Study on the hydraulic characteristics of the gradually expanding and gradually contracting watercourse with different width-narrow ratios

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Abstract. The characteristics of the water flow in the gradually expanding and gradually contracting watercourse are very complicated, and the width-to-narrowness ratio has a significant influence on the hydraulic characteristics of the gradually expanding and gradually contracting watercourse. Five three-dimensional hydraulic calculation models with different width-to-narrowness ratios were established to study its hydraulic characteristics. The results show that: (1) river flow gradually appears as the recirculation zone with the increase of the width-to-narrowness ratio. The recirculation zone increases gradually with the increase of the width-to-narrowness ratio and the shapes are different. The flow velocity in the recirculation zone is negatively correlated with the width-to-narrowness ratio. (2) When the width-to-narrowness ratio is small, the shearing force distribution of gradually expanding and gradually contracting sections are basically in “Hump-shape” along the Y-axis; When the width-to-narrowness ratio is large, the section basically shows a trend of “parabola-like” change that increases first and then decreases near the shore, and the average shearing force of the expanding section is larger than that of the contracting section. (3) As the width-to-narrowness ratio of the watercourse increases, the shearing force at the widest part of the river section gradually decreases, and the shearing force of the side wall at the contracting section is larger than that of the expanding section.

1. Introduction
The topography of southwestern China is mainly mountainous. Narrow channels formed by geological processes in the canyon area, and after a long riverbed succession, it is easy to form a wide and narrow watercourse. It is of engineering significance to study its water flow characteristics for river regulation. Nguyen Thanh Hoan [1] used LDV method to observe and analyze the flow velocity distribution of the river’s gradually expanding 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. Through a large number of investigations, Lucy et al. [3] have shown 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. Wu Huali et al. [5] introduced in detail the research results of the characteristics of water and sediment movement in wide and narrow rivers at home and abroad, which pointed out that in the river wide variation, the flow velocity distribution, turbulence structure, resistance characteristics and scouring and silting characteristics mechanism of river flow can be considered in the future research. Zhou Sufen et al. [6] carried out numerical simulation of plane flow in wide and narrow rivers, and simulated two-dimensional flow characteristics such as the width gradient influence of wide and narrow channel on water depth and flow velocity. Wang Shuying et al [7] based on the indoor generalization experiment, tested and analyzed the characteristics of partial water flow movement such as the water level of gradually expanding and gradually contracting watercourse, the section circulation, and the water flow separation area. In recent years, many scholars started from numerical simulations on different watercourses, analyzed and studied the characteristics of the water flow. Ma Fuxi et al. [8] used the VOF method to track the free surface, and used the modified k-ε model to solve the Reynolds equation and performed a three-dimensional numerical simulation of the water flow with irregular boundaries, which proved that it can simulate complex water flow phenomena well.; Yan Xufeng et al [9] proposed a significant influence on the water flow structure and the variation law of the local head loss coefficient along the path was analyzed based on the SMS hydrodynamic numerical simulation. Zhang Guangbi et al. [10] used the VOF method to track the simulated free surface to conduct numerical simulation of the velocity field before and after the construction of the embankment within a range of 2500m on the upper and lower reaches of the embankment, which provided technical support for design and decision-making. Miao Shuting et al [11] established a three-dimensional water flow calculation model for wide and narrow rivers in mountainous areas, and explored the characteristics of water flow structure such as average cross-section flow velocity and bed shearing force under different flow rates, and then derived the evolution law of river channels.

In order to obtain a deeper understanding of the water flow characteristics of the expanding and contracting watercourses under different width-to-narrowness ratios, based on the previous studies, this paper uses the three-dimensional numerical model of the gradually expanding and gradually contracting water courses to explore the water flow structure characteristics, and provides a theory support for flood control projects of wide and narrow rivers during the mega-flood period.

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:

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

Momentum equation:

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

k equation:

$$\frac{\partial (\rho u_i k)}{\partial t} + \frac{\partial (\rho u_i u_j k)}{\partial x_j} = \frac{\partial}{\partial x_i} \left[ \mu + \frac{\mu_t}{\sigma_s} \frac{\partial k}{\partial x_i} \right] + G + \rho \varepsilon$$
\[ \epsilon \text{ equation:} \]
\[ \frac{\partial (\rho \epsilon)}{\partial t} + \frac{\partial (\rho u_i \epsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_{\epsilon}} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\rho \epsilon^2}{k} - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \]
\[ (4) \]
\[ \mu_t = \frac{\rho C_{\mu} \kappa^2}{\epsilon} \]
\[ (5) \]
\[ G = \mu \left[ \frac{\partial u_j}{\partial x_j} + \frac{\partial u_j}{\partial x_j} \right] \frac{\epsilon_{ij} \epsilon_{ij}}{\epsilon} \]
\[ (6) \]
\[ \frac{\partial \alpha_w}{\partial t} + u_i \frac{\partial \alpha_w}{\partial x_i} = 0 \]
\[ (7) \]

In the above formula: \( P \) is the pressure term considering gravity; \( \rho \) and \( \mu \) are density and molecular viscosity coefficients respectively; \( \delta_\kappa \) and \( \delta_\epsilon \) are turbulent Prandtl numbers of \( k \) and \( \epsilon \), respectively, taking \( \delta_\kappa = 1.0, \delta_\epsilon = 1.3 \); \( C_{1\epsilon} \) and \( C_{2\epsilon} \) are the constants of the \( \epsilon \) equation, taking \( C_{1\epsilon} = 1.44, C_{2\epsilon} = 1.92 \); \( C_{\mu} \) is the empirical constant in equation (5), taking \( C_{\mu} = 0.09 \), turbulent viscosity coefficient \( \mu_t \) from turbulent energy \( k \) and turbulent dissipation rate \( \epsilon \). 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 different width-to-narrowness ratios of the gradually expanding and decreasing watercourse sections will lead to different water flow structures and have a great influence on the stability of watercourses and bank slopes [12-13]. In order to better study the water flow characteristics of the gradually expanding and gradually contracting watercourses under different width-to-narrowness ratios, the experimental study model of the gradual expansion and contraction of river flow characteristics in Sichuan Key Laboratory [7] was simulated, as shown in Figure 1. The model simulates a river with a total length of 225m, a slope of 10‰ and a height of 6m. The distance between the two narrowest sections is 40m, and the narrowest section is 10m. The working condition is the widest part of the working condition. It is 20m, 30m, 40m, 50m, 60m, and the side line is a sinusoid of \( Y = \pm (B \sin 0.15708x + 0.5) \). The value of working condition 5 to B is 5, 10, 15, 20, 25 in order. The control flow rate of the model is 120m³/s, and the width-to-narrowness ratio of working condition 1 to working condition 5 is 2:1, 3:1, 4:1, 5:1, 6:1, and there are 5 typical cross sections in the middle. (The figure is indicated by a broken line and is numbered 1-9 from upstream to downstream), and the water flow direction is as shown in Fig. 1.

![Figure 1 Typical section and dimensions of the model](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 outlet is set as the mixed outlet of the water flow and the atmosphere, the type is the pressure outlet boundary; the side wall is the condition of no slip solid wall surface; the upper part of the model is set as atmospheric imports, the type is the pressure import boundary.
3. Modeling results and analysis

3.1 Water level changes along the river

The variation of the water level change of this gradually expanding and gradually contracting watercourse is shown in Figure 2. The variation of the water surface line under the five working conditions is basically gradually increasing to the gradually decreasing water level, and the water level is falling near the narrowest section. The downstream is from the rapid flow to the slow flow, and the narrow section and the widest section are formed. The water level between the two is quite different. The water surface line of the upstream divergent section X=-36m to X=-20m is relatively smooth. The water level is increased along the downstream tapered section X=-20m to X=-6m, and the water level is about 3.70m. In the tapered section X = -6 m, the minimum value of 2.49 m appears near the narrow section X = 2 m. In the section X=-6m, the water falls from the slow flow to the rapid flow, and the water surface line is reduced to the lowest at the section X=2m, which is about 2.66m; the flow state of the downstream transition section is slow flow, and a hydraulic jump occurs from section X=2m to section X=6m.

![Figure 2 Water level distribution along the watercourse](image)

3.2 Average flow rate of different sections

Different width-to-narrowness ratios have a great influence on the average flow velocity of the divergent and tapered sections. The average flow velocity of the sections under the five conditions shown in Figure 3 is distributed along the path. With the increase of the width-to-narrowness ratio of the watercourse, the average flow velocity of each section is gradually reduced, and the average section velocity of the gradient section is more susceptible to the aspect ratio than the widest section. The average flow velocity of the narrowest section X=0 is about 1.86m/s, and the average flow velocity of the section is larger than that of the transition section. The average flow velocity of the channel under this condition is the same as the average flow velocity of the same section. The maximum cross-sectional average flow rate is about 32%, and the average flow velocity of the section from the working condition 2 to the working condition 5 is 53%, 64%, 74%, and 75%, respectively. It can be seen that as the width-narrow ratio increases. The average flow velocity of the section changes gradually. The working conditions are as follows: the five-segment expansion section x=-30m average flow rate is 1.72m/s, 1.14m/s, 0.98m/s, 0.82m/s, 0.63m/s, tapered section x=-10m The average flow rate is 1.55m/s, 1.06m/s, 0.96m/s, 0.85m/s, and 0.81m/s. It can be seen from the data that the working condition 1, 2, and 3 are due to the tapered section X=-10m. The action of muddy water hinders the movement of water flow, which causes the average flow velocity of the section to decrease. The average flow velocity of the tapered section is smaller than that of the gradually expanding section. Under the working condition 4and 5, the slope of the tapered section X=-10m is larger, resulting in the flow velocity. The flow rate is larger than that of the diverging section, that is, there is a special channel width between working condition 3 and 4, which determines the relative size of the average section flow velocity of the diverging section and the tapered section.
3.3 Typical watercourse speed field

The flow velocity vector of different working conditions in the transition section is shown in Figure 4 (the solid line represents the flow line of the recirculation zone). It can be seen from the figure that the larger the width-to-narrowness ratio, the smaller the flow rate variation of the narrowest section, and the recirculation zone. The larger the range. The width of the widest part is 20m, and the flow velocity distribution of the wide section and the narrow section is relatively uniform. According to the streamline, it can be seen that the streamline near the widest point is straight and there is no reflow; as the width-to-narrowness ratio increases, the reflow gradually occurs. The working area 2 to the working condition 5 recirculation area accounted for 36%, 50%, 56%, and 63% of the water surface of the typical river section. As the width ratio increases, the range of the recirculation zone also increases. The shape of the recirculation zone is different; the condition of the recirculation zone has obvious reflow, and the shape of the recirculation zone of the upstream wide section is elliptical. The condition of the recirculation zone of the upper section of the working condition 2 to the working condition 5 recirculation zone shape like a sharp triangular, and the sharp portion appears at the end of the tapered section.

Figure 3 Flow velocity distribution along the central axis of the section

Figure 4 Flow rate near the surface of a typical river section under different conditions

Under the same flow rate, as the width-to-narrowness ratio increases, the average flow velocity variation in the narrow section of the channel is small, and the average flow velocity in the
recirculation zone decreases relatively slowly; when the width-to-narrowness ratio of the channel is 2:1, there is basically no recirculation zone. As the width-to-narrowness ratio increases, the recirculation zone gradually appears. The range of the recirculation zone gradually increases as the aspect ratio increases, and the shape of the recirculation zone changes continuously with the shape of the side wall.

3.4 Shearing force of river bed

The shearing force of the bed surface under typical working conditions is shown in Fig. 5. When the width and width are relatively small, the shearing force distribution of the progressively expanding and tapered section is basically "hump-like" along the Y-axis; when the width-to-narrowness ratio is large, the section is basically It shows the trend of "parabola" which decreases first and then decreases near the shore, and has a "hump" shape in the middle, and changes sharply near the 1/4 or 3/4 position near the water bank. Under the working condition, the shearing force of the bed with the widest section X=-20m presents a "hump-like" distribution. As the width-to-narrowness ratio increases, the bed shearing force of the widest section presents a "parabolic" distribution near the shore. The maximum shearing force of the bed surface from the working condition 1 to the working condition five section X=0 is 20.02Pa, 18.84Pa, 19.15Pa, 18.41Pa and 18.80Pa, which is less affected by the change of the width-to-narrowness ratio. The average bed shearing force of the divergent section X=10m and the tapered section X=-10m of the working condition 1 to the working condition 5 are 9.60 Pa and 7.30 Pa, respectively, and the water level of the tapered section is larger than the divergent section due to the hydrophobicity. The shearing force of the bed surface of the dilating section of the working condition 1 to the working condition 5 X=10 m is larger than that of the tapered section X=-10 m.

3.5 Shearing force of the side wall

Figure 6 as the shearing force distribution of the side wall of each section of the transition section under typical working conditions. The shearing force of the side wall changes with height: the shearing force of the side wall decreases with the increase of height at the near water surface. Small, basically showing a vertical trend distribution. When the width-to-narrowness ratio is 2:1, the shearing force distribution of the edge of the gradient section is concentrated, and the minimum is 3.69Pa and the maximum is 9.96Pa. When the width-to-narrowness ratio is 3:1, the shearing force of the side wall of the narrowest section X=0 reaches the maximum at the bottom of the channel, which is about 13.47Pa, while the maximum value of the shearing force of the side wall of the section is generally located under other conditions. 83% water depth. The average shear force of the divergent section X=10m and the tapered section X=10m is 7.31Pa and 4.32Pa, respectively. The trend of the two changes is the same: first increase with height and slowly increase, near the water surface The height is increased and decreased, and the shearing force of the side wall of the diverging section is greater than the shearing force of the side wall of the tapered section. As the width-to-narrowness ratio
increases, the shear strength of the side wall of the tapered section $X=-10m$ increases with respect to the width and width, and the width of the diverging section $X=10m$ and the shear wall of the widest section decreases relative to the hour.

(a) Condition 1
(b) Condition 4

Figure 6 Sidewall shearing force under typical conditions

The distribution of the average side wall shearing force of a typical section under different operating conditions can be seen from Figure 7. With the increase of the width-to-narrowness ratio, the average side wall shearing force of the widest section of the channel $X=-20m$ and $X=20m$ gradually decreases with the increase of the width-to-narrowness ratio of the channel, and the average side wall of the two sections under the working condition The shearing force is the largest, 7.47Pa and 7.65Pa respectively; the average side wall shearing force of section $X=0$, $X=-10m$, and $X=10m$ shows a decreasing trend when the aspect ratio is less than 3:1, and the aspect ratio is from The average side wall shearing force increases gradually from 3:1 to 4:1. When the width to width ratio is 4:1, the average side wall shearing force changes substantially. Under normal conditions, the average side wall shearing force of each section is small, the average side wall shearing force of the widest section $X=0$ is 10.16Pa, and the average side wall shear of the widest section $X=-20$ and $X=20m$. The shearing force is greater than the gradient section $X=-10m$ and $X=10m$. The main reason is that the recirculation zone has an effect on the flow velocity of the water flow, and the flow gradient of the gradient section is smaller.

![Graph showing the distribution of average side wall shearing force under different working conditions](image)

Figure 7 Average side wall shearing force under five working conditions

4. Conclusion

(1) Under the same flow rate, as the width-to-narrowness ratio increases, the flow velocity of the whole watercourse gradually decreases. With the increase of the width-narrow ratio, the recirculation zone gradually appears on the widest part of the river channel, and the shape of the recirculation zone increases with the width-narrow ratio. The gradual change gradually, the cross-sectional flow velocity in the recirculation zone is negatively correlated with the width-to-narrowness ratio.

(2) When the width-to-narrowness ratio is small, the shearing force distribution of gradually expanding and gradually contracting sections are basically in “Hump-shape” along the Y-axis; When the width-to-narrowness ratio is large, the section basically shows a trend of "parabola-like" change that increases first and then decreases near the shore. The maximum shearing force of the bed surface
appears in the narrowest section, the minimum value appears in the gradually contracting section, and the river bed surface shearing force of the expanding section of the river section is larger than that of the contracting section.

(3) As the width-to-narrowness ratio of the watercourse increases gradually, the shearing force of the side wall at the widest part of the river section gradually decreases; the shearing force of the side wall of the gradually expanding and gradually contracting section and its changing trend are basically the same, and the side wall shearing force of expanding section is greater than the contracting section.

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