Discharge Coefficient of a Spillway with a Riser Perforated by Rectangular Orifices

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Abstract: Perforated riser principal spillways are widely used in check dams, and rectangular orifices are the preferred orifice geometry for risers constructed of brick. However, there is little research based on risers perforated with rectangular orifices. This paper discusses the discharge coefficient of such a structure, based on the experimental data and data collected from literature, during which an estimation of the discharge equations for a riser perforated with circular orifices was made. First, an existing equation for a riser with circular orifices is selected based on the coefficient of determination (R^2) index and the Nash–Sutcliffe efficiency (NSE) index. Then, an equation for the discharge coefficient of a riser perforated with rectangular orifices is proposed ($R^2 = 0.95$, NSE $= 0.91$) considering the factors of the diameter of the riser pipe, the width of the rectangular orifice, and the head over the centerline of the orifice. This work is expected to provide a reference for the design and investigation of a perforated riser principal spillway. **DOI: 10.1061/(ASCE)IR.1943-4774.0001425.** © *2019 American Society of Civil Engineers.*

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Introduction

A perforated riser principal spillway usually consists of a riser perforated with circular or rectangular orifices and a barrel. It is extensively used in check dams (Ministry of Water Resources of the People's Republic of China 2003), sedimentation basins (Fennessey and Jarrett 1997), terraces (Visser et al. 1988), and feedlots (Linderman et al. 1976). Utilization and corresponding investigations date from the 1900s, and several studies have been carried out to illustrate the hydraulic characteristics (Phillips 1969; Hua et al. 1989; Barlow and Brandes 2015). However, the majority of previous research has focused on risers perforated with circular orifices; there are few papers based on rectangular orifices.

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Because the major function of a check dam is to capture sediment to prevent the soil erosion and form cultivatable land (Li et al. 2019; Shi et al. 2019; Xu et al. 2019), its direct economic benefits are not immediately apparent; considering its comparatively small size, the cost of a check dam project is consequently expected to be as low as possible. Therefore, for a check dam, for which one of the primary discharge structure types is the perforated riser principal spillway, the riser is often made from bricks, owing to low cost, simple construction, and durable service. Consequently, for the convenience of brick construction, rectangular orifices (as shown in Fig. 1) are more common than circular ones. Therefore, the hydraulic characteristics of risers perforated with rectangular orifices should be investigated.

Discharge Coefficient of Orifices on Riser

Numerous studies have been carried out on the flow through orifices on risers, and it is believed that the discharge coefficient of the orifice on a riser is related to factors such as the size of the orifice, the head over the orifice, the curvature of the wall, and the distance between the orifice and the bottom of the tank; the expressions of the discharge coefficient are usually functions of some or all of these factors. Equations proposed in the literature for the discharge coefficient of perforated risers are summarized, shown as Eqs. (1)–(7), and the application ranges and the corresponding discharge equations of them are shown in Table 1:

Visser et al. (1988)

$$C_d = 0.71 \tag{1}$$

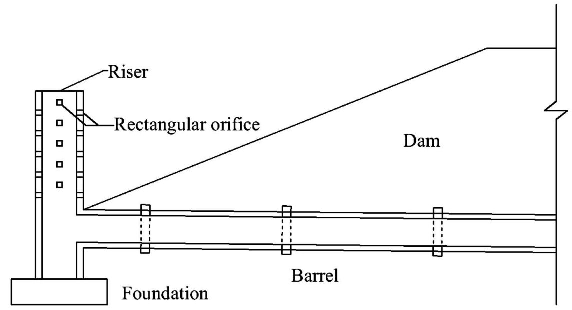
Prohaska et al. (2010)

$$C_d = a + \frac{b}{(h_o/d)^p} + \frac{c}{(h_t/d)^q} \tag{2}$$

Hussain et al. (2010)

$$C_d = 0.670 - 0.076\mathrm{F_r} - 0.136\frac{d}{B} \tag{3}$$

(a)



(b)

Fig. 1. (a) A perforated brick riser used in a check dam in Shaanxi, China (image courtesy of Zhao Binhua); and (b) sketch of a perforated riser principal spillway profile.

Table 1. Summary of the application ranges and the corresponding discharge equations for the discharge coefficient equations of perforated risers

Reference	Orifice shape	Riser type	Discharge
Visser et al. (1988)	Circular	Pipe	$Q = \frac{2}{3} CnA(2g)^{0.5} H^{1.5}$
Prohaska et al. (2010)	Circular	Pipe	$q = C_d A\sqrt{2gh_o}$
Hussain et al. (2010)	Circular	Flat plate	
Hussain et al. (2011)	Rectangular		
McLemore et al. (2013)	Circular	Pipe	
Barlow and Brandes (2015)	Circular	Flat plate	$q_f = C_d A\sqrt{2gh_o}$ $q_p = C_w L_w h_b^{3/2}$

Note: The discharge equations of Prohaska et al. (2010), Hussain et al. (2010, 2011), and McLemore et al. (2013) are recycled.

Hussain et al. (2011)

$$C_d = 0.714 - 0.066\mathrm{F_r} - 0.354\frac{L}{B} \tag{4}$$

McLemore et al. (2013)

$$C_d = 0.610 - 0.458\left(\frac{d}{D}\right)^{0.647} + 0.309\left(\frac{h_o}{d}\right)^{-0.169} \tag{5}$$

Barlow and Brandes (2015)

for $h_b/d < 1.05$: $C_d = 0.55$

for $1.05 \leq h_b/d \leq 2.5$: $C_d = 0.6357(h_b/d - 1)^{0.0464}$

for $h_b/d > 2.5$: $C_d = 0.65$ (6)

$$C_w = 2.9199 C_d \tag{7}$$

where C_d = discharge coefficient; a, b, and c = parameters whose value varied with the ratio of the orifice diameter to the riser pipe diameter; h_o = head over the centerline of the orifice; h_t = distance of the center of the orifice above the tank floor; d = diameter of the circular orifice; $\mathrm{F_r}$ = Froude number; B = width of the main channel; L = width of rectangular orifice; D = diameter of the riser pipe; h_b = head over the bottom of the orifice; and C_w = weir coefficient for the partially submerged orifice.

Numerous studies have investigated the flow through circular orifices on pipe risers. Visser et al. (1988) regarded the discharge coefficient as a constant in their investigation on the hydraulic performance of terrace inlet risers perforated with circular orifices, and they believed that the discharge coefficient of the orifice on a pipe riser is larger than that on a flat plate. Prohaska et al. (2010) evaluated the discharge coefficient of circular orifices in riser pipes experimentally, and they believed that the discharge coefficient is a function of the head over the orifice, the location of the orifice above the floor of the tank, and the ratio of the orifice diameter to riser pipe diameter. McLemore et al. (2013) discussed the effect of different factors and combinations on the discharge coefficient based on experimental analysis, and they believed that the location of the orifice has an insignificant effect on the discharge coefficient.

For the rectangular orifice case, most of the studies focus on the flow of an orifice on a flat plate (Hussain et al. 2014; Ebtehaj et al. 2015; Azimi et al. 2017b); the comparison between the performance of circular orifices on a flat plate and the rectangular orifice case has also been studied in existing literature. Barlow and Brandes (2015) proposed different functions for fully and partially submerged orifice flow to describe C_d based on the test data and some other flow models (Henderson 1966; Chamberlain 1986; Brandes and Barlow 2012). Hussain et al. (2010, 2011) studied the flow characteristic of sharp-crested circular and rectangular orifices under free flow conditions in open channels and found that the value of C_d for a circular orifice was higher than the value for a rectangular orifice when L/B or $d/B < 0.2$ (where L is the width of the rectangular orifice, B is the width of the main channel, and d is the diameter of the circular orifice); for L/B or $d/B > 0.2$, the findings were opposite.

Method of Equation Evaluation

In this study, the accuracy of the existing equations describing the discharge coefficient of the side orifices on risers is quantified by the coefficient of determination (R^2) and the Nash–Sutcliffe efficiency (NSE). It is well known that R^2 indicates the percent of the variation that can be explained by the regression equation. The NSE, ranging from $-\infty$ to 1, is widely used to evaluate prediction models in hydrology. The closer the NSE is to 1, the better the model fits the observed data, and if the NSE < 0, the performance of the model is believed to be unacceptable (Gupta et al. 2009; Wang et al. 2009). In addition, Ritter and Muñoz-Carpena (2013) classified the NSE into four levels with the threshold values of 0.65, 0.8, and 0.9, i.e., ($-\infty$, 0.65) as unsatisfactory, [0.65, 0.80) as acceptable, [0.80, 0.90) as good, and [0.90, 1.00) as very good. NSE is computed as

$$\mathrm{NSE} = 1 - \frac{\sum_1^N (Q_c(h_i) - Q_o(h_i))^2}{\sum_1^N (Q_o(h_i) - \overline{Q_o})^2} \quad (8)$$

where N = number of observations; Q_c = calculated discharge at a head of h_i; Q_o = observed discharge at a head of h_i; and $\overline{Q_o}$ = average of the observed discharges.

Experiments

The experiments were performed in the State Key Laboratory of Eco-Hydraulics in the Northwest Arid Region of China at Xi'an University of Technology. The experimental arrangement was a scale model of a typical perforated riser principal spillway of a check dam, and water was supplied by a laboratory recirculation system, as shown in Fig. 2. A rectangular experimental tank that can be regarded as a generalized reservoir was constructed of polyvinyl chloride sheets, with one side replaced by a transparent acrylic sheet for observation. The experimental tank, with overall dimensions of $1.0 \times 1.2 \times 1.0$ m ($w \times l \times h$), was divided by a perforated filtering sheet into a test tank and a detention tank with dimensions of $1.0 \times 1.0 \times 1.0$ m and $1.0 \times 0.2 \times 1.0$ m, respectively. The perforated riser, made of a plexiglass pipe with an inner diameter of 0.1 m and a height of 0.19 m was installed at the center of the test tank floor. The dimensions of the rectangular orifices were 1.5×1.5 cm, with six rows of orifices on the riser. For each row, there are two opposite orifices; the centerline of the two orifices has a 90° angle and a distance of 3.0 cm from the adjacent rows, as shown in Fig. 3. A plexiglass vertical pipe with a sealed end was joined to the perforated riser with a flange, and the length of the vertical pipe was 0.96 m, as shown in Fig. 4. A barrel with an inner diameter of 0.08 m was joined to the vertical pipe with a transition. The transition is a gradual contraction pipe with a length of 0.05 m, and the transition pipe invert was 0.1 m above the vertical pipe invert at their connection. The barrel had a slope of 0.01 and a length of 7.4 m. Both the transition and the barrel were made of plexiglass pipe.

Experiments were performed to collect the discharge data at various heads (H). The change of head was controlled by the valve of the pump and a valve installed on the outlet pipe, as shown in

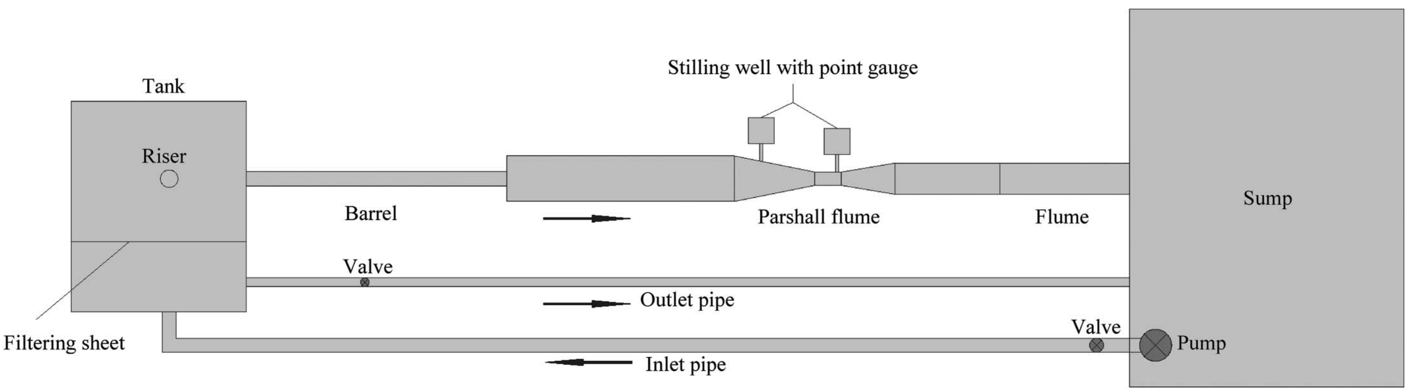


Fig. 2. Experimental setup.

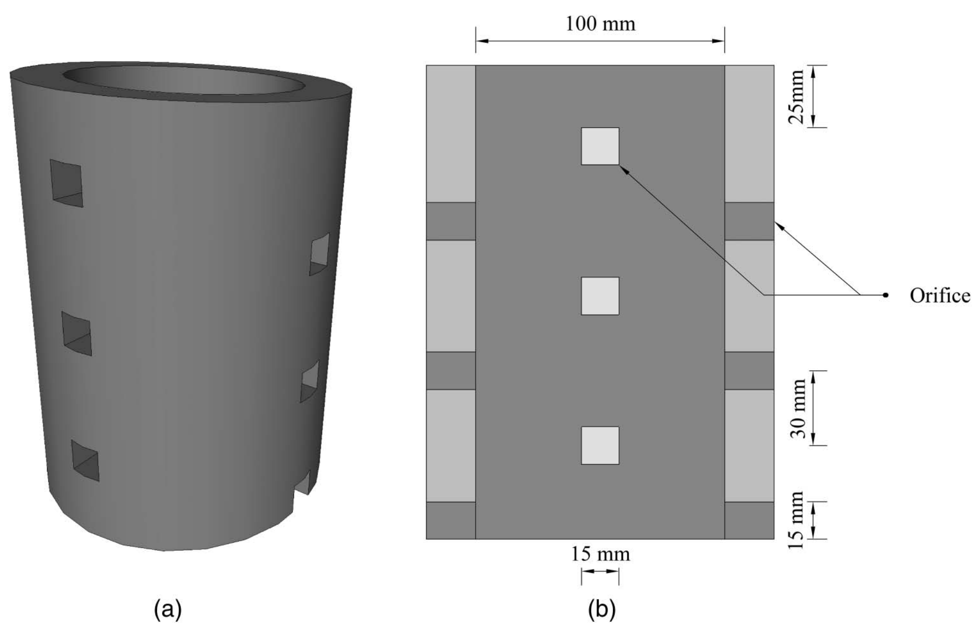


Fig. 3. (a) Three-dimensional diagram of experimental riser perforated with rectangular orifices; and (b) profile of the riser perforated with rectangular orifices.

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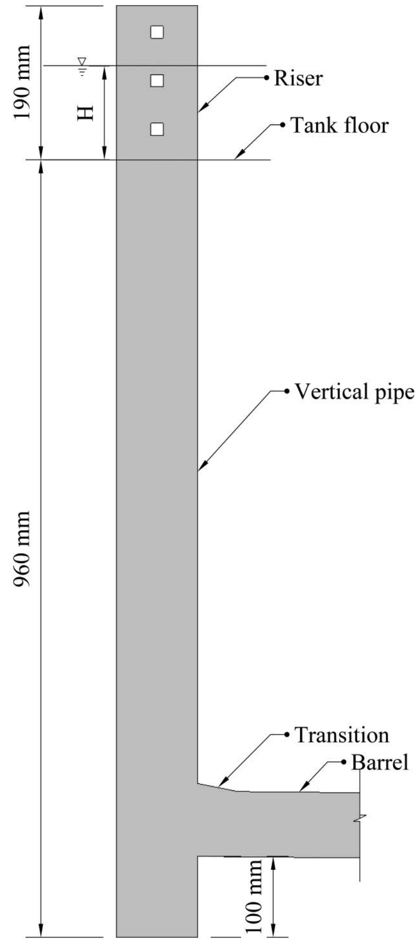

Fig. 4. Profile view of the experimental perforated riser principal spillway.

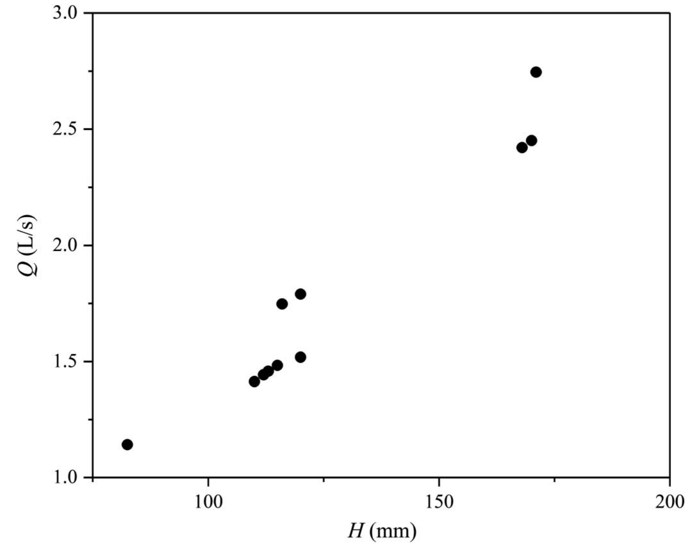

Fig. 5. Head discharge curve of the observed data.

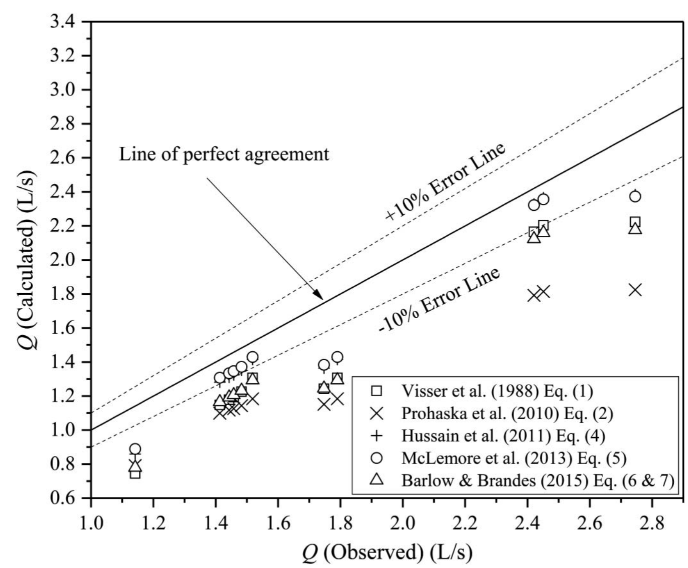

Fig. 6. Comparison between calculated and observed discharges.

Fig. 2. A period of 15 min was allowed before recording the data after every change of head, in order to attain a steady flow. For each head, recordings were repeated three times at an interval of 30 s, and the average observations are adopted. The water head was measured by a ruler installed outside the transparent side of the tank, and the discharge was measured by a Parshall flume installed behind the barrel.

During the normal work condition, i.e., the case in which the tank water surface was below the crest of the riser, the perforated riser principal spillway discharged below the water surface, and the barrel remained partially filled. The H–Q curve of observed data is shown in Fig. 5.

Results and Discussion

Applicability of the Existing Discharge Equations for Experimental Data

The discharge coefficient of the orifices and the corresponding discharge in circular riser pipes were calculated using the models outlined previously, i.e., Eqs. (1)–(6) in Table 1. In calculating C_d, d is substituted with L. The comparison of the calculated discharges and the observed data is shown in Fig. 6, which shows that except for some data from Eqs. (4) and (5), the calculated discharges are more than 10% lower than the observed discharges. Considering that the equations used are all based on a circular orifice of a circular riser pipe [except for Eq. (4)], the result indicates that the discharge capacity of rectangular orifices in circular riser pipes is underestimated. Hussain et al. (2011) obtained similar results in their research. Although Eq. (4) is intended for rectangular orifices on a flat plate riser, and the performance is better than most of the others, the calculated discharge is still less than the observed discharge, which coincides with the point proposed by Visser et al. (1988), where they assign a higher value to the discharge coefficient of an orifice on a pipe than for an orifice on a flat plate.

The R^2 and the NSE values of the models were calculated to evaluate model accuracy quantitatively; the results are shown in Table 2. The R^2 values of the models show that all of the equations can explain more than 90% of the variation, and there are fine collinear relationships between the observed discharge and the discharges calculated by all the five models; however, the NSE of Eq. (2) is unacceptable and according to the classification in Ritter and Muñoz-Carpena (2013), the NSE values of Eqs. (1) and (6) are

Table 2. Coefficient of determination and Nash–Sutcliffe efficiency of models

Equation	Model	NSE	R^2
Eq. (1)	Visser	0.50	0.95
Eq. (2)	Prohaska	−0.12	0.94
Eq. (4)	Hussain	0.78	0.95
Eq. (5)	McLemore	0.80	0.95
Eqs. (6) and (7)	Barlow	0.48	0.95

unsatisfactory. In general, the performance of Eqs. (4) and (5) for the present data are acceptable, but the discharge capacity is still underestimated. Therefore, a discharge coefficient equation orientated toward the flow through the rectangular orifice on the pipe riser should be proposed.

The data collected by Deng (2008), in their study of the flow of a riser pipe perforated by a rectangular orifice, is used in proposing the discharge equation, so the performance of the existing discharge equations was also checked using these data. The comparison of the calculated discharges and the observed data is shown in Fig. 7. The performances of Eqs. (1), (2), and (5) here are similar to the present study data, i.e., for Eqs. (1) and (2), the calculated discharge is more than 10% lower than the observed data; for Eq. (5), some calculated estimates of discharge are within 10% of the observed data, but most estimates are more than 10% lower than the observed data. Most of the calculated discharge from Eq. (4) ranges between 1.0 and 1.1 times the observed data, which is different from the model's performance for the present study data. The difference probably exists because Eq. (4) is suited to the case of a channel, and the variable B is the width of the main channel, i.e., the width orthogonal with the flow direction in the main channel; in the present study, due to the existence of the detention section and the position of the riser, which is on the center of the test tank floor, the predominating flow direction in the test tank is parallel with the long edge of the experimental tank. For this reason, B is believed to be the width of the experimental tank when using Eq. (4) to calculate discharge with the present study data; whereas in the Deng (2008) study, the riser was installed near a corner of the test tank; therefore, using the width of the test tank to define B may cause the error. The performance of Eq. (5) is much better than that for the present study data; except for a few data points, most of the calculated discharge is well within 10% of the observed discharge. For most of the data of Deng (2008), $h/L > 2.5$, so the discharge coefficient is calculated as a constant.

Applicability of the Existing Discharge Equations for Circular Orifices

Because there is an abundance of models that have been developed from investigations on the discharge of circular orifices in circular riser pipes, it is wise to use these models as references in deriving the discharge equation for a rectangular orifice case. The observed discharge data of Hua (1987), collected from a test on risers perforated by circular orifices with two different orifice row spacings of 102 and 64 mm, were used to evaluate the performance of the models for the discharge of circular orifices in circular riser pipes. Fig. 8(a) shows that most of the estimated discharges are within 10% of the observed data, whereas Fig. 8(b) indicates that except for most of the discharges estimated from Eq. (5), the calculated discharge is more than 10% lower than the observed data. The R^2 of the models shows that all of the equations can explain more than 99% of the variation according to Table 3, and the NSEs of Eqs. (3), (5), and (6) are more than 0.90 for both row spacing cases. Accordingly, the performance of Eq. (5) is better than that of the other equations.

In Eqs. (5) and (6), the head above the orifice is believed to have an effect on the discharge coefficient. In the study of McLemore et al. (2013), where Eq. (5) is proposed, the factor d/D is also regarded as an important factor to the discharge coefficient, whereas the position of the orifice, i.e., h_b, is not; the investigation of Deng (2008) found a similar conclusion.

Proposed Equation for the Coefficient of Discharge

According to the results from the analysis of applicability of the existing discharge equations for a riser perforated by circular orifices, the function of d/D and h_o/d can explain most of the variation and fits the observed data well. Thus, the formation of Eq. (5) was chosen to be the foundation in developing the new equation, i.e., $C_d = c_1 + c_2(d/D)^p + c_3(h_o/d)^q$. To determine the discharge coefficient, the observed data of Deng (2008), collected from a test

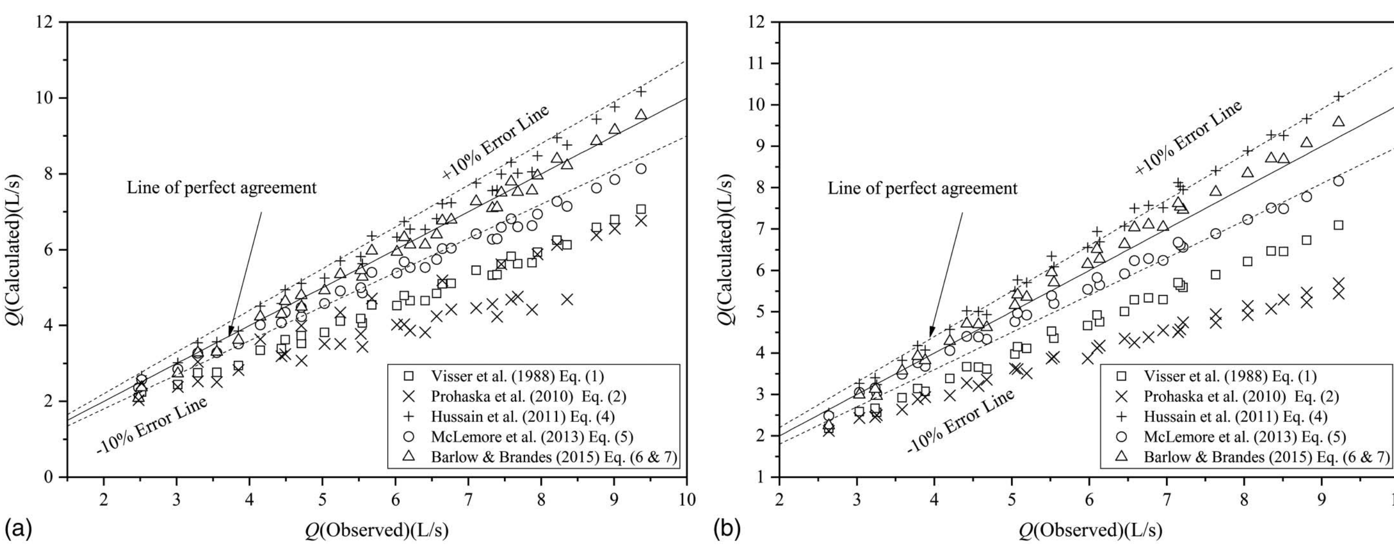

Fig. 7. Comparison between calculated and observed discharges of Deng (2008) for the angle between the plane of the orifice and the direction of the barrel of (a) 0°; and (b) 90°.

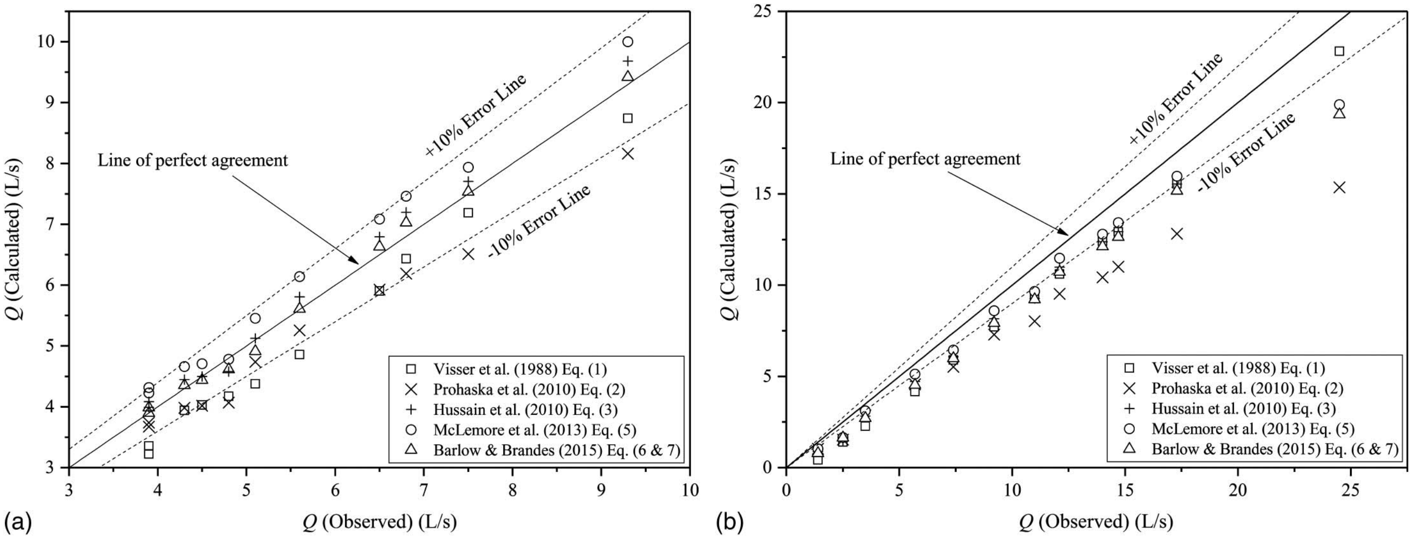

Fig. 8. Comparison between calculated and observed discharges of Hua (1987) using data of the risers perforated by circular orifices with hole row spacing of (a) 102 mm; and (b) 64 mm.

Table 3. Coefficient of determination and Nash–Sutcliffe efficiency of the models using circular orifice data of Hua (1987)

		NSE		R^2	
Equation	Model	*a*	*b*	*a*	*b*
Eq. (1)	Visser	0.88	0.95	0.99	1.00
Eq. (2)	Prohaska	0.86	0.69	0.99	0.99
Eq. (3)	Hussain	0.98	0.92	0.99	1.00
Eq. (5)	McLemore	0.92	0.94	0.99	1.00
Eqs. (6) and (7)	Barlow	0.99	0.90	1.00	1.00

Note: a = data of the risers perforated by circular orifices with hole row spacing of 102 mm; and b = data of the risers perforated by circular orifices with hole row spacing of 64 mm.

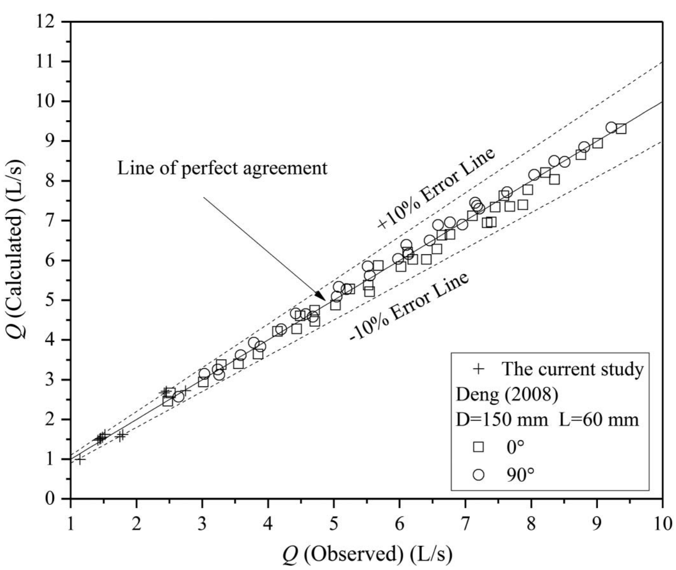

Fig. 9. Comparison between calculated discharge and observed discharge for proposed equation. 0° and 90° are the angles between the normal direction of the orifice and the direction of the barrel.

on a riser perforated by rectangular orifices, are used. The equation for C_d for the rectangular orifices of circular riser pipes, developed from the experimental data, is

$$C_d = 0.620 + 0.001\left(\frac{L}{D}\right)^{-2.737} + 0.055\left(\frac{h_o}{L}\right)^{-1.278} \tag{9}$$

The comparison of the calculated discharges from Eq. (9) and the observed data is shown in Fig. 9. The R^2 and the NSE values are 0.95 and 0.91, respectively. Therefore, it is appropriate to describe C_d with Eq. (9).

Partial derivative sensitivity analysis (PDSA), which differentiates a formula with input variables, is believed to assess the effect of input variables on the equation (Azimi et al. 2017a; Shabanlou et al. 2018). The calculated sensitivities of L/D and h_o/L on Eq. (9) are -2.74×10^{-3} and -0.07, respectively, which means the discharge coefficient of a riser perforated with rectangular orifices decreases with an increase in L/D and h_o/L. The pattern is similar to the circular case, as the calculated sensitivities of d/D and h_o/d on Eq. (5) are -0.30 and -0.05, respectively.

Conclusion

The discharge coefficient of a perforated riser was investigated using both the observed data of the current experiment and the tests recorded in the literature. For circular orifices, the existing equations are estimated using the experimental data of Hua (1987), and the performance of Eq. (5) proposed by McLemore et al. (2013) is superior. For rectangular orifices, the performance of Eqs. (4) and (5) are acceptable; furthermore, an equation is proposed based on the observed data of the current study and Deng (2008). The work in this paper is expected to be helpful in the design of a discharge structure with a riser perforated by circular or rectangular orifices, as well as other relative investigations.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

Acknowledgments

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Notation

The following symbols are used in this paper:

A = orifice area;
B = width of the main channel;
C_d = discharge coefficient;
C_w = weir coefficient for the partially submerged orifice;
D = diameter of the riser pipe;
d = diameter of the circular orifice;
F_r = Froude number;
g = gravitational acceleration;
H = vertical distance from the bottom of the lowest side orifice to the water surface outside the riser;
h_b = head over the bottom of the orifice;
h_o = head over the centerline of the orifice;
h_t = distance of the center of the orifice above the tank floor;
L = width of rectangular orifice;
n = number of side orifices per unit length of riser, and nH means the total number of submerged side orifices;
Q = discharge of the perforated riser; and
q = discharge of a single orifice.

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