Equilibrium Sediment Transport and Evolution Trend Simulation of the Lower Yellow River

Shaolei GUO, Dongpo SUN, Xiuru WANG

1 College of Soil and Water Conservation, Beijing Forestry University, Beijing 10008, P. R. China
2 North China University of Water Resources and Electric Power, Henan Zhengzhou 450011, P. R. China

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Abstract: The non-equilibrium development of the scouring and silting evolution of the Lower Yellow River is caused by the different characteristics of river channel. On the basis of the water and sediment data of the Lower Yellow River between 1960 and 2008, statistic method was used to analyze the sediment transport of different discharges flow. The combination of $2500 \text{ m}^3/\text{s} < Q < 4000 \text{ m}^3/\text{s}$ and $20 \text{ kg/m}^3 < S < 60 \text{ kg/m}^3$ is considered a better combination for the Lower Yellow River. Combined with the model experiments data, the evolution trend of the Lower Yellow River channel in the later sediment-retaining period of Xiaolangdi Reservoir were analyzed, and the importance of the equilibrium development of the upper and lower reaches in the later sediment-retaining period of Xiaolangdi Reservoir was pointed out.

Keywords: Model test, Lower yellow river, Equilibrium sediment transport, Regulation value.

1. Introduction

In the Lower Yellow River, there are three types of river channels: wandering, transitional, bending. When the flow transmits in the Lower Yellow River (Fig.1), the scour and silting characteristic of the three reaches which are different because of the different characteristics of river channels often result in the disadvantageous phenomenon that upstream scour and downstream silting or upstream silting and downstream scour. The sediment transporting capacity of some reaches can not be fully which influence the effect of sediment transporting, and that is caused by the non-equilibrium development scour and silting evolution of the Lower Yellow River. Facing with increasingly scarce water resources, the channel of the Lower Yellow River can develop equilibrium at what water and sediment condition, and how can achieve this condition by joint operation of reservoirs. Those have great help to solve the problem of silting and flood control of the Lower Yellow River.

It is well-known that the water and sediment condition of the Lower Yellow River is complicated and variable. Many scholars have given different regulation values of the water and sediment condition from different aspects based on the condition of balance sediment transport [1-11]. However, it is difficult to achieve balance sediment transport because of the complicated relationship of sediment transport, scouring and silting, the rapid change of the boundary condition of the riverbed under the influence of the flow, the changeable river channel and water and sediment condition. Moreover, balance is relative in nature, unbalance is absolute. So Equilibrium sediment transport, an approximate balance sediment transport, is more feasible in the Lower Yellow River [12, 13]. In this condition the scouring and silting variation is not serious ($< 10\%$), and in a long period of time the sediment transport is balanced. Han proved it from theory [12].
In order to find the controllable relation between discharge and sediment in which condition equilibrium sediment transport could be achieved in the Lower Yellow River, statistic method would be used to analyze the different discharge and the sediment concentration of flow on the basis of water and sediment data of the Lower Yellow River between 1960 and 2008. Also the scouring and silting trend would be forecasted in the later sediment-retaining period of Xiaolangdi Reservoir on the basis of the Lower Yellow River physical model tests. All of these would provide theoretical support to equilibrium sediment transport of different reach in the Lower Yellow River.

2. Materials and Methods

2.1. Measured data and Methods

The Lower Yellow River measured data of Huayuankou hydrologic station, Jiahetan hydrologic station, Gaocun hydrologic station, Aishan hydrologic station and Lijin hydrologic station between 1960 and 2008 are used in this article. And all the data is in the condition that the discharge and sediment concentration have not large change (<20 %) in 3-5 days, no overflow, no hyper-concentrated flow and the average discharge of flow is more than 1000 m$^3$/s.

During the analysis, the Lower Yellow River is divided into four reach: Huayuankou–Jiahetan, Jiahetan–Gaocun, Gaocun–Aishan, Aishan–Lijin. Huayuankou–Jiahetan and Jiahetan–Gaocun are wandering reach. Gaocun–Aishan is transitional reach. Aishan–Lijin is bending reach. First the data of Huayuankou hydrologic station are selected. Then other hydrologic station’s data are selected on the basis of flow velocity. Transport rate method, which is based on the data of sediment transport rates, is used to calculate the sedimentation amount. Statistic method is used to analyze the different magnitude and the sediment concentration of flow of the Lower Yellow River.

2.2. Model Test

The model is built to study the fluvial process in the different use period of Xiaolangdi Reservoir. The main model scales are in Table 1. The model has been used during the beginning sediment-retaining period of Xiaolangdi Reservoir. Its reliability has been verified.

After the beginning sediment-retaining period of Xiaolangdi Reservoir, the reservoir is changed over to sediment-retaining period for the designed usage. In order to forecast the evolution trend of the Lower Yellow River channel in that period, the discharge and sediment process which is designed by the actual data of 1990-2008+1956-1960 is used in the model. And cross section method which is based on the cross section data is used to calculate the scouring and silting.

Table 1. The Main Model Scale.

<table>
<thead>
<tr>
<th>Scale name</th>
<th>Model Scale</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal scale $\lambda_h$</td>
<td>600</td>
<td>According to the site conditions and test requirement</td>
</tr>
<tr>
<td>Vertical scale $\lambda_v$</td>
<td>60</td>
<td>Meet the geometry deformation limit condition, etc.</td>
</tr>
<tr>
<td>Geometry deformation $D$</td>
<td>10</td>
<td>$D = \lambda_v / \lambda_u$</td>
</tr>
<tr>
<td>Velocity scale $\lambda_v$</td>
<td>7.75</td>
<td>$\lambda_v = \lambda_v^{1/3}$</td>
</tr>
<tr>
<td>Roughness scale $\lambda_s$</td>
<td>0.626</td>
<td>$\lambda_s = \lambda_v^{1/3} \lambda_u^{-1/3}$</td>
</tr>
<tr>
<td>Time scale of flow movement $\lambda_t$</td>
<td>77.5</td>
<td>$\lambda_t = \lambda_v / \lambda_u$</td>
</tr>
<tr>
<td>Sediment diffusion scale $\lambda_d$</td>
<td>1.38</td>
<td>$\lambda_d = \lambda_v (\lambda_v / \lambda_u)^{1/4}$</td>
</tr>
<tr>
<td>Grain-size scale $\lambda_d$</td>
<td>0.81</td>
<td>$\lambda_d = (\lambda_v / \lambda_u)^{1/3}$ Little adjustment with water temperature</td>
</tr>
<tr>
<td>Sediment concentration scale $\lambda_c$</td>
<td>1.8</td>
<td>$\lambda_c = \lambda_v$ and with the verification test($\lambda_c$ is suspended sediment)</td>
</tr>
<tr>
<td>Time scale of riverbed deformation $\lambda_r$</td>
<td>83</td>
<td>$\lambda_r = \lambda_v \lambda_u / (\lambda_v \lambda_u)$ and with the verification test</td>
</tr>
</tbody>
</table>
3. Results and Discussion

In order to analysis the scouring and silting law in channel with different discharge, channel scouring-silting rate of reach was introduced. Channel scouring-silting rate for the reach was the ratio of scouring and silting amount to incoming sediment amount.

The Figs. 2-5 was given after analyzing the relationship of channel scouring-silting rate and sediment concentration when the discharge was between 1000 m$^3$/s and 5000 m$^3$/s in the years 1960-2008. The correlation of channel scouring-silting rate and sediment concentration in the four reaches could be expressed in the formula 1-12.

3.1. The Discharge Between 1000m$^3$/s and 2000 m$^3$/s

\[
\frac{\Delta W_S}{W_S} = 37.72 \ln S - 115.53 
\]

\[
\frac{\Delta W_S}{W_S} = 40.73 \ln S - 122.4 
\]

\[
\frac{\Delta W_S}{W_S} = 46.86 \ln S - 130.51 
\]

\[
\frac{\Delta W_S}{W_S} = 68.28 \ln S - 186.2 
\]

Here $\Delta W_S$ is scouring or silting amount of the reach, $W_S$ is incoming sediment amount of the reach and $S$ is sediment concentration.

As shown in the Fig. 2, the channel scouring-silting rate of the four reaches increased with the increase of sediment concentration. The channel scouring-silting rate of Huayuankou–Gaocun was close to 0 when the sediment concentration of Huayuankou and Jiahetan was about 18 kg/m$^3$. The channel scouring-silting rate of Gaocun–Lijin was close to 0 when the sediment concentration of Gaocun and Aishan was about 15 kg/m$^3$.

3.2. The Discharge between 2000m$^3$/s and 3000 m$^3$/s

\[
\frac{\Delta W_S}{W_S} = 43.62 \ln S - 150.75 
\]

\[
\frac{\Delta W_S}{W_S} = 55.17 \ln S - 201.74 
\]

\[
\frac{\Delta W_S}{W_S} = 33.21 \ln S - 113.86 
\]

\[
\frac{\Delta W_S}{W_S} = 48.81 \ln S - 164.87 
\]

Fig. 2. The relation of Sediment Concentration and the channel scouring-silting rate in the lower Yellow River between 1000 m$^3$/s-2000 m$^3$/s.
According to the Fig. 3 presented, the channel scouring-silting rate of the four reaches increased with increase of sediment concentration. The channel scouring-silting rate of Huayuankou–Jiahetan was close to 0 when the sediment concentration of Huayuankou was about 30 kg/m$^3$. The channel scouring-silting rate of Jiahetan–Gaocun was close to 0 when the sediment concentration of Jiahetan was about 30 kg/m$^3$. The channel scouring-silting rate of Gaocun–Aishan was close to 0 when the sediment concentration of Gaocun was about 30 kg/m$^3$. The channel scouring-silting rate of Aishan–Lijin was close to 0 when the sediment concentration of Aishan was about 28 kg/m$^3$.

3.3. The discharge between 3000 m$^3$/s and 4000 m$^3$/s

\[ \Delta W_s/W_s = 29.31 \ln S - 118.77 \]  \hspace{1cm} (9)
\[ \Delta W_s/W_s = 32.25 \ln S - 120.43 \]  \hspace{1cm} (10)
\[ \Delta W_s/W_s = 37.82 \ln S - 144.97 \]  \hspace{1cm} (11)
\[ \Delta W_s/W_s = 26.86 \ln S - 108.28 \]  \hspace{1cm} (12)

According to the Fig. 4 presented, the channel scouring-silting rate of the four reaches increased with increase of sediment concentration. All the reaches were scouring except the larger sediment concentration.

3.4. The discharge between 4000 m$^3$/s and 5000 m$^3$/s

\[ \Delta W_s/W_s = 42.56 \ln S - 158.36 \]  \hspace{1cm} (13)
\[ \Delta W_s/W_s = 37.43 \ln S - 138.13 \]  \hspace{1cm} (14)
\[ \Delta W_s/W_s = 55.29 \ln S - 204.1 \]  \hspace{1cm} (15)
\[ \Delta W_s/W_s = 44.47 \ln S - 167.71 \]  \hspace{1cm} (16)

As could been seen in the Fig. 5, all the reaches were scouring when the discharge was more than 4000 m$^3$/s.
It could be seen from the Figs. 2-5 that when the combination of discharge and the sediment concentration was different, the scouring-silting of the four reaches has different. But when the combination of discharge and the sediment concentration changed in the range of 2000 m³/s < Q < 3000 m³/s and 20 kg/m³ < S < 60 kg/m³, the scouring-silting of the four reaches were close to 0 (<10 %).

Combining the cognition to the sediment carrying capacity and the actual discharge and the sediment concentration of the lower Yellow River, the combination of 2000 m³/s < Q < 3000 m³/s and 20 kg/m³ < S < 60 kg/m³ was considered a better combination for the Lower Yellow River equilibrium sediment transport in long period of time. It could be used as the control condition of Hayuankou. Considering the decrease of the flow when the flow flowed Hayuankou to Lijin, the control discharge could be 2500 m³/s < Q < 4000 m³/s. In this condition, the four reaches might be scouring or silting in a short period of time. According to the adjustment of the flow and channel in a long period of time, Equilibrium sediment transport could be achieved. Also single combination of discharge and the sediment concentration should be avoided when the Xiaolangdi Reservoir was used to regulate the discharge and the sediment concentration.

### 3.5. The Forecast of Scouring and Silting Trend in the Later Sediment-retaining Period of Xiaolangdi Reservoir

It could be seen from graph 6 that silting distribution increased generally from Tiexie to Taochengpu. That was because some river training works which decrease the wandering range of channel were built up between Tiexie and Huayuankou. And in the initial operation stage of Xiaolangdi Reservoir, the channel geometry of that reach became better and better. Overflow of that reach became less in the later sediment-retaining period of Xiaolangdi Reservoir and the main channel was scouring. Between Huayuankou and Jiahetan, river training works were also built up, overflow was not too much. The silting in that reach was not serious. Between Jiahetan and Taochengpu, the silting was very serious. As was shown in Fig. 6, the deposition amount increased sharply in that reach. That was because overflow was too much and there were three big floodplain areas. The sediment that carried by the overflow deposited in quantity on the floodplain area.

It could be seen from the analysis that the sediment transporting capacity of upstream and downstream in the Lower Yellow River had great difference. If the
quondam discharge and the sediment concentration were used in the later sediment-retaining period of Xiaolangdi Reservoir, silting is inevitable below Jiahetan. Equilibrium sediment transport could solve this problem if the combination of $2500 \text{ m}^3/\text{s} < Q < 4000 \text{ m}^3/\text{s}$ and $20 \text{ kg/m}^3 < S < 60 \text{ kg/m}^3$ was used.

![Fig. 5. The relation of Sediment Concentration and the channel rate of silting in the lower Yellow River between 4000 m$^3$/s-5000 m$^3$/s.](image)

![Fig. 6. The accumulated scour of the model test between Tiexie and Taochengpu.](image)
4. Conclusions

The analysis of model test results shows that the sediment transporting capacity of upstream and downstream in the Lower Yellow River had great difference. If the quondam discharge and the sediment concentration were used in the later sediment-retaining period of Xiaolangdi Reservoir, silting is inevitable below Jiahetan. But equilibrium sediment transport can solve this problem. The combination of discharge and the sediment concentration changed in the range of $2500 \text{ m}^3/\text{s} < Q < 4000 \text{ m}^3/\text{s}$ and $20 \text{ kg/m}^3 < S < 60 \text{ kg/m}^3$ is considered a better combination for the Lower Yellow River equilibrium sediment transport in long period.

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