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RESEARCH PAPER

Investigation of Free Flow Under the Sluice Gate with the Sill Using Flow-3D Model

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Abstract

Sluice gates are widely used in irrigation networks, in order to control the water level and regulate the flow that enters the intakes. Creating a sill under the sluice gate reduces the height of the gate and the construction costs of the irrigation network and also affects the discharge coefficient. The main aim of this study is evaluation of the effect of the shape, height and location of the sill on the sluice gate's discharge coefficient. In order to evaluate the effect of the shape and height of the sill on the hydraulic flow, Flow-3D model was employed and two different sill shapes (rectangular and semicircular) with different heights were used under the sluice gate. The results indicate that creating a sill under the sluice gate increases the discharge coefficient and the shape and height of the sill are the most important factors in its increase. When the ratio of the rectangular and semicircular sills' height to the gate opening is 2 and 0.5, respectively, the discharge coefficient is maximum value and 8.3% and 23% more than the case without sill, respectively. In order to correct the discharge coefficient of sluice gate with sill, equations for rectangular and semicircular sills have been presented.

Keywords Sluice gate · Discharge coefficient · Sill · Flow-3D model · Irrigation network

1 Introduction

Due to the water shortage in developing countries, increasing the hydraulic performance and increasing the efficiency of water distribution in irrigation networks are necessary. One of the strategies for improving the efficiency of agricultural water productivity is increasing the accuracy of discharge measurement and controlling the water level. Gates are needed in order to control the amount of water released from dams and for regulating the water level in irrigation networks. There are different types of gates, and the most common types of gates are sluice gates and radial gates. Gates are used widely in irrigation networks; therefore, choosing small dimensions for the gates can reduce the channel costs. One of the ways for reducing the dimensions of the gate is to create a sill at the bottom of the canal and install the gate on the sill, so the design height of gate is reduced and it is economically affordable. Estimation of the discharge coefficient of gate and consequently the amount of flow is one of the most important issues in hydraulics. The coefficient of discharge for free flow sluice gates without the sill depends on the upstream water level and the gate opening. Several studies have been conducted concerning the sluice gate discharge coefficient without the sill. Henry (1950) studied the sluice gate's discharge coefficient under free flow and submerged conditions and presented a chart based on the opening and relative tail water for the discharge coefficient. Rajaratnam and Subramanya (1967), by performing multiple experiments, presented a new definition for the sluice gate's discharge coefficient under free flow and submerged conditions. Swamee (1992) considered coefficient of discharge for free flow sluice gates a function of $H^* = y_0/w$ where y_0 is the upstream water depth above the channel bed and w is the gate opening, and based on the data gained by digitizing Henry's (1950) chart, an equation for calculating the discharge coefficient was presented. Alhamid (1998) showed that the flow discharge estimated by Swamee's equation is 3.9% less than the actual flow discharge and presented a more accurate equation according to the experimental data.

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He also examined the effect of the sill shape on the sluice gate's discharge coefficient under free flow condition and showed that creating a sill under the sluice gate increases the discharge coefficient. Habibzadeh et al. (2011) presented an equation for estimating the sluice gate's discharge coefficient under free flow and submerged conditions by using the continuity and momentum equations and considering the energy loss. They stated that the effect of the gate's energy dissipation increases the accuracy of estimating the discharge coefficient; therefore, they presented the average amount of the gate's energy loss coefficient under free flow and submerged conditions. Jalil et al. (2016) studied effect of prismatic sill on the sluice gate's discharge coefficient under free flow. Their study was carried out in laboratory flume on four different prismatic sill heights. The prismatic sill increased the discharge coefficient up to 25% for several models.

In order to simulate the flow passing through gates, experimental and numerical methods can be used. In the recent decades due to the significant development of computers and numerical methods, the researches' tendency toward simulation of flow using numerical models has increased. According to recent CFD studies, volume of fluid (VOF) method is a powerful computational tool for the numerical simulation of free surface flow. Applications to laminar and turbulent flows were presented widely (Li et al. 2000; Savage and Johnson 2001; Ashgriz et al. 2004; Ataki and Bart 2004; Gu et al. 2004; Sarker and Rhodes 2004).

Kim (2007) used the Flow-3D model for determining the characteristics of the flow passing through sluice gates. He considered the dimensions of the modeling region as a function of the gate opening and chose hydrostatic boundary condition for the inlet, outflow boundary condition for the downstream, wall and symmetry boundary condition for the bottom and the upper part. Akoz et al. (2009) studied the effect of computational mesh on the accuracy of the ANSYS model's results by measuring the velocity profile upstream of the sluice gate. They used the VOF model for simulating the free flow surface and used the $K-\varepsilon$ and $K-\omega$ turbulence models for simulating the flow. Their results showed that in order to increase the numerical models' accuracy the size of the computational grid under the gate (where velocity changes are significant) and also near the free flow surface must be small. Cassan and Belaud (2012) studied the flow characteristics upstream and downstream of a sluice gate using experimental and numerical model data. They first used the experimental data of the velocity profile in free flow and submerged conditions to estimate the accuracy of the FLUENT hydrodynamic model output and then used the numerical model to present equations for the compression ratio and sluice gate energy dissipation in free flow and submerged conditions.

The objective of this paper is to investigate the effect of characteristics of sill such as the shape, height and location on the discharge coefficient for free flow sluice gates. To achieve this goal, first the Flow-3D model's output results for simulation of flow passing through a sluice gate are validated using the experimental data and then the effect of the sill on the flow passing through a gate is examined. Also, an equation for the estimate of the discharge coefficient for silled sluice gates is developed.

2 Materials and Methods

2.1 Governing Equations

The equations governing the flow field in fluids are the continuity and momentum equations, which are expressed as Eqs. (1) and (2) for incompressible turbulent flow with constant viscosity and density (Flow Science Inc 2014):

$$v_{\mathrm{f}}\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i A_i\right) = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{1}{v_{\mathrm{f}}}\left(u_j A_j \frac{\partial u_i}{\partial x_j}\right) = \frac{1}{\rho}\frac{\partial p}{\partial x_i} + g_i + f_i \quad (2)$$

where u_i is the velocity in the x_i direction which are x, y and z directions, t is the time, v_{f} is the volume fraction of fluid in each cell, ρ is the fluid density, A_j is the fractional area open to flow in the j direction, p is the hydrostatic pressure, g_i is gravitational acceleration in the j direction, and f_i indicates the Reynolds stresses for which a turbulence closure model is required.

Using clear and simple equations for determining the gate discharge has always been of interest to researchers and engineers. Therefore, equations have been presented for determining the discharge passing through the gate by using laboratory data, field data and output results from hydrodynamic models. The most common equation governing the amount of discharge passing through gates in free flow condition is presented as Eq. (3) (Bos 1989; Henderson 1966):

$$q = C_{\mathrm{d}} w \sqrt{2 g y_0} \quad (3)$$

where q is the discharge per unit width, w is the gate opening, C_{d} is the gate discharge coefficient, and y_0 is the upstream water depth where in the condition with sill, it is estimated from difference between the upstream water level and the sill crest. Alhamid (1998) presented Eq. (4) for calculating the sluice gate's discharge coefficient in free flow condition:

$$C_{\mathrm{d}} = 0.63\left(\frac{H^* - 1}{H^* + 15}\right)^{0.065} \quad (4)$$

2.2 Numerical Model Description

According to the development of computer facilities, as well as providing robust software in the field of computational fluid dynamics it is possible to study complex flow using numerical simulation. Among the software that can be used by considering characteristics such as speed, optimum accuracy and simple mesh building, the Flow-3D software has been chosen for this research. This model has been developed by the Flow Science Company in 1980 and is very popular among the users; one of the reasons for this models popularity is its great graphical results. This software solves the 3D transient Navier–Stokes equations with finite volume approximations. This program evaluates the location of the flow obstacles and rigid boundaries by FAVOR technique and tracks the free flow surface by VOF technique. The flow region is divided into cubic cells, and for each cell, there are mean values of dependent quantities.

2.3 Experimental Investigation

In this paper, Alhamid's (1998) and Akoz et al.'s (2009) experimental data were used for evaluating the accuracy of the Flow-3D model results. Alhamid's (1998) experiments were conducted in a rectangular laboratory flume with 9.45 m length and 0.305 m width. The flow discharge was measured using a V-shaped weir, and the water depth was measured by point gauges. The observed data consist of 11 series of experiments in free flow condition, where the range of discharge passing through the gate is 12.9–22.33 l/s, the water depth upstream of the gate is 12.88–48.2 cm, and the gate opening is 4–5 cm. This experimental data are used for validation of the sluice gate's discharge coefficient for non-silled free gate flows. Akoz et al.'s (2009) experimental data were also used to validate the velocity and pressure profiles upstream of the sluice gate. Their experiments were conducted in a horizontal canal with a glass wall with 2.4 m length and 0.2 m width. The velocity profile has been measured in the *x* and *z* directions at a 4.4-cm distance from the sluice gate with 12 mm opening, and the pressure profile has been measured at various points on and under the gate. In their experiments, the flow discharge and the water depth upstream of the gate were considered 2.1 l/s and 10.7 cm, respectively.

2.4 Solution Domain, Boundary and Initial Conditions

In this research, the flow field passing through the gate was studied in two dimensions. One of the factors that affect the simulation is determining the solution domain. If the solution domain is considered too small, the computational error increases, and if it is big, the simulation time increases. Kim (2007) considered a length equivalent to 20 and 6 times the gate opening in the upstream and downstream of the gate, respectively, and a height equivalent to 12 times the gate opening for simulating the flow passing through the sluice gate; his results were used in this research. Choosing initial and boundary conditions for the implementation of unsteady flow with Flow-3D model is one of the essential steps of simulation. The boundary conditions used for two-dimensional numerical modeling are defined in Fig. 1. At the inflow boundary of the computational domain was inlet velocity, and the downstream boundary conditions were outflow at the channel end. The lower boundary coincided with the solid channel bed and considered wall and symmetry used for upper boundary condition. By knowing the flow discharge and using the empirical equation presented by other researchers, the flow depth was calculated and was considered as the initial condition.

One of the important factors in numerical simulations is the building of a suitable mesh. Improper computational mesh can cause many problems during the simulation such as lack of convergence and stability, increase in the required memory and increase in the simulation time. Kim (2007), for simulating the two-dimensional flow passing through a gate, considered the sizes of the mesh cells in the x direction between 0.025 and 0.265 times the gate opening and in the *z* direction between 0.025 and 0.07 times the gate opening. In this research, a mesh sensitivity analysis was conducted where 5 different grids were tested and meshed with the cells size of 0.07, 0.05, 0.035, 0.025, 0.02 times the gate opening in the *x* and *z* directions. Figure 2 gives the results of the mesh sensitivity study on the estimated upstream water depth. As can be seen, if the cell size is smaller than 0.025 times the gate opening, it does not affect the accuracy of simulation and so this cell size was selected.

In order to determine the appropriate simulation time of the model, the discharge outlet from the downstream boundary, as well as water depth in the upstream boundary, was plotted in different times as shown in Fig. 3. A transient flow analysis was carried out for a total time period of 35 s,

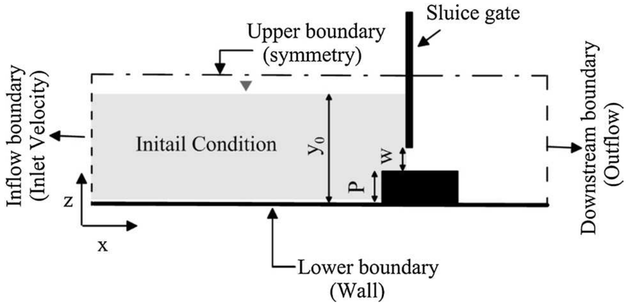


Fig. 1 Boundary and initial conditions used for two-dimensional numerical modeling

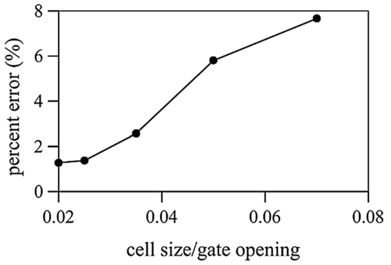
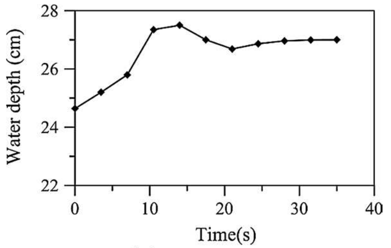
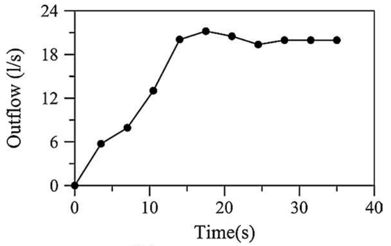


Fig. 2 Error of the estimated water level upstream of the gate versus cell size/gate opening



(a) Upstream boundary



(b) Downstream boundary

Fig. 3 Water depth and outflow in the upstream and downstream boundary versus time simulation

when a steady state was reached. The second-order scheme and the RNG $k - \varepsilon$ turbulence model were used for separating the momentum equation. Since one of the objectives of this study is to investigate the effect of the shape, height and location of the sill on the sluice gate's discharge coefficient, two different sill shapes (rectangular and semicircular) with 7 different heights (1.25, 2.5, 5, 7.5,10, 12.5, 15 cm) were used. It must be noted that for the semicircular sill, the gate was located on the crest of the sill and the rectangular sill was of fixed length equal to 20 cm and the gate was located at three different locations from the upstream edge of the sill; the locations were 5, 10, 15 cm from the edge.

3 Results

3.1 Validity of the Flow-3D Model Results

In this research, experimental data from Akoz et al. (2009) have been used to validate the velocity and pressure profiles upstream of the sluice gate. After determining the geometric characteristics of the solution domain, building the mesh and applying the boundary conditions, the Flow-3D model was run and its results were compared with the observed data. The observed and calculated velocity and pressure profiles are shown in Fig. 4, where v and u are vertical velocity and horizontal velocity, respectively, U_0 is the average flow velocity, and y is the vertical distance from the bottom of the channel. It should be noted that the flow discharge and the water depth upstream of the gate were considered 2.1 l/s and 10.7 cm, respectively, and the velocity profile has been measured at a 4.4-cm distance from the sluice gate.

A quantitative evaluation of the computed and measured dimensionless velocity profiles and pressure head distributions was made by the mean square error (MSE).

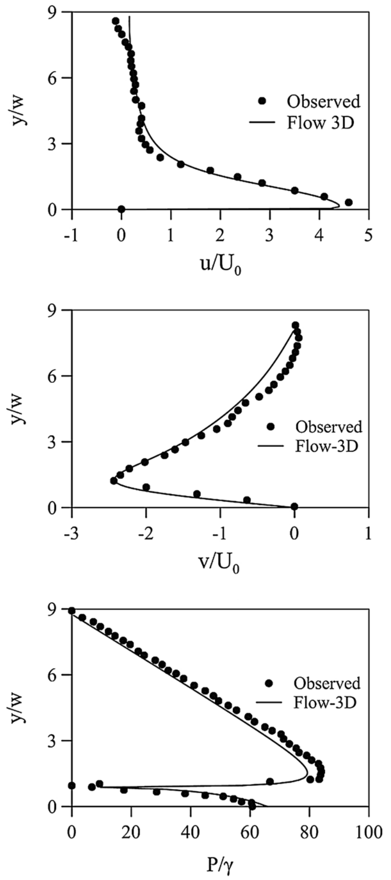


Fig. 4 Comparisons of computed and measured vertical and horizontal velocity profiles and pressure head distributions on gate

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{M^2}\left(s_i - m_i\right)^2 \tag{5}$$

where s_i and m_i are computed and measured parameter (dimensionless velocity and pressure head) and n and M are total number and the average of measured values, respectively. The lower limit for MSE is zero and indicates a more accurate simulation. The results for MSE using Eq. (5) for computed vertical and horizontal velocity profiles are 0.04 and 0.08, respectively, and for computed pressure head distribution is 0.005, which are suitable for predicting the characteristics of flow passing through a gate.

Alhamid's (1998) experimental data are used for validation of the discharge coefficient for sluice gate in free flow condition. After constructing the mesh and applying the boundary conditions for the selected experiments, the Flow-3D model was run and the water depth was calculated. Then, the discharge coefficient was determined using Eq. (3). The observed and calculated discharge coefficients for free flow sluice gate are shown in Fig. 5.

Figure 5 indicates that by increasing the H^*, the sluice gate discharge coefficient also increases. The gate's discharge coefficient calculated by the Flow-3D model is very close to the observed data. The average and maximum relative errors of the numerical model in estimating the discharge coefficient are 1.16% and 3%, respectively, which are suitable for predicting the characteristics of flow passing through a gate.

3.2 The Effect of the Sill Height under the Sluice Gate on the Hydraulic Flow Characteristics

In this research, two different sill shapes (rectangular and semicircular) with 7 different heights ($P = 1.25$, 2.5, 5, 7.5,10, 12.5, 15 cm) were used. The rectangular sill height was 20 cm and the gate opening was considered 5 cm. The gate was located on the crest of the semicircular sill and at a distance of 5 cm from the beginning of the rectangular sill. After simulation for different discharges, the water depth upstream of the gate and the sluice gate's discharge coefficient were calculated. The effects of the rectangular and semicircular sills' height on the sluice gate's discharge coefficient are shown in Fig. 6.

This figure shows that the sluice gate's discharge coefficient in the condition with sill is higher than in the condition without sill. Figure 6 also shows that sill height has an important effect on C_d values; as the sill height increases, the discharge coefficient for free flow sluice gates increases until a specific height is reached, and then C_d values start decreasing. Tested rectangular sill of 10 cm and semicircular sill of 2.5 cm gave the highest discharge coefficient. The semicircular and rectangular sills with 5 cm height increase the discharge coefficient 17.5% and 4%, respectively. By setting the sill under the gate, the separation of the flow line occurs and negative pressure in the crest sill is created. The negative pressure causes the increase in the discharge coefficient. Pressure on the crest of semicircular sill due to curvature and centrifugal force is less than the rectangular sill, and so the semicircular sill increases the sluice gate's discharge

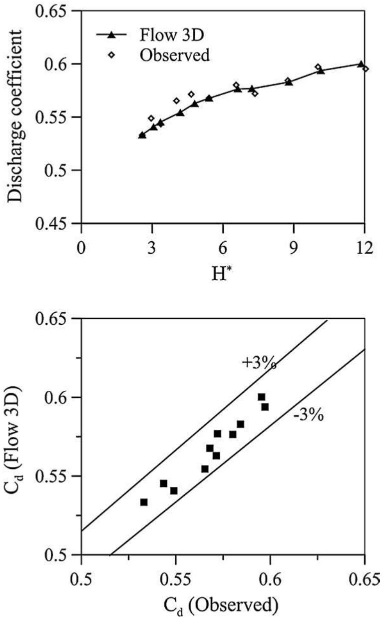
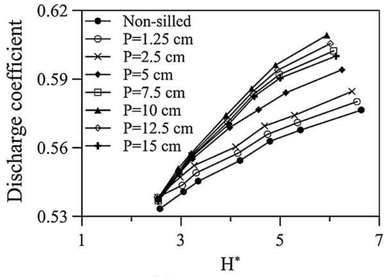
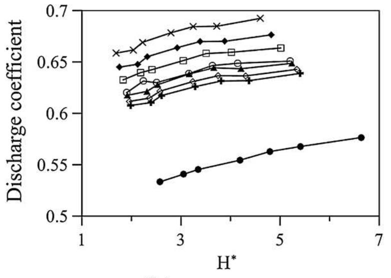


Fig. 5 Observed and calculated discharge coefficients regarding Alhamid's experiments



(a) Rectangular sill



(b) Semicircular sill

Fig. 6 The effects of the rectangular and semicircular sills' height on the sluice gate's discharge coefficient

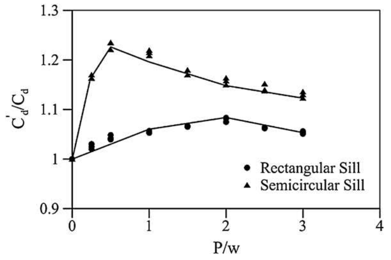


Fig. 7 The effect of the *P*/*w* of the sills on the discharge coefficient for free flow sluice gates

coefficient more than the rectangular sill. The effect of the ratio of sill height to the gate opening (*P*/*w*) on the discharge coefficient is shown in Fig. 7. It should be noted that in Fig. 7, the C_d and C'_d variables are the sluice gate discharge coefficients without sill and with sills, respectively.

Figure 7 shows that *P*/*w* of the sills has an essential effect on the discharge coefficient; as the *P*/*w* increases, the C_d values increase until a specific *P*/*w* is reached, and then C_d values start decreasing. The rectangular sill with $P/w = 2$ and semicircular sill with $P/w = 0.5$ have the highest discharge coefficient for free flow sluice gate and increase the discharge coefficient 8.3% and 23%, respectively. Using nonlinear regression analysis, in order to correct the discharge coefficient for silled gate, Eqs. (6) and (7) are presented for rectangular and semicircular sills, respectively:

$$C'_d = 0.63\left(\frac{H^* - 1}{H^* + 15}\right)^{0.065}\left[1 + 0.2\left(\frac{p}{W}\right)^{-1.2}\exp\left(-1.2\left(\frac{p}{W}\right)^{-5}\right)\right] \tag{6}$$

$$C'_d = 0.63\left(\frac{H^* - 1}{H^* + 15}\right)^{0.065}\left[1 + 1.6\left(\frac{p}{W}\right)^{-0.5}\exp\left(-0.1\left(\frac{p}{W}\right)^{-1.6} + 20\right)\right]. \tag{7}$$

In order to validate the presented equations, the Flow-3D model was run for the experimental model with different characteristics and the discharge coefficient was calculated and compared with Eqs. (6) and (7). The discharge coefficient calculated by the hydrodynamic model and presented equations is shown in Fig. 8.

Creating a sill at the bottom of the gate changes the pressure distribution. Figures 9 and 10 show the effect of rectangular and semicircular sills' height on the pressure distribution, respectively, for 18.61 l/s discharge and 5-cm opening.

The increase in the sill's height causes the water level to increase relative to the canal bottom, and therefore, the pressure exerted on the bottom of the canal increases. Given that the rectangular sill increases the water level relative to the bottom of the canal more than the semicircular sill, therefore the pressure exerted on the bottom of the canal for the rectangular sill is more than for the semicircular sill. In the semicircular sill, the negative pressure in the crest and downstream of it is caused because of the flow line separation and by increasing the sill height the negative pressure increases. The sill also decreases the pressure on the gate and creates a negative pressure at the vicinity of the bottom edge of the gate. Figure 11 shows the effect of sill's height on the pressure profile exerted on the sluice gate and on the bottom of the canal. Figure 11 indicates that the effect of the semicircular sill on the pressure is more than that of the rectangular sill. The amount of pressure head (p/γ) on the crest for semicircular and rectangular sills with 5 cm height is 3.2 and 15 cm, respectively.

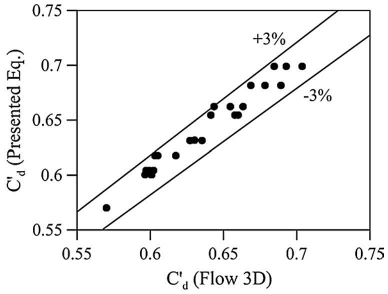


Fig. 8 The discharge coefficient calculated by the Flow 3D and presented equations for silled gate

3.3 The Effect of the Installation Location of the Sluice Gate on the Rectangular Sill on the Discharge Coefficient

The installation location of the sluice gate relative to the beginning of the rectangular sill is one of the factors that affects the gate's discharge coefficient. In this research, the gate's discharge coefficient is calculated in the condition where the rectangular sill's height is 5 cm and the installation location of the sluice gate relative to the beginning of the sill is 5, 10 and 15 cm, and the results are shown in Fig. 12.

By increasing the distance of the gate's installation location relative to the beginning of the sill, the sluice gate's discharge coefficient decreases, and therefore, the effect of the rectangular sill on the discharge coefficient reduces. For a discharge of 22.42 l/s, if the sluice gate is installed at a distance of 5 and 15 cm from the beginning of the sill, the discharge coefficient increases 3.1% and 1.4% relatively compared to the condition without sill.

4 Conclusions

In this research, the effect of sill on the sluice gate's discharge coefficient in free flow condition has been studied. Therefore, evaluation of the effect of the height, location

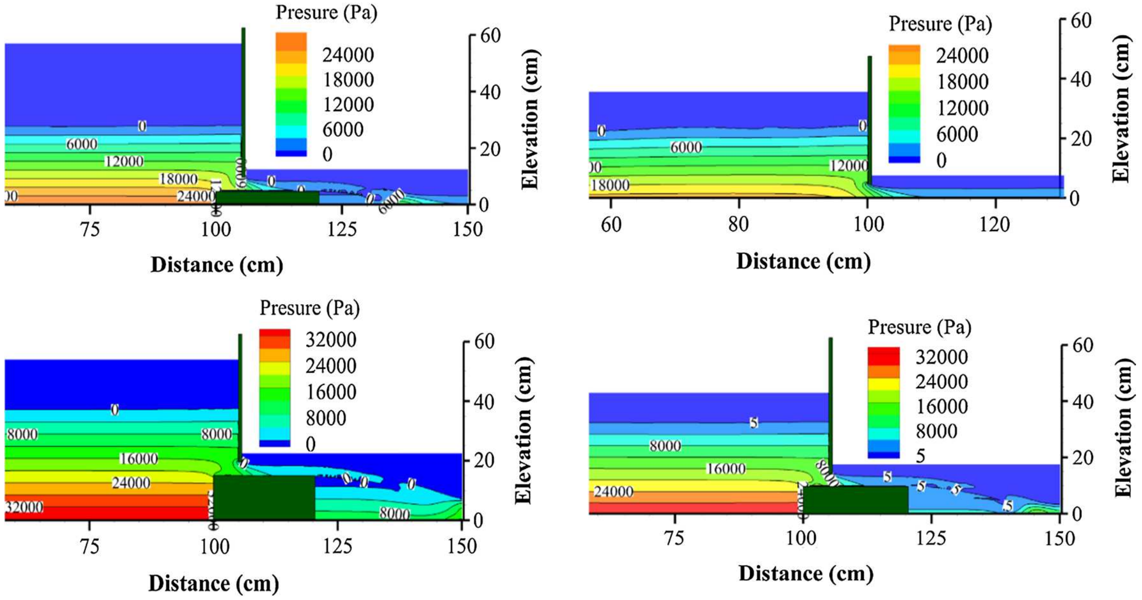


Fig. 9 The effect of rectangular sill's height on the pressure distribution near the sluice gate

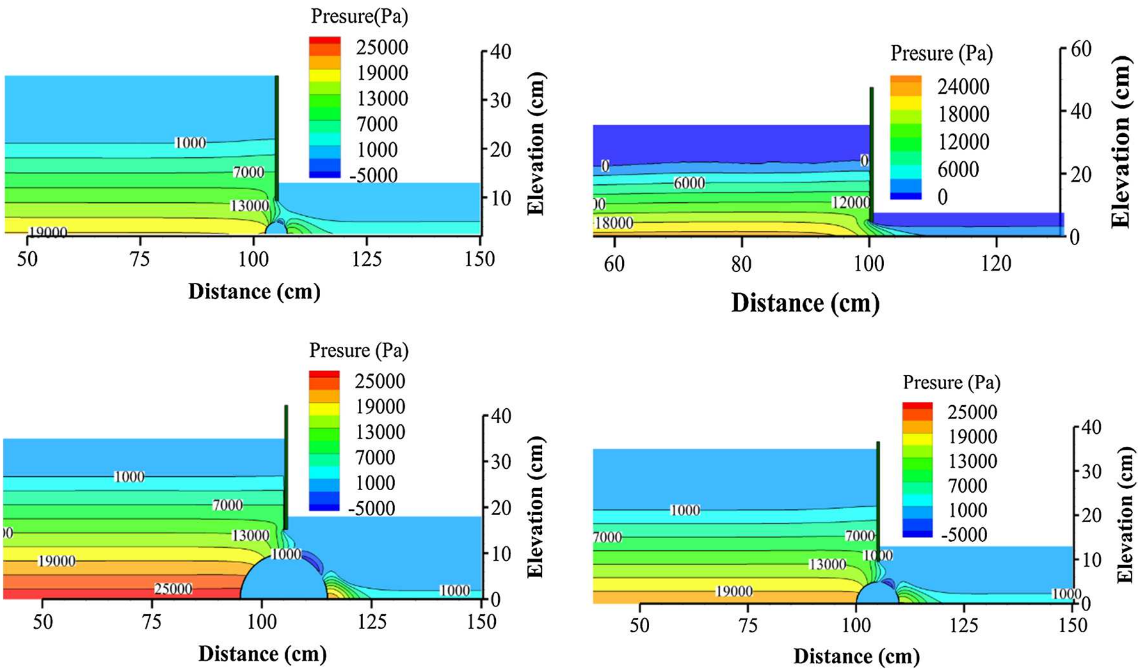
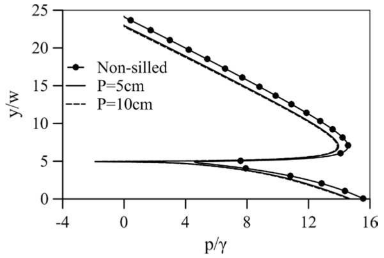
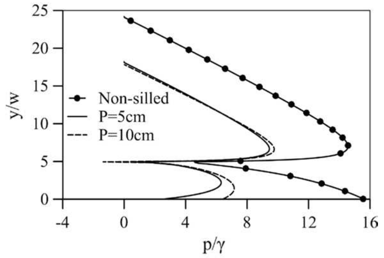


Fig. 10 The effect of semicircular sill's height on the pressure distribution near the sluice gate

and shape of the sill has been considered. The results indicate that creating a sill under the sluice gate increases the discharge coefficient; also the semicircular sill increases the sluice gate's discharge coefficient more than the rectangular sill. One of the variables that affect the sluice gate's discharge coefficient is the ratio of the sill height to the gate opening (P/w), and the maximum sluice gate discharge coefficients for rectangular and semicircular sills are in P/w equal to 2 and 0.5, respectively, where in this case the sluice gate's coefficient increases 8.3% and 23%, respectively.



(a) Rectangular sill



(b) Semicircular sill

Fig. 11 The effect of sill's height on the pressure distribution on the sluice gate

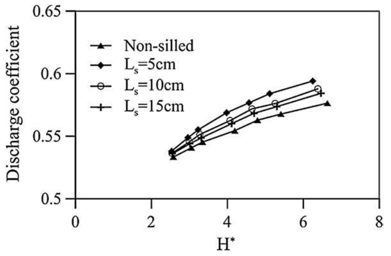


Fig. 12 The effect of the installation location of the sluice gate relative to the rectangular sill on the discharge coefficient

Another factor that affects the sluice gate with a rectangular sill's discharge coefficient is the installation location of the gate relative to the beginning of the sill. By increasing the distance of the gate relative to the beginning of the sill, the discharge coefficient starts decreasing. In other words, the effect of the sill on the discharge coefficient diminutions. In this study, the Flow-3D model was used to present equations for calculating the sluice gate's discharge coefficient with rectangular and semicircular sills. According to the models' output, the maximum error of these equations is 3%.

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