Three-dimensional numerical simulation of water flow characteristics in wide and narrow rivers

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Abstract. In the mountainous area, due to the influence of the topography and the incoming water, it is easy to form a wide and narrow river channel. The water flow structure is different from the single river channel, and the change trend is related to the river channel section shape and flow. The three-dimensional numerical model is established by simulating the wide and narrow rivers in the mountainous area of Sichuan. The results show that the average cross-sectional velocity of the narrow section is positively correlated with the flow rate, but the variation is not obvious in the wide section; the shear stress of the bed surface is basically symmetrically distributed along the cross-sectional direction; the shear stress of the side wall of the narrow section is negatively correlated with the height of the side wall, and the maximum value appears on the water surface, due to the influence of the recirculation zone, the shear stress of the side wall increases firstly and then decreases with the shear height of the side wall; the shear stress of the side wall has a scouring effect on the river bank, which makes the narrow section of the river bed having a tendency to continuously cut down, and the wide section of the river bed is continuously widened.

1. Introduction
The topography of southwestern China is mainly mountainous. The canyon zone is formed by narrow geological processes. After a long riverbed succession, it is easy to form a wide and narrow river channel. It is of engineering significance to study its water flow characteristics for river regulation. Nguyen Thanh Hoan [1] used LDV to observe and analyze the flow velocity distribution of the river's gradually widening open channel and the related laws of water flow turbulence. Singha et al. [2] found that changes in the geometry of the river channel will change the distribution of turbulent energy in the water flow. Lucy et al. [3] had shown through a large number of investigations that the important factor affecting the evolution of riverbeds is the change of river width. Armellini et al. [4] studied and analyzed that the bank shape is also an important factor affecting the structure of the separation zone of the river flow. Yan Xufeng et al. [5] proposed a significant influence on the water flow structure through the tank model test, and analyzed the variation law of the local head loss coefficient along the Path based on SMS hydrodynamic numerical simulation. Zhou Sufen et al. [6] carried out numerical simulation of plane flow in wide and narrow rivers, and better simulated two-dimensional flow characteristics such as the influence of wide and narrow river channel width gradient on water depth and flow velocity. Wang Shuying et al [7] based on the indoor generalization experiment, tested and analyzed the characteristics of local water flow movement such as the divergent water level, the section circulation and the water flow separation area of the wide and narrow rivers; Miao Shuting et al. [8] established the three-dimensional flow calculation of the wide and narrow rivers in the
mountainous area. The model explores the characteristics of water flow structure such as average cross-section flow velocity and bed shear stress under different flow rates, and then derives the evolution law of the river channel.

In order to further understand the water flow characteristics of wide and narrow rivers, this paper based on the previous research and the generalized field model, further explores the water flow structure characteristics of the three-dimensional numerical simulation of wide and narrow rivers, and provides theoretical support for the wide and narrow river channel engineering.

2. Model establishment

2.1. Model governing equation

Numerical experiments were carried out by using a Standard k-ε two-equation model and VOF method for tracing simulated free surface. The Standard k-ε model is a turbulence model governing equation for jointly solving the kinetic energy-k equation and the dissipation rate-ε equation to obtain the turbulent viscosity coefficient, which is discretized using the finite volume method. The dissociation of each Parameter adopt the first-order precision upwind precision format. The coupling of speed and pressure is processed using the SIMPLEC algorithm. The governing equations for the model are as follows:

Continuous equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}
\]

Momentum equation:

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

k equation:

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

ε equation:

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} [\left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j}] + C_\mu \frac{\varepsilon}{k} G - C_\rho \rho \varepsilon^3 \tag{4}
\]

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}
\]

\[
G = \mu \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \frac{\partial u_i}{\partial x_j} \tag{6}
\]

\[
\frac{\partial \alpha}{\partial t} + u_i \frac{\partial \alpha}{\partial x_i} = 0 \tag{7}
\]

In the above formula: P is the pressure term considering gravity; \( \rho \) and \( \mu \) are density and molecular viscosity coefficients respectively; \( \delta_k \) and \( \delta_\varepsilon \) are turbulent Prandtl numbers of k and ε, respectively, taking \( \delta_k = 1.0, \delta_\varepsilon = 1.3 \); \( C_{1\varepsilon} \) and \( C_{2\varepsilon} \) are the constants of the ε equation, taking \( C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92 \); \( C_\mu \) is the empirical constant in equation (5), taking \( C_\rho = 0.09 \), turbulent viscosity coefficient \( \mu_t \) from turbulent energy k and turbulent dissipation rate ε. It is also obtained according to equation (5); the turbulent energy generation term can be defined by equation (6); \( G \) is the turbulent energy generation term caused by the average velocity gradient; and equation (7) is the control differential equation of the
water volume fraction $\alpha_w$, and the solution is solved. Controlling the differential equation is to simulate the tracking of the water-air interface, $\mu_i$ and $\chi_i$ are the velocity component and the coordinate component, respectively, and $t$ represents time.

2.2 Model size and boundary conditions
The change of river width in the wide and narrow river sections will lead to different water flow structures and have a great influence on the stability of river courses and bank slopes [9]. The model is generalized according to the actual river channel of the Xihe River branch of Baoxing River (Fig. 1.). The total simulated river section is 290m. The maximum water depth is 4m, the narrowest is 16m, the widest is 56m, the wide section ($Y=110-230m$) is 16‰, and the narrow section ($Y=95-110m$) is 35‰. The trapezoidal cross section of the curved bottom. The model has six flow conditions, 30 m$^3$/s, 60 m$^3$/s, 90 m$^3$/s, 120 m$^3$/s, 150 m$^3$/s, 180 m$^3$/s.

![Fig. 1. Generalized model size](image)

Boundary condition setting: the bottom end of the water tank is set as the water flow inlet, the type is the speed inlet boundary; the upper part of the whole model is set as the air inlet, the type is the pressure inlet boundary; the outlet is set as the mixed outlet of the water flow and the atmosphere, and the type is the pressure outlet boundary; the side wall is a condition of no slipping solid wall surface.

3. Modeling results and analysis

3.1 The speed field of velocity
The typical cross-sectional velocity vector distribution of the wide and narrow phase channels is shown in Figure 2, which represents the effect of different flow rates on the vector velocity distribution of the wide section. It can be seen from Fig. 2. that the flow velocity is symmetrically distributed on both sides of $X=0$ under the six conditions, and the flow rate is positively correlated with the velocity.
The flow velocity at the outlet of narrow section from condition 1 to condition 6 is larger, and the maximum flow velocity is 1.85 m/s, 2.00 m/s, 2.50 m/s, 2.75 m/s, 3.10 m/s and 3.50 m/s respectively. In condition 2, there is no recirculation zone. In the case y = 120-160m, there is only 15m wide flow in the center of the river channel, and the average flow velocity in the narrow and wide sections is 1.69 m/s and 1.45 m/s respectively. In condition 3, the flow velocity in the center of the river channel is widened to 20m, and the average flow velocity in the narrow section is 1.85 m/s, and that in the wide section is 1.29 m/s. In condition 5, the average flow velocity is 1.33 m/s, and the flow range in the river channel is wider. In this case, there is a recirculation zone (in the figure). It is mainly concentrated in the area enclosed by x = ±(15-30m) and y = 170-200m, accounting for about 1/4 of the whole wide section area; under the condition 6, there are two reflow zone, the average flow rate is about 0.11 m/s, and the range of it is respectively enclosed by x = ±(8-30m) and y = 140-165m, enclosed by x = ±(8-30m) and y = 165-210m, and the area of recirculation zone accounts for about 1/3 of the whole wide section area.

### 3.2 shear stress of river bed

The bed shear stress distribution of narrow section (y = 102m) and wide section (y = 126m, y = 170m, y = 214m) of wide and narrow inter channel is shown in Figure. 3. It can be seen from figure (a) that the bed shear stress has little change in the middle section of x = ±6m, and the bed shear stress at both ends suddenly increases or decreases. The maximum bed shear stress from condition 1 to condition 5 is 22.52Pa, 25.96Pa, 29.61Pa, 31.63Pa, 32.76Pa and 34.86Pa in turn. From figure (b), it can be seen that the bed shear stress of y = 126m in the wide section is positively related to the flow rate, and its value is from condition 1 to condition 6, they are 35.04Pa, 42.00Pa, 48.36Pa, 51.39Pa, 53.52Pa, 56.51Pa. The shear stress of wide section y = 126m is larger than that of wide section y = 214m. The maximum values of the two are 56.51Pa and 17.08Pa in turn. Both of them increase with the increase of flow, and the shear stress on the bed surface increases. In figure (c), the reflow area appears with wide section y = 170m and y = 214m, and the shear stress on the bed surface in the reflow area is about 5.0Pa. The shear stress in condition 5 and 6 appears inflection point at x = ±18m, and the shear stress on the bed surface changes rapidly within X = ±18m. The distribution of shear stress on the first and second conditions is first increasing and then decreasing, which is similar to the wide section y = 214m. The distribution trend of bed shear stress in the section with width y = 214m and y = 170m is similar, which is "large in the middle and small at both ends". Different from the distribution of bed shear stress in the section with width y = 126m, the shear stress corresponding to most areas within X = ±15m has a stable value. The wide section y = 126m and y = 214m are symmetrical with respect to the upstream and downstream of the widest section y = 170m. The reason for the inconsistency of the change of the shear stress on the two beds is that the gradually shrinking section has backwater area and the shear stress is generally small.
3.3 shear stress of the side wall

Figure 4. below shows the wall shear stress of four typical sections under different conditions. In figure (a), the shear stress of the six side wall decreases in a straight line along the height of the side wall from condition 3 to condition 6; it can be seen that the smaller the flow rate is, the smaller the change range of the shear stress of the side wall is. From condition 1 to 6, the maximum shear stress of the side wall with y = 103m section is 10.95Pa, 11.65Pa, 12.52Pa, 13.08Pa, 14.23Pa and 14.91Pa. Because the velocity gradient of the narrow section is positively related to the shear stress, the shear stress of the narrow section changes linearly with the height of the side wall. In the gradual expansion section y = 150m, as there is no return flow in condition 3, the shear stress on the side wall is still positively related to the height, but the shear stress on the side wall in condition 4, 5 and 6 turns with the height, and the positions of the turning points are 0.56m, 0.56m and 1.24m respectively. It can be seen from the figure that the turning point in condition 6 is closer to the water surface, with the size of 5.78Pa; in the wide section y = 170m, the four conditions are all out, Now, the inflection point is located at the height of 0.60m, 0.60m, 1.20m and 1.16m respectively, and the corresponding shear stress is 4.58Pa, 3.84Pa, 5.04Pa and 1.85Pa. The maximum height of the shear stress of the side wall under the four conditions starts to move up from the bed surface, and the average shear stress of the side wall in this section is smaller than that of other sections; under the four conditions, at the gradient section y = 214m, the shear stress changes basically with the height of the side wall first. The turning point appears at the height of 1.12m, 1.20m, 1.72m and 1.76m, and the corresponding shear stress values are 4.79Pa, 5.81Pa, 4.32Pa and 5.31Pa.
4. Conclusion

(1) The larger the flow rate, the larger the difference between the flow velocity values of the wide section and the narrow section. The average cross-sectional velocity of the narrow section is positively correlated with the flow rate, but the variation is not obvious in the wide section.

(2) The shear stress of the bed surface is basically symmetrically distributed along the cross-sectional direction. The tapered section appears to be drowning, and the shear stress of the bed surface is ‘saddle’. The distribution of the shear stress of the bed section and the tapered section is different; as the range of the drowning water expands, the maximum bed shear stress value increases accordingly.

(3) The shear stress of the side wall of the narrow section is negatively correlated with the height of the side wall, and the maximum value appears on the water surface; due to the influence of the recirculation zone, the shear stress of the side wall increases first and then decreases with the shear height of the side wall; the shear stress of the side wall has a scouring effect on the river bank, which makes the narrow section of the river bed have a tendency to continuously cut down and the wide section of the river bed is continuously widened.

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