Study on Processes of Changshou Waterway after 175m Experimental Impoundment of the Three Gorges Reservoir

Yuchen Li 1, Qianqian Shang 2*, Ji Jiang 3, Bing Da 3 and Yajun Gao 2

1 State Key Lab of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, Hubei, 430072, China
2 Key Lab of Port, Waterway and Sedimentation Engineering of the Ministry of Communications, Nanjing Hydraulic Research Institute, Nanjing, Jiangsu, 210024, China
3 Nanjing Yunda Decoration Company Limited, Nanjing, Jiangsu, 210029, China
*Corresponding author’s e-mail: qqshang@nhri.cn

Abstract. In 2008, the normal pool level in front of the Three Gorges Dam was set at 175m, and afterwards the spatial distribution of sedimentation in fluctuating backwater region changed significantly. Moreover, with the operation of Xiluodu and Xiangjiaba Reservoirs in the upstream of Yangtze River, sedimentation in fluctuating backwater area has also changed accordingly. In order to analyse the characteristics of erosion and deposition in the fluctuating backwater area under new water and sediment conditions, Changshou Waterway which located in the middle section of the fluctuating backwater region is chosen as one typical waterway, and the measured data of Changshou Waterway is then investigated. Results show that: the riverbed of the middle section in the fluctuating backwater area is changed from silting to slight scouring, there is no accumulated deposition after the experimental impoundment of the Three Gorges Reservoir, and the riverbed deformation in the Zhongshui Moraine of the Changshou Waterway is much more sensitive to water and sediment conditions while the downstream curved channel near Matou Moraine is relatively stable.

1. Introduction
The fluctuating backwater region of a reservoir has the dual nature of both reservoirs and rivers. During the storage period in the flood season, the water level in front of the dam rises and the backwater end moves upward, and then the fluctuating backwater area shows a nature of reservoirs. During the drawdown period, the backwater end moves downward, and the upper segment of the backwater region becomes natural river channel again, then the fluctuating backwater region has the property of scouring and silting of the natural river channel. After September 2008, TGP was put into operation with the water storage stage of 175-145-155m, and the Changshou Waterway was located in the middle of the fluctuating backwater region, which was significantly affected by the backwater. The Changshou Waterway is one of the key river sections in the upstream of the Yangtze River. The evolution of the riverbed was complex in natural conditions and becoming much more complicated after the external conditions change greatly. Therefore, it is of great significance to understand the channel deformation rules in the fluctuating backwater region, during the different operation periods of TGP, so as to optimize the staging impoundment and dispatching of the Three Gorges Reservoir.
The Changshou Waterway is a slightly curved braided reach, and the waterfront is quite uneven. The reefs and stones such as Xiaojia Stone Plate, Manyu Reef, Liangzi Moraine, and Mopan Reef penetrate into the deep trough, causing a disordered flow pattern in the channel, where the sediment is extremely easy to deposit and the navigation condition can be seriously affected. After the impoundment operation of TGP, although the navigation condition is improved, the requirements of the large-scale vessels for the navigation channel scale have also been much higher. Moreover, the Changshou Waterway is affected by sediment deposition and complex river channel characteristics a lot, therefore, the situation of navigation obstruction is still severe. Therefore, channel regulation projects were taken one after another in recent years. In 2006, the channel regulation project from Fuling to Tongluoxia section was taken out, some of the nozzles and reefs were removed, and then the flow condition was improved to a certain extent. Then in 2012, maintenance dredging was carried out and the channel scale was expanded. According to statistics, from 2008 to May 2012, the Tongluoxia to Fuling section were silted in the mass with a total quantity of 10.67 million m³. The sedimentation was mainly occurred from the Luoqi to Changshou section and the Huangcaoxia to Lidu section[1, 2]. Along with TGP operated at the water level of 175m, serious backwater appears in the Changshou Waterway at the end of the flood period each year, which inevitably increased the channel siltation. According to researches based on the water and sediment series of 1961-1970, after TGP is operated at a normal pool level of 175m, the sedimentation in fluctuating backwater region can be very serious, and silting shoals can be formed on both sides of the river, and most of the ports would be silted and abandoned, also the navigation condition in upper segment of fluctuating backwater region would be deteriorated[3, 4]. However, those bad situations don’t happen, with the establishment of large-scale reservoirs such as Xiangjiaba and Xiluodu Reservoirs and the improvement of upstream vegetation conditions, sediment is significantly reduced compared with the assumptions of the above arguments. Therefore, the sedimentation of fluctuating backwater area and reservoir area decreased [5-10]. L Q Zuo et al.[1] explained the influence of the change from water and sediment conditions of the Yangtze River on the scouring and silting in the backwater fluctuation area, and also obtained that fluctuating backwater area only had a small amount of sedimentation in the uneven bend of the local waterfront, meanwhile, there was almost no deposition in the remaining sections. Based on the recent measured hydrological and topographic data, this paper concentrates on the main reasons for the evolution of the fluctuating backwater region and predict the riverbed evolution to provide a reference for the channel regulation.

2. Briefing on study reach

2.1. General situation of study reach
The Changshou Waterway is located between Fuling and Luoqi in the upstream of the Yangtze River. It is 9km long, and has a famous shoal Wangjiatan seen in Figure 1. This waterway is a typical mountainous river section with many moraines. There is Zhongshui Moraine lying in the middle of the river and divides the channel into left and right branches. Since the left wing of Zhongshui Moraine silts up and squeezes the deep trough of the left branch, making the curved radius of the channel at the entrance only about 500m wide. As for the right branch, Xiaojia Stone Plate penetrates into the river, and the head of the Zhongshui Moraine is silted up, making the deep trough transit from the left bank to the right bank (figure 1) and the inlet reach of right branch abnormally curved. Additionally, different reefs, such as the Liangzi Moraine, the Hengban Reef and the Mopan Stone, are located on the right side of the right branch, leading to a narrow channel and a poor flow condition. The tail of Zhongshui Moraine, the upper wing of Matou Moraine and submerged reefs such as the Zhaomenzi Reef, the Chengan Moraine and the Guancai Reef, are distributed along the both river sides and block the channel. During the dry season, the water depth is shallow, flow path is bending and water flows rapidly. When TGP operated at level 156m, during the flood season, water level in front of the dam rose not much, and Changshou Waterway was in natural state; during the dry season, water level in front of the
dam raised gradually, at that time Changshou Waterway was at the end of the fluctuating backwater area with small backwater height and short time range. After the flood period in 2008, the water level in front of the Three Gorges Dam raised to 175m, and then in dry season, Changshou Waterway was in the middle section of the fluctuating backwater area with a backwater height of 7~23m and a longer duration.

2.2. Runoff and sediment conditions
The Cuntan Hydrological Station is located upstream Changshou Waterway, and there are no large tributaries. Therefore, the measured data of the Cuntan Station can represent the flow and sediment conditions. The riverbed of Changshou Waterway mainly consists of cobble, the variation range of maximum particle size is 162~183mm, and the variation range of the median particle size is 31.5~146mm.
After the construction of the TGP, the discharge process doesn’t change much, with an average annual runoff of 325 billion m³, and the runoff from June to October accounts for about 72% of the annual runoff (See figure 2). But the amount of sediment has reduced significantly in recent years. Especially after the operation of the upstream reservoirs after 2012, the average annual sediment transport is only 0.69 billion tons, which is only 37.3% of that from 2004 to 2012.

3. Riverbed evolution characteristics

3.1. Adjustment of deposition and erosion before the experimental impoundment

Under natural conditions, during the flood period, deposition mainly happens in the backflow zones or a broad-shallow area. During the dry period, the Zhongshui Moraine emerges and the flow is concentrated to scour the sediment. Therefore, the Changshou Waterway basically follows the characteristics of deposition during the flood period and erosion during the dry period.

In the flood period, flow separates at the head of Zhongshui Moraine, and two backwater areas form downstream Qimaqiao and the Xiaojia Stone Plate respectively where cobbles accumulate. When the Zhongshui Moraine is submerged, the flow dynamic axis goes through the surface of Zhongshui Moraine and then shifts to the right bank. The channel gets wider at the tail of Zhongshui Moraine, and sediment deposits around the Chenggan Moraine. After the flood period, flow goes back to the trough scouring the sediment of the channel. The crossflow is intercepted to the right trough by interactions of the spur dikes at Zhaomenzi and the tailing dam at Zhongshui Moraine. Then the flow of left branch concentrates in the shallow area and scours the accumulated sediment, but still sedimentation occurs in the transition section of the Matou Moraine. Some researchers[11] believe that the deposition and erosion are interconnected with the upper and lower parts. Deposition at Matou Moraine is caused by the sediment scoured around Chenggan Moraine.

After the TGP operated with a water level of 156m, overall, it is accumulated in this river section. In the dry period, the channel was basically a natural channel, and the riverbed was eroded. However, during the storage period, the water surface gradient reduced in the Changshou section due to the impact of backwater, and the deposition is more obvious than that of before the water storage period, and it is characterized by siltation on both the beach and trough. Until 2008, the amount of silting in this river section was 2.792 million m³.

3.2. Adjustment of deposition and erosion after experimental impoundment

3.2.1. Characteristics of deposition and erosion within the year. Under the experimental impoundment condition, the elevation operation plan in front of the Three Gorges Dam is 175m-156m-145m. The periodic variation of the erosion basis at permanent backwater region changes the deposition and erosion characteristics in the fluctuating backwater region to certain extent. The riverbed deformation process of Changshou Waterway transforms into three stages including scouring during the drawdown period, siltation during the flood period and siltation during the storage period. Figure 3 and figure 4 show the deposition and erosion distribution of each period in 2012 and 2013, respectively.

The drawdown period is the main sediment transport period during the year, and it is also the key period of scouring the channel.

However, from November 2011 to May 2012, deposition happened during the drawdown period. Mainly because after the riverbed scouring in the drawdown period of 2011, only small amount of sediment came from the upstream in the following flood period, making the sediment not adequately replenished, and then in the drawdown period of 2012, the amount of sediment coming from the upstream increased significantly, leading to a large amount of sediment deposition in the Changshou section. The mean deposition thickness was about 0.5m at the surface of Zhongshui Moraine, and 1~3m was at the left branch and 1~2m at Zhaomenzi spur dikes area. In other years, as the reservoir characteristic weakened and the erosion basis declined, the sediment cumulated in the previous year was washed away mainly during the drawdown period.
From November 2012 to May 2013, the deep trough of Zhongshui Moraine’s left branch was scoured affected by the Xiangbizi longitudinal dam, and the maximum scouring depth was about 3m; a maintenance dredging of about 40,000 m³ was taken out in the right branch of Zhongshui Moraine; and the deep trough on the right branch near Mopanshi reef was scoured 3–5m. The sediment from upstream accumulated in the backwater area of the Zhaomenzi spur dike. The concave bank of left branch near the Matou Moraine was silted up, and the deep trough was scoured in the convex bank with an average scouring depth of 1m.

Before the operation of cascade reservoirs in the upstream, the hydro-sediment dynamics made the Changshou Waterway generally in a deposition state. Before flood season, water level in front of the dam drops, and the Changshou Waterway return to its natural state. After flood season, water level continues to rise due to the water storage operation, leading to a declining sediment transporting capacity. From May to November in 2012, the total sediment deposition was 285,100 m³, of which 25,100 m³ was in the deep trough, accounting for 87.7%. The deposition mainly located at the entrance on the right branch of Zhongshui Moraine, the deep trough near Xiangbizi in the left branch of Zhongshui Moraine and deep trough at the right-side of Zhongshui Moraine’s tail. Also, a slight siltation happened in the convex bank of curved channel near the Matou Moraine, with a deposition thickness of about 0.5~1m.

After the operation of the cascade reservoirs in the upstream, the amount of incoming sediment load is significantly reduced, leading to reduction deposition in the Changshou Waterway during the flood season and the storage period to achieve an equilibrium state between silting and scouring. From May to November in 2013, due to the decrease of incoming sediment, the erosion-deposition of deep trough varies not much. The deep trough erosion only appeared at the left branch of Zhongshui Moraine and the curved top of Matou Moraine with a scour depth of about 1m. And deposition occurred at the convex bank of Matou Moraine due to the circulation flow, with a deposition thickness of 1~2m.
3.2.2. Interannual deposition and erosion characteristics. As shown in figure 5, the interannual deposition and erosion distribution. It can be seen that the main channel position of the Changshou Waterway is stable, and the deep trough on the left branch of Zhongshui Moraine is changed from silting to scouring, and the deep trough on the right branch remains in a state of scouring. From November 2005 to November 2012, the 4.5m isobath gradually moved upwards 50m on the head of Zhongshui Moraine, indicating that sediment deposited here. Since October 2012, after the operation of large reservoirs such as Xiangjiaba Reservoir, the amount of incoming sediment is decreased drastically. From November 2012 to May 2015, the 4.5m isobath gradually moved downward 30m at the head of Zhongshui Moraine, indicating that riverbed was scoured away here.

2012 is a year of water-in-abundance, and the riverbed of Changshou Waterway generally deposited for more than 0.5m, of which, 509,200 m³ was in the surface of Zhongshui Moraine, backwater area of Xiangbizi longitudinal dam and river section near the Zhaomenzi spur dike, accounting for 42.82% of the total sediment deposition. Deposition occurred in the deep troughs of both left-branch and right-branch, especially at the entrance zone of the right branch. Compared with 2008, the width of 4.5m isobath narrowed by 3m. The deposition thickness in the backwater area of Zhaomenzi spur dike went up to 5m, which effectively decreased the sedimentation in the deep trough. After the operation of Xiangjiaba Reservoir, the runoff does not change much, but the amount of sediment transport reduces greatly. Therefore, in 2013 the Changshou Waterway was in a state of micro-deposition, and the deposition mainly happened between the 165-175m beach, with a mount of 55,500 m³ accounting for 60.7% of the total sediment deposition. And the deep trough was slightly scoured. The right branch of Zhongshui Moraine was scoured for 120,500 m³, mainly caused by the maintenance dredging in 2013. 2014 is a year of water-in-abundance with relatively small incoming sediment, the amount of sediment transport reduced by 64%. And the deep trough of this section was generally scoured with an average depth of about 0.3m, and the beach was in a state of relative equilibrium. Compared with the right branch of Zhongshui Moraine, the left branch was scoured much more intensively, and the amount of erosion was 138,500 m³, which was three times that of the right branch. 2015 is a normal year with small incoming sediment, compared with the topographic data from May to December, it can be seen that the channel was slightly silted up, with a total sediment deposition of 258,800 m³, of which 42.5% was silted in deep trough area. Compared with 2012, the 4.5m isobath was generally wider, and the scour strength at the entrance of the right branch of Zhongshui Moraine was smaller with a broadened width of only 1m.
Figure 6 shows the changes of transverse profiles at Zhongshui Moraine and Matou Moraine in different periods after the experimental operation of the TGP. It can be seen that the scouring and silting on the beach was small, and that of the deep trough varied with wide range. The scouring and silting near Matou Moraine were basically balanced with a relatively stable river regime. There was a continuous scouring in the deep trough of the right branch near Zhongshui Moraine, and the average scouring depth was about 2.5m and 1.8m for the periods 2007~2011 and 2011~2015. Although a lot of sediment deposited in the deep trough of Zhongshui Moraine’s left-branch, the topography in 2015 then basically recovered to that of December 2007 after the erosion process from November 2011 to April 2015.

Figure 5. Erosion and deposition distribution

Figure 6. Transverse profiles at Zhongshui Moraine and Matou Moraine in different periods

4. Analysis of evolution factors after the experimental operation of the TGP
After the experimental impoundment of the TGP, the normal pool level of the reservoir is set at 175m, and the deep trough is still the place that changes the most significantly in the year, where a large
amount of sediment accumulates during the flood season. However, due to the effect of storage operation after the flood season, the sediment accumulated in the flood season cannot be effectively washed away after the flooding, and it can be scoured until the drawdown period in next year. Meanwhile, the main sediment transport period is postponed from flood season to the drawdown period in the next year.

The entrance of the Changshou Waterway is controlled by the node of Xiaojia stone plate, making the mainstream shift to the left branch of Zhongshui Moraine and most of the sediment transported along the left branch. Before the operation of the cascade reservoirs upstream, the amount of incoming sediment was quite large. And The sediment deposited in the broad-shallow area of the left branch due to the sudden widening of the channel. The coarser sediment accumulates at the entrance of the left branch of Zhongshui Moraine, while the finer sediment continues to move downstream along the left branch. When the finer sediment approaches the Xiangbizi longitudinal dike, the sediment is silted up at the transition section between the Zhongshui Moraine wing and the Xiangbizi due to the circulation effect of the curved channel. However, since much less sediment is transported along the right branch of Zhongshui Moraine, deposition in the broad-shallow area of the left branch is small but the scouring is relatively strong during the drawdown period, leading to erosion in the deep trough of right branch with an annual average scouring depth of about 0.5m. Although the amount of incoming sediment is large, the deposition mainly occurs in the deep trough of the left branch of Zhongshui Moraine, which reduces the amount of sediment transporting into the curved channel of Matou Moraine. Therefore, the erosion and deposition in the curved section of Matou Moraine is basically balanced, and the topography does not change much.

Since the operation of large-scale cascade reservoirs such as Xiluodu and Xiangjiaba Reservoirs, a dramatic sediment load reduction of the Changshou section has received great attention. The incoming sediment load during the flood season and the storage period is significantly reduced. The erosion intensity of the Changshou Waterway does not change much, and the deep trough of Zhongshui Moraine is in a state of scouring. The erosion intensity of deep trough in the right branch is basically the same as that before the completion of the cascade reservoirs, and the annual average scouring depth is still about 0.5m. For the left branch of Zhongshui Moraine, since the incoming sediment load is significantly reduced and sediment-carrying capacity of flow is greater than sediment content, the deep trough shows an interannual scouring. With the scouring of the Zhongshui Moraine section, the sediment is supplemented locally, making a relatively equilibrium state in curved section of Matou Moraine.

Therefore, the right branch of the Zhongshui Moraine is barely affected by the water and sediment conditions, it is mainly affected by the adjustment of the TGP. In contrast, the left branch of Zhongshui Moraine is the main channel for sediment transport, and its evolution of scouring and silting is mainly affected by the incoming water and sediment conditions. After the operation of experimental impoundment, the curved section of Matou Moraine remains a balance state of erosion and deposition under the new conditions of water and sediment.

5. Conclusions
(1) The measured data shows that the amount of incoming sediment load reduces dramatically in recent years. After the experimental impoundment of the TGP, the Changshou Waterway is then affected by the backwater, and the power of sediment transporting is insufficient during the year. Constrained by the reduction of incoming sediment and the rising of the local base level, accumulated sedimentation doesn’t happen in this section after the experimental impoundment of the TGP.

(2) Due to the operations of the TGP and upstream reservoirs, the amount of incoming sediment load is significantly reduced. The deep trough of the Changshou Waterway is in a state of slight scouring during the drawdown period, and in a balance of scouring and silting during the flood season and the storage period. Under the conditions of medium water and sediment and medium water and small sediment, the deep trough is in a relatively balanced state of scouring and silting during the year, which is nearly the ideal water and sediment conditions for river stability.
(3) The boundary conditions of Zhongshui Moraine are complicated, and the riverbed deformation is quite sensitive to water and sediment conditions. With the reduction of the incoming sediment load, the left branch is transformed from deposition to erosion, which is beneficial to the stability of the left branch. Meanwhile, great attention should be paid to the year with abundant water and large amount of sediment load, in order to prevent the navigation obstruction from occurring. The deep trough of right branch is basically in the state of scouring while the curved channel near Matou Moraine maintains the balance of scouring and silting under the new water and sediment conditions.

Acknowledgments
This work was financially supported by the National Key Research and Development Program of China (2017YFC0405206).

References
[1] Zuo L.Q., Lu Y.J., Liu H.X. (2015) River channel evolution of Luoqi to Wangjiatan Reach in fluctuating backwater area of Three Gorges Project. Journal of Sediment Research, 3:15-20.
[2] Yuan J., Xu Q.X., Dong B.J., Zhu L.L. (2015) Study on sediment erosion and deposition characteristics in fluctuating backwater area of Three Gorges Reservoir in the drawdown period. Journal of Sediment Research, 3: 15-20.
[3] Dou G.R., Wan S.G., Lu C.S. (1995) Investigation on sedimentation in varying backwater zone of Three Gorges Project. Journal of Hydraulic Research Institute, 4: 327-335.
[4] Yuan M.Q., Zhang X.Q. (2002) Analysis of river bed evolution and control measures about Luoqi to Wangjiatan Reach in fluctuating backwater area of Three Gorges Project in period of construction and 175m initial stage. In: The "Nine Five" Research Results Assembly on the Sediment Problem in Three Gorges Project, Vol. 5. Beijing: Intellectual Property Publishing House Co., Ltd. pp. 263-287.
[5] Li Y.T., Chen J., Deng J.Y., Gan F.W., Xie B.L. (2008) Influence of reservoir construction upstream on the navigation channel in the fluctuating backwater area of the Three Gorges Reservoir. Journal of Sediment Research, 5:31－37.
[6] Lu Y.J., Zuo L.Q., Ji R.Y., Mao J.X. (2009) Changes of sediment deposition and erosion at Chongqing reach in backwater area of Three Gorges Project after reservoir adjusting of the upstream in the Yangtze River. Advances in Water Science, 40(3):318－324.
[7] Zhao J.Q., Li Y.T., Deng J.Y. (2010) Influence on sediment deposition and morphology evolution in Qingyanzi reach caused by the change of water silt conditions of TGP. Journal of Hydroelectric Engineering, 3:109－125.
[8] Chen J., Li Y.T., Deng J.Y., Gan F.W., Xie B.L. (2008) Influence on deposition of the Three Gorges Reservoir caused by the change of water silt conditions. Journal of Hydroelectric Engineering, 27(2):97-102.
[9] Zhang X.J., He J.C., Mu D.W. (2010) Impact of incoming run off and sediment on sediment deposition along the Chongqing reach. Hydro-Science and Engineering, 1:23-29.
[10] Jin Z.W., Fan B.L., Xu H.T. (2009) Study on sedimentation with in fluctuation backwater area of Three Gorges Reservoir. Water Resources and Hydropower Engineering, 40(5):14-18.