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Flow rate measurement in gravity irrigation systems using sluice gates

Determinación de caudales utilizando compuertas en sistemas de riego por gravedad

Determinação de vazões por comportas em sistemas de irrigação por gravidade

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Abstract

Gates are used to divert water to rice production plots in eastern Uruguay. In this study, the operating curves of rectangular gates installed at the entrance of circular section pipes are determined for submerged discharge conditions, which can be also used as gauging structures. For the tests, the gates were mounted at the inlet end of 6-m-long,sanitary-type PVC pipes, and with a nominal diameter of 250 and 315 mm. This configuration is analogous to that used in gravity irrigation systems. The derivation of the operating equations of the gates in this configuration is presented. The discharge coefficients (Cd) experimentally obtained show that discharge under the gate is dependent on the opening and on the upstream and downstreamdifference in depth, in addition to the Reynolds number under the gate. The dependence on the Reynolds number, which is usually omitted in other applications, is relevant in the case of rice irrigation, given the low velocities, and allows its use as a regulation structure and water gauging in these systems.

Keywords: irrigation, discharge coefficient, gates, discharge measurement

Resumen

Las compuertas se utilizan para la derivación de agua a parcelas de producción de arroz en el este de Uruguay. En este trabajo se determinan las curvas de funcionamiento de compuertas rectangulares instaladas al ingreso de tuberías de sección circular en condiciones de descarga sumergida, pudiendo entonces utilizarlas como estructuras de aforo. Para los ensayos las compuertas fueron montadas en el extremo de entrada de tuberías de PVC tipo sanitario de 6 m de longitud y diámetro nominal de 250 y 315 mm. Esta configuración es análoga a la utilizada en sistemas de riego por gravedad. Se presenta la derivación de las ecuaciones de funcionamiento de las compuertas en esta configuración. Los coeficientes de descarga (Cd) obtenidos experimentalmente muestran que la descarga bajo la compuerta es dependiente de la apertura y la diferencia de tirantes aguas arriba y aguas abajo, además del número de Reynolds bajo la compuerta. La dependencia del número de Reynolds, que usualmente se omite en otras aplicaciones, es relevante en el caso del riego de arroz, dadas las bajas velocidades, y permite su uso como estructura de regulación y aforo de agua en estos sistemas.

Palabras clave: riego, coeficiente de descarga, compuertas, medición de caudal

Resumo

As comportas são usadas para desviar a água para os campos de produção de arroz no leste do Uruguai. Neste trabalho são determinadas as curvas de operação de comportas retangulares instaladas na entrada de tubos de seção circular em condições de descarga submersa; podendo então utilizá-los como estruturas de aferição. Para os testes, as comportas foram montadas na entrada de tubos de PVC do tipo sanitário com 6 m de comprimento e diâmetros nominais de 250 e 315 mm. Esta configuração é análoga àquela usada em sistemas de irrigação por gravidade. A derivação das equações de funcionamento das comportas nesta configuração é apresentada. Os coeficientes de descarga (Cd) obtidos experimentalmente mostram que a vazão sob a comporta é dependente da abertura e da diferença de profundidade a montante e a jusante, além do número de Reynolds sob a comporta. A dependência do número de Reynolds, que normalmente é omitido em outras aplicações, é relevante no caso da irrigação do arroz, dadas as baixas velocidades e permite sua utilização como estrutura de regulagem e medição de água nesses sistemas.

Palavras-chave: irrigação, coeficiente de vazão, comportas, medição de vazão

1. Introduction

The performance of collective irrigation systems, concerning water use, is primarily evaluated based on their supply. Continuous recording of the flow rates is necessary for this purpose. In most irrigation systems, there are hydraulic structures that can be calibrated to measure the flow rate, and gates are an example of these structures[1-3].

A gate is a movable, flat, or curved plate that, when lifted, creates an opening between its lower edge and the sides and bottom of the hydraulic structure (pipe, dam, canal, etc.) on which it is installed. Gates are typically used for flow regulation and also for the closure and complete isolation of parts of the system[4].

Gates have been used since the early days of agriculture to control and measure water flow in irrigation canals[4]. Due to their importance, there is extensive literature on the calibration of gates of different sections, discharging either freely or submerged[1-2][5-7]. Beyond the geometric characteristics of the gate and its opening, if the gate discharges freely, the discharge flow rate will be controlled solely by the upstream water level; whereas if the gate discharges submerged, the discharge flow rate will be controlled by both the upstream and downstream water levels[5-6][8].

This study analyzed the type of gates used in diverting water through canals to rice and sugar cane irrigation fields in Uruguay. Both crops are exclusively cultivated under gravity irrigation in the country[9]. Structurally, they consist of a rectangular plate installed at the entrance of a circular pipe, with the outlet of the pipe submerged (Figure 1 and Figure 2).

Farmers install these gates to control the flow, but it is of particular interest to be able to use them to determine the flow rate passing through them based on upstream and downstream level measurements. This way, an existing installation is used to assess and efficiently manage irrigation water use, simply and cost-effectively.

In the literature, information is available for gates used in large irrigation systems, where the smallest reported diameter for experiments is 0.30 m[10-11]. In this study, we focused on gates at the entry points to smaller fields in irrigation systems, for which no information was found in the consulted literature.

Therefore, this study aimed to develop formulations and expressions for the discharge coefficient for small gates with the geometric and location characteristics used in the mentioned irrigation systems. To achieve this objective, numerous hydraulic experiments were conducted, and expressions for the discharge coefficients were adjusted, linking the discharged flow rate with the opening of the gate and the upstream and downstream water levels. The found expressions allow for a reliable estimation of the flow rate diverted to the fields in gravity irrigation systems in Uruguay.

Figure 1. Pipe gate installed at the entrance of a production plot

1.1 Theory

1.1.1 Introduction to theory

Figure 2 depicts a schematic of the analyzed systems: a pipe with a diameter D, placed above a level canal, with the gate placed at the entrance of the pipe, and the pipe's outlet submerged because its upper edge is below the water level in the canal.

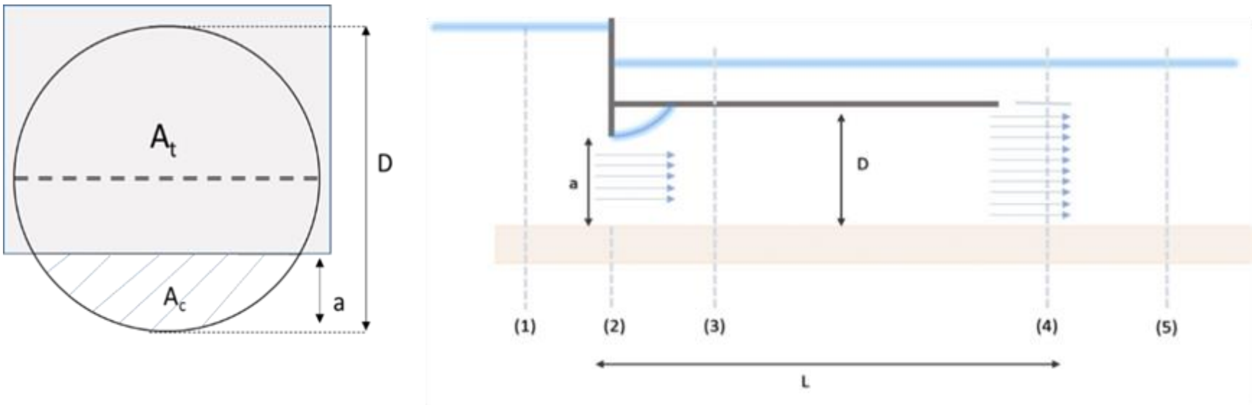

Figure 2. Left: sketch of a gate installed on a pipe. Right: gate installed on a canal

The gate has an opening *a*, an opening area A_c, and the pipe area is A_t.

The discharge through a gate can be approximated by the equation of discharge in a hole [(4)]:

$$Q = C_d A_c \sqrt{2g\Delta H} \qquad [1]$$

Where Q is flow rate, C_d is the discharge coefficient, A_c is the gate opening area, *g* is the gravitational acceleration, ΔH is the difference in depth between upstream (y_1) and downstream (y_2) of the gate.

If the flow rate and tie rods are measured independently,C_d value can be determined as:

$$C_d = \frac{Q}{A\sqrt{2g\Delta H}} \qquad [2]$$

Hydraulic head losses, from upstream of the gate to downstream in the canal, result from the sum of head losses between each of the sections indicated in Figure 2. Highlighted among them: the head loss under the gate, ΔH_{12}, the head loss from the gate to the expansion of the flow, where it starts to occupy the entire pipe, ΔH_{23}, the head loss along the pipe, ΔH_{34}, and the head loss in the expansion of the flow in the discharge of the pipe to the canal, ΔH_{45}.

$$H_1 - H_5 = \Delta H_{12} + \Delta H_{23} + \Delta H_{34} + \Delta H_{45} \qquad [3]$$

Each of these parameters is calculated as follows: ΔH_{12} as a head loss coefficient *k* by the kinetic term below the gate:

$$\Delta H_{12} = k\frac{Q^2}{2gA_c^2} \qquad [4]$$

with A_c being the opening area of the gate, and k the head loss coefficient, which is considered a function of the opening of the gate a and the Reynolds number Re under the gate:

$$k = k\left(\frac{a}{D}, Re_c\right) \qquad [5]$$

with the Reynolds number defined as:

$$Re = \frac{U\emptyset_h}{\upsilon} \qquad [6]$$

where *Øh* is the hydraulic diameter associated with the opening of the gate, *U* is the average velocity of the section, and υ is the kinematic viscosity of the water.

The head loss between 2 and 3 is determined as the difference of kinetic terms under the gate and in the full section of the pipe:

$$\Delta H_{23} = \frac{Q^2}{2gA_c^2} - \frac{Q^2}{2gA_t^2} \qquad [7]$$

where A_t is the area of the pipe section:

$$A_t = \frac{\pi D^2}{4} \qquad [8]$$

$$A_c = \left(\frac{\pi D^2}{4}\right) F\left(\frac{a}{D}\right) \quad [9]$$

with F being a function ranging from 0 to 1, which can be determined by considering that:

$$A_c = \frac{\pi D^2}{8\pi}(\theta - sin\,\theta) \quad [10]$$

Then:

$$F\left(\frac{a}{D}\right) = \frac{A_c}{\left(\frac{\pi D^2}{4}\right)} = \frac{1}{2\pi}(\theta - \sin\theta) \quad [11]$$

where according to Figure 3,

$$\theta = 2\cos^{-1}\left(1 - 2\frac{a}{D}\right) \quad [12]$$

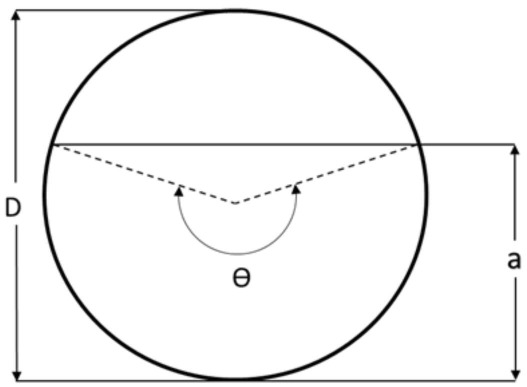

Figure 3. Geometry of pipe section with gate opening

The head loss along the pipe is determined as a distributed head loss, which depends on the roughness of the pipe ε and the Reynolds number in the pipe(4).

$$\Delta H_{34} = f\frac{L}{D}\frac{Q^2}{2gA_5^2} f\left(\frac{\varepsilon}{D}, Re_t\right) \quad [13]$$

Finally, the head loss between the final section within the pipe and the canal when the flow has already expanded results from the difference of the kinetic terms in the pipe and in the canal:

$$\Delta H_{45} = \frac{Q^2}{2gA_t^2} - \frac{Q^2}{2gA_5^2} \quad [14]$$

Returning to Equation 3, the terms H_1 and H_5 are:

$$H_1 = \frac{Q^2}{2gA_1^2} + y_1 \quad [15]$$

$$H_5 = \frac{Q^2}{2gA_5^2} + y_5 \quad [16]$$

Replacing and simplifying:

$$y_1 - y_5 = \frac{Q^2}{2g}\left[\frac{1}{A_1^2} + \frac{k+1}{A_c^2} + \frac{f\frac{L}{D}}{A_t^2}\right] \quad [17]$$

where y_1 is the depth at 1, and y_5 is the depth at 5.

If it is assumed that $Ac \ll A1$, and using Equation [9]:

$$\Delta_y = y_1 - y_5 \approx \frac{Q^2}{2gA_c^2}\left[k + 1 + f\frac{L}{D}F^2\left(\frac{a}{D}\right)\right] \quad [18]$$

Then, the flow rate can be estimated with the following equation:

$$Q = C_d A_c\sqrt{2g\Delta_y} \quad [19]$$

C_d being defined as:

$$C_d = \cdots \left[k\left(\frac{a}{D}, Re_c\right) + 1 \ldots + f\left(\frac{\varepsilon}{D}, Re_t\right)\frac{L}{D}F^2\left(\frac{a}{D}\right)\right]^{-\frac{1}{2}} \quad [20]$$

Noting that the Reynolds in the Re_t pipe and under the Re_c gate are linked by an *a/D function*

$$Re_c = \frac{QP_c}{A_c^2\nu} = \frac{QP_t}{A_t^2\nu}G\left(\frac{a}{D}\right) = Re_t G\left(\frac{a}{D}\right) \quad [21]$$

where $G(a/D)$ is a function of the relative opening of the gate, P_c is the wet perimeter under the gate, and P_t is the perimeter of the pipe. We can see that C_d can be considered dependent on the Reynolds number inside the pipe Re_t and the relative opening of the *a/D gate*.

2. Material and methods

The gates tested in this study are composed of a rectangular flat plate that slides along a straight vertical frame, closing the entrance of the circular section pipe, leaving an opening between the lower part of the circular section and the straight edge of the gate leaf. The tested pipes were 6 meters long PVC sanitary pipes with nominal diameters of 250 mm and 315 mm. The gates used in the experiments (Figure 4) were provided by Comisaco SA, the concessionaire responsible for the administration of the India Muerta dam in Rocha, Uruguay.

The experiments were conducted at full scale in one of the canals at the hydraulic laboratory of the Institute of Fluid Mechanics and Environmental Engineering (IMFIA by its Spanish acronym) of the Engineering College, University of the Republic, Uruguay. The dimensions of the canal are the following: width 1.50 m, depth 0.80 m, and length 18 m. A weir was built in the canal, where the pipes were connected (Figure 4). Water in the canal was circulated using a pumping system equipped with a frequency converter to regulate the pumped flow rate.

Figure 4. Photos of gates used in the test

The pipes were placed on the bottom of the canal with zero slope. In general, field pipes have zero or very low slopes. The pipe discharge was submerged in all the tests.

During the experiments, water entered directly from the canal to the gate. In the field, pipes can be installed either parallel or perpendicular to the flow direction. Since the velocities in the canals are low, no significant effect is expected in the pipe entrance due to flow orientation.

The flow rate through the pipeline was measured using an ultrasonic velocity profiler (UVP-duo, Met-Flow, Switzerland). The UVP uses ultrasound pulses and analyzes the Doppler shift of sound to determine velocity in the direction collinear with the transducer. To obtain an accurate flow measurement, two perpendicular velocity profiles were measured inside the pipe using two sensors perpendicular to each other, each forming a 60-degree angle with the pipe's axis. To fix the UVP sensors, a small hole was drilled in the pipe wall, and each sensor was secured with a specially prepared acrylic piece, ensuring the angle between the sensor and the pipe wall. The precision of this angle is critical to the final flow value and was determined with an accuracy of 1°, introducing a 3% uncertainty in the flow. For each tested condition, profiles were recorded every 40 ms for 3 minutes (4500 samples in total), which were averaged to obtain a mean velocity profile for each transducer. These profiles were integrated to obtain the mean velocity in the section and the flow rate for each experiment.

A spillway located at the end of the canal allowed the regulation of water depth downstream of the test section, ensuring submerged discharge and allowing variation in downstream levels of the gate. The levels were measured in the canal upstream and downstream of the gate for different flow rates after flow stabilization and with gate openings of 25%, 50%, and 75% of the diameter. To measure these openings, the correct zero point was marked on the stem (above the frame), that is, when the lower edge of the gate is aligned with the lower edge of the pipe's inner diameter. The flow rate range used in the test for the gate installed in the DN 315 mm pipe was between 26 and 59 Ls^{-1}, while for the gate installed in the DN 250 mm pipe, it was between 11 and 46 Ls^{-1}.

3. Results

A total of 18 experiments were conducted for the gate installed in the 250 mm pipe, and 16 experiments were conducted for the gate installed in the 315 mm pipe. The results are summarized in Table 1.

Empirical values of Cd were obtained for two rectangular gates of different sizes, operating in submerged flow, with gate openings of 50% and 75% of the diameter.

For the gate in the DN 315 mm pipe, it was not possible to perform the test with a gate opening of 25% of the diameter. This was due to the dimensions of the canal not allowing it because the water height upstream of the gate exceeded the free edge of the canal legs, posing a risk of overflow.

3.1 Analysis

The discharge coefficient, Cd, calculated using Equation 2 considering the gate's opening area for the two gates tested in this study, is presented in Figure 5, categorized by the opening relative to the diameter, as a function of the Reynolds number.

Figure 5 shows that for the chosen configuration, there is a dependence of Cd on both the opening and the Reynolds number. This last dependence on the Reynolds number is expected since the velocities inside the pipes are low, but it has not been reported in previous studies.

It is possible to perform a simple fit for the data for each of the tested openings as follows:

$$C_d = 0.77 - \frac{B}{Re} \quad [22]$$

Where B depends on the relative gate opening and equals 8500 for a 75% opening and 5000 for a 50% opening.

Figure 6 shows the comparison between the flow rates estimated using Equation 19 with Cd calculated according to Equation 22. A very good agreement can be observed between the measurements and the estimates based on the opening for both pipe diameters tested, with all estimates, except for the lowest recorded flow rate, falling within ±10% of the measurements.

Table 1. Summary of tests data

Opening,Temp. Water°C	Q m³/s	y1 m	y5 m	Δy m	D m	a m	Cd
DN 250 3/4 21°	0.01	0.37	0.358	0.01	0.24	0.18	0.66
	0.02	0.44	0.405	0.03	0.24	0.18	0.71
	0.03	0.48	0.41	0.07	0.24	0.18	0.68
	0.03	0.50	0.413	0.08	0.24	0.18	0.72
	0.04	0.51	0.415	0.10	0.24	0.18	0.72
	0.04	0.53	0.415	0.11	0.24	0.18	0.74
	0.04	0.55	0.415	0.13	0.24	0.18	0.73
	0.04	0.56	0.418	0.14	0.24	0.18	0.76
	0.05	0.51	0.335	0.17	0.24	0.18	0.74
	0.05	0.52	0.335	0.18	0.24	0.18	0.74
	0.05	0.49	0.335	0.16	0.24	0.18	0.78
DN 250 1/2 19°	0.02	0.453	0.380	0.07	0.24	0.12	0.72
	0.03	0.587	0.390	0.20	0.24	0.12	0.74
	0.04	0.575	0.327	0.25	0.24	0.12	0.73
	0.04	0.653	0.335	0.32	0.24	0.12	0.76
	0.05	0.73	0.335	0.40	0.24	0.12	0.75
DN 250 1/4 19°	0.01	0.460	0.340	0.12	0.24	0.06	0.79
	0.02	0.718	0.345	0.37	0.24	0.06	0.72
DN 315 3/4 21°	0.03	0.49	0.430	0.06	0.30	0.23	0.67
	0.03	0.51	0.475	0.04	0.30	0.23	0.68
	0.04	0.52	0.478	0.04	0.30	0.23	0.69
	0.04	0.48	0.425	0.06	0.30	0.23	0.72
	0.05	0.49	0.430	0.06	0.30	0.23	0.74
	0.05	0.51	0.430	0.08	0.30	0.23	0.73
	0.06	0.52	0.430	0.09	0.30	0.23	0.73
DN 315 1/2 21°	0.03	0.46	0.440	0.02	0.30	0.15	1.16
	0.03	0.50	0.415	0.08	0.30	0.15	0.73
	0.04	0.52	0.420	0.10	0.30	0.15	0.75
	0.04	0.53	0.420	0.11	0.30	0.15	0.74
	0.04	0.57	0.423	0.14	0.30	0.15	0.74
	0.05	0.60	0.425	0.17	0.30	0.15	0.74
	0.05	0.62	0.426	0.20	0.30	0.15	0.75
	0.06	0.66	0.428	0.23	0.30	0.15	0.74
	0.06	0.64	0.385	0.25	0.30	0.15	0.75

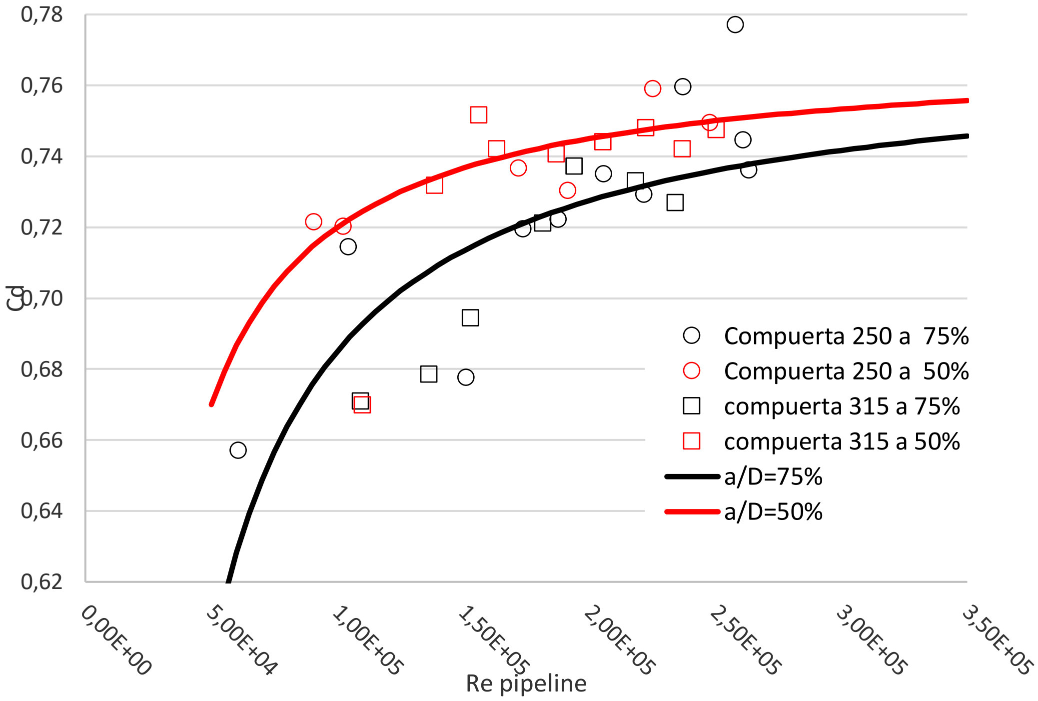

Figure 5. Discharge coefficients relative to the Reynolds number for gate openings of 50% and 75% for the two tested pipe diameters, 250 mm and 315 mm, are shown in the graph. The lines represent the fit provided by Equation 22

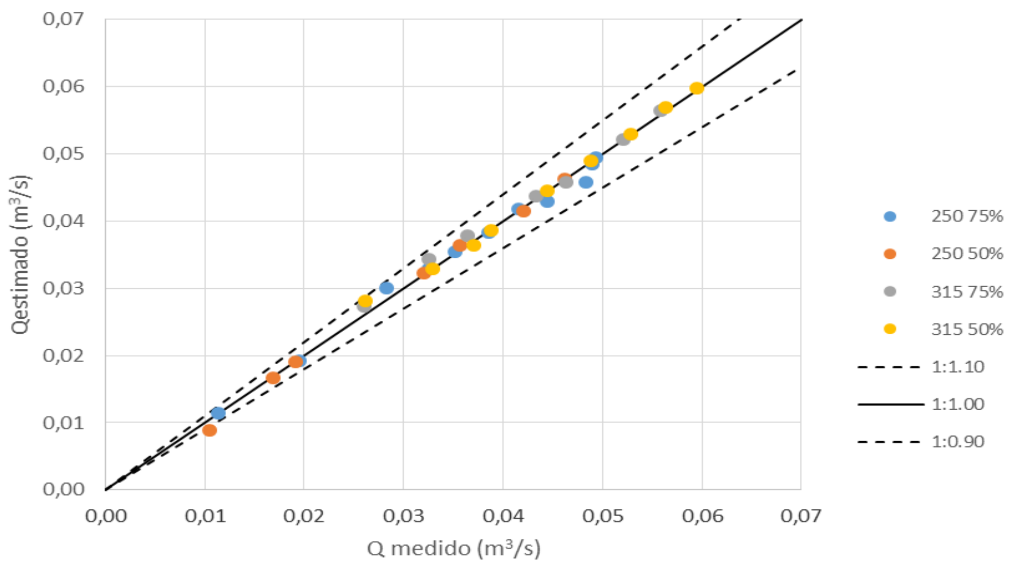

Figure 6. Comparison of flow rates estimated by Equation 19 considering *CD* of Equation 22 and the flow rates measured by the UVP

3.2 Comparison with previous work

Howes and Burt[10], using rectangular screen gates similar to those used in this study but for slightly larger pipe diameters (0.46 m), found C_d values very similar to those found in this study, both for openings of 50% and 75%. They also found values of C_d somewhat higher, ranging from approximately 0.65 to 1.10 for the same pipe diameters and openings when using circular screen gates[9].

Both Howes and Burt[9] and Lozano and others[1] report a dependence of C_d on the gate opening. However, Lozano and others worked with rectangular gates installed in rectangular canals. The dependence on the gate opening that we found in our study is mild, but this could be attributed to the fact that our experiments did not include very small openings, which is where these authors found a clearer dependence.

Furthermore, these same authors did not report a dependence on the Reynolds number, which is a contribution of our experiments. This is to be expected since the C_d presented in our study is not limited to the gate alone, but includes the pipe as well.

Nevertheless, a detailed reanalysis of Howes and Burt's[10] data to explore the possible dependence of C_d on the Reynolds number is presented in Figure 7. The figure shows a trend where lower C_d values are associated with lower Reynolds numbers. This trend may not have been easily observable in the original article. Additionally, significant fluctuations in the values are observed, likely associated with drift in their pressure measurement system.

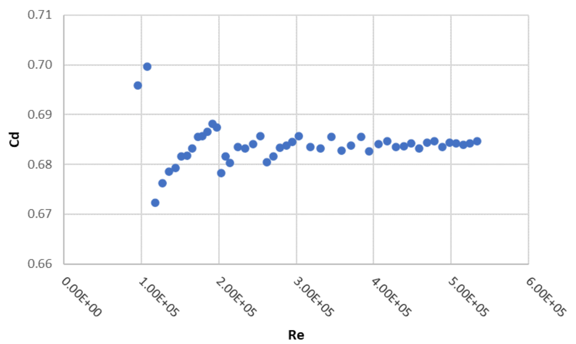

Figure 7. Discharge coefficient C_d as a function of the Reynolds number, data taken from Howes and Burt[10]

Finally, the Re found in our experiments ranged from 1.89E+04 to 1.99E+05 for the two pipe diameters used. In Howes and Burt's experiments[9] for 0.46 m diameters, Re ranged from 3.798E+04 to 1.06E+06, and for 0.61 m diameters it ranged from 3.73E+04 to 1.24E+06. Therefore, in more than 40% of the experiments reported by Howes and Burt[9], the Reynolds numbers are substantially higher than ours, which would explain why these researchers found it more challenging to observe the Reynolds number effect. Additionally, Howes and Burt[9] worked with corrugated pipes, specifically corrugated polyethylene tubes with a Manning roughness coefficient of n≈0.012, while the pipes used in our study were PVC pipes with a Manning roughness coefficient of n≈0.009. The higher roughness of the pipes favors conditions for establishing fully rough turbulent flow, which also justifies why previous studies did not detect dependencies on the Reynolds number.

4. Final summary and conclusions

In this study, a simple empirical formulation was determined for the discharge coefficient, Cd, for flat gates of the type used in gravity irrigation systems in Uruguay. Having the discharge coefficient allows gates to be used as gauging structures, requiring only the measurement of water levels upstream and downstream of the gate.

A particular feature of our work is that it incorporates the variation of Cd due to the Reynolds number, Re. While using a fixed Cd might be practical, we demonstrated in this study that, due to the low velocities, differences in water levels in gravity irrigation systems, and the type of pipes used, it is not possible to ignore the dependence of Cd on Re.

Author contribution statement

LB: carried out the original idea, gathered and analyzed data, interpreted results, and wrote the article; FP: conceptualized the experiment, contributed to data analysis, and edited the article.

Transparency of data

Available data: The entire data set that supports the results of this study was published in the article itself.

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