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EVALUATING FLOW 3D'S ACCURACY IN PREDICTING HYDRAULIC CHARACTERISTICS OF CIRCULAR SPILLWAYS

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ABSTRACT

Spillways are among the most important hydraulic structures and have the greatest impact on flood control systems. Circular spillways are often used in narrow valleys and with earth dams. Previous studies have focused on this type of spillway due to its sensitivity and importance. One of the most crucial elements affecting a circular spillway's performance is its discharge coefficient. This coefficient gauge shows how effectively a spillway can move water over a range of dimensions. In this research, we established a physical model in the Irrigation and Hydraulics Laboratory. Department of Civil Engineering, Faculty of Engineering, Al-Azhar University, Cairo. Twenty laboratory experiments were conducted and their measurements were taken and compared with the results obtained from the numerical model that was generated by Flow 3D software. The purpose of the comparison is to validate the numerical model, which can be used to predict the hydraulic characteristics of circular spillways in the future based on the results, It was clear that the numerical model is highly efficient, with an average error rate of no more than 10% in calculating the water height above the spillway crest and no more than 12% in measuring the discharge coefficient. So, the numerical simulation in the flow 3D software is capable of simulating flow over a circular spillway.

KEYWORDS: Circular spillway, Discharge coefficient of the spillway, Shape of the spillway crest, FLOW3D

تقييم دقة برنامج FLOW 3D في تنبؤ الخصائص الهيدروليكية للمفيضات الدائرية

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الملخص

المفيضات الدائرية هي من بين أهم المنشآت الهيدروليكية ولها تأثير كبير على أنظمة مواجهة الفيضانات. وتستخدم غالبًا االمفيضات الدائرية في الأودية الضيقة ومع السدود الترابية. ركزت الدراسات السابقة على هذا النوع من السدود بسبب حساسيته وأهميته. ومن بين العناصر الأكثر حساسية التي تؤثر على أداء المفيضات الدائرية هو معامل التصريف. يقيس هذا المعامل فعالية المفيض لنقل المياه عبر مجموعة من الأبعاد. في هذا البحث، أنشأنا نموذجًا فيزيائيًا في مختبر الري والهيدروليكا، قسم الهندسة المدنية، كلية الهندسة، جامعة الأزهر، القاهرة. تم إجراء عشرين تجربة في المختبر وتم قياس قياساتها ومقارنتها بالنتائج التي تم الحصول عليها من النموذج العددي الذي تم إنشاؤه بواسطة برنامج (Flow 3D). الهدف من المقارنة هو التحقق من صحة النموذج العددي، الذي يمكن استخدامه لتوقع الخصائص الهيدروليكية للمفيضات الدائرية في المستقبل. استنادًا إلى النتائج، أصبح من الواضح أن النموذج العددي فعال للغاية، بمعدل خطأ متوسط لا يتجاوز 10٪ في حساب ارتفاع الماء فوق قمة المفيض ولا يتجاوز 12٪ في قياس معامل التصريف. لذلك، فإن المحاكاة العددية في برنامج Flow 3D قادرة على محاكاة تدفق الماء عبر السدود الدائرية.

الكلمات المفتاحية : المفيضات الدائرية، معامل التصرف، نموذج طبيعي، نموذج رقمي عددي، الخصائص الهيدروليكيه، قمة المفيض، Flow 3d sofware.

1. INTRODUCTION

A circular spillway is an essential hydraulic structure used in dams to manage water flow from the reservoir to the downstream. The spillway features a circular design with a concave shape, concrete walls, and a controlled crest to regulate water discharge.

The significance of circular spillways lies in their efficient regulation of large water discharges, which reduces the risk of downstream flooding that can damage property, destruction of aquatic habitats, and loss of life [1].

The primary purpose of a circular spillway is to ensure a controlled and safe outlet for excess water to prevent flooding and maintain the water level. With their straightforward construction and reliable performance, circular spillways are crucial to safeguard downstream communities and maintaining ecological balance. The circular spillway moves water downstream by utilizing various components, including a crest, a conical transition, a vertical shaft, a bend, and an outlet tunnel [2].

There are three ways to measure the amount of water flowing through a circular spillway, which vary depending on the water level. The first method is called "crest-regulated flow," which occurs when the water level drops below the spillway crest, allowing water to flow freely. As the water level rises, the spillway becomes covered with water and acts like an orifice, regulating the flow. This is known as "orifice-controlled flow." Finally, if the water level rises even further and completely submerges the spillway, the flow will be controlled by pressure and may result in "tunneling" or "pipe control" [3].

Equations 1 and 2, provide methods to calculate the discharge through a circular spillway under free flow and orifice flow conditions, respectively. The equations are as follows:

$$\boldsymbol{Q = C_d(2\pi R)H^{1.5}} \qquad \textbf{(Eq. 1)}$$

$$\boldsymbol{Q = C_d\pi r^2\sqrt{2gH_0}} \qquad \textbf{(Eq. 2)}$$

In these equations, Q represents the discharge through the circular spillway, Cd is the discharge coefficient, R is the crest radius, r is the radius of the conical transition, H is the water level over the spillway crest, H0 is the distance between the water level and the entrance to the conical transition diameter, and g is the acceleration due to gravity [4].

Numerous theoretical and empirical investigations have been conducted over the last half-century to explore the hydraulic properties of circular spillways. In an experimental study conducted on morning glory spillways, researchers investigated the effects of polyhedral spillway crests on discharge intensity and coefficient. To conduct the study, they developed physical hydraulic models of the spillways and performed a total of 180 experiments. The outcomes of the research demonstrated that the implementation of a polyhedral spillway crest resulted in an increase in the discharge coefficient of the morning glory spillway. Moreover, the polyhedral crest led to an expansion in the discharge passing over it. Upon analyzing the test data, the researchers found that the use of a polyhedral spillway crest contributed to an improvement in the hydraulic efficiency of the circular spillway [4].

The research on flow states in the Morning Glory Spillway revealed a significant finding: when the water conveying tube is submerged without aeration, turbulent flow occurs at the spillway. The study emphasized the crucial role of aeration in preventing the development of turbulent flow in the Morning Glory Spillway. Aeration, in this context, helps maintain a stable and smooth flow, avoiding the undesirable turbulence that could otherwise occur [5].

In a series of laboratory experiments, researchers created a physical model of the Morning Glory Spillway to investigate the impact of vortex breaker blades on the spillway's discharge coefficient. The primary objective was to examine how varying the number and thickness of these blades would influence the spillway's ability to discharge water effectively. The researchers hypothesized that increasing the number and thickness of the vortex breaker blades would enhance the spillway's capacity for water discharge. After conducting the experiments, the study's findings supported their postulation. It was observed that by increasing the number and thickness of the vortex breaker blades, the spillway's discharge coefficient was significantly improved. As a result, the spillway exhibited an increased capacity to discharge water efficiently and effectively. This discovery highlights the importance of vortex breaker design in optimizing the hydraulic performance of the Morning Glory Spillway [6].

the researchers conducted a study to examine how anti-vortex plates impact the discharge coefficient of the Morning Glory Spillway. Their findings revealed that reducing the alignment angle of the plates on the spillway led to an increase in the discharge rate coefficient. Furthermore, the research concluded that the most effective configuration, in terms of discharge coefficient, consisted of five anti-vortex plates with a positioning edge of 60 degrees [7].

The control of vortices in a vortex breaker is influenced by various blade dimensions, such as length, height, orientation, and thickness. Among these dimensions, the length of the blades was found to have a more significant impact on vortex control compared to the number of blades used. [8]. In a research study, scientists constructed a physical model of the morning glory spillway to examine the influence of the number and shape of pyramidal vortex breakers on the spillway's discharge coefficient. The findings indicated that incorporating six vortex breakers resulted in a remarkable enhancement of the Performance Index for the discharge coefficient. Specifically, there was an improvement of up to 50.97% in crest control and up to 16.13% in orifice control compared to the standard morning glory spillway without vortex breakers. These results suggest that utilizing pyramidal vortex breakers can effectively increase the discharge capacity of morning glory spillways [9].

The impact of different vortex shapes and stepped chamber conduct on spillway flow was analyzed. The researchers investigated pressure and flow velocity parameters on the spillway surface at different locations concerning the input discharge to the spillway. Through their analysis, they determined that the most effective type of spillway, with the highest discharge coefficient, consisted of a smooth spillway design with vortex breakers in the form of ogee triangles, with three such structures positioned along the spillway crest. This configuration was found to optimize the spillway's flow performance and enhance its discharge capacity [10].

In a conducted study, the impact of varying numbers and angles of vortex breakers on the discharge coefficient of the morning glory spillway was examined. The researchers carried out 170 experiments on a physical model of the spillway. Their findings revealed that the most effective configuration for enhancing the discharge coefficient involved installing six vortex breakers at a 45-degree angle. This arrangement yielded the highest improvement in the spillway's discharge coefficient, indicating its effectiveness in maximizing the spillway's performance [11].

The study was focused on investigating the effect of pier location and geometry on a morning glory spillway flow behavior and discharge capacity. The study aimed to provide valuable insights into optimizing the morning glory spillway's flow behavior and enhancing its discharge capacity. [12]. The researchers conducted a physical model study to investigate the swirling flow in vertical shaft spillways with a unique shape and circular piano-key (CPK) intake. Their research demonstrated that the swirling flow strength in the CPK spillway was considerably lower than in simple shaft spillways [13]

In a study , the researchers focused on predicting the discharge coefficient for the stepped Morning Glory spillway. They conducted experiments to obtain data and used it to predict the discharge coefficient. The results showed that the discharge coefficient of the stepped Morning Glory spillway decreased as the ratios of head/length and head/radius increased [14].

Flow-3D models were used to assess the impact of installed breaker blades on the morning glory spillway and compared the results to experimental data. Installing blades led to a 42% increase in the discharge coefficient and a 25% decrease in the upstream water level. The six-blade model produced the best results among the three different blade arrangements tested [15].

a study was conducted on the hydraulic design of Labyrinth Morning Glory Spillway using a physical model with square and circular inlets. The results showed that the discharge coefficient decreases as the length of the spillway and zigzag increases. Moreover, the study found that the square inlet had a higher discharge coefficient than the circular inlet and did not exhibit vortex formation [16].

Researchers investigated the hydraulic performance of a marguerite-shaped inlet as an alternative to the traditional inlet of vertical shaft spillways. The study found that the swirling flow in a marguerite-shaped inlet is significantly lower than in a plain shaft and morning glory spillway. Additionally, the developed crest length is at least six times larger than the original shaft spillway, thanks to using marguerite-shaped inlets [17].

By using 3D simulations created with Flow 3D software. The researchers compared four flow rates to determine the optimal placement of the blades. Results showed that using 12 blades with an eight-meter length was the best scenario, which led to a decrease in the water level and an increase in the discharge coefficient [18].

This research aims are evaluating the numerical model of circular weirs created on Flow 3D software for predicting hydraulic characteristics in all flow conditions.

2. METHODOLOGY AND MATERIALS

The methodology and materials used in the research study are described in this section. The researchers describe in detail the physical model of the spillway, including its dimensions and components. They also represent the testing setup and measurement equipment for collecting water level and discharge coefficient data. Furthermore, the researchers describe the various scenarios that were tested.

2.1-Dimensional analysis

The discharge coefficient (Cd) of a circular spillway can be described using Equation (3), which considers the spillway's geometric characteristics.

$$C_d = f\,(\rho, Q, D_c, \mu, N, H_n, H_c, H, P_n, P_c, g, d, S_n) \qquad \textbf{(Eq. 3)}$$

The Equation includes variables such as density (ρ), dynamic viscosity (μ), gravity acceleration (g), discharge (Q), water level over the spillway crest (HC), head above the weir edge (Hn), Ht = Hc + Hn, crest diameter (Dc), spillway throat diameter (d), the perimeter of the spillway crest (Pc), the perimeter of the notches edge (Pn), coefficient reflecting the notches shape (Sn), and the number of notches (N). Using the Buckingham method, reducing the number of variables by subtracting the dimensions (M, L, T) from the total number of variables is possible. The resulting number of dimensionless equations can be seen in Table 1.

Table 1: Buckingham Method Applied to Equation (3) To Determine the Number of Dimensionless Equations

Л NO	Л -Terms	Dimensional analysis	Notes
π_1	ρ^{a1} D^{b1} Q^{c1} μ	Dc μ/ρQ	**Eq. 4**
π_2	ρ^{a1} D^{b1} Q^{c1} d	d/Dc	**Eq. 5**
π_3	ρ^{a1} D^{b1} Q^{c1} Hc	Hc/Dc	**Eq. 6**
π_4	ρ^{a1} D^{b1} Q^{c1} Hn	Hn/Dc	**Eq. 7**
π_5	ρ^{a1} D^{b1} Q^{c1} Ht	Ht/Dc	**Eq. 8**
π_6	ρ^{a1} D^{b1} Q^{c1} Pc	Pc/ Dc	**Eq. 9**
π_7	ρ^{a1} D^{b1} Q^{c1} Pn	Pn/ Dc	**Eq. 10**
π_8	ρ^{a1} D^{b1} Q^{c1} g	Dc^5g/Q^2	**Eq. 11**
π_9	ρ^{a1} D^{b1} Q^{c1} Sn	Sn	**Eq. 12**
π_{10}	ρ^{a1} D^{b1} Q^{c1} N	N	**Eq. 13**

According to Buckingham Pi-theorem, the overall form of the relationship between these variables is written in Equation (4).

$$Cd = \mathbf{f}\left(\frac{Dc\mu}{\rho Q}, \frac{d}{Dc}, \frac{Hc}{Dc}, \frac{Hn}{Dc}, \frac{Ht}{Dc}, \frac{Pc}{Dc}, \frac{Pn}{Dc}, \frac{Pc}{Dc}, \frac{gDc^5}{Q^2}, Sn, N\right) \quad \text{(Eq. 4).}$$

A replacement dimensionless equation is created using multiplication or division of two dimensionless equations. Therefore, (by division of the third and the fifth. and division of the fourth and fifth and division of the sixth and seventh) dimensionless equations (Eq. 5 - Eq. 7):

$$\pi 10 = Hc/Ht \quad \text{(Eq. 5)}$$

$$\pi 11 = Hn/Ht \quad \text{(Eq. 6)}$$

$$\pi 11 = Pn/Pc \quad \text{(Eq. 7)}$$

The final functional relationship is reduced to be as in Eq. 8.

$$Cd = \mathbf{f}\left(\frac{Dc\mu}{\rho Q}, \frac{d}{Dc}, \frac{Hc}{Ht}, \frac{Hn}{Ht}, \frac{Pn}{Pc}, \frac{gDc^5}{Q^2}, Sn, N\right) \quad \text{(Eq. 8)}$$

2.2 Experimental Work

The study's objectives were achieved by testing the physical model in the hydraulic laboratory of the civil engineering department at Al Azhar University in Cairo, Egypt, which was created based on Fig. 1.

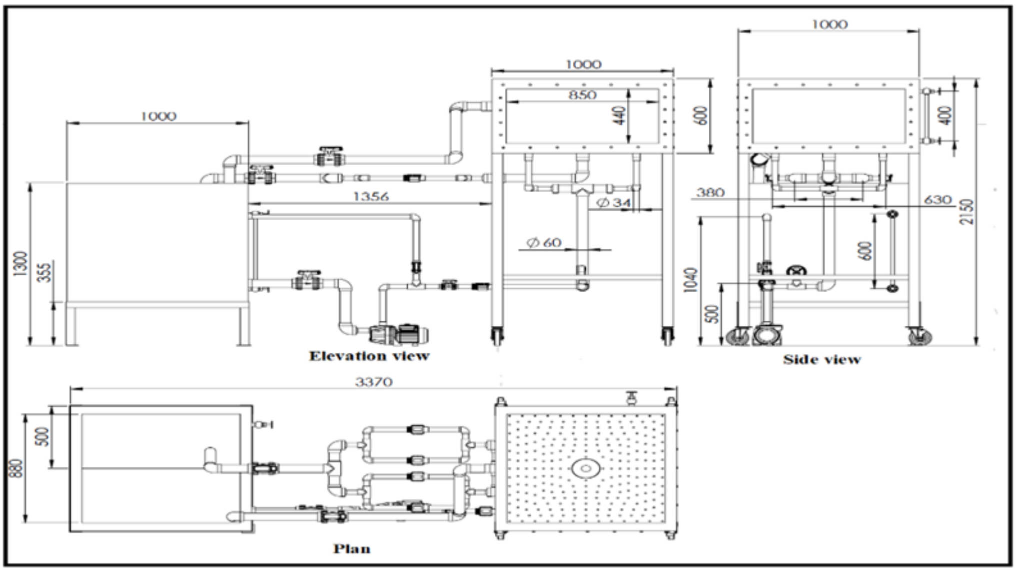

Fig. 1: A physical model was used in the laboratory

Fig. 2 depicts the components of the model, including:- A main tank that is 100cm * 100cm * 100cm in size and has a capacity of 1000 liters, with two vents - one containing a piezometer for volume measurement and calibration. The main flume, which houses the funnel-shaped part of the morning glory spillway, has a length of 100 cm, a width of 100 cm, and a height of 60 cm with a capacity of 600 liters. The flume's sidewalls are made of eight-millimeter-thick Plexiglas, while the other two sidewalls and the bottom of the canal are made of steel and anchored with angle irons. A field tee with two valves connects the basin reservoir to the spillway reservoir to adjust the inlet discharge. A pump with a capacity of 1.3 hp and a discharge rate of 100 liters/minute transfers water from the main tank to the flume.A 1" diameter PVC feeding net with control valves and a flow meter provides a uniform flow in the four water inlets in the flume. A metal screen controls the volatility and turbulence inside the reservoir. The spillway consists of a fixed steel main structure and proposed shapes for the spillway's crest that are movable and made of reinforced plastic, with different diameters (two inches, four inches, six inches, and eight inches) produced by 3D printing. Fig. 3 illustrates the spillway's shapes. A 2" diameter shaft pipe with 4 flow meters represents the outlet of the spillway and connects the spillway to the source tank. Calibration was completed using the volumetric approach before beginning the actual studies.

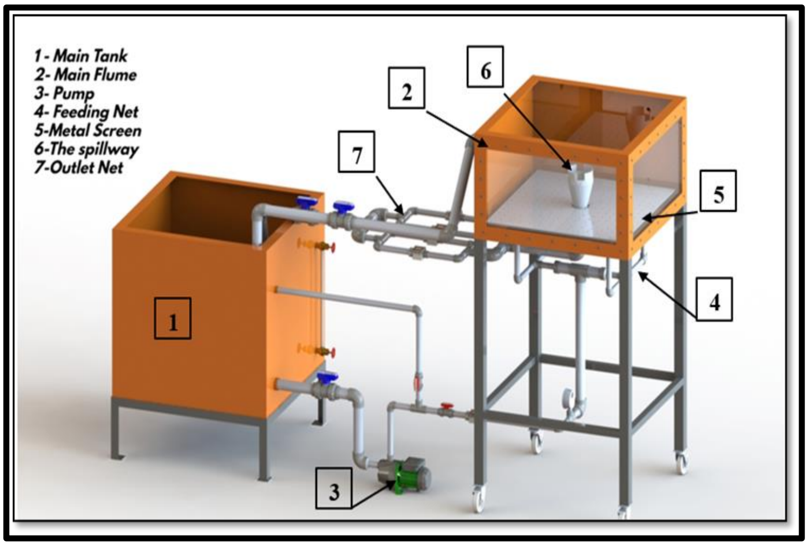

Fig. 2: Display physical model's in the laboratory

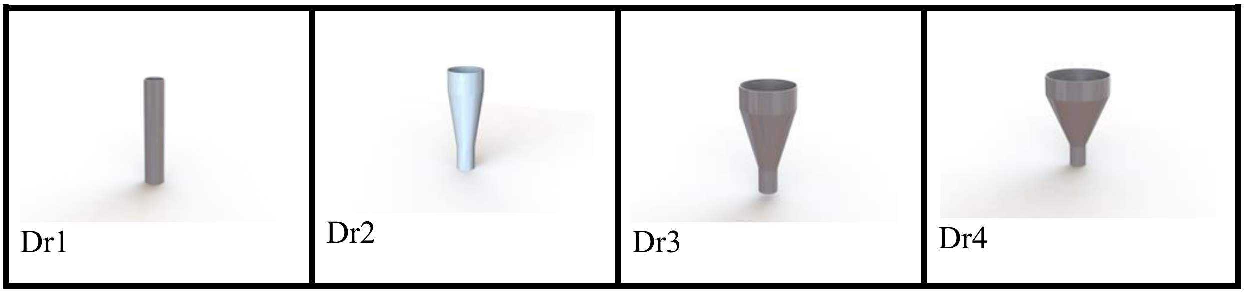

Fig. 3: displays the spillway shapes.

2.2.1 Calibrating the Measuring Devices

The measuring devices used in the experiments were calibrated based on the continuity equation, which states that the inflow (Qin) must be equal to the outflow (Qout) for a steady system. To achieve this, the discharge was measured by collecting a specific volume of water within a certain time using a piezometer, which measured changes in differential water height over 30 seconds. This measurement was denoted as "Q measured." Additionally, the discharge was calculated using a flow meter, which provided a reading represented as "Q calculated." A relationship between Q measured and Q calculated was established, and the results were presented in Fig. 4, which showed a strong agreement between the two measurements.

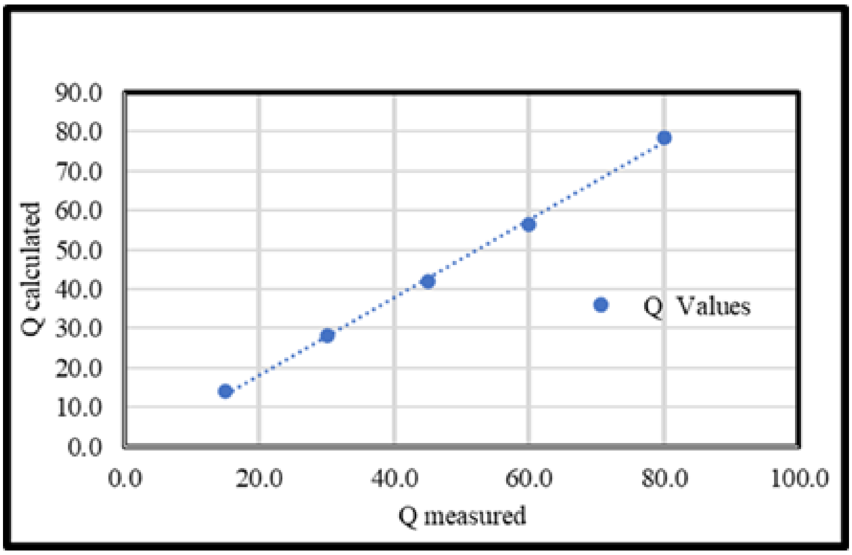

Fig. 4. Model Calibration

2.2.2 Experimentation Following the Experimental Programmer

After calibration, experiments were conducted based on a predetermined experimental program involving several contributing parameters. These parameters included the diameter of the spillway (D), which had four different values (D1 = 2, D2 = 4, D3 = 6, and D4 = 8 inches), the Shape of the spillway (S), which had one circular value (S = C), and the discharge, which had five different values (Q1 = 84, Q2 = 60, Q3 = 45, Q4 = 30, and Q5 = 15). The discharges were related to Q1 = 122 l/s, which were equal to Qr1, Qr2, Qr3, Q4, and Q5, equal to 0.689, 0.492, 0.369, 0.246, and 0.123, respectively. These parameters were systematically varied to investigate their effects on the spillway's discharge and discharge coefficient. The experiments were conducted confidently in the calibration process. The results were compared to findings produced by a three-dimensional model generated using Flow 3D software to ensure effectiveness.

2.3 Numerical Simulation

The advanced computational fluid dynamics (CFD) code Flow 3D, which solves the Navier-Stokes Equations, was used to simulate the circular spillway. This software utilizes finite volume approximations of mass, momentum, and energy in three dimensions to analyze complex fluid problems. It also includes models for sediment transport, moving rigid bodies, and flows in porous media. A hydraulic model of the circular spillway was designed using SolidWorks software and imported into FLOW-3D to observe the water surface elevation with varying diameters, shown in Figure 5. The primary goal of the numerical modeling was to investigate the effects of changing the geometric properties of the circular spillway crest on discharge rates and coefficients. To achieve this, experiments were conducted, and the resulting data were compared with the findings generated by the FLOW-3D software. Simulations were performed using four different diameter circular spillways and five different discharge rates to verify the effects of changes in the spillway crest's geometric properties.

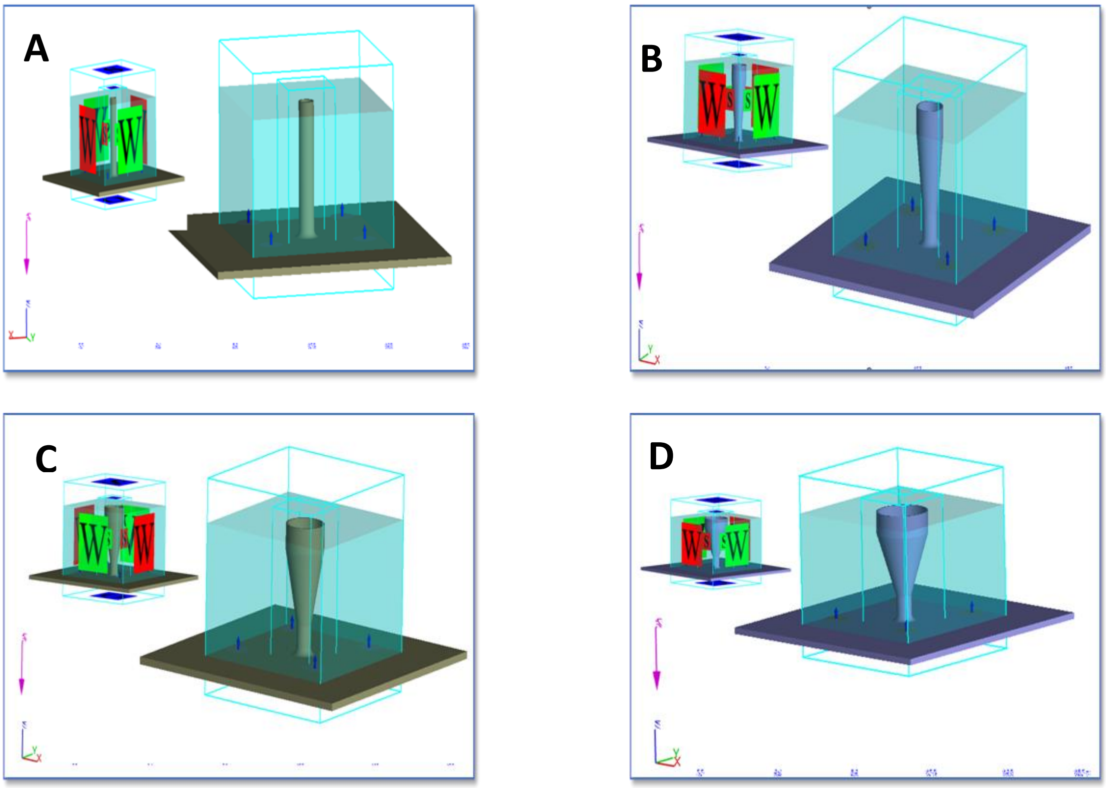

Fig. 5: Simulation Model & Boundary Conditions of Model At (A) Dr1, (B) Dr2, (C) Dr3, (D) Dr4

3. RESULTS AND DISCUSSION

The primary goal of comparing the numerical and physical models is to evaluate the accuracy of the numerical model's prediction of the discharge coefficient for circular spillways. The physical model was conducted at the irrigation and hydraulics laboratory in the civil department of the Faculty of Engineering at Al-Azhar University. In contrast, the numerical model was analyzed using Flow-3D. The two models were compared and examined based on the total heads (Hc) over the circular spillway crest and the discharge coefficient. Tables 2, 3, 4, and 5 display the total head over the circular spillway and discharge coefficients obtained from the numerical and physical models.

Table 2. Results Obtained from Models at Dr1

Qr	Physical Model		Numerical Model		error%	
	Hc	Cd	Hc	Cd	Hc error %	Cd error %
0.689	1.9	0.713136	1.952	0.703573	2.631579	-1.34096
0.492	1.5	0.573291	1.62	0.55165	6.666667	-3.77496
0.369	1.3	0.852233	1.39	0.770816	3.846154	-9.55328
0.246	1	0.842135	1.04	0.794021	4	-5.7134
0.123	0.55	0.688203	0.665	0.51764	9.090909	-24.7838
ERROR AVERAGE					5.2470618	-9.03328

Table 3: Results Obtained from Models at Dr2

Qr	Physical Model		Numerical Model		error%	
	Hc	Cd	Hc	Cd	Hc error %	Cd error %
0.689	1.35	0.899157	1.4	0.85142	3.703704	-5.30902
0.492	1.1	0.873211	1.1	0.873211	0	0
0.369	0.8	0.703952	0.9	0.589949	12.5	-16.1948
0.246	0.625	0.679621	0.7	0.573376	12	-15.6329
0.123	0.4	0.663692	0.41	0.63956	2.5	-3.63614
ERROR AVERAGE					6.1407408	-8.15457

Table 4: Results Obtained from Models at Dr3

Qr	Physical Model		Numerical Model		error%	
	Hc	Cd	Hc	Cd	Hc error %	Cd error %
0.689	1.1	0.827892	1.05	0.887726	-4.5454545	7.227228
0.492	0.9	0.799045	0.88	0.826439	-2.2222222	3.428388
0.369	0.7	0.582449	0.75	0.525186	2.8571429	-9.83143
0.246	0.55	0.557532	0.55	0.557532	-5.22E-13	0
0.123	0.35	0.549138	0.35	0.549138	-8.57E+00	0
ERROR AVERAGE					-2.4963925	0.164837

Table 5: Results Obtained from Models at Dr4

Qr	Physical Model		Numerical Model		error%	
	Hc	Cd	Hc	Cd	Hc error %	Cd error %
0.689	1	0.725532	0.85	0.925823	-15	27.60615
0.492	0.85	0.661302	0.7	0.884874	-17.6471	33.80777
0.369	0.6	0.557534	0.5	0.732898	-16.6667	31.45341
0.246	0.5	0.488599	0.4	0.682837	-20	39.75425
0.123	0.325	0.466179	0.3	0.525648	-7.69231	12.75691
ERROR AVERAGE					-15.401222	29.0757

To provide a more objective comparison of the model results, graphs are utilized. Specifically, Fig. 6, 7, 8, and 9 compare the total head over the crest of the circular spillway between the physical and numerical models and the relationship between the discharge coefficient (COD) in the physical and numerical models for all cases. The figures and tables indicate the following:

- The total head (Hc) and discharge coefficient results obtained from the numerical and physical models are mostly in agreement.
- Flow-3D can accurately predict total heads (Hc) and corresponding discharge values, with an average error percentage of less than 10 percent in cases Dr1, Dr2, and Dr3.
- However, there are some discrepancies in the results between the models in case Dr4, which can be attributed to the high turbulence in this region. Additionally, the waving of the water surface during physical experiments may lead to less precise measurements of water flow depths.
- Overall, Flow-3D produces acceptable results for water surface profiles, as shown in Fig. 10

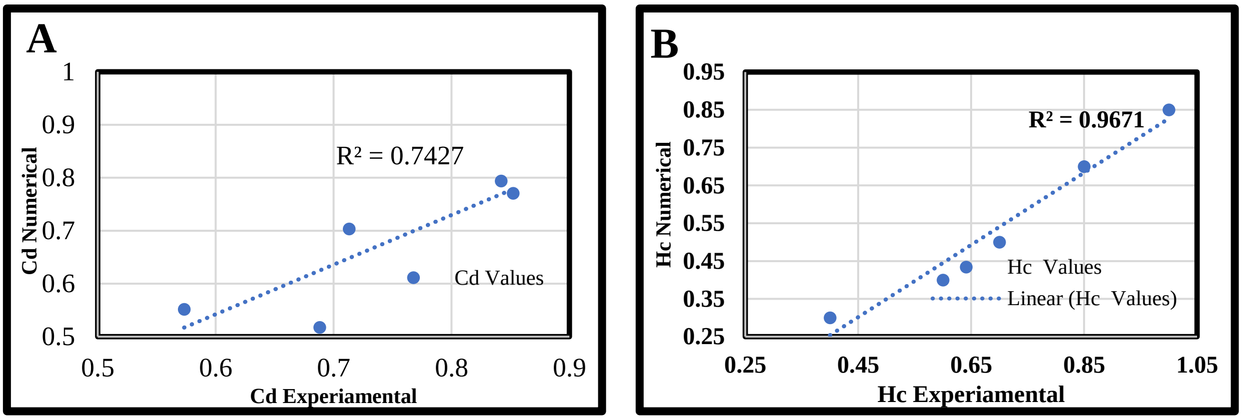

Fig. 6: Validation of A Numerical Model Circular Spillway at Dr1 (A) for Cd and (B) for Hc

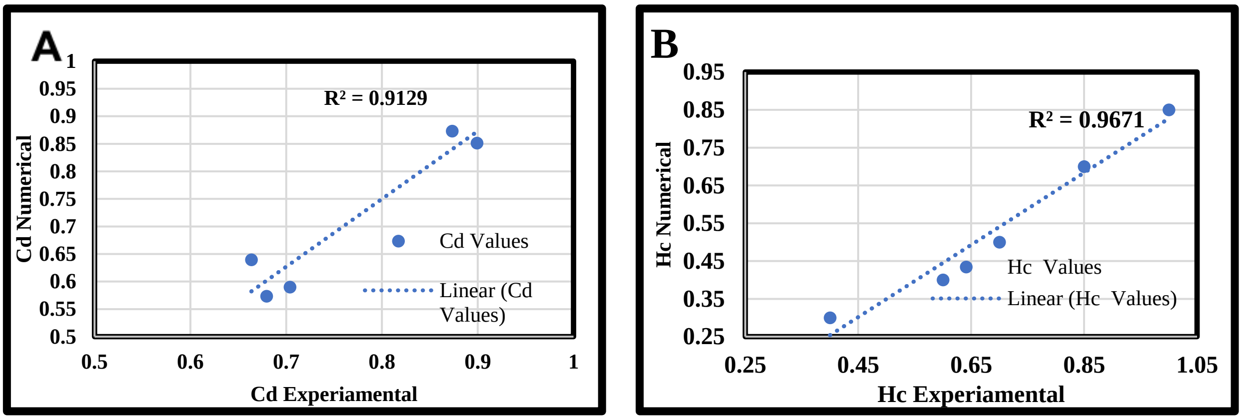

Fig. 7: Validation of A Numerical Model Circular Spillway at Dr2 (A) for Cd and (B) for Hc

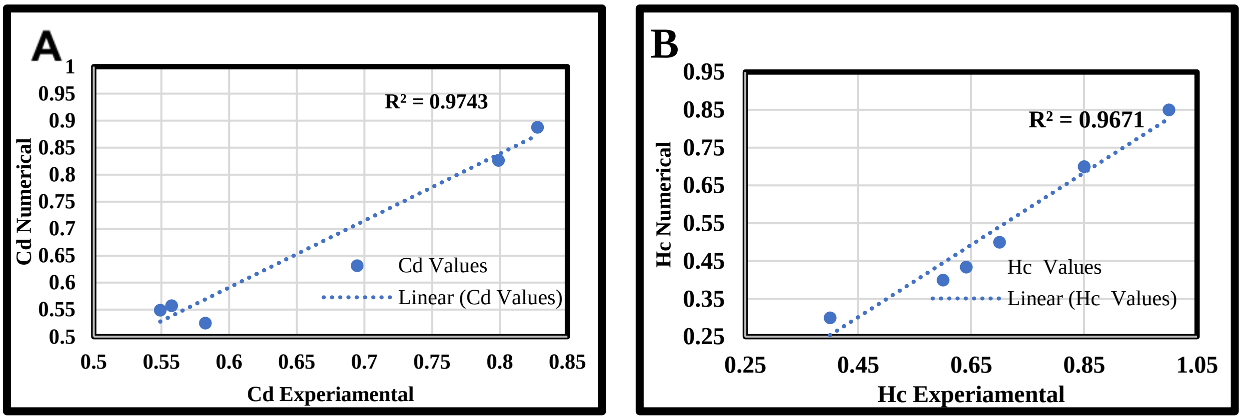

Fig. 8: Validation of A Numerical Model Circular Spillway at Dr3 (A) for Cd and (B) for Hc

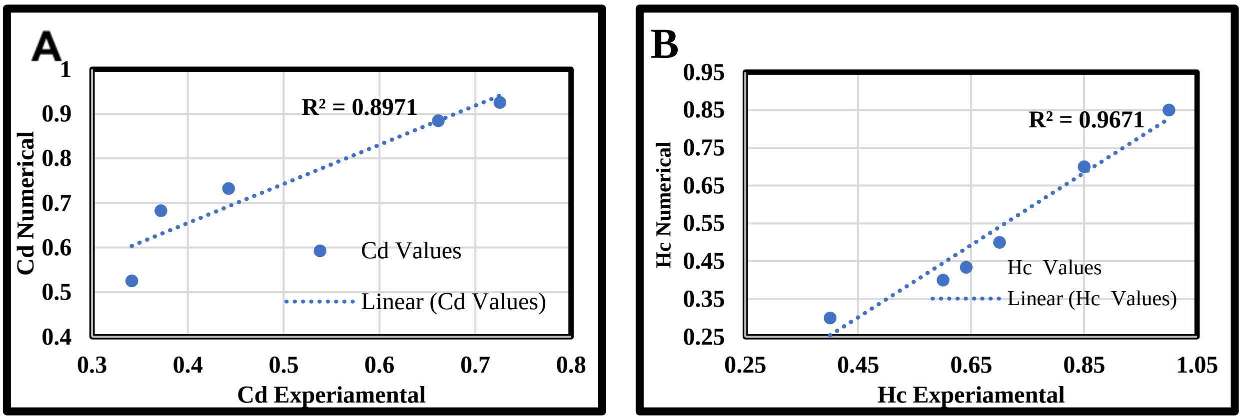

Fig. 9: Validation of A Numerical Model Circular Spillway at Dr3 (A) for Cd and (B) for Hc

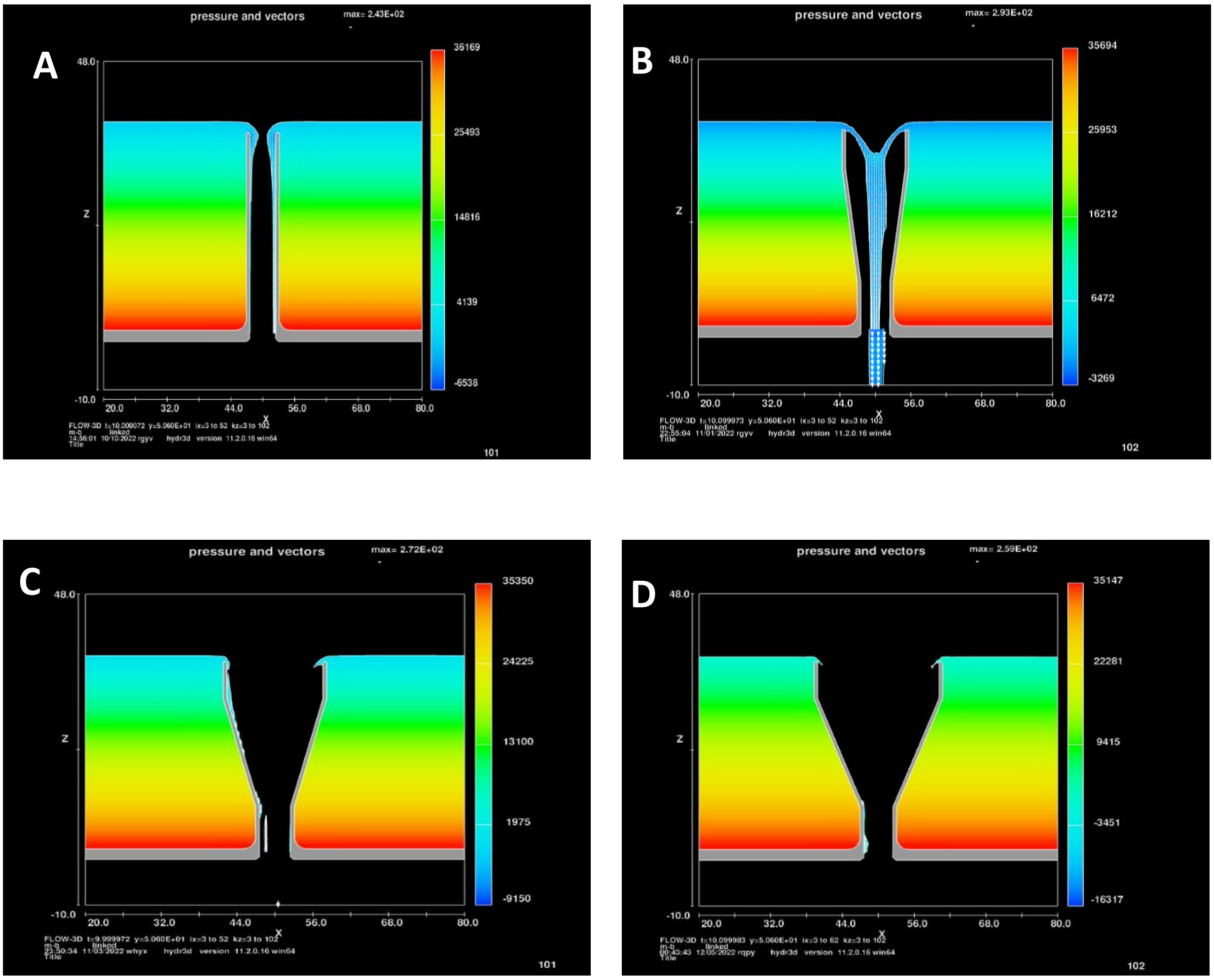

Fig. 10: Water surface profile get from Flow-3D (A) Dr1, (B) Dr2, (C) Dr3, and (D) Dr4

SUMMARY AND CONCLUSIONS

In this research, two models were created , one physical and one numerical , and twenty laboratory experiments were conducted, and their results were measured. The experimental results were compared with those generated by the numerical model to evaluate its accuracy. The following conclusions were obtained based on the analysis of the measurements.

- The experimental results confirmed the accuracy of the discharge values obtained by Flow-3D compared to a physical model.
- The study demonstrated the advanced capabilities of numerical tools based on RANS equations for simulating flow over a circular spillway.
- The numerical model is sufficiently capable of predicting the hydraulic performance of circular spillways.

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