Study on the Flow-sediment Conditions and River-bed Erosion and Deposition of Chongqing Reach after the Impoundment of Three Gorges Reservoir

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Abstract. Chongqing city is the important node of golden waterway of Yangtze River. As the promotion of the Yangtze River economic belt strategy and normal operation of Three Gorges Reservoir (TGR), more and more attention has been paid to the sediment problem of Chongqing reach. After the experimental storage of 175m in the TGR, Chongqing reach is located in the fluctuating backwater area, with export boundary conditions and river-bed erosion and deposition changed. In recent years, with the water storage of cascade reservoirs in the lower reaches of Jinsha River, the condition of water inflow and sediment in this section has changed and the river-bed is adjusted accordingly. According to prototype observation data from 2003 to 2017, the flow-sediment conditions and river-bed erosion and deposition of Chongqing reach after the impoundment of TGR at different stages were compared and analyzed. Results showed that during the initial storage period of TGR, from June 2003 to May 2008, sediment erosion and sediment was mainly related to water and sediment of upstream, with whole reach in a state of erosion and intensity was about 140.8 million m3 every year. After the impoundment of TGR, from September 2008 to October 2012, the condition of incoming water and sediment in Chongqing reach maintained original change trend and sediment erosion was mainly related to impoundment of TGR, with whole reach in a state of erosion, but intensity was small. From October 2012 to December 2017, sand from upstream of Chongqing reach reduced greatly, so river bed was drastically adjusted and scour intensity increased significantly, was about 312.2 million m3 every year. It concluded that decrease of upstream sediment is one of the important reasons for increased scour intensity in Chongqing reach.

1. Introduction

The Three Gorges Project (TGP) is the largest water control project in the world. It consists of a dam, a reservoir, a power station and a navigation building. The reservoir covers total area of 1,084 square kilometers and 21 counties or cities in Hubei province and Chongqing city. In June 2003, the three gorges project began to store water for the first time. In September 2008, TGP began experimental water storage of 175m, and the water level in front of dam reached 172.8m at that time. In October 2010, TGP stored water to 175m successfully for the first time. In October 2012, the water level in front of dam reached normal water level of 175m for the third time. The figure 1 gives the process of water level in front of Three Gorges Dam (TGD) since its filling began in 2003.
Chongqing city is located at the confluence of Jialing River and Yangtze River. So, the reach of Chongqing consists of two parts, which are Yangtze River section from Dadukou to Tongluoxia and Jialing River section from Jingkou to Chaotianmen. Before the initial impoundment stage of Three Gorges Reservoir (TGR), Chongqing reach has not been affected by the backwater of the reservoir and is in the natural state. The scale of scouring and silting is related to the incoming water and sediment in that year. The results show that the Chongqing reach is close to the balance of scour and sedimentation.

Since the experimental impoundment of TGR, with the rise of the water level in front of dam, the backwater ends extend, and Chongqing begins to be affected by the backwater of TGR. Chongqing reach is located in the upper section of the fluctuating backwater area of TGR, which has the dual characteristics of the reservoir and the natural river. Affected by the backwater of the reservoir, its water depth increases to some extent compared with the natural condition, and the flow rate decreases to some extent. The sediment erosion and deposition in Chongqing reach is related to the operation of TGR, so it has always been the focus attention by water conservancy workers. Especially, with the normal operation of TGR, it has been the focus of attention. Based on the latest hydrological and sediment data of long time series collected, the paper analyzes the regulation rules of Chongqing reach, under the new background. The research has certain reference value in the river regulation project of this section and the desilting operation of TGR tail.

2. Study area
Chongqing reach includes two parts, which are the Yangtze River section and the Jialing River section. The Yangtze River section is about 40km long, from Dadukou to Tongluoxia and the Jialing River is about 20km long, from Jingkou to Chaotianmen. Before the impoundment of Three Gorges Reservoir experimental, Chongqing reach is in the natural state and follows the rules of natural river sediment movement. In September 2008, the TGR started 175m impoundment which brought the Chongqing reach in the fluctuating backwater area of TGR, due to which it exhibiting the property of reservoir and river at the same time[1]. Figure 2 gives the relative location of Chongqing reach in the TGR.
Influenced by geological processes, Chongqing reach is in the state of progressive bending on the plane, and bend section is about the same length as the straight section\cite{2}. The shoreline of it is uneven. In the flood period, width of the Yangtze River section is about 700~800m and the widest is about 1500m in the braided reach, observed at Jiulongpo, the narrowest is the only 530m, at Danzishi. Width of the Jialing river is about 400~500m, the widest is about 850m, at Linjiangmen, the narrowest is the only 370m.

Along the Chongqing reach, there are many harbours and docks, the main of which are Jiulongpo work zone, Chaotianmen work zone and Cuntan work zone\cite{3}. Chongqing reach is a single channel and the flow of water through it gets retarded due to channel bend, narrow and shallow rivercourse in the low flow period. In recent years, to meet the demand for municipal construction and flood control, a large number of highways along the river, large cargo wharf, flood control structures and bridge across the river, have been built along the banks of Chongqing reach.

3. Data sources and Method

The study is mainly based on hydrologic and sediment observation data and underwater topographic data of Zhutuo, Beibei and Cuntan hydrologic stations. The above datas come from Yangtze River Waterway Bureau and Changjiang River Scientific Research Institute.

Zhutuo and Beibei hydrological stations are the inlet control stations of Chongqing reach. Cuntan hydrological station is the outlet control station and it also the inlet control station of TGR, which is located in the main stream of the Yangtze River and about 7km away from the estuary of Jialing River and Yangtze River. The relative location of the above control stations is shown in figure 2. Information of main control stations of import and export is shown in table 1.

| Name of station | River          | Catchment area / ten thousand km² | Observed series   |
|----------------|----------------|----------------------------------|-------------------|
| Zhutuo         | Yangtze River  | 69.47                            |                   |
| Beibei         | Jialing River  | 15.67                            | 1956-2016         |
| Cuntan         | Yangtze River  | 86.66                            |                   |
In this paper, hydrological and sediment datas are analyzed mainly by mathematical statistical method and sliding average method, so as to eliminate frequent random fluctuations in the data and show the smooth change trend of water and sediment data. The analysis of underwater topographic data mainly adopts the method of section [4].

4. Variation characteristics of water-sand conditions

4.1. water flow and sediment in the upper of Chongqing reach

The water and sediment of Chongqing reach mainly come from the upper Jinsha River, Minjiang River and Jialing River. The sediment in the Chongqing reach is mainly suspended load, with relatively small amount of bed load. The suspended load mainly comes from Jinsha River and Jialing River. According to the measured hydrological data from 1956 to 2016, the variation process of runoff and sediment transport in Zhutuo hydrological station and Beibei hydrological station were statistically analyzed, and the 5-year sliding average value was calculated, as shown in figure 3. The statistical results show that:

1) The interannual variation process lines of runoff in the stations show the alternation of abundant and dry years, with strong randomness. The sediment transport quantity also presents alternation change, and the randomness is stronger than runoff.

2) According to the variation trend of the 5-year sliding average, in the past 60 years, the runoff of two stations basically fluctuated up and down around an area, with relatively small changes, while the sediment transport volume showed a significant downward trend, especially Zhutuo station.
Since the impoundment of TGP was put into use in 2003, the inflow of water in the Chongqing reach remained at a stable level, while the sediment inflow decreased significantly, especially in the main stream of Yangtze River. In 2003, at the initial impoundment stage of TGR, the annual sediment transport volume of Zhutuo station was 191 million t. In 2008, the experimental storage of TGR, Zhutuo station annual sediment transport volume was 212 million t. In 2012, xiangjiaba reservoir was initially filled with water, and the annual sediment transport volume of Zhutuo station was 189 million t. In 2017, the annual sediment transport volume of Zhutuo station was only 27.4 million t. The change of Beibei station was relatively small, from 30.6 million t to 5.6 million t. It can be seen from this that the sediment inflow and sediment in Chongqing reach are significantly affected by the cascade hydropower development in the upstream. After xiangjiaba and xiluodu hydropower stations of Jinsha River in the upstream of Chongqing reach were used, the sediment of Zhutuo station decreased significantly.

4.2. Outlet level of downstream

The outlet of Chongqing reach is located at the famous Tongluoxia gorge. According to the research of Changjiang River Scientific Research Institute, the backwater effect of Tongluoxia gorge during flood season is an important factor affecting the flood level of Chongqing reach[5]. After the impoundment of TGR, Chongqing reach is located in the fluctuating backwater area of TGR, and the change of its water level is affected by the impoundment of TGR.

After the experimental storage of 175m in the TGR, the water level along Chongqing reach rises due to the influence of water level elevation in front of TGD. According to analysis of the measured data, when the water level in front of TGD is 174-175m, the maximum rise of Cuntan station water level is 14.85m, at this time the flow rate of it is 4170m³/s. With the rise of water level in front of dam, the rise of water level increases.

The double change of the upstream inflow and sediment conditions and the downstream outlet control water level will lead to corresponding adjustment of riverbed in Chongqing reach. Based on the underwater topography data of long time series, the following paragraphs will analyze the change of riverbed in Chongqing reach after storage of TGR. The research results are expected to provide technical support for the subsequent operation and application of TGP.

5. Characteristics of bed erosion and deposition

Figure 4 shows the typical cross-sectional variation of the upper and lower reaches in Chongqing reach. CY13 cross section is located near danzishi in the main stream of Yangtze River, which is located at the downstream of the confluence of Jialing River and Yangtze River. While CY26 cross section is located near caiyuanka in the upstream of the confluence of Jialing River and Yangtze River. Since the impoundment of TGP was put into use in June 2003, the shape of river section in the Chongqing reach has been basically stable.

According to the measured underwater topography data from 2003 to 2017, the amount of scouring and silting of riverbed was calculated by using section method, as shown in figure 5. From December 2003 to May 2008, Chongqing reach has not been affected by the impoundment of TGR, and the scour and deposition is mainly affected by the upstream runoff, sediment and riverbed boundary morphology. The riverbed changes follow the laws of natural evolution and are generally dominated by scour, with scour and deposition occurring in a year and a slight state of scour between years.

In September 2008, TGR began to store water. It can be seen from figure 5, since September 2008, Chongqing reach was in the state of scouring as a whole, only from November 2009 to December 2010, it was silting state. In the two time, from October 2012 to December 2013 and from December 2013 to December 2014, the erosion quantity was larger, up to 6.463 million m³ and 4.992 million m³. From October 2012 to December 2014, xiangjiaba and xiluodu hydropower stations in the downstream of Jinsha River were successively impoundment and operation, which significantly changed the sediment conditions entering Chongqing reach and riverbed underwent dramatic adjustment.
6. Conclusion

According to the above research, it can be seen:

Since TGP was put into use (from June 2003 to May 2008), the riverbed erosion and silting in Chongqing reach was mainly related to the upstream inflow and sediment. After 175m experimental water storage in TGR, Chongqing reach is located in the fluctuating backwater area of TGR. In addition, the upstream of Jinsha River cascade reservoir are used for water storage, so the inlet and outlet boundary conditions of Chongqing reach are changed. From September 2008 to October 2012, the inflow and sediment conditions in Chongqing reach maintained the original change trend. The scouring and silting was mainly related to the impoundment of TGR, and the whole reach was in a
scour situation with the scouring intensity of about 0.438 million m³ yearly, which was greatly reduced compared with that before the impoundment of TGR. In October 2012 to December 2017, with xiluodu and xiangjiaba hydropower stations in the upstream of Chongqing reach were put into use, the sediment into Chongqing reach decreased significantly. At the time, the annual sediment discharge of Zhutuo station reduced from 0.189 billion to 0.0274 million t.

Comprehensive analysis shows that one of the important reasons of scour in Chongqing reach is significant decrease of upstream sediment after the application of TGR. So, it is necessary to further study about the influence of the cascade reservoir operation on Chongqing reach.

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