Experimental investigation of discharge characteristics of float type sluice gate

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Abstract. Sluice gates are commonly used in canals for control and measurement of the flow. The discharge under sluice gates can be determined through different discharge methods. The present study proposed a new equation to accurately predict the discharge through floating type sluice gate by reading the depth of water at upstream of the gate and it reveals relationship between the gate opening and water depth. It also derived a theoretical equation for variations of sluice gate discharge coefficient under free flow condition. Effects of factors on discharge coefficient were investigated. This new model can be used to predict the performance of sluice gates with different sizes under free -flow situations.

1. Introduction
Water resources management is closely related to the depletion of water resources. Measuring river discharge is crucial for water resources management [1,2]. Some hydraulic structures are widely used to measure flow discharge. Gate is an important part of the hydraulic structure and a control facility for intercepting flow, controlling water level, regulating flow and discharging sediment. Sluice gates are commonly used in open channel flows and branches as water regulators and flow measurement devices according to the tailwater depth values and gate openings. This type of gate features simplicity of design, construction, safety and few maintenance requirements, which are the reasons for its wide use in branch canals, in particular for irrigation. Because of these important, sluice gates have been put into practice for many years. However, more investigations on sluice gates are specialized at free flow condition [3] due to the strict conditions for free flow which request that the downstream water level is lower than the gate opening, so the flow rate can be accurately calculated by the upstream depth and gate opening. Thus, the primary disadvantage is the complex calibration needed for free flow equations.

In some irrigation district of China, sand from the upper beach is deposited in canal which can lead to sluice gate opening hard and damage. Meanwhile, a high sediment concentration water will affect the flow behavior before the gate and will reduce its measuring accuracy. Thus, discharge estimation is intended to take the surface clean water from canals for flow measuring purposes of use. The discharge under sluice gate can be determined using different flow equations. These equations are applied to distinct operating conditions of the gate, upstream water depth and the coefficient of discharge. The classical energy and momentum (EM) methods could be used to determine the free flow discharge. Henry [4] first proposed the experimental trend of $C_d$, and he use energy momentum...
method to determine the discharge with an unique $C_d$ for free and submerged flows [5]. The coefficient of discharge for free flow can be expressed as:

$$C_d = \frac{C_c}{\sqrt{1 + C_c(e / H)}}$$  \hspace{1cm} (1)

where $e$ is the gate opening; $H$ is the upstream water depth above centreline of the float type sluice gate; $C_c$ is the contraction coefficient that defined as the relation between the downstream water depth after centreline of the float type sluice gate; $A_c$ is the vena-contracta; $A_0$ is the cross-sectional area of flat sluice. Then Henry’s discharge function (HDF) for free flow can be expressed as:

$$Q = C_{be} \left( 2gh \frac{H}{H + H_d} \right) \sqrt{2gh}$$  \hspace{1cm} (2)

where $b$ is the width of the gate; $g$ is the acceleration due to gravity. Rajaratnam & Subramanya proposed new definitions of sluice gate discharge coefficient for free and submerged flow conditions [6]. Based on Henry nomogram, Swamee performed a nonlinear discharge function (SDF) and determined the discharge coefficient with depth of flow $H$ and gate opening $e$ under free flow conditions [7]:

$$Q = 0.611eb \sqrt{2gh} \left( \frac{H - e}{H + 15e} \right)^{0.972}$$  \hspace{1cm} (3)

Ferro deduced a stage-discharge relationship for free flow according to the $\Pi$-theorem of the dimension analaysis and the incomplete self-similarity theory [8]. However, Ghodsan found that the coefficient of discharge of sluice gate also depends on the approach flow Froude number. Based on the EM method [9], Clemments et al. proposed a new approach for the evaluation of $C_d$ and discharge under radial gates, and this discharge computation is also for sluice gates [10]. Clemments et al discharge function (CDF) for free flow condition is estimated by:

$$Q = C_{be} \sqrt{\frac{2gh(H_0 - C_d e)}{1 + e}}$$  \hspace{1cm} (4)

where $H_0$ is the upstream energy head. $\zeta$ is defined as an energy loss coefficient; Habibzadeh et al identified a feasible root that allows the determination of $C_d$ for the free and submerged flow condition [11]:

$$C_d = C_c \left[ \frac{1}{\beta} \left( 1 + k - \frac{1}{\beta^2} \right) \right]$$  \hspace{1cm} (5)

where $\beta$ is the dimensionless parameter defined as:

$$\beta = \frac{y_1}{y_2} = \frac{y_1}{C_c}$$  \hspace{1cm} (6)

where $y_1$ is the upstream water depth; $y_2$ is contracted supercritical water depth. Silva et al conducted experiments to test different discharge methods, and the results shows that the evaluation of the discharge under sluice gates for free and submerged flows through the methods based on the energy method had better results [12]. Accurate determination of flow rates through a hydraulic structure is critically important to its operation and maintenance. However, as already observed, no suitable data are available for float type sluice gate. Therefore, the purpose of this paper is to study the flow characteristics of float type sluice gate under free flow through analysis and experiments. It also aims to develop the relationship between the discharge coefficients and gate openings, head of water above the centreline of the orifice, discharge.
2. Theoretical consideration

One way to determine the discharge in gates is using the energy-momentum method (EM). The energy equation for free flow under the gate with a rectangular cross section (free hydraulic jump at downstream), can be written as:

$$\beta = \frac{y_1}{y_2} = \frac{v_1}{c_e}$$  \hspace{1cm} (8)

where $\alpha_o$ is the velocity distribution coefficient in the main channel before the float type sluice gate, $\alpha_d$ is the velocity distribution coefficient in the main channel after the float type sluice gate, $v_0$ is the velocity in the main channel before the float type sluice gate, $v_d$ is the velocity in the main channel after the float type sluice gate, $h_w$ is defined as $h_w = \zeta \frac{v_o^2}{2g}$ (the coefficient of local head loss, $\zeta$).

The solution of equation (8) requires the energy losses between section 1 and 2. This part is a rapidly varied flow and the distance between section 1 and section 2 is short. Considering $h_w$ only includes local head loss, and then equation (8) can be expressed as follow:

$$H + \frac{\alpha_o v_0^2}{2g} = H_d + (\alpha_d + \zeta) \frac{v_d^2}{2g}$$  \hspace{1cm} (9)

Replace $H + \frac{\alpha_o v_0^2}{2g}$ in equation (9) with the upstream energy head $H_0$, then equation (1) can be expressed as follow:

$$V_d = \frac{1}{\sqrt{\alpha_d + \zeta}} \sqrt{2g(H_0 - h_d)}$$  \hspace{1cm} (10)

It can be written as:

$$V_d = \phi \sqrt{2g(H_0 - h_d)}$$  \hspace{1cm} (11)

where the velocity coefficients $\phi = \frac{1}{\sqrt{\alpha_d + \zeta}}$

According to the calculation formula of discharge ($Q = Av$), then the discharge can be written as:

$$Q = \phi \beta H_d \sqrt{2g(H_0 - h_d)}$$  \hspace{1cm} (12)

Equation (12) is expressed as a function of the gate opening, $e$, and the upstream water depth, $H$, we introduced these parameters:

$$H_d = e \varepsilon$$  \hspace{1cm} (13)

$$\mu_0 = e \varphi$$  \hspace{1cm} (14)

Then the discharge for free flow can be expressed as:

$$Q = \mu \beta \varepsilon \sqrt{2g(H_0 - e \varepsilon)} = \mu \beta \varepsilon \sqrt{1 - \frac{\varepsilon}{H_0} \sqrt{2gH_0}}$$  \hspace{1cm} (15)

$$Q = \mu \beta \varepsilon \sqrt{2gH_0}$$  \hspace{1cm} (16)

where $\mu$ is the
\[ \mu = \mu_0 \sqrt{1 - \frac{\phi}{H_0}} = \varepsilon \phi \sqrt{1 - \frac{\phi}{H_0}} \] (17)

3. Experimental program

Smooth rectangular open channel at the China Agricultural University (CAU) were used in the experiments. The flume with length of 10.5 m and width of 0.8 m is showed in figure 1. During the experiment, the depths of water in the channel were measured in real time by using the pointer gauge of accuracy +0.1mm and the discharges through the channel were measured by ultrasonic flow meter.

Under the premise of satisfying various hydraulic conditions in the whole channel, the purpose of floating gate design is to devise a tapered float body (the parameters include the radius of upper bottom \( r_1 \), the lower bottom \( r_2 \), the height \( L \) and tapered angle), which can meet end of the channel diversion flow in the situation of actual irrigation terrain. In this paper, the size of the floating gate is determined by the comparison of the channel design parameters. The size of float model and the float design are showed in table 1 and figure 2 respectively. A stainless steel material with a thickness of 1 mm was selected as raw material for float.

![Figure 1. The sketch of rectangular open channel and floating gate.](image)

![Figure 2. Effect of floating design.](image)

Table 1. The size of floating gate.

| The upper bottom \( r_1 \) (cm) | The lower bottom \( r_2 \) (cm) | The height \( L \) (cm) | The tapered angle \( \alpha \) | Opening range \( e \) (cm) |
|---------------------------------|---------------------------------|------------------------|-----------------------------|----------------------------|
| 15                              | 5                               | 30                     | 18.5                        | 24                         |

The gate plate with circle hole is the more important part of the floating gate. The gap between the floating gate and the gate plate is viewed as the water area of the gate. Therefore, it is necessary to design the size of the circle radius in order to ensure the accuracy of the diversion flow through the gate. The size of the gate plate is designed according to the size of the float body. In order to avoid the friction between floating gate body and the edge of gate plate in the process of lifting and closing, the hole radius should be slightly larger than the radius of upper bottom \( r_1 \). The size and the effect of the gate plate with circle hole are showed in table 2 and figure 3 respectively. A stainless steel material with a thickness of 2 mm was selected as the production of materials. The stainless steel plate is manufactured as three parts, part A is located vertical to the bottom for block sand, and part B is a hole plate with diameter 0.3 m, part C is located on the hole plate in order to block the surface waves, improving this way the approach conditions. The downstream water depth was regulated with an adjustable float type plug. Gates used in canals for control and measurements of flow and the vertical movement of the gate controls the gate opening and the corresponding flow to downstream.
Table 2. The size of the gate plate with circle hole.

| the length of gate plate (cm) | the width of gate plate (cm) | the height of gate plate (cm) | the hole diameter D (cm) |
|------------------------------|-----------------------------|-----------------------------|------------------------|
| 80                           | 60                          | 35                          | 30.5                   |

Figure 3. Effect of the gate plate with circle hole.

The determination of model test is a very important, the appropriate test program can make the test easier and the data processing simpler. The overflow condition of the float gate in this experiment is similar to the orifice outflow, therefore combined with the knowledge of orifice outflow, the outflow form of the experimental gate is further determined.

According to the form of the orifice outflow, the outflow of the float gate type studied in this paper can be considered as free orifice outflow. Since the purpose of this experiment is to explore the relationship between flow coefficient and gate opening, water head at the upper reaches of the centre line of the orifice, discharge. The flow range suitable for free outflow was measured in the test process, and the opening of the gate was also determined. The opening of gate is determined to be 0.15 m, 0.12 m, 0.10 m, 0.08 m and 0.05 m and the discharge ranges from 20 m$^3$/h to 60 m$^3$/h. Record the head of water above the centerline of the orifice when the flow is stable after the change of the opening of the gate and discharge.

4. Analysis of experimental results under free flow

4.1. Formulation of equation for free flow

Randomly select the experimental data on gate opening $e$ and water depth $H$ at different flow discharges. By analyzing the data and using the energy and momentum equations, the relationship between gate opening $e$ and depth $H$ are proposed. It is first seen that there is a good polynomial relationship between the gate opening $e$ and the water depth $H$ when the flow is constant.

The following relationship between $e$ and $H$ is:

$$e = -A \ln (H) - B$$  \hspace{1cm} (18)

where $A$ and $B$ are two coefficients that need to be determined. For the range of flows studied the relationship is fairly linear as shown in the figure. Flow rate in channel strongly affects the relation of $e$ to $H$, thus the functional relationship for $e$ and $H$ is first plotted as figure 4 when the discharge is 20 m$^3$/h.
Correlation for gate opening and water depth when the discharge is 20 m$^3$/h are obtained by the experimental study result as:

$$ e = 2.856 \ln(H) - 2.4649 \tag{19} $$

It reveals that the water depth $H$ decrease with the gate opening $e$ when the discharge is constant. Relational expression between coefficient, $A$, and discharge, $Q$, can be obtained by experimental data as:

$$ A = 0.9314Q^{-0.22} \tag{20} $$

Figure 4. The relationship between gate opening $e$ and $H$ ($Q=20$ m$^3$/h).

Figure 5. The relationship between coefficient $A$ and discharge $Q$. Figure 5 shows the coefficient $A$ versus discharge $Q$ for the present data together with equation (20).
The calculation results are in agreement with the actual data. Relational expression between coefficient, $B$, and discharge, $Q$, can be obtained by experimental data as:

$$B = -0.642\ln(Q) - 0.8261$$

(21)

Figure 6 shows the coefficient $B$ versus discharge $Q$ for the present data together with equation (21). Contrast the conclusion among formula and experimental data, results showed that the data are in good agreement.

Figure 6. The relationship between coefficient $B$ and discharge $Q$.

It is seen that both equations fit well with the data. Figure 6 shows that $B$ decreases as the discharge increases.

According to the relationship of $Q$ and coefficient $A$ and $B$, fitting out formula of the gate opening $e$ and the water depth $H$ (equation (18)) when in different discharge:

$$e = -0.8314Q^{-0.22}\ln(H) + 0.642\ln(Q) + 0.8261$$

(22)

4.2. Effect of various parameters on discharge

Flow coefficient is of great importance for measuring the river discharge. The coefficient is variable, which can be influenced by many factors. The experimental data on main factors are selected in this study to analyse the effect of non-dimensional parameter of $e/H$ on coefficient of discharge $C_d$. We selected the main relevant factors for regression analysis. The data collected in the present study have been used to analyse the effect of non-dimensional parameter of $e/H$ on coefficient of discharge $C_d$. Figure 7 shows the variation of the observed coefficient of discharge $C_d$ with the $e/H$, and it reveals that the value of $C_d$ decreases with the increase of the $e/H$, when other parameters such as the size of the orifice. The data set selected to evolve relationship for $C_d$, and equation (23) is proposed for $C_d$ as:

$$C_d = -0.11\ln\left(\frac{e}{H}\right) + 0.1$$

(23)
5. Conclusions
A float type sluice gate was designed for flow measurement. A theoretical equation has been proposed to calculate the discharge under free flow condition in rectangular channel. An equation for coefficient of discharge for orifices is also presented. The new equation can be used to predict the performance of sluice gates with different sizes under free flow situations. The equation includes variable parameters, each of which is affected by the sizes of the gate, thus it has better practicability.

- Float type sluice gate consists of gate plate with circle hole and floating design was used for model test. The size of the gate was designed accurately to ensure the accuracy of the diversion flow through the gate.
- According to experimental data, the relationship between gate opening e and the water depth H in different discharge was proposed. And it is revealed that the water depth H decrease with the gate opening e when the discharge is constant.
- The singular of the discharge coefficient of sluice gates in rectangular channels was proposed and its validity was proved. The influence of non-dimensional parameter of e/H on the discharge. It showed that the charge coefficient decreases with increment of e/H, and when the parameters of e/H are small, the charge coefficient is relatively more sensitive to it.

Acknowledgment
The authors express gratitude for the financial support from the National Key R & D Program of China (Grant Nos. 2017YFC0403203, 2016YFC0400207, 2017YFD0701000 and 2016YFD200700), National Natural Science Foundation of China (Grant No. 51509248), Jilin Province Key R & D Plan Project (20180201036SF), Jilin Province Education Department "13th Five-Year" Science and Technology Project (JJKH20170519KJ), and Jilin Province Science and Technology Department key scientific and technological projects (20170204008SF)

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