Numerical simulation study on hydraulic behavior at the confluence of Yangtze River and Jialing River

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Abstract

The confluence phenomenon is fairly common in the natural river. The research on the complicated and distinctive hydraulic behavior of confluence is of great practical and theoretic significance. The finite element model of Yangtze River and Jialing River is established based on two-dimensional depth-averaged surface-water flow and the hydraulic behavior at the confluence is investigated. The analysis shows that discharge ratio of mainstream to its confluent tributary is a crucial factor which dominates location of junction point, junction line and width of backflow zone near the lower reaches of confluence, the bigger is discharge ratio, the closer junction point is to shazui at Chaotianmen, the nearer junction line is on the side of Jialing River, and the smaller of width of backflow is. The water surface slope of the upper confluence depends on water level lifting up each other, when discharge ratio minish, the water surface slope of Yangtze River decreases, while the gradient of Jialing River increases. The water surface slope in the flow mixing region is direct proportional to Yangtze River’s discharge and negative correlation to the discharge ratio.

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Selection and/or peer-review under responsibility of Society for Resources, Environment and Engineering

Keywords: Confluence, Discharge ratio, Hydraulic behavior, Numerical simulation;

Nomenclature

- \( q_1 \), \( q_2 \): respectively unit flow rate in the x, y direction
- \( H \): water depth
- \( z_b \): bed elevation

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1. Introduction

The confluence phenomenon is fairly common in the natural river[1-2]. In the confluence regions, two mutual mixing streams lead to unique hydraulic behavior such as flow field changing, spiral flow, convex water surface, local flow stagnation, and so on. In the confluence region the flows mutual mix so violently as to lose energy very greatly, so the original equilibrium state of mainstream and tributary is broken, which weaken highly sediments and pollutants transport, impact water ecological environment and seriously reduce river flood discharge capacity. Therefore the confluence problem has been a focus of attention of water conservancy, shipping, flood control and environmental protection department.

Since Taylor firstly put up with the confluence problem of rectangle open channel in 1944, the hydraulic behavior at the confluence is already studied detailed based on theoretical analysis and sketch model experiment at home and abroad[3~5], but the study on hydraulic behavior of natural river confluence is not sufficient. The confluence of Yangtze River and Jialing River is the aquatic gate of two river shipping in Changing, where the flow is so complicated and varied as to seriously endanger shipping safety. The hydraulic behavior of the confluence of Yangtze River and Jialing River is researched in detail by numerical simulation in this paper.

2. Mathematical model

2.1. Governing equation

Governing equation of two-dimensional depth-averaged surface-water flow is as fellows. Continuity equation of flow:

$$\frac{\partial z_w}{\partial t} + \frac{\partial q_1}{\partial x} + \frac{\partial q_2}{\partial y} = 0$$  \hspace{1cm} (1)
X-Momentum equation:

\[
\frac{\partial q_1}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_1^2}{H} + \frac{1}{2} gH^2 \right) + \frac{\partial}{\partial y} \left( q_1 q_2 \right) + gH \frac{\partial z_h}{\partial x} + H \frac{\partial p_a}{\partial x} - \Omega q_2 \\
+ \frac{1}{\rho} \left[ \tau_{hx} - \tau_{sx} - \frac{\partial (H \tau_{sx})}{\partial x} - \frac{\partial (H \tau_{sy})}{\partial y} \right] = 0
\]  

(2)

Y-Momentum equation:

\[
\frac{\partial q_2}{\partial t} + \frac{\partial}{\partial y} \left( \frac{q_1^2}{H} + \frac{1}{2} gH^2 \right) + \frac{\partial}{\partial x} \left( q_1 q_2 \right) + gH \frac{\partial z_h}{\partial y} + H \frac{\partial p_a}{\partial y} + \Omega q_1 \\
+ \frac{1}{\rho} \left[ \tau_{hy} - \tau_{sy} - \frac{\partial (H \tau_{sy})}{\partial x} - \frac{\partial (H \tau_{sy})}{\partial y} \right] = 0
\]  

(3)

Time term discretization applies difference method, finite element discretization of Convection-Diffusion is deduced by means of the Galerkin weighted residual method, nonlinear algebraic equations are solved by Newton-Raphson method.

2.2. Simulation range and calibration

Allow for the influence area of water level lifting up each other, the whole simulation range includes (see figure 1) that Jialing River is from junction point to Hualong bridge, 9.33km length, Yangtze River is from junction point to Jiulongpo, 9.93km length, the downstream is from junction point to Cuntan, 6.74km length. Using six-noded triangle isoparametric element, the Computational domain is meshed for 25661 elements and 52676 nodes (see figure 2).

Fig.1 The river regime of Yangtze river and Jialing river
Adjusting roughness coefficient and turbulent diffusion in different partition make model similar to prototype, the velocity calibration shows the calculated results are good agreement with the measured data.

3. Analysis of Hydraulic Behavior of the Confluence

3.1. Discharge ratio frequency distribution

The discharge discrepancy between the mainstream and the tributary is a key factor that affects hydraulic behavior of the confluence. The discharge ratio of mainstream to its confluent tributary can describe the discrepancy, which is defined as ratio of mainstream discharge to tributary discharge, namely
\[ R = \frac{Q_i}{Q_j} \]. Figure 4 displays frequency distribution of the discharge ratio under different discharge which is counted based on the every day average flow statistics data of Yangtze River and Jialing River, it is thus clear that the discharge ratio is generally within 1–10, that the smaller the total discharge is, the larger the discharge ratio distribution range is, the bigger \( R_p \) corresponding the highest frequency is, when the total discharge is bigger, the conclusion is opposite, that is the flood peak phase of Yangtze River and Jialing River is in substantial agreement[6].

![Fig.4 R’s frequency distribution under different total discharge](image)

### 3.2. Analysis of water surface slope

**Calculation programme** The calculating programme(see table 1) is drawed up according to figure 4, which includes seven stage discharges and each stage discharge consists of the maximum discharge ratio \( R_{\max} \), the minimum discharge ratio \( R_{\min} \) and the discharge ratio of peak frequency \( R_p \).

<table>
<thead>
<tr>
<th>Item</th>
<th>( R_{\max} )</th>
<th>( R_{\min} )</th>
<th>( R_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_i )</td>
<td>( 5000 \text{ m}^3/\text{s} )</td>
<td>( 7500 \text{ m}^3/\text{s} )</td>
<td>( 15000 \text{ m}^3/\text{s} )</td>
</tr>
<tr>
<td>( R_{\max} )</td>
<td>24.0</td>
<td>11.1</td>
<td>9.0</td>
</tr>
<tr>
<td>( R_{\min} )</td>
<td>1.1</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>( R_p )</td>
<td>5.1</td>
<td>4.9</td>
<td>4.0</td>
</tr>
</tbody>
</table>

### Analysis of water surface slope in upper reach of confluence

Figure 5 shows that the water surface slope in upper reach of Yangtze River and Jialing River confluence is dominated by discharge ratio \( R \) and no obvious relation to discharge respectively. With the discharge ratio \( R \) increasing, the water surface slope of Yangtze River \( J_c \) increases, but that of Jialing River \( J_j \) decreases. Its reason is that the water surface must keep continuity, when the discharge ratio \( R \) is small, the discharge of Jialing River is rather large, so that the high water level of Jialing River lifts up the water level of Yangtze River to pull down \( J_c \) and increase \( J_j \). On the other hand, when \( R \) is big, the water level of Yangtze River lift up that of Jialing River.
River. So water level of mainstream or tributary is not only the function of its own flow, but also close correlation to the discharge ratio $R$.

![Fig.5 the relation between $J_c$, $J_j$ and $R$](image1)

![Fig.6 the relation between $J_e$, $R$ and $Q_c$](image2)

**Analysis of water surface slope in mixing zone** In mixing zone geography varies greatly, flow turbulence is intensive and the energy loses largely, so that the water surface declines obviously. Calculated results (see figure 6) indicate the water surface slope of mixing zone $J_e$ is direct proportion to $Q_c$ and negative correlation to $R$.

### 3.3. Junction regime and width of backflow

Jialing River tributary joints with Yangtze River mainstream by approaching 90°, there generates backflow zone at Muguantu near downstream left bank of confluence. With the discharge ratio $R$ changing, the junction regime and width of backflow is varies accordingly. It is clear from figure 7 that the location of junction point and junction line is decided by the discharge ratio $R$ and Yangtze River’s discharge $Q_c$. The bigger is discharge ratio $R$, the closer the junction point is to shazui near Chaotianmen, the nearer junction line is on the side of Jialing River, and the smaller of width of backflow is.

![Fig.7 the junction shape of Yangtze river and Jialing river ($Q=60000m^3/s$)](image3)
4. Conclusions

The discharge ratio $R$ of mainstream to its confluent tributary is the most key factor that affects hydraulic behavior of the confluence. With the total discharge $Q_t$ increasing, the the discharge ratio distribution range narrow down, the discharge ratio of peak frequency enlarges $R_p$ and the discharge ratio $R$ diminish.

With the discharge ratio $R$ increasing, the water surface slope of Yangtze River $J_c$ increases, but that of Jialing River $J_j$ decreases. The water surface slope in mixing zone $J_e$ is direct proportion to $Q_c$ and negative correlation to $R$.

The bigger is discharge ratio $R$, the closer the junction point is to shazui near Chaotianmen, the nearer junction line is on the side of Jialing River, and the smaller of width of backflow is.

Acknowledgement

This work was partly supported by West Transport Construction Science Foundation of China (Grants no. 2008328881409).

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