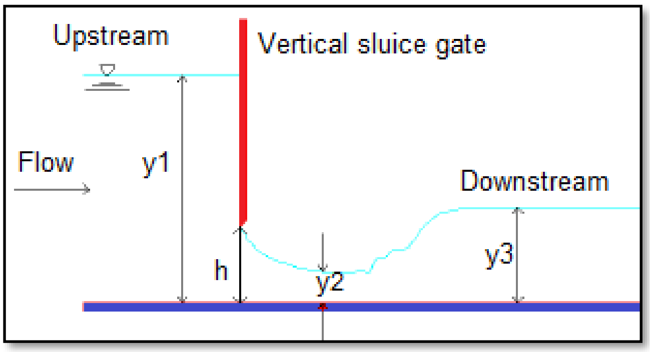

Figure 1. The flow pattern under the vertical sluice gate

Also, the discharge coefficient (C_d) under the sluice gate could be established in terms of coefficients of contraction (C_c).

$$C_d = \frac{C_c}{\sqrt{1 + \frac{C_c . b}{y_1}}} \tag{3}$$

The coefficients of contraction can be defined as the ratio between the water depth just after the sluice gate (y_2) to the gate opening height (h).

$$C_c = \frac{y_2}{h} \tag{4}$$

Theoretically, the coefficient of contraction can range between 0.598 and 0.611 for vertical sluice gates with a sharp edge. At the same time, the studies and experimental results have shown that its value ranges between 0.61 and 0.74 and can be used in engineering applications [24].

3. DIMENSIONAL ANALYSIS

One way to compare and contrast physical quantities is through the use of dimensional analysis, which is One of the most effective methodical techniques for examining and contrasting scientific problems according to their basic dimensions (Length (L), Mass (M), Time (T)), particularly when used in conjunction with experimental research [25]. Dimensional analysis provides guidance on elements that have a major influence on the phenomena under study. This approach is extensively employed in engineering, physics, and applied mathematics to verify the correctness of equations, reduce the complexity of complicated connections, derivation of dimensionless numbers, and inform the design of experiments and physical models [26].

Dimensional analysis, using Buckingham's Pi Theorem (π-Theorem), is a recognized mathematical approach for solving numerous theories and studies related to physical experiments. The foundation of dimensional analysis lies in establishing a functional relationship between several physical variables and reducing them to the smallest possible number of variables and dimensionless groups. The implementation of such an analysis using this theorem aims to reveal the true correlation among the variables [27]. In studying the hydraulic characteristics of flow under vertical sluice gates in open channels, the dimensional analysis might be a powerful simplification technique. The variables used in the dimensional analysis were selected based on their influence and inserted into the experimental procedures. Table 1 summarizes the experimental sample used in this work and all parameters that affected the discharge coefficient.

Table 1. The dimensional analysis of the current study parameters in the MLT system

Variable	Definition	Dimension
Q	Flow discharge	$L^3 T^{-1}$
ρ	Density of fluid	$M L^{-3}$
g	Gravity acceleration	$L T^{-2}$
b	Gate width	L
h	Gate opening	L
y_1	Height of upstream water	L
y_2	Height of downstream water	L

Therefore, the function that expressed the correlation of discharge related to the following variables:

$$f_1(Q, h, b, y_1, y_2, g, \rho) = 0 \tag{5}$$

By following the dimensional analysis process using π-Theorem (Buckingham Pi Theorem), the number of π-groups is 7-3 = 4 (m = 3, number of dimensions), and if the variables (ρ, g, y_1) are initial repeated variables that can be written the formula as follows:

$$f_2(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \tag{6}$$

$$\pi_1 = {y_1}^{a_1} g^{b_1} \rho^{c_1} Q \tag{7}$$

$$\pi_2 = {y_1}^{a_2} g^{b_2} \rho^{c_2} h \tag{8}$$

$$\pi_3 = {y_1}^{a_3} g^{b_3} \rho^{c_3} b \tag{9}$$

$$\pi_4 = {y_1}^{a_4} g^{b_4} \rho^{c_4} y_2 \tag{10}$$

By following the dimensional analysis approach for estimating the value of π_1

$$\begin{gathered} \pi_1 = {y_1}^{a_1} g^{b_1} \rho^{c_1} Q \\ M^0 L^0 T^0 = (L)^{a_1} (LT^{-2})^{b_1} (ML^{-3})^{c_1} (L^3 T^{-1})^1 \\ For\ M: c_1 = 0 \\ For\ L: a_1 + b_1 - 3c_1 + 3 = 0 ;\ a_1 + b_1 + 3 = 0 \\ For\ T: -2b_1 - 1 = 0 ;\ b_1 = -\tfrac{1}{2} ;\ a_1 = \tfrac{5}{2} \\ \pi_1 = \frac{Q}{{y_1}^{5/2} \sqrt{g}} \end{gathered} \tag{11}$$

Similarly, the other non-dimensional parameters analysis leads to the following:

$$\frac{Q}{{y_1}^{5/2} \sqrt{g}} = f\left(\frac{y_1}{b}, \frac{y_1}{h}, \frac{y_1}{y_2}\right) \tag{12}$$

4. EXPERIMENTAL WORKS

The experiments were conducted in a laboratory flume, as shown in Figure 2, with a rectangular cross-section measuring 2.5 m in length, 6.5 cm in width, and 40 cm in depth. The flume has glass walls and is carried by a steel stand. The water was supplied to the channel by a water pump with a manually adjusted valve with a maximum discharge equal to (5200) l/hr. The actual discharge passing through the flume will be calculated by using a flowmeter. The sluice gate used in the research was made of fiberglass, with dimensions of 6.5 cm in width, 50 cm in height, and 10 mm in thickness. It had a slope edge with 45° (the face parallel to the channel bottom) and was positioned in the center of the flume.

The gate was installed vertically with four gate openings (h) were used, measuring 1 cm, 2 cm, 3 cm, and 4 cm. Ten discharges Q were passed for each gate opening, ranging from 1000 l/hr to 5200 l/hr. Also, the point gauge is used to measure the depth of water upstream and downstream of the sluice gate, as shown in Figure 3.

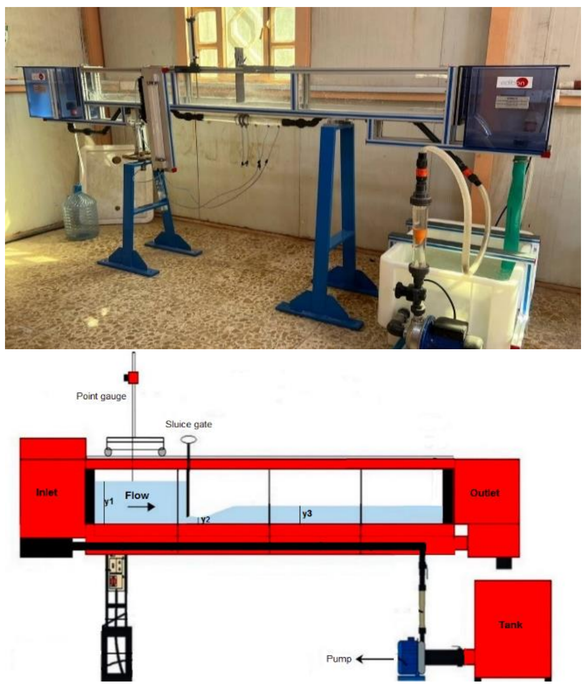

Figure 2. Laboratory flume used in the experimental work

Figure 3. Laboratory process for data collection

5. RESULTS AND DISCUSSION

The variation in the opening of the sluice gate not only influences the behavior of the passing flow, but also, this variation in gate opening can play a significant role in managing the quantity of flow as well. Besides the discharge, the depth of flow upstream and downstream of the sluice gate can be subjected to a certain number of differences, which help to control the water surface elevation in the open channels and can be considered a great tool in water resources management. In this case, measured water releases from sluice gates may vary from those estimated theoretically. However, the discharge coefficient would be used to approximate and correct the theoretical measurements. Therefore, each parameter that may impact the discharge coefficient should be addressed individually, and a practical way to be used for establishing this coefficient.

First, the impact of the water depth upstream to the gate opening ratio on the discharge coefficient was inspected. Figure 4 indeed illustrates the impact of the ratio of the water depth upstream to the gate opening on the discharge coefficient. The change greatly influences the discharge coefficient, which increases rapidly at small values of the ratio of the water depth upstream to the gate opening. The discharge coefficient jumped fast from 0.35 to 0.65 when the ratio of the water depth upstream to the gate opening changed from 1 to 4. However, the discharge coefficient becomes nearly constant after the ratio of the water depth upstream to the gate opening gets bigger than 5, and its average becomes close to 0.68. The main reason behind this is that the flow will be more stable, and the difference variation in the amount of measured flow experimentally compared to that calculated numerically is insignificant.

Then, the ratio of the upstream water depth to the downstream water depth of the sluice gate associated with different gate openings and its effect on the amount of flow through the sluice gate was checked. Figure 4 represents the correlation between the ratio of the upstream water depth to the downstream water depth and discharge for different gate-opening scenarios. The results showed that increasing the ratio will lead to an increase in the amount of flow, which fulfills the concept of the specific energy difference. Also, for the same ratio of the upstream water depth to the downstream water depth of the sluice gate, increasing the gate opening will yield an increase in the amount of flow due to increasing the mass transfer through the sluice gate.

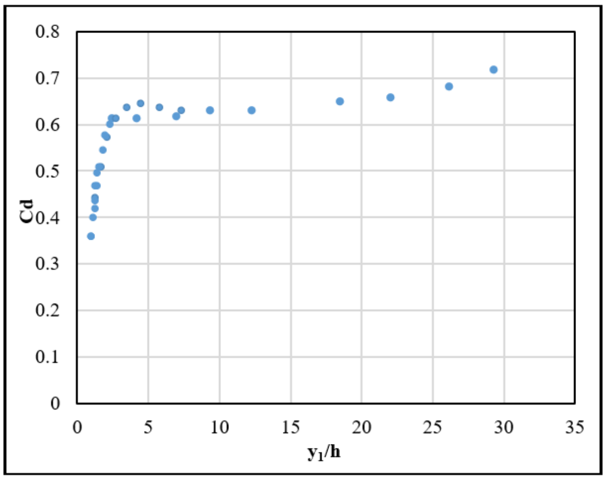

Figure 4. The discharge coefficient related to the ratio of upstream water depth to gate opening

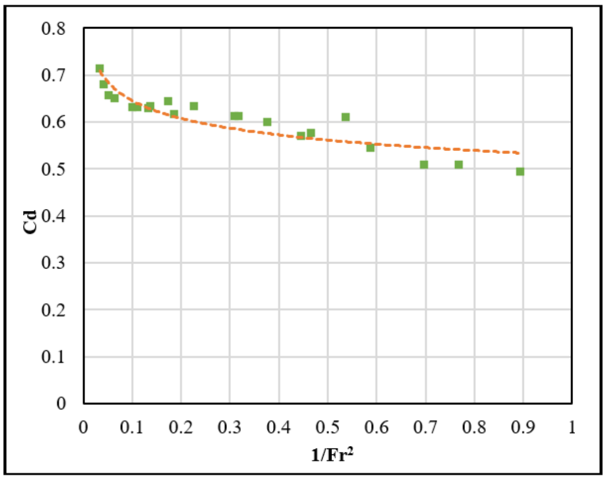

Figure 5. The discharge coefficient related to the froude number

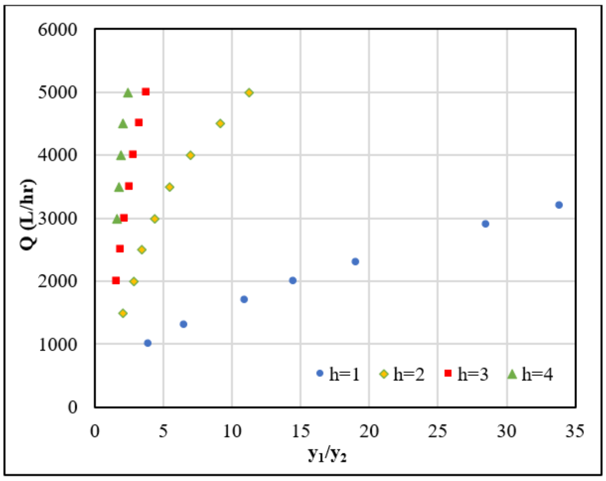

Figure 6. Upstream to the downstream water depth ratio associated with discharge under sluice gates

Furthermore, Figure 5 shows the correlation between the discharge coefficient and Froude Number (Fr). It is clear from Figure 6 that increasing the value of Fr would increase the value of the discharge coefficient. This increase in discharge coefficient is due to the fact that the flow regime becomes more entrained in the supercritical zone, which requires an increase in the water mass transfer through the gate and then leads to an increase in the discharge.

Finally, for all gate-opening scenarios, it was obvious that increasing the amount of discharge would lead to an increase in the discharge coefficient value, as shown in Figure 7. However, increasing the gate opening will reduce the discharge coefficient to pass the same amount of water through the sluice gate. This is because of the increase in the flow area that occurs when the gate opening increases, which will less the required energy applied to the mass of water passing through the sluice gate.

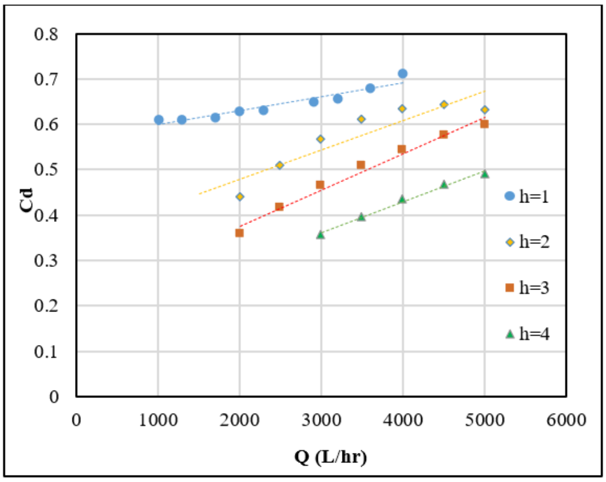

Figure 7. The relation of discharge coefficient related to flow under different gate openings

6. REGRESSION ANALYSIS

Regression analysis is considered one of the best approaches in statistics and data analysis that can help scientists study and recognize the relationship between different variables. Regression analysis is mainly used to estimate the results and find outlines depending on a set of data in several scientific zones, such as, but not limited to, economy, medical, and engineering [28]. Nowadays, regression analysis is utilized to analyze and find correlations between variables that may influence certain phenomena. Therefore, regression analysis is employed herein to establish an equation that can be used for estimating the discharge based on the established correlation from the parameters of the dimensional analysis. This section provides a very straightforward explanation of the Non-linear regression technique, which can carry numerous other forms and shapes; however, more in-depth details can be found in multiple earlier studies and textbooks [29, 30].

$$P = f(X, \delta) + \alpha \tag{13}$$

where, X is the prediction vector for the dependent variable, δ is the parameter vector of phenomena, and α is the error term.

Many programs were utilized to be used for managing data analysis precisely, and SPSS is one of these software programs [31, 32]. The SPSS program can provide significant capabilities for handling variables and can link them to linear or nonlinear relationships. It also provides a suitable environment for creating diverse models based on the different dependent and independent variables used in studies related to data diversity [33]. The relationship between the dependents and their parameters was shown early in the dimensional analysis, as shown in Eq. (12). Therefore, this correlation will be implemented in SPSS to establish the value of each parameter.

To create a relationship between the parameters, 70% of the data derived from the laboratory work was used within the SPSS program to generate an equation linking the discharge values passing under the vertical sliding gates for various openings and conditions. The resulting equation is shown in Eq. (14).

$$Q = {y_1}^{2.5}\sqrt{g}\,\frac{(\frac{y_1}{h})^{0.163}}{(\frac{y_1}{b})^{1.1} * (\frac{y_1}{y_2})^{0.99}} \tag{14}$$

where, Q in m^3/sec, (y_1, y_2, b, h) in m, and g in m/sec^2.

The remaining laboratory data, representing 30% of the total laboratory results, were used to verify the validity and reliability of Eq. (14) above. The statistical indices R^2 and Nash–Sutcliffe efficiency (*NSE*) were used to test the reliability of this equation by comparing experimental and theoretical results [34, 35].

$$NSE = 1 - \frac{\sum(Q_o - Q_s)}{\sum(Q_o - \overline{Q_o})} \tag{15}$$

where, Q_o is the experimental discharge measurements, Q_s is the predicted discharge from the model, $\overline{Q_o}$ is the average experimental discharge measurement.

The equation derived from this study for calculating discharge values under the gates increases in reliability as the values of the statistical parameters approach 1. Table 2 shows the values of these statistical parameters.

Table 2. The statistical parameters results

The Statical Parameters	
***R*²**	***NSE***
0.996	0.962

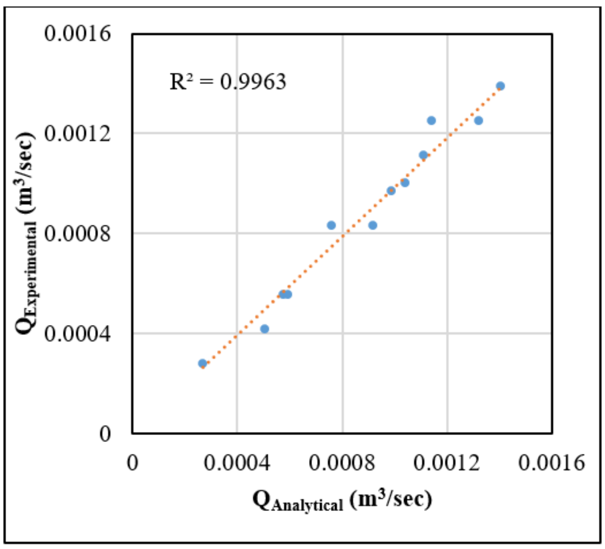

Figure 8. Fitting of experimental and analytical flow

Finally, Figure 8 represents the graphical fitting between the estimated discharge from the analytical approach (Eq. (14)) and the experimental work. It is clear that the analytical approach for estimating the flow under the vertical sluice gates showed acceptable results compared to those measured experimentally.

7. CONCLUSIONS AND RECOMMENDATIONS

Sluice gates are devices used to control and regulate water flow in open channels. Measuring the flow passing the sluice gate would be subjected to several variables. Therefore, this study aims to establish an analytical approach to estimate the amount of flow based on the variable that may impact this flow. The findings of this study can be summarized as follow:

- It was found that increasing the ratio of the water depth upstream of the gate to the gate opening would lead to an increase in the discharge coefficient and then increase the passing flow under the sluice gate.
- Also, increasing the difference in the ratio of the upstream water depth to the downstream water depth would lead to an increase in the passing flow. In fact, the increment in the gate opening will increase this amount of the passing flow under the same condition of the difference in water depth between the upstream and downstream of the gate.
- Furthermore, the dimensional analysis approach was used in a way to create a non-dimensional equation that represents the shape of the correlation between the parameters that impact the flow under the vertical sluice gate.
- Then, the regression analysis, using the non-linear analysis, was utilized to establish an analytical equation for calculating the discharge based on the parameters of the dimensional analysis. The developed analytical equation showed a great fitting with the results that were calculated experimentally. The accuracy of the analytical equation was inspected by two well-known statistical parameters (R^2 and NSE), and their results were 0.996 and 0.962, respectively.

This methodology can be utilized for further investigation to address the flow characteristics for the sluice gate under different cases of inclinations and flow scenarios.

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