2012, Scienceline Publication

Journal of Civil Engineering and Urbanism

Volume 2, Issue 2: 72-74 (2012) (Received: November 23, 2011; Accepted: February 08, 2012; Published: March 30, 2012) ISSN-2252-0430

Numerical Investigation of Sluice Gates' Shape Factor on Contraction Coefficient

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ABSTRACT:
The behavior of flow under sluice gate and determining the water profile is one of the important issues in hydraulic engineering. In this study the contraction coefficient is studied and the effect of slice gate's shape is observed numerically by CFD model. The turbulence model k-ε (RNG) and unsteady flow mode are used in analysis of two dimensional gates. Three types of slice gate's shapes are analyzed and contraction coefficient of these cases is presented and compared with experimental and theoretical results of other researchers. It is worth mentioning that for these cases the equations in terms of the ratio of gate opening to depth of approaching flow behind gate, are collected. So the gate's shape has significant role on contraction coefficient and between 3 types of gate's shapes that are investigated in this research, contraction coefficient of the sluice gate with shape of two side slope (case 3) has larger amount of this coefficient.

Keywords: Sluice Gate, CFD model, Contraction Coefficient, Turbulence Model k-ε (RNG)

ORIGINAL ARTICLE

INTRODUCTION

Sluice gate with a throughout width in span is one of commonplace structure in hydraulic engineering. Consequently many researches have been done in this field. Some analytic determination of contraction coefficient is done through potential flow theory by von Mises (1917) [1]. Monte (1997) presented numerical model of potential flow for determining the contraction coefficient. His numerical method is based on an inverse method of solution of Laplace's equation in free surface. Also he used inclined sluice gate with free downstream flow [2]. Beloud et al. (2009) presented a theoretical framework based on energy and momentum conservation, as well as on a recently developed description of pressure field on the upstream face of the gate for both free and submerged flow [3]. Experimental values of contraction coefficient are higher than theoretical prediction. Some part of these results are illustrated on Figure 3 such as Fawer (1937) [4], Rajaratnam (1977) [5], Defina and Susin (2003) [6] and Benjamin (1956) [7]. The results of Benjamin indicates that by variation of gate opening and for constant ratio of gate opening to depth of approaching flow, contraction coefficient is changed. In other words by decreasing gate opening and with constant ratio of gate opening to depth of approaching flow, the amounts of contraction coefficient decrease.

In this study, flow behavior under sluice gate is simulated numerically and the effect of gate's shapes on contraction coefficient is investigated. As illustrated in Figure 2, three types of gate's shapes are modeled. The results of shape factor and variation of contraction coefficient is described by some equations.

Governing Equations

The Navier-Stokes equations are the basic governing equations for a viscous fluid. It is a vector equation obtained by applying Newton's Law of Motion to a fluid element and is also called themomentum equation. It is supplemented by the mass conservation equation, also called continuity equation and the energy equation. The general form of the equations of fluid motion is:

$$\rho\left(\frac{\partial v}{\partial t}+v.\nabla v\right)=-\nabla p \qquad (1)$$

Where v is the flow velocity, ρ is the fluid density, p is the pressure and ∇ is the delta operator.

In this research the turbulence model k-ε (RNG) is used for modeling of turbulent flow. The RNG model was developed using Re-Normalization Group (RNG) methods by Yakhot et al. [8] to renormalize the Navier-Stokes equations, to account for the effects of smaller scales of motion. The equations of this method are given by Equation 2 and 3.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+P_k-\rho\varepsilon \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P_k-C^*_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (3)$$

Where $C^*_{2\varepsilon}=C_{2\varepsilon}+\frac{C_\mu\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3}$, $\eta = Sk/\varepsilon$ and $S=(2S_{ij}S_{ij})^{1/2}$. Also the constants are:

$C_\mu = 0.0845$, $\sigma_k = 0.7194$, $\sigma_\varepsilon = 0.7194$, $C_{\varepsilon 1} = 1.42$, $C_{\varepsilon 1} = 1.68$, $\eta_0 = 4.38$ and $\beta = 0.012$.

Numerical Analysis of Sluice Gate

As mentioned before, in this paper for investigating the effect of gate's shape, flow under sluice gate is modeled. The dimensions and boundary conditions are according to Figure 1. It worth mentioning that the opening and thickness of the sluice gate for all cases are, respectively, 2.6cm and 1cm. For simulating experimental channel the inlet boundary is divided to inlet of air and inlet of water.

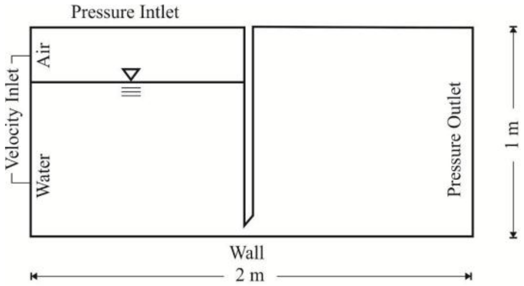

Figure 1. Geometry and boundary condition

The type of meshing that is used in this study is quadrant and map, and the details of meshes for 3 cases are illustrated in Figure 2. Also the number meshes for case 1, 2 and 3 are, respectively, 13488, 13488 and 13390 so the number of meshes is approximately equal. As it is obvious in Figure 1, for conceiving the behavior of flow under the sluice gate, the size of meshes is fined at this area.

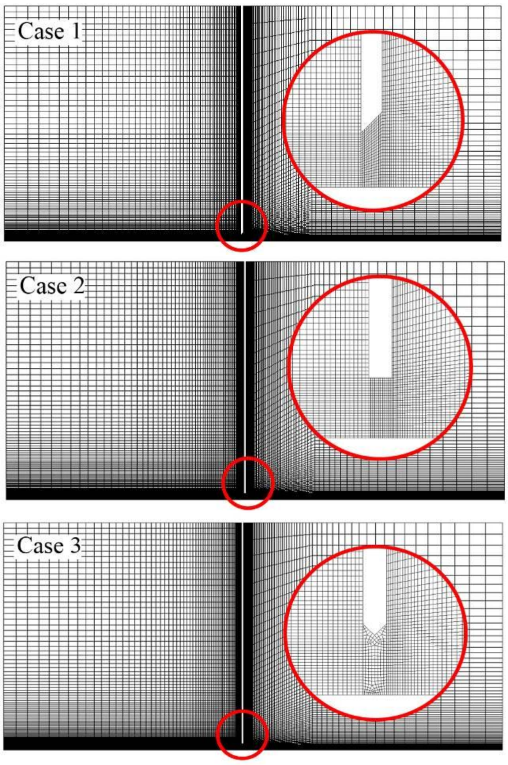

Figure 2. The details of meshes for 3 cases

As mentioned before, numerical solution is done by CFD model. Creating flow domain and meshing are done by Gambit. During analysis, the value of 0.005s is selected for time step via sensitivity analysis.

In Figure 3, the behavior of flow under the sluice gate for different ratio of gate opening to depth of approaching flow is illustrated. In this figure the amount of this ratio for case 1, 2 and 3 are, respectively, 0.0617, 0.0625 and 0.0696.

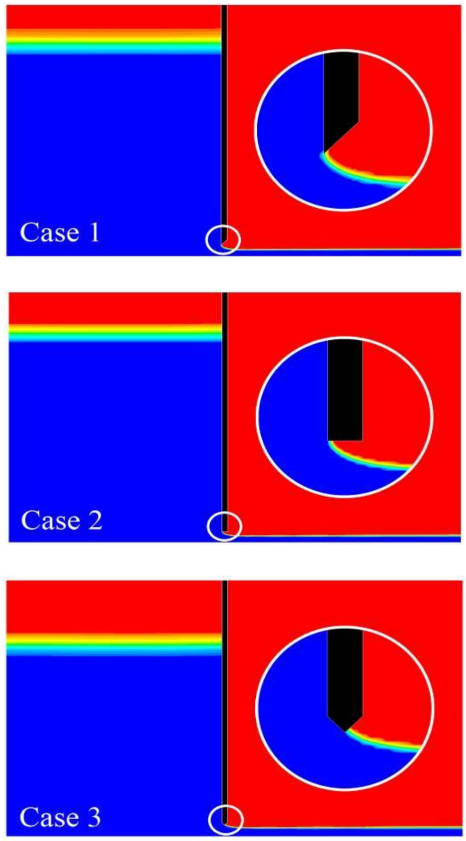

Figure 3. The details of meshes for 3 cases

By applying different values for water depth behind the sluice gate and consequently different ratio of gate opening to depth of flow behind the gate, different values of contraction coefficient are registered and plotted in Figure 4. Other experimental and analytical results are presented in that figure. It is worth mentioning that the horizontal axis is defined as the ratio of gate opening to depth of approaching flow and vertical axis defined as contraction coefficient. As it is obvious in Figure 4, contraction coefficient for case 3 and case 1 have, respectively, higher and lower amount and the result of case 2 is located near case 1.

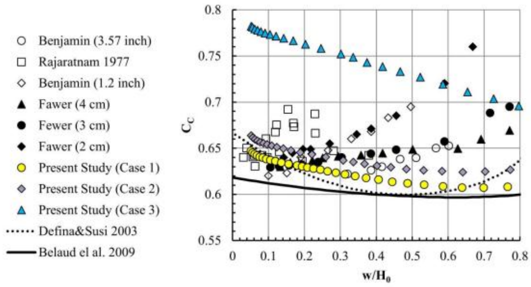

Figure 4. The results of contraction coefficient

As it was shown in Figure 5, the results of contraction coefficient for 3 cases were fitted by quadratic equations. The amount of R-square for case 1, 2 and 3 are,

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respectively, 0.995, 0.994 and 0.999 and the equations are, respectively, according to 4, 5 and 6 equations.

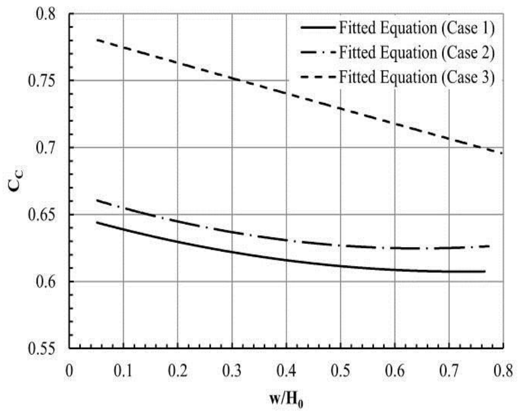

Figure 5. Fitted equations for 3 cases

$$C_c = 0.0806(w/H_0)^2 - 0.1169(w/H_0) + 0.6497 \quad (4)$$

$$C_c = 0.1011(w/H_0)^2 - 0.1307(w/H_0) + 0.6669 \quad (5)$$

$$C_c = 0.0025(w/H_0)^2 - 0.1156(w/H_0) + 0.7862 \quad (6)$$

If the case 1 is considered as a base case, the ratio of contraction coefficient to base case, for the maximum and minimum values are, respectively, 1.04 and 1.03 for case 2. Also this ratio for the maximum and minimum values are, respectively, 1.21 and 1.15 for case 3. So the case 3 has maximum depth and consequently minimum velocity and energy.

CONCLUSION

In this study the behavior of flow under sluice gate is simulated numerically and the effect of gate's shape factor is investigated. For this purpose, three types of gate's shape are modeled and the result of each one is observed. The results show that minimum and maximum values of contraction coefficient related to, respectively, case 1 and 3 and the result of case 2 are located near case 1. So the shape of sluice gate is one of the effective and important factors of this coefficient. Likewise the results of contraction coefficient were fitted by quadratic equations with high R-square values that can be used for predicting this coefficient. Finally with regard to the maximum values of contraction coefficient for case 3 and consequently increasing the initial depth of hydraulic jump and decreasing the secondary depth and also decreasing energy loss, this case is recommended for sluice gates.

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