Study on Characteristics of Water Flow Under Different Riverbed Structures in River Narrowing Section

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Abstract. In this paper, a numerical simulation research on the flow characteristics of dammed river under four kinds of riverbed structures is studied by using the turbulence model and the VOF model. The results show that: ① Due to the influence of the riverbed structure, the water flow vortex area of different riverbed structures is obviously different. The backwater and the reflux are the most obvious in a simulated bucket basin model of step-pool structure. ② The average velocity of the section of the bucket basin riverbed and the clustered riverbed is small, and the steady flow velocity is not large. Combined with the base pressure distribution of the riverbed, the pressure distribution of the bucket basin riverbed and ribbed riverbed is relatively regular. This shows that the bucket basin structure is of great help to improve the stability of riverbed. ③ The bucket basin model has better effect of energy dissipation than the other three types.

1 Research Background

The mountain rivers in the river valleys and bank slopes are affected by certain geological and geomorphological conditions to cause collapse, landslides, mudslides and other activities, forming deposits to block the original river channels, resulting in significant narrowing of the river channels and changing the characteristics of the water flow, and the riverbed slope becomes larger. In the narrowing river channel, various types of riverbed structure will be formed, which will affect the river flow characteristics and water and sediment movement. Some scholars have done related research. Wang Shuying^[1] etc. studied the influence of geological conditions and river bed evolution in mountainous areas, and compared the model calculated value with the result of hydrodynamic SMS software to obtain the flow structure characteristics of the wide and narrow rivers. Zhou Sufen^[2] etc. tested the calculated value of flow mathematical model and the water flow of wide and narrow flume. It is concluded that the wide and narrow river channel's width gradation will cause the water depth and flow velocity to change. The water depth is the lowest where velocity is the largest at the narrowest section of the river. The water depth reaches the peak at the widest section of the river where velocity is the smallest. WANG^[3] etc. studied the types of riverbed structures. Jong and Ergenzinger^[4] etc. explored the influencing factors in the development of riverbed structures, such as hydraulics and topography, etc. Liu Huaixiang^[5] etc. statistically analyzed the geomorphological characteristics and riverbed structure development of typical inferior river regions in China. The study shows that the riverbed structure is the embodiment of the self-regulation of the river system,

forming a negative feedback mechanism of 'downcutting - collapse and landslide - river structure development - suppressing downcutting'. It also discussed the energy dissipation effect of riverbed structure on water flow. Yu Guoan^[6] etc. observed and analyzed the bed load particles motion of mountain rivers in three typical riverbed structures, and initially studied the restrictive relationship between bed load motion and riverbed structure development. It is an inevitable trend to study and solve the problem by generalizing the entity into a physical model and a mathematical model and combining the two in the study of the characteristics of river flow. However, in terms of the research content, the research on wide and narrow river channels in mountainous areas mainly focuses on the change of flow velocity and water level. There are not many studies on the pressure distribution at the bottom of riverbed. The understanding of the movement mechanism of the water flow characteristics in the narrowing river is not enough, and there are few studies on the use of engineering design.

In this paper, a numerical simulation of four riverbed structures is carried out to study the characteristics of water flow movement in narrowing sections of mountain rivers under the conditions of right-angled stepped, bucket basin model, ribbed and clustered riverbed structures.

2 Theoretical basis of numerical simulation

2.1 Numerical Simulation Methods

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The motion of three-dimensional water flow is complicated, so it is important to choose a suitable numerical simulation method. After a lot of practice tests, it is found that the simulation accuracy and effect are better in the simulation of natural rivers by using the two-equation turbulence model of time-average Reynold equations. It is relatively a mature method. In this paper, a VOF model of water-air two-phase flow and two-equation turbulence model are combined to carry out numerical simulation; 3-D orthogonal curvilinear coordinate system with the finite volume method and SIMPLEC algorithm are adopted to have a coupling calculations of pressure and speed; A point implicit scheme Gauss-Seidel iterative method is used to solve the finite equations.

The VOF model used in this paper performs a simulation tracking of the free surface by solving the individual momentum equations and calculating the volume of the fluid in the grid cell; it is suitable for processing the steady and transient of the gas-liquid interface. The governing equation for this method consists of volume fraction equation and a conservation equation.

2.2 Governing Equation

The water flow movement changes with the river path, water depth and river width, and it is a three-dimensional problem. A combination of k - ε turbulence model and VOF model is used to perform a simulation in this study.

In k - ε Turbulence Model, Continuity Equation, Momentum Equation, k Equation and ε Equation are expressed as follows:

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (1)$$

Momentum Equation:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \quad (2)$$

k Equation:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G + \rho \varepsilon \quad (3)$$

ε Equation:

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (4)$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

$$G = \mu_t \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \frac{\partial u_i}{\partial x_j} \quad (6)$$

$$\frac{\partial \alpha_w}{\partial t} + u_i \frac{\partial \alpha_w}{\partial x_i} = 0 \quad (7)$$

In the above formula: ρ and μ represent the density and molecular viscosity coefficient; P represents the pressure term under gravity condition; σ_k and σ_ε represent the turbulent Prandtl number of k and ε , where $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ represent the constants of ε equation, where $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$. The turbulent energy k and turbulence dissipation rate ε are put into equation (5) to obtained the turbulence viscosity coefficient μ_t . In equation (5), C_μ represents the empirical constant, where $C_\mu=0.09$; G represents the turbulent energy caused by average velocity gradient which can be defined by equation (6); Equation (7) is the control differential equation for the water volume fraction α_w . Solving this control differential equation is to perform a simulation tracking of air-water interface. u_i and x_i represent the velocity component and the coordinate component, and t represents time.

3 River Flow Simulation Calculation

Figure 1. Planar graph

As shown in figure 1, the model will be divided into 3 critical sections: the import section, the wide section and the narrow section, and the length of the simulated channel is 210m in total, the widest segment is 20m and the narrowest segment is 10m. the width of the narrow segment is unchanged and the wide segment is elliptic. The slope of the narrow segment is 13.5% and the wide segment is horizontal. Four models of right-angled stepped, bucket basin model, ribbed and clustered riverbed structures are set up as follows.

As shown in Figure 2, it is a right-angled stepped model where the channel is stair-stepping on the narrow segment. In total, there are 5 steps, the height of each step is 1m and the length is 7.5m. When the water flows through the steps, there will be a vertical falling buffer, so as to reduce the flow rate and achieve the purpose of energy dissipation. As shown in figure 3, it is a bucket basin model which stimulates the step-pool structure. This model changes the general staircase shape to form the model of water cushion. The height difference between the exit and the lowest point is 2m, and the upper pick height is 1m. When water flows through, there will be a process of “up and down”, so as to increase the turbulence. As shown in figure 4, it is a ribbed model. 5 stone rectangular clusters, which are 10m in length, 1.2m in width and 1m in height are set up on the narrow section. When water flows through the narrow section, it needs to continuously flow through five rectangular stone clusters, and the water speed will gradually slow down, so as to achieve the purpose of

energy dissipation. As shown in figure 5, it is a clustered riverbed model, 13 stone rectangular clusters, which are 2.5m in length, 1.2m in width and 1m in height are set up on the narrow section. The gap between each stone cluster is 1.25m, and all stone clusters are uniformly distributed according to the rule of “32323”.

Figure 2. Right-angled Stepped Model

Figure 3. Bucket Basin Model

Figure 4. Ribbed Model

Figure 5. Clustered Riverbed Model

Figure 6. Meshing Sketch of the Critical Sections

As shown in figure 6, it is a meshing sketch of the critical sections, the whole model is composed of multiple individuals. The mesh division is more accurate.

The flow inlet is defined as the velocity inlet boundary, the upper boundary as the pressure inlet boundary, and the downstream outlet as the pressure outlet boundary. The wall surface adopts the non-slip condition, and the standard wall function method is used to simulate the near-wall surface, and the total number of dividing grids is controlled between 200,000 and 300,000

4 Numerical simulation results and analysis

4.1 Distribution map of water surface profile

Figure 7 is a distribution map of water surface profile of the width and narrow section ($X=80\text{m}$ to $X=130\text{m}$) $Y=0$ profile of the four models, reflecting the water volume fraction in the wide and narrow section ($X = 80$ microns to $X = 130$ meters) $Y = 0$ profile under different riverbed structures and the flow field of the narrow section. It can be seen from the figures that the narrow section of the stepped riverbed model 1 has smooth flow and minimal water depth; Under the condition of model 2, the streamline of the narrow section of the river is curved, and the water depth is the deepest among the four models; Under the condition of ribbed riverbed model 3, the water surface at the narrow section of the river has a large fluctuation; Under the condition of clustered riverbed model 4, the water flow fluctuation is the most obvious. In conclusion, the characteristics of flow field in different riverbed are different.

4.2 Velocity field distribution of narrow section

Figure 8 is a velocity vector distribution profile of the narrow section ($X=124\text{m}$ to $X=128\text{m}$) $Y=0$ profile of the four models, reflecting water movement on the $Y=0$ profile under different riverbed structures of narrow section. It can be seen from the figures that under the Model 1 riverbed structure, the falling water flow forms a local reflow; In model 2, the bucket forms a water cushion, which causes the reflow phenomenon to be more pronounced and plays a significant role in the energy consumption of the water flow; In model 3, due to the resistance of the ribbed slab, the water flow also begins to reflow; Model 4 has a larger contact area with the water flow along the flow direction, and has a greater blocking effect on the water flow, increasing the turbulence intensity of water flow. Model 1 utilizes a continuous step to create a horizontal roll at the starting position of each step of the drained water flow, and a strong mixing effect with the main flow of the step to increase the turbulence of the water flow; Model 2 is to let the water flow into each step, form a water cushion on the ladder, and consume the energy of the water flow; Model 3 and model 4 have similar mechanisms. By increasing the resistance of the riverbed, the water flow produces strong turbulence, and most of the kinetic energy is converted into turbulent kinetic energy to achieve energy dissipation.

4.3 Average flow rate of wide and narrow section

Figure 9 below shows the distribution of the average flow velocity along the narrow section (X=86m to X=140m) under four different models. The overall trends of the average flow rate of modes 1, 2, 3, and 4 are roughly equal, all are increase - fluctuation - decrease, and finally stabilize. The average flow velocity of model 3 begins to decrease at X = 122 m, and models 1, 2, and 4 begin to decrease at X = 126 m. The outlet section flow velocity values are similar in model 2, 3, and 4, which is about 0.54 m/s, and the model 1 is 0.94 m/s, which is obviously higher than the others. Throughout the change process, the model 2 has a water cushion formed by the arc shaped of the riverbed, which makes the water body involved in more energy dissipation. Therefore, the overall fluctuation is more severe, the amplitude is larger, but the stability is better. The model 3 variable amplitude value reaches the highest of all models. Among the four models, the average flow velocity maximum appeared at 3.07 m/s when X = 102 m at model 3, and the minimum value appeared at 0.20 m/s when X = 98 m at model 2.

4.4 Pressure Distribution at the Bottom of the Riverbed

Figure 10 is a pressure distribution of the along the bottom of the riverbed for each model in the narrow section (X = 80m to X = 130m). It can be seen from the figures that the maximum pressure of the bottom of the riverbed in model 1 is 12KPa at the X=96m downstream of the narrow section while model 2 is at X=104m; With the changes of water surface line, the position of the pressure peak at the bottom of the riverbed change to downstream in model 3 and 4.

In the step of model 1, the pressure at the bottom of the river bed changes very little, about 10 KPa, and the pressure at the bottom of the riverbed appears at X = 96 m with a peak of 12 KPa. From the cloud map of the narrow section of the model 2, it can be seen that the pressure value at the bottom of the riverbed at all levels are relatively regular, and the pressure value is around 14KPa, the most highest pressure region at the bottom of riverbed occurs at X=104m, which is 20KPa due to the large difference between the front and back of the bucket. The pressure distribution at the bottom of the riverbed in the narrow section of Model 3 is different from model 1. At the earliest stage, the pressure peak at the bottom of the riverbed is 20KPa at X=104m, and the pressure at the

bottom of the riverbed at X=130m is increased compare to the upper part of the narrower section X=80m, and the distribution along each step is more regular. It can be seen from the figure that under the condition of model 4, the maximum pressure at the bottom of the riverbed appears at the X=98m upstream of the narrow section which is 18KPa.

In summary, riverbed structure varies accordingly with the pressure peak position at the bottom of the riverbed in the narrow section of the river channel, which change with a wide range, and the distribution is not evenly distributed at wide sections.

4.5 Estimation of Energy Dissipation

Due to its special riverbed structure, The water flows, the energy of water flow is consumed to varying degrees through the narrow sections of the models 1, 2, 3, and 4. The writer calculate the energy dissipation ratios under the four models by total flow energy equation. The comparison of energy dissipation ratios under the four models is shown in Figure 12. Selecting X=86m for the upper section of the river channel and X=140m for the downstream section of the river channel and listing the energy equations of the upstream and downstream sections and calculate the equation of energy dissipation ratio:

$$\frac{\alpha_1 U_1^2}{2g} + d_1 + H_s = \frac{\alpha_2 U_2^2}{2g} + d_2 + h_f \quad (8)$$

$$\beta = \frac{h_f}{\frac{\alpha_1 U_1^2}{2g} + d_1 + H_s} \quad (9)$$

In the equation, U_1 and U_2 are the average flow velocity of the upstream and downstream sections, respectively; d_1 and d_2 are the water depths of the upstream and downstream sections; H_s is the step height, that is, the height difference of the bottom of the riverbed in the upstream and downstream sections; α_1 and α_2 are the kinetic energy correction coefficients of upstream and downstream; h_f is the head loss; g is the acceleration of gravity, β is energy dissipation ratio.

After calculation, the energy dissipation ratio of model 1 is the lowest, which is 74.98% while model 2 is the highest, which is 79.01%, model 3 and model 4 is between the two. It proves that the energy dissipation effect of the bucket style of riverbed structure is better than the other three models.

(a) Model 1 wide and narrow section Y = 0 profile

(b) Model 2 wide and narrow section Y = 0 profile

Figure 7. Distribution map of water surface profile

Figure 8. Distribution map of $Y=0$ profile Velocity vector of narrow section

Figure 9. Statistical Graph of the average flow velocity along the wide and narrow sections of different models

Figure 10. Pressure distribution at the bottom of the riverbed under different models

Figure 11. Comparison of energy dissipation ratios of different models

5 Conclusions

(1) Influenced by the structure of the riverbed, the flow field distribution of different riverbed structures are quite different. For the model of the simulated step-pool and bucket basin structure, the reflux is most obvious and the turbulence is more severe

(2) The variation amplitude of average velocity of the section of bucket basin and cluster riverbed structure is small. Combined with the pressure distribution at the bottom of the riverbed, the bucket basin riverbed structure and the ribbed riverbed structure are more regular, which illustrates that bucket basin riverbed structure is of great help to improve the stability of the riverbed. Through comprehensive comparison, the structure of the bucket basin riverbed is more conducive to inhibiting the current scour of the riverbed surface and protecting the riverbed.

(3) The effect of energy dissipation of the bucket basin riverbed structure is better than the other three types, which reduces the requirements of the

downstream energy dissipation facilities of the river channel, saving construction costs and improving efficiency.

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