Numerical simulation of hydraulic performance with free overfall flow

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Abstract. Recently, free overfall flows have attracted attention of many researchers in the world. It is because the free overfall can be used as a tool in measuring the discharges and flows in any open channel systems or water collection systems for various flow regime at different shape of channels. In this study, the hydraulic performances of free overfall flow were explored using numerical simulation for three shapes of open channels including uniform rectangular, rectangular circumscribed, and rectangular inscribed steps. The hydraulic performances discussed in this study are including the flow regime, the maximum pressure, drop length and the energy dissipation rate. Numerical simulations were performed under different discharges $Q$ (between 0.0005 m$^3$/s and 0.0015 m$^3$/s) and excise repair densities ($y/H$) for 1:2, 1:3 and 1:4. Visual observations identified various flow regimes with largely identical flow patterns in different discharges and configurations. Comparisons of properties indicated that there is a better depressurization and energy dissipation performances at the open channel with the shape of rectangular inscribed steps compare to the uniform rectangular in the small charge. Comparative study also revealed that the large excise repair densities of rectangular circumscribed steps might be optimal in terms of energy dissipation performances.
Keywords: Free overfall, Flow regime, Energy dissipation, Numerical simulation

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1. Introduction

Water conservancy project is a key imperative project for people's livelihood in the world [1-5], such as in China [6-8]. As an important and basic project for people's well-being, water conservancy engineering is of great significance to improve people’s production and living conditions. Especially in China, those countries with abundant water resources are always considered as having a very important strategic position. Notably, in various water conservancy engineering, there is a rather common phenomenon named free overfall flow [9]. With further investigation in the function of this phenomenon like energy dissipation [10-12], flow measurement and slowdown, it is widely applied in stepped spillway dam, agricultural hydraulic engineering, municipal overfall flows, landscape design [13], etc. Take ecological restoration work in rural rivers for example, free overfall flow is utilized to accelerate aeration process in natural water, improving river quality by inhibiting the release of organic substance from the river sediment. To be more specific in the application of stepped spillway dam, like Mencesville Dam [14] in the United States, Dachaoshan Reservoir [15] of Yunnan, and Baise Reservoir [16] of Guangxi, with the aim of mitigating erosion and damage to downstream channels, multi-stage overfall flow is adopted to dissipate energy. As it is stated above, free overfall flow plays a vital role in many aspects.

In recent years, a wide range of experts and scholars in the world have conducted lots of scientific research and practice on free overfall flow, providing rich theoretical knowledge and practical engineering application. In 1995, Rand [17] fitted a formula for calculating drop length by consulting materials and experimental research. Later when critical water depth and drop height was determined, Chanson [18] obtained an empirical formula of water drop by fitting their test data with previous one. In addition, Hubert Chanson [19] studied the effect of step shape and cavity on energy dissipation of free overfall flow. In China, Zhong Tian [20] and Jianing Tian [21] also investigated the hydraulic characteristics of stepped spillway.

In terms of numerical simulation of water drop, Ramamurthy et al. [22] explored the distribution of pressure head and velocity in free overfall flow of three-dimensional open channels by establishing a VOF model, which effectiveness was verified through analyzing experimental data and the numerical results. In China, Qing Wang et al. [23] also carried out three-dimensional simulation for water flow of steep slope curves in Flow-3D. Mingjun Diao et al. [24] studied energy dissipation in two-phase flow (including water and gas) based on model tests and two-dimensional simulation, and numerical results suggest that the simulation is highly effective.

Currently, most of research work have focused on single-width flow, slope and model size of free overfall flow, but less attention is paid on body shape of the overfall flow model [25]. In the past, two-dimensional numerical simulation on overfall flow appears more frequent than the counterparts in practical engineering. Hence this paper proposes two new overfall flow models with rectangular circumscribed and rectangular inscribed steps respectively. Furthermore, by inputting different discharge volume, the influence of step shape on flow regime, maximum pressure and energy dissipation rate [26-27] are investigated in three-dimensional numerical simulation. The contribution of research here is to provide certain insights for reconstruction and expansion of some comparable engineering.
2. Materials and Methods

2.1 Water Drop Model

In this paper, the uniformed rectangular steps model is modified into the one with rectangular circumscribed and inscribed steps respectively. Based on the uniform rectangular steps, the rectangular circumscribed one is formed by filling some parts, and the other one is obtained by cutting some parts. These three models are illustrated as the following (Figure 1 and Figure 2):

![Uniform Rectangular Model](A) ![Rectangular Inscribed Model](B) ![Rectangular Circumscribed Model](C)

**Figure 1.** Schematic diagram of rectangular circumscribed and rectangular inscribed steps models.

![Rectangular Inscribed Model](B) ![Rectangular Circumscribed Model](C)

**Figure 2.** Schematic diagram of model parameters of rectangular circumscribed and rectangular inscribed.

In figure 2, \( H \) is model height, \( h \) is the average depth of the section at the drop point, \( v \) is the average velocity of the section at the drop point, \( y \) is the vertical height corresponding to the cut or finished part, \( y' \) is the horizontal length corresponding to the cutting or patching part. Since the oblique angle of the section in this simulation is 45°, corresponding \( y \) is equal to \( y' \). \( P_{\text{max}} \) is the maximum pressure of the bottom surface obtained by numerical simulation. \( L \) is the drop length, the horizontal distance between the maximum pressure points and the drop point, \( y/H \) is the degree of cutting and patching, \( L/H \) is the drop degree, and the drop length is dimensionless. Table 1 presents the values of water discharges for various model in this study.
Table 1. Model parameters.

| The model number | H(cm) | y(cm) | y/H | θ(°) | Q(m³/s) |
|------------------|------|------|-----|------|---------|
| A                | 10   | /    | /   | /    | 0.0005–0.0015 |
| B₁               | 10   | 5    | 1:2 | 45   | 0.0005–0.0015 |
| B₂               | 10   | 3.33 | 1:3 | 45   | 0.0005–0.0015 |
| B₃               | 10   | 2.5  | 1:4 | 45   | 0.0005–0.0015 |
| C₁               | 10   | 5    | 1:2 | 45   | 0.0005–0.0015 |
| C₂               | 10   | 2.5  | 1:3 | 45   | 0.0005–0.0015 |
| C₃               | 10   | 3.33 | 1:4 | 45   | 0.0005–0.0015 |

2.2 Mesh partitioning and boundary conditions

In order to better simulate the upstream discharge, the size of inlet rectangular block is set as 0.1 m × 0.01 m (0.1 m and 0.01 m refer to the value of initial inflow depth and model width correspondingly). The distance between flow inlet and drop point is predetermined as 0.1 m to allow for full development of discharge. For grid setting, the unit size is 0.0025 m × 0.0025 m × 0.0025 m. And given that y/H = 1:2, local refinement is added into the corner part (see those solid lines in figure 3).

Figure 3. Schematic Diagram of Model Grid Partition.

For ensuring the stability of upstream discharge, boundary type of wall is selected at X_min. In case appearance of reflux affects regime of free overfall flow at X_max, the boundary type is determined as Outflow, and other boundaries are all set as symmetry. One reason is for the authenticity in numerical simulation, and the other one is to reduce variables regardless of the influence in other directions [22,28].

2.3 Model validation

Following the Ting Chen’s research work [29], model verification process in this study is conducted based on two models in height of 11cm and 13cm. Under identical condition of upstream discharge, the situation of downstream discharge is monitored and recorded several times. Then data error is compared
and error rate is calculated as well. The values of drop length at different flow rates when the height \(H = 11\) cm and \(H = 13\) cm are showed in Table 2 and Table 3, respectively. Then, Figure 4 presents the model verification for upstream water depths at different water discharge (Q).

**Table 2.** Traditional drop length at different flow rates (\(H = 11\) cm).

| \(Q\) (m\(^3\)/s) | The upstream water depth (m) | Measured values in literature | Simulated value in this paper | Error (%) |
|---------------------|-----------------------------|-------------------------------|-------------------------------|-----------|
| 0.0004226           | 0.0152                      | 0.069                         | 0.067                         | -2.90%    |
| 0.0003568           | 0.0141                      | 0.063                         | 0.0659                        | 4.60%     |
| 0.0002864           | 0.0130                      | 0.058                         | 0.059                         | 1.72%     |
| 0.0002445           | 0.0123                      | 0.053                         | 0.0549                        | 3.58%     |
| 0.0001975           | 0.0112                      | 0.048                         | 0.047                         | -2.08%    |

**Table 3.** Traditional drop length at different flow rates (\(H = 13\) cm).

| \(Q\) (m\(^3\)/s) | The upstream water depth (m) | Measured values in literature | Simulated value in this paper | Error (%) |
|---------------------|-----------------------------|-------------------------------|-------------------------------|-----------|
| 0.0001721           | 0.0096                      | 0.045                         | 0.044                         | -2.22%    |
| 0.0002064           | 0.0102                      | 0.051                         | 0.0495                        | -2.94%    |
| 0.0002445           | 0.0113                      | 0.057                         | 0.0555                        | -2.63%    |
| 0.0002864           | 0.0130                      | 0.063                         | 0.0633                        | 0.48%     |
| 0.0003323           | 0.0135                      | 0.069                         | 0.067                         | -2.90%    |

**Figure 4.** Model verification for upstream water depths at different Q.

From the above results, it can be detected that error between simulation data in this paper and
measured one in literature is within 5%, indicating that the simulation process is effective and can accurately reflect the real-life situation of flow.

3. Results and Discussion

3.1 Influence of discharges on the flow regime

In order to study the influence of discharges on the hydraulic performances, different discharges $Q$ (0.0005 m$^3$/s–0.0015 m$^3$/s) were set for the models. The following figure (Figure 5) shows the simulation results of the uniform rectangular, rectangular circumscribed and rectangular inscribed steps models.

![Fig. 5 Schematic diagram of different types of drop models under different discharges.](image)

For the uniform rectangular steps, the surface of the free overfall flows is parabolic. When the water falls to the floor, part of the water flows to the left to form a back flow area, and the rest of the water continues to flow to the right due to inertia. With the increase of discharges, the water in the back flow area decreases gradually, and the falling water flows more towards the development area.

The flow regime of the rectangular inscribed steps is similar to the uniform rectangular steps. When the discharge is small, the water depth in the back flow area is slightly higher than that of the uniform rectangular steps, and the drop length is slightly smaller than that of the uniform rectangular steps. When the discharge is large, there is little difference from the uniform rectangular steps. Because the shape is rectangular inscribed, there is little connection between the flow and the cut surface in the process of falling, so the effect of the free overfall flow regime is not obvious.

There is a great difference between the flow regime of rectangular circumscribed and the uniform rectangular steps. When the discharge is small, the water drops along the section, and there is a large amount of water in the back flow area, and the vortex is formed. When the discharge increases gradually, the flow tends to break away from the section. Because the shape is rectangular circumscribed, the water...
flow mainly falls along the cut surface in the process of falling. When increasing the falling speed, the drop length is obviously smaller than that of the uniform rectangular steps.

3.2 Maximum Pressure characteristic results and analysis

The characteristics of maximum pressure in the rectangular circumscribed (C_{2}) model is shown in Figure 6 below.

![Pressure contours](image)

**Figure 6.** Pressure diagram of Q = 0.0015 m^{3}/s in the rectangular circumscribed (C_{2}) model.

Based on Figure 6, it demonstrates that for rectangular circumscribed step, it mainly has a great influence on the flow regime due to the existence of cut surface, and the overall pressure reduction effect of the rectangular circumscribed steps is more obvious than the rectangular inscribed steps. The higher of the cut and complement degree, the depressurization is more obvious in rectangular inscribed steps. In addition, at the drop point, local negative pressure may produce cavitation erosion phenomenon, so it also need to pay special attention.

3.3 Drop length results and analysis

In order to facilitate the comparison and analyses between different models, the discharge and drop length are setup to be dimensionless. Drop degree L/H is calculated to analyze the changes between the maximum pressure and the drop length degree under different Froude number $Fr = \frac{v}{\sqrt{gh}}$, where $v$ is the average velocity of the section at the drop point, $g = 9.81$ m/s, is the gravity acceleration, and $h$ is the average depth of the section at the drop point. Figure 7 and Figure 8 present the changes of drop length degree and $Fr$ in uniform rectangular and rectangular inscribed steps.
Figure 7. Changes of drop length degree and $Fr$ in uniform rectangular and rectangular inscribed steps.

Figure 8. Changes of drop length degree and $Fr$ in uniform rectangular and rectangular circumscribed steps.

The change of the rectangular circumscribed steps is more obvious than the rectangular inscribed steps, and the drop length degree is also significantly affected by the different degree of excise repair densities variable ($y/H$). For type $C_1$, in the process of the discharges gradually increasing, the water gradually breaks away from the cut surface. Under the condition of high $Fr$, the drop length degree is obviously greater than type $C_2$ and type $C_3$.

4. Conclusion

In this paper, the comparison among the uniform rectangular steps, the rectangular circumscribed and rectangular inscribed steps are analyzed under different flow conditions which are corresponding to the change of three aspects: the flow regime, the maximum pressure, and the drop length. The main conclusions are as follows:
• The rectangular inscribed steps have little effect on the flow regime. In the case of low Froude number, the pressure reduction effect on the floor is obvious, but in the case of large discharges, the maximum pressure is similar to the uniform rectangular steps. Because the existence of the cur surface has no obvious effect on the flow regime, the drop length is similar to the uniform rectangular steps.

• The rectangular circumscribed steps have obvious influence on the flow regime. The type C₁ steps do not flow along the cut surface in the fall process, and the overall drop length is between the uniform rectangular steps, type C₂ and type C₃. In the fall process of type C₂ and type C₃, the water drops along the surface, and there is a large amount of water in the back flow area, and there is a large amount of turbulent water. Therefore, the overall depressurization effect is obvious and the drop length is significantly reduced. The greater the cut and complement degree, the greater the energy dissipation rate. However, in the case of large discharges, it should be noted that there is a local negative pressure area at the drop place, which may cause cavitation erosion.

• In general, both the rectangular circumscribed and rectangular inscribed steps have effects on free overfall flows, but the rectangular circumscribed steps have a greater effect, and have obvious effects on pressure reduction and the energy dissipation rate. However, in the actual construction, attention should be paid to the protection of the vacuum area in the drop place of the rectangular circumscribed steps under the condition of high discharges.

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