ABSTRACT

The Liantuo is one of the most typical navigation-obstructing shoals between the Three Gorges Project (TGP) and the Gezhouba Project. It is a deep-water rapid. When the discharge from TGP is larger than 25000m$^3$/s, high velocity and turbulent flow are much more unsafely to navigating ships. So it is very necessary to improve navigation flow condition under large discharge. The normal physical model with the scale of 1:100 is built and validated. And the two remote-control self-propelled ship models are used to test ship navigating safety. By the series of tests under large discharge, flow characteristics are analyzed and navigation-obstructing reasons are obtained. Then ideas for channel regulation are proposed, including expanding the upper part, lifting the lower part, and making overall plan. The schemes of single engineering are tested and analyzed, such as underwater reef-blasting or filling deep pool. And comprehensive improvement schemes are proposed, tested, and optimized. The results show that, navigation condition with the proposed scheme has been improved obviously. The limited discharge of safety navigation has been improved above 5000m$^3$/s under different discharge. So the proposed regulation measures and comprehensive schemes are effective for the shoals with deep water and rapids.

Keywords: Deep-water rapids; navigation-obstructing characteristics; navigation regulation; physical model, self-propelled ship model

1 INTRODUCTION

The reach between the Three Gorges Project and the Gezhouba Project, is very important for navigation in the Yangtze River. The reach between the two dams has double flow characteristics of reservoir area and natural river. And river regime and riverbed morphology cause the special flow condition with deep water, steep slope of water level and high velocity under large discharge which is larger than 25000m$^3$/s.

There are some famous navigation-obstructing shoals with “four shoals and one bend”. Four shoals are Liantuo, Xitan, Dashaba and Piannao respectively, and one bend is Shipai. Liantuo is the most typical and dangerous shoal of them for ship navigation. It is a deep-water rapid and has complicated flow patterns. Under large discharge, the velocity is over 3.0m/s and even close to 5.0m/s, local slope of water level is over 7.5‰. There exist backflow, boil-vortex flow, and scissors-like flow. And boil-vortex flow is randomly variable in intensity and location. Backflow reduces efficient navigation width. Boil-vortex flow causes ships worse steerage. Scissors-like flow makes main flow concentrate. These navigation-obstructing flow characteristics are much more obvious with larger discharge. So it is very necessary to improve navigation condition of Liantuo Reach under large discharge.

There have some successful regulation experiences about rapid shoals of mountain rivers since the 1950s in China (Changjiang Waterway Bureau, 1998; 2004). Some achievements are relatively macroscopic (Yuan 2012, Chang 2010, Pan 2003), while a few results put forward the comprehensive regulation means of “dredging on the left and elevating on the right” (Chen 2010, Jia 2015), which is effective to shallow rapids and ineffective to deep-water rapids. The author has also conducted relevant researches on upstream Letian Reach and downstream Shipai Reach with the three-dimensional numerical simulation (Feng et al., 2008, 2010, 2013). However, the Liantuo Reach has a more complex flow structure than the others and the three-dimensional flow mathematical model can’t simulate them accurately. Therefore, fixed-bed physical model must be used to carry out this research.

2 CHANNEL CHARACTERISTICS

The reach takes on a micro-bend shape in the plane, as shown in Figure 1. From Dingtouzhen to the downstream, it is straight and contracting in upper cross section, while bent and broadening in lower cross section. The contracting rate of left bank is significantly greater than that of right bank. And it is broadening...
mainly in left bank. The talweg elevation variation is shown in Figure 2. It is relatively flat from Dingtouzhen to Liantuo, while drops sharply by about 32.9m from Liantuo to the center of deep pool, and then rises sharply about 47.0m. The left of deep pool is covered by the underwater rugged shoal, and the right is smoother. It is one of main reasons to have complicated flow patterns under large discharge.

Figure 1. Plane Map and Talweg Elevation of Liantuo Reach

3 MODEL BUILDING AND VALIDATION

3.1 Range and scale
The reach is about 9km long. It adopts the topographic map measured in March 2013 with a scale of 1:500. Based on river regime and topographic features, the normal fixed-bed physical model is chosen and its geometric scale is 1:100 to ensure the similarity in geometry and flow movement. According to the gravity similarity criterion and the similarity of ship models, different model scales are calculated as shown in Table 1. Based on these scales and topographic map, the built physical model is shown partially in Figure 2.

Table 1. Model Scales

<table>
<thead>
<tr>
<th>Physical model</th>
<th>Scale</th>
<th>self-propelled ship model</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric scale</td>
<td>$\lambda_L=\lambda_H=100$</td>
<td>Geometric scale</td>
<td>$\lambda_L=\lambda_H=100$</td>
</tr>
<tr>
<td>Flow velocity scale</td>
<td>$\lambda_v=10$</td>
<td>Draft scale</td>
<td>$\lambda_M=\lambda_L=100$</td>
</tr>
<tr>
<td>Flow scale</td>
<td>$\lambda_Q=100000$</td>
<td>Displacement scale</td>
<td>$\lambda_W=\lambda_Q=1000000$</td>
</tr>
<tr>
<td>Time scale</td>
<td>$\lambda_t=10$</td>
<td>Velocity scale</td>
<td>$\lambda_v=\lambda_L^{1/2}=10$</td>
</tr>
<tr>
<td>Roughness factor scale</td>
<td>$\lambda_n=2.15$</td>
<td>Time scale</td>
<td>$\lambda_t=\lambda_L^{1/2}=10$</td>
</tr>
</tbody>
</table>

Figure 2. Local Diagram of the Fixed-bed Physical Model

3.2 Model verification
The model is validated by water level, cross-section velocity distribution and flow track line under the four discharges of 25000m³/s, 30000m³/s, 35000m³/s, 40000m³/s.

The results of water level show that the largest deviation between tested and measured data is no greater than 0.05m under 25000m³/s, 30000m³/s; and 0.07m under 35000m³/s, 40000m³/s. They are also less than 0.10m. Then flow resistance is similar between the prototype and the model.

The results of velocity distribution show that, under all the discharges, the largest closing error in cross-section discharges is 2.23% which is less than 5%, as shown in Table 2. The tested velocity distribution of the model is also basically consistent with that of the prototype, and the velocity deviation is mostly no greater than 0.1m/s.
The results show that flow track lines are in consistency with those of the prototype in the distribution of main flow, the ranges of backflow, and secondary flows in Liantuo Reach. So the model is similar with the prototype in the distribution of flow pattern.

Table 2. Comparison of Prototype and Model Discharge

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Prototype discharge (m³/s)</th>
<th>Model discharge (m³/s)</th>
<th>Δ (%)</th>
<th>Cross section</th>
<th>Prototype discharge (m³/s)</th>
<th>Model discharge (m³/s)</th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST1</td>
<td>25000</td>
<td>24860</td>
<td>-0.56</td>
<td>XT1</td>
<td>25000</td>
<td>24753</td>
<td>-0.99</td>
</tr>
<tr>
<td>ST1</td>
<td>30000</td>
<td>30611</td>
<td>2.04</td>
<td>XT1</td>
<td>30000</td>
<td>30549</td>
<td>1.83</td>
</tr>
<tr>
<td>ST1</td>
<td>35000</td>
<td>34564</td>
<td>-1.25</td>
<td>XT1</td>
<td>35000</td>
<td>34733</td>
<td>-0.76</td>
</tr>
<tr>
<td>ST1</td>
<td>40000</td>
<td>40890</td>
<td>2.23</td>
<td></td>
<td>40000</td>
<td>40647</td>
<td>1.62</td>
</tr>
</tbody>
</table>

Figure 3. Flow Track Lines of Prototype and Model

3.3 Ship model verification

By analyzing navigation ships in the Yangtze River, 1500t dry bulk carrier and 300TEU container ship has been chosen as the tested ships. Based on their design drawings, the two remote-control self-propelled ships are produced and their similarities are calibrated with actual ships, including the opposite minimum ship speed to the banks, steering angle, drift angle, etc.

4 NAVIGATION-OBSTRUCTING CHARACTERISTICS AND REGULATION IDEA

4.1 Navigation-obstructing characteristics

It tests from 25000m³/s as the initial large discharge to 45000m³/s as prohibited discharge to ship navigation. As above mentioned, the flow is more turbulent under these discharges. At the entrance of the shoal, there has steep slope of water level and high velocities. In the middle, the two face-to-face backflows exist on both sides of main flow belt which have wide range and high intensity. The left backflow is about 1100m long and 250m wide, which is larger than that of the right about 780m long and 170m wide. The width of them accounts for 66% of the total river width. Then main flow belt is narrow and the velocities increase significantly. The velocity is above 3.0m/s under 30000m³/s and close to 5m/s under 45000m³/s. Clustered boil-vortex flow exists between backflow and main flow and forms navigation-obstructing flow belts. And turbulent flow varies randomly, as shown in Figure 3.

4.2 Regulation idea

By analyzing channel characteristics and flow variation, the navigation-obstructing reasons are analyzed. The width of river sudden-expansion and sudden-contract causes scissors-like flow and backflow. The sharp rises and falls of riverbed elevation make flow conversion between kinetic energy and potential energy which leads to boil-vortex flow. Most of cross sections present like "U" or "V" type and have deep water. Increasing rate of wetted cross-section area is less than that of the discharges. So the velocity is higher and flow pattern is more turbulent with larger discharge. Then ideas for channel regulation are proposed. They are expanding the upper part, lifting the lower part, and making overall plan, which can expand discharge sectional area, adjust velocity distribution and banish most factors that cause flow energy conversion.

5 REGULATION SCHEMES AND EFFECTS

5.1 Tentative tests of single engineering measure

Based on regulation idea, three tentative tests of single engineering measure in different zones have been carried out with the fixed-bed model, including filling deep pool, expanding the left bank by reef blasting, and expanding the right bank by reef blasting.

(1) Filling deep pools
The deep pools are filled to different elevations, respectively -5m, -10m. The test results show that the measure plays a limited role in the regulation of the "rapid" at the entrance, but are effectively on the "turbulent flow" in the middle. Excessive filling will reduce the wetted cross-section area, and increase the local velocity. So it is necessary to study the volume, position in more detail.

(2) Underwater reef blasting near the Shaijingping

Underwater reefs near the Shaijingping are blasted and cleaned to the elevation 25.0m and underwater slope 1:0.2 near the bank. It can be seen from the tests that backflow intensity on the left is significantly decreased and secondary flows are weakened. The boil flow intensity in the backflow on the left is decreased, but its density is still large. The main flow velocity in the deep pool is decreased, the variation slope of the velocity is reduced in cross-section, and turbulent flow is significantly restricted. So reef blasting near the Shaijingping is beneficial for the improvement of "turbulent flow" of the bend.

(3) Underwater reef blasting near the Shuitianjiao

Underwater reefs near the Shuitianjiao are blasted and cleaned to the elevation 30.0m and slope 1:0.2 near the bank. It can be seen from the tests that backflow range on the right is contracted slightly and the main flow belt width is slightly expanded, and the main flow at the entrance still inclines towards the right and the effect is poor on improving the upstream navigation conditions. The cross-section velocity distribution at the bend is also not improved, the main flow velocity of the downstream has a small change, and the effect is poor on restricting turbulent flow at the deep pool.

5.2 Comprehensive regulation schemes and effects
5.2.1 Scheme design

Comprehensive regulation measures integrate underwater reef blasting near the Shaijingping with filling deep pools. Based on multi-scheme tests and comparison, three comprehensive regulation schemes are formed. As an example, plane layout with scheme 30.0 is shown in Figure 4. The bottom elevation is respectively 35.0m, 30.0m and 25.0m in underwater reef blasting near the Shaijingping, and the underwater slope near the bank is 1:0.5, and the left of the deep pool is filled into a gentle slope. They are named respectively as scheme 35.0m, scheme 30.0m and scheme 25.0m.

![Figure 4 Schematic Diagram of Plane Layout (scheme 30.0m)](image)

5.2.2 Regulation effects
(1) Water level slope

They reduce the right slope respectively by 1.59‰, 2.13 ‰ and 2.33 ‰. Due to the smaller reef-blasting volume, the results of scheme 35.0m show that it is poor to reduce water level slope of the right. The improvement of scheme 30.0m is approximate to that of scheme 25.0m.

(2) Velocity along the ship upstream route

Upstream reach of the Shuzixi: The left is upstream route of the ships. Due to the relatively large reef-blasting volume in Shaijingping, the velocity increases compared with that before the engineering. For scheme 25.0m, the maximum increase of velocity is about 0.2m/s; and for scheme 30.0m and scheme 35.0m, they are about 0.1m/s.

Traverse zone: In this area, upstream route is from the right to the left and traverse the main flow. Due to reef blasting and flow suction effects on the left, the velocity slightly increased. Under the scheme 25.0m, 30.0m and 35.0m, the maximum velocity reduction in the right is about 0.5m/s, 0.6m/s and 0.2m/s respectively.

The reach between Shuitianjiao and Shizinao: The right is upstream route of the ships. Reduction area of high velocity emerges in the downstream of Shizinao and near the Shuitianjiao. For scheme 35.0m, the improvement from the scheme 35.0m is the lowest. And the maximum velocity reduction is about 0.3m/s near the downstream of Shizinao, and 0.1m/s at the Shuitianjiao, and 0.45m/s near the downstream of Shuitianjiao. The effect of velocity reduction is basically the same for scheme 25.0m and scheme 30.0m. And that of scheme 25.0m is slightly better.
(3) Velocity variation of downstream route

The velocity along the downstream route takes on a trend of decreasing, and the maximum reduction appears from Shuzixi to Shuitianjiao. For scheme 35.0m, 30.0m and 25.0m, average velocity reduction is respectively 0.09m/s, 0.21m/s, and 0.26m/s, and maximum velocity reduction is 0.19m/s, 0.33m/s and 0.36m/s respectively.

(4) Turbulent flow

Table 3 provides turbulent flow before and after the project. There has decreased backflow intensity and width, reduced intensity of secondary flow in obstructing navigation, and increased the width of main flow belt in different degree.

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Before the project</th>
<th>Scheme 35.0m</th>
<th>Scheme 30.0m</th>
<th>Scheme 25.0m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Backflow intensity (m/s)</td>
<td>1.47</td>
<td>1.35</td>
<td>1.3</td>
<td>1.14</td>
</tr>
<tr>
<td>2</td>
<td>Backflow width (m)</td>
<td>250</td>
<td>210</td>
<td>200</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>Intensity of secondary flow</td>
<td>Strong</td>
<td>Relatively weak</td>
<td>Weak</td>
<td>Weak</td>
</tr>
<tr>
<td>4</td>
<td>Main flow belt width</td>
<td>170</td>
<td>220</td>
<td>220</td>
<td>230</td>
</tr>
</tbody>
</table>

(5) Self-propelled ship movement

Before the regulation project, it is the most difficult for ascending rapids from Shuitianjiao to Shizinao. On the left, the ship has to go through the boundary between main flow and backflow, where flow pattern is more turbulent. With slack-water ship speed of 18km/h as an example, when the discharge is larger than 35000m³/s, it is difficult for the tested ships to go upstream and to control downstream, and navigation safety decreases significantly.

After the regulation project, when the discharge is larger than 40000m³/s, it is difficult the tested ships to go upstream and to control downstream. The discharge increases 5000m³/s for ship upstream, as shown in Table 4.

<table>
<thead>
<tr>
<th>Item</th>
<th>1500t</th>
<th>3000t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slack-water ship speed (km/h)</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Maximum discharge before the project (m³/s)</td>
<td>35000</td>
<td>30000</td>
</tr>
<tr>
<td>Maximum discharge after the project (m³/s)</td>
<td>40000</td>
<td>37500</td>
</tr>
<tr>
<td>Increased discharge(m³/s)</td>
<td>5000</td>
<td>7500</td>
</tr>
</tbody>
</table>

(6) Comprehensive comparison

All the three schemes have achieved some engineering effects. Scheme 30.0m and scheme 25.0m have performed obviously better than scheme 35.0m on velocity improvement. For velocity reduction on the upstream route, reef-blasting elevation of 35.0m-30.0m is significantly greater than that from reef-blasting elevation of 30.0m-25.0m. Although the regulation effect of scheme 25.0m is better than that of scheme 30.0m, but the improvement is not obvious, while reef-blasting volume of scheme 25.0m is significantly larger than that of scheme 30.0m. So scheme 30.0m of reef-blasting bottom elevation is recommended.
6 CONCLUSIONS

By analyzing channel characteristics and flow variation, navigation-obstructing reasons are obtained and regulation ideas are proposed. They are expanding the upper part and lifting the lower part, which can expand wetted cross-section area, adjust velocity distribution and banish most factors that cause flow energy conversion.

From the results from fixed-bed physical model, the single measures are tested and comprehensive scheme is recommended. It is effective obviously to improve the navigation flow condition for deep-water rapids by combining reef-blasting near the shaijingping with filling the left of deep pool. Then the discharge for safety navigation increases by more than 5000m³/s.

REFERENCES


