Research on atypical evolution characteristics of convex bank of typical bend in lower Jingjiang river under changing environment

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Abstract: Since Three Gorges Reservoir was put into operation, the water and sediment conditions have changed significantly, and the lower reach of the project have been adjusted to adapt to this change. The continuous bend of the Jingjiang section of the lower reach of the reservoir (Tiaoguan-Laijiapu) is selected as the research reach. The research methods of prototype data observation and physical model test were carried out, and the continuous erosion evolution and channel shape change characteristics of the reach are analyzed. The results show that the convex bank at the upper of the bend is eroded, the concave bank is deposited, the deep groove is moved to the right, widened and cut down, the deep groove at the lower of the bend is widened and brushed deep, the convex bank at the upper of the Laijiapu bend is scoured, the concave bank gradually deposited, and the deep groove of the whole bend is widened and deep scoured after Three Gorges Reservoir was built and used. The change of runoff conditions after the construction of the reservoir provide dynamic conditions for the continuous scouring of the convex bank. The main factors for the continuous erosion of the convex bank are the substantial reduction of sediment inflow downstream of the dam caused by reservoir sediment interception, sand mining and soil and water conservation. This study is universal and can provide reference for the research on evolution characteristics of the downstream bend reach of other large water conservancy projects.

1. Introduction
After Three Gorges Reservoir impoundment and influenced by human activities, soil and water conservation and sediment mining in the upper reach of the river, the runoff conditions and sediment inflow in the lower reach of the dam change greatly, the amount of sediment entering the lower reach of the river decreases greatly, which breaks the relative balance between river evolution and water and sediment movement under natural conditions and presents new characteristics in river evolution. The evolution of the bend channel in the lower reach of the dam presents a new law that compared with the law of convex bank deposition, concave bank erosion or erosion and siltation keep relative balance in the past, after Three Gorges Reservoir was built, the evolution characteristics of continuous erosion of convex bank appeared in some bend sections of Jingjiang river (such as Tiaoguan-Laijiapu, Xiongjiazhou, Guanyinzhou and Qigongling bend). The regulation of river course evolution may affect the utilization of shoreline, river (navigation) regulation, flood control and disaster mitigation. Many scholars have done a lot of work on the study of the evolution characteristics of the lower reach of the dam. For example, based on the observation and analysis of the natural evolution characteristics of the lower reach of the dam, Fang Xinrui [1] has analyzed the evolution trend of the lower reach of the dam after the construction of Three Gorges Reservoir. Xue Xinghua [2] observed the lower reach of the dam
before and after the impoundment of Three Gorges Reservoir by using remote sensing observation technology. He found that the salient shore of the bend channel of the lower Jingjiang river was scouring and retreating, and analyzed the scouring and silting characteristics of the shore of the Jingjiang river. Based on hydrological observation data, Fan Yongyang [3] systematically combed the driving factors of convex bank erosion and concave bank deposition in the lower Jingjiang river bend section from a macroscopic point of view, and found that the driving factors are boundary conditions, upstream and downstream river regime, water and sediment conditions and the influence of Dongting Lake top bracket. Zhu Lingling [4] analyzed the formation factors of erosion and deposition of convex bank and concave bank in the sharp bend section of Lower Jingjiang river by observing and analyzing the prototype data and the characteristics of erosion and deposition of channel and beach. Based on the measured data, Chen Li [5] analyzed the evolution characteristics of Xiantao-Xiaochenjiatai continuous bend downstream of Danjiangkou Reservoir. It was found that the single scour of the deep channel in this reach decreased. Due to the change of runoff conditions, the river section appeared the phenomenon of bend bypassing and shoal cutting. Based on the physical model test, Tangfeng [6] studied the scouring and silting process of the Tiaoguan bend and predicted the trend of river regime adjustment. Zen [7] analyzed the evolution characteristics of The Tagliamento river bend by using the laser radar observation technology and most of the measured data and mainly considers the influence of the existence of river plants on the evolution of meandering rivers. Its research analyzed the influence of plants on the structure of riverbanks and the flow of floodplains in meandering rivers. This study provides a reference basis for us to think over the influence of river plant factors in the generalization of natural river model tests. In the future, more research work can be done to verify the effects of bent river plants on river flow and bed deformation. Ruanchengtang [8] found that after the construction of the reservoir in the Three Gorges Project, the subsaturated flow cause the curved channel flow line and the deep sag oscillated violently, and the cross-section shape of the river changed from V-shape to W-shape. Based on the analysis of hydrological data measured in Jingjiang reach and by analyzing the changes of flow, sediment and river regime in the lower reach of Three Gorges Reservoir after impoundment, the evolution characteristics of Jingjiang reach of the Changjiang river after impoundment of Three Gorges Reservoir are explained. Li.et al [9] pointed out that the changes of water and sediment conditions and the influence of river boundary conditions are the main factors for the adjustment of river regime in Jingjiang river after impoundment of Three Gorges Reservoir. In previous studies, great progress has been made in understanding the overall evolution characteristics and river characteristics of meandering rivers and provide a basis for later scholars to study meandering rivers. Previous scholars mostly studied the evolution characteristics of the lower reach of the dam after Three Gorges Reservoir was built through the analysis of prototype observation data and made some progress. However, for the study of the continuous erosion of the convex bank of the lower Jingjiang river bend after Three Gorges Reservoir was built, most scholars analyzed its factors from a macro perspective, and few scholars studied its internal mechanism. In this paper, through the combination of prototype data observation and physical model test, two bends with large difference in bend radius are selected to study, focusing on the internal reasons for the continuous erosion of the convex shore of the bend in Tiaoguan-Laijiapu. It can provide reference for river (navigation) road regulation, flood control and bank line utilization in this section, and enrich the concentration of riverbed evolution.

2. Basic condition of the study river reach

2.1. General situation of river reach

The Tiaoguan bend of the lower Jingjiang river arises from Nianziwan and goes down to Bashizhang, the length of the channel is about 27 km and Laijiapu bend is located in the lower reach of the Tiaoguan bend and down to the upper end of the Jianli bend (Figure 1). Research reach consists of three consecutive reverse bends: the Nianziwan bend, the Tiaoguan bend and the Laijiapu bend adjacent to the lower reach. It is a typical meandering channel with large lateral swing of the deep groove line and frequent bend bypassing and shoal cutting. From the end of 1960s to the beginning of 1970s, the upper
section of the Tiaoguan-Laijiapu bend has undergone natural bend cut off on the Shatanzi bend, the lower section has undergone artificial bend cut off on the Zhongzhouzi bend and the river regime has undergone drastic adjustment and the river has evolved dramatically. In recent decades, large-scale bank protection projects and river regime control projects have been implemented in lower Jingjiang river. The fluctuation amplitude of the river course has been significantly reduced, and the stability of the shoreline has been significantly enhanced. The free development before the construction of the reservoir has been transformed into restrictive development.

Figure 1. Location of the studied section

2.2. Channel boundary conditions
Part of the right bank of the reach is hilly terrace with strong anti-scouring ability, while the left bank is alluvial plain, and the bank is composed of lower sand layer and upper clay layer, which has poor anti-scouring ability. The riverbanks are mostly binary structures of modern river sediments, and the top elevation of the lower sand layer are higher, generally above the low water level, mainly medium and fine sand, with a thickness of more than 30 m; the upper part are the alluvial clay layer with a thickness of 3 ~ 14m, silty clay and silty loam are the main types and the scour resistance of riverbank is weaker than that of upper Jingjiang river. The lower Jingjiang riverbed is composed of medium-fine sand with a median particle size of about 0.165 mm, and the gravel layer is deep below the bed surface.

2.3. Channel water and sediment conditions
Before and after the construction of Three Gorges Reservoir, the water and sediment conditions in the lower reach of the dam have changed. Shashi and Jianli hydrological station are selected as the control stations for analysis. By analyzing the measured data of water and sediment from 1981 to 2017 at Shashi Hydrological station (Figure 2), it is found that the annual average runoff of Three Gorges Reservoir does not change significantly before and after the construction of Three Gorges Reservoir. The annual average sediment discharge tends to decrease from 1992 to 2002 before the construction of Three Gorges Reservoir and from 2003 to 2017 after the construction of Three Gorges Reservoir, the annual average sediment discharge decreases significantly. From Table 1, the annual average runoff of Shashi hydrological station decreases slightly after the construction of Three Gorges Reservoir, with a change rate of -5.95% (The multi-year average from 2003-2017 compared with the multi-year average from 1981-2002). The annual average sediment discharge of the Shashi hydrological station decreases significantly after the construction of Three Gorges Reservoir, and the sediment discharge change rate is -86.7% (The multi-year average from 2003-2017 compared with the multi-year average from 1981-2002). According to the measured data of Jianli Station from 1986 to 2016 (Table 2), before the
construction of Three Gorges Reservoir, the average median grain size of sediment in Jianli hydrological station is 0.009 mm (The multi-year average from 1986-2002) and after the construction of Three Gorges Reservoir, the average median grain size of sediment in Jianli hydrological station is 0.017 mm (The multi-year average from 2002-2016) and the proportion of sediment weight with particle size greater than 0.125 mm increases from 9.6% to 31.4% (The multi-year average from 1986-2002 to the multi-year average from 2002-2016) .To sum up, the reservoir impoundment has more impact on the downstream incoming water and sediment conditions, the main manifestation are reservoir sediment trapping, the amount of sediment coming from the lower reaches is greatly reduced and the sediment grain coarsening in the river channel is obvious.

![Annual runoff in Shashi](image1)

![Annual sediment discharge in Shashi](image2)

Figure 2. Average runoff and annual average sediment discharge amount from 1981-2017 in Shashi Hydrological Station

Table 1. Average annual runoff and sediment transport volume of Shashi hydrological station

| Year       | 1981-1991 | 1992-2002 | 2003-2007 | 2008-2017 | 1981-2002 | 2003-2017 |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Date (y)   | 1975      | 1980      | 1985      | 1990      | 1995      | 2000      | 2005      | 2010      | 2015      | 2020      |
Table 2. Sediment weight percentage and median grain size of different grain size classes at Jianli hydrological station

| Range     | \(d \leq 0.031\) (mm) | \(0.031 < d \leq 0.125\) (mm) | \(d > 0.125\) (mm) | Median particle size |
|-----------|------------------------|-----------------------------|--------------------|---------------------|
| 1986-2002 | 71.2                   | 19.2                        | 9.6                | 0.009               |
| 2003-2016 | 55.03                  | 13.57                       | 31.4               | 0.017               |
| Change in value | -16.17                 | -5.63                       | 21.8               | 0.008               |

3. Flow characteristics

3.1. Oscillating characteristics of stream power axis

According to previous studies, the swing characteristics of stream power axis in bend are closely related to the size of flow level and the curvature radius of bend channel. For the same bend, with the increase of flow level, the stream power axis swings to the convex bank of bend channel. For the same flow level, the axis trajectories of stream power axis are different in bend with different curvature radius. For bend with small curvature radius, the location of stream power axis is inclined to convex bank; For bend with large curvature radius, the location of stream power axis is inclined to concave bank. Relying on the Changjiang River Flood Control Model Hall, according to the "Rules for River Model Testing" and the requirements of the test concentrations, the physical model of 1/10000 river channel topography measured naturally in Tiaoguan-Laijiapu in 2002 was selected to study, and the swing characteristics of the stream power axis under different flow levels are drawn (Figure 3). Through the method of circle test, the curvature radius of the Tiaoguan bend is approximately 1062m, and the curvature radius of the Laijiapu bend is approximately 1524m. The bend degree of Laijiapu bend is relatively small, and the change of stream power axis is on the convex bank at the entrance of the bend, then gradually transfers to the concave bank, and reach the nearest point to the concave bank at the top of the bend. With the increase of flow level, the radius of stream power axis decreases gradually, the top impact point moves down gradually, showing a gradual trend towards the convex bank. At the position of the bend top, the swing amplitude is large and gradually closes at the exit of the bend. The bend degree of the Tiaoguan bend is relatively large, and the stream power axis shows different laws. The stream power axis is near the convex bank at the entrance of the bend channel, and gradually swings to the concave bank. Compared with the Laijiapu bend channel, the position of the top impulse point of the mainstream line moves downward, and the bend radius of the stream power axis is relatively small. With the increase of flow level, the bend radius of stream power axis decreases to a relatively large extent and the top impact point moves downward obviously, showing a sudden swing to the convex bank, with obvious swing at the upper end of the bend top, and gradually close at the lower end of the bend top. To sum up, the stream power axis in curved reach gradually swings from convex bank to concave bank with the increase of flow level. With the increase of curved degree of curved channel, it changes from progressive swing to mutational swing.
3.2. The flow level changes in days before and after Three Gorges Reservoir construction

After Three Gorges Reservoir impoundment, the upstream inflow is regulated and stored, and the frequency of different flow levels in the downstream of the dam has changed. The days of multi-year average flow levels in Shashi hydrological station are selected for analysis as shown in Table 3. According to the storage characteristics of Three Gorges Reservoir, the flow level changes in days of Shashi hydrological station are analyzed in four periods. Before the construction of Three Gorges Reservoir, periods are divided into 1981-1991 and 1992-2002. After the construction of Three Gorges Reservoir, periods are divided into 2003-2007 and 2008-2017. In addition to, 1981-2002 before the construction of Three Gorges Reservoir and 2003-2017 after the construction of Three Gorges Reservoir are analyzed. The results of the analysis show that the frequency of flow level changes significantly before and after impoundment of Three Gorges Reservoir. The main manifestations are that the frequency of maximum and minimum flow level decrease, the frequency of medium and small flow level increase. The frequency of flow below 5000 m³/s decreases gradually from the pre-impoundment period to the post-impoundment period. Shashi hydrological station decreases from 20.82% before impoundment (1981-2002) to 5.48% after impoundment (2003-2017). The frequency of 5 000 m³/s-15 000 m³/s discharge increases significantly. Shashi hydrological station increases from 45.75% before impoundment (1981-2002) to 67.4% after impoundment (2003-2017). The frequency of 15 000 m³/s-30 000 m³/s discharge before and after impoundment does not change significantly, before impoundment
(1981-2002) is 27.26% and after impoundment (2003-2017) is 24.74%. The frequency of discharge above 30 000 m³/s decreases from 1981-2002 to 2003-2017. The frequency of discharge at Shashi Station decreases from 6.13% before impoundment (1981-2002) to 2.41% after impoundment (2003-2017). The oscillating characteristics of the stream power axis indicate that the frequency of small flow level decreases after Three Gorges Reservoir impoundment, the time of the stream power axis on the concave bank of the bend is reduced, the stream power axis oscillates from the convex bank provides a dynamic condition for the continuous erosion of the convex bank.

Table 3. The number of days changes at different flow levels in Shashi hydrological station

| Jingjiang Flow level (m³/s) | 0-5000 | 5000-10000 | 10000-15000 | 15000-20000 | 20000-25000 | 25000-30000 | 30000-35000 | 35000-40000 | >40000 |
|-----------------------------|--------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|--------|
| 1981-1991(d)                | 83     | 104         | 50          | 50          | 34          | 21          | 14          | 6          | 4      |
| 1992-2002(d)                | 69     | 117         | 65          | 51          | 26          | 8           | 5           | 7          |        |
| 2003-2007(d)                | 51     | 150         | 62          | 49          | 26          | 12          | 8           | 7          | 1      |
| 2008-2017(d)                | 4      | 180         | 84          | 53          | 27          | 13          | 4           | 1          | 0      |
| 1981-2002(d)                | 76     | 110         | 57          | 50          | 30          | 19          | 11          | 6          | 6      |
| 2003-2017(d)                | 20     | 170         | 76          | 51          | 27          | 13          | 6           | 3          | 0      |

4. Evolution characteristics of Tiaoguan-Laijiapu bend

4.1. Changes in evolution characteristics of Tiaoguan - Laijiapu bend

The Tiaoguan bend section is a dangerous area which is famous in history. Its main stream transits from this section to the Baishizhang section, then to the downstream Laijiapu bend. From 2000 to 2001, the key embankment concealment project of the Changjiang river carried out the reinforcement and transformation of the original revetment project from the Tiaoguan to the Baishizhang section. Since 2008, the bend section of Tiaoguan has been affected by the bend cutting beach, which caused the erosion and collapse of the upper part of the bend convex bank and widened the lower part of the bend convex bank year by year. The 25 m shoreline on the left bank in 2016 is about 130 m larger than that in 2002. In the transition section of the bend entrance, the mainstream falls, the top impact point of the bend mainstream moves down, and the deep trench gradually swings to the convex bank. After 2008, due to the phenomenon of bend bypassing and shoal cutting of the Laijiapu bend section, the convex bank of the entrance to the right bank of the corner was washed away and retreated. In 2016, the 25m coastline in 2016 is about 380m larger than the largest collapse in 2002. The lower part of the right bank of the bend correspondingly becomes silted and widened year by year. In 2016, the 25m shoreline is about 200m larger than the largest siltation in 2002. After Three Gorges Reservoir impoundment, from 2002 to 2016, the Tiaoguan-Laijiapu reach is mainly affected by the change of incoming water and sediment, the main manifestations are scouring, beach scouring and deep channel siltation and scouring in the transition section of bend. The large variation of the scouring and silting range is still mainly concentrated in Tiaoguan bend section. The maximum scouring depth is about 13m, and the maximum sediment thickness is about 18m (Figure 4). At the same time, the river trough gradually deepens and widens, and the deep ditch also swings from the entrance of the Tiaoguan section to the exit of the Laijiapu section along the direction of the convex bank. The phenomena of scouring on convex bank and silting on concave bank are very obvious in the two bend sections of Tiaoguan and Laijiapu. The main difference is that the phenomenon of Tiaoguan is "convex scouring, concave silting" at the upper of the bend top, while the phenomenon of Laijiapu bend is more obvious at the top of the bend.
4.2. Cross Section Change of Typical Bend
Before the construction of Three Gorges Reservoir, the flow and sediment concentration during the flood period are large, and the water level of the floodplain and bank-full water flow are high and water surface gradient is small. Due to the influence of the river channel shape, the beach and deep trough are in a silt state. In dry season, the flow and sediment concentration are small, but the water level is low and water surface gradient is large. The radius of the flow power axis of the return channel is small, which causes the deep channel of the bend produce greater erosion. Then, the riverbed of the bend is mainly manifested in the transverse deformation, namely, the concave bank keep scouring and the convex bank keep silting and the bend top keep moving downstream. In the variable process of frequent collapse of the concave bank and silting of the convex bank, the river length gradually increased. After the construction of Three Gorges Reservoir, the water and sediment conditions changed, and the Laijiapu bend occurs the phenomenon of bend bypassing and shoal cutting, and the concave bank begin to produce silting, the concave shore began to silt up, the convex bank is scoured, and the channel deep groove is gradually transferred to the convex bank, but the cross section of the river is still V-shape (Figure 5-a). Before the construction of Three Gorges Reservoir, the evolution law of Tiaoguan bend is similar to that of Laijiapu bend, namely, the concave bank is washed the convex bank is silted. After the
construction of Three Gorges Reservoir, the phenomenon of "convex bank erosion and concave bank deposition" begin to appear in the Tiaoguan bend section, and this phenomenon intensified as the water and sediment conditions changed with the storage of Three Gorges Reservoir. At the Tiaoguan bend section, the convex bank is scoured, and the concave bank is silted and the near shore central bank is formed on the concave bank. The bend channel is widened and the cross section of the river of the bend section changes from V-shape to W-shape (Figure 5-b).

![Figure 5. Cross section in typical position of Tiaoguan-Laijiapu bend](image)

5. Atypical evolution mechanism of convex bank in typical bends
Riverbed evolution is the mutual adaptation and development of riverbed and water and sediment conditions. When the water and sediment conditions change, the riverbed will make adjustments to adapt to this change. Taking the bend reach of Jingjiang river in the lower reach of Three Gorges Reservoir as an example, the runoff of the reach has not changed significantly before and after the construction of Three Gorges Reservoir, but the flow process has changed significantly. The main manifestation is that after the construction of Three Gorges Reservoir(5000-20000m³/s), the time of water flow level increases, and the time of large and small water flow level (>35000m³/s, <5000m³/s) decrease. According to the research on the flow and power axis of Tiaoguan-Laijiapu bend, when the flow level is small, the stream power axis of the inlet section of the bend or the upper section of the bend leans to the side of the convex bank of the bend. After entering the bend, the stream power axis gradually transfers to the concave bank. At the top of the bend, the stream power axis leans to the concave bank,
and the stream power axis is close to the concave bank within a considerable distance below the main flow point. When the flow level is relatively small, the stream power axis goes down the concave bank, but with the gradual increase of the flow level, the stream power axis gradually deviates from the concave bank to the convex bank. Under natural conditions, when the upstream and downstream river regime do not change greatly, the convex bank is in the state of slight silt. However, with the impoundment of Three Gorges Reservoir, the sediment concentration of water flow has been greatly reduced. In addition, due to the regulation reasons, the duration of reclaimed water has increased. On the one hand, the salient shore of the bend section has been eroded due to the dramatic reduction of sediment supply, on the other hand, the erosion force of the salient shore has been increased with the increase of the middle water duration in the year. The curvature radius of bend river section influences the swing of stream power axis. For the Tiaoguan bend, the curvature radius is small, and the stream power axis swings violently at the upper section of the bend, which shows an abrupt swing. Therefore, the erosion is most serious at the convex bank at the upper of the bend, and the channel section changes from V-shape to W-shape. However, in the Laijiapu bend, the curvature radius is large, and the maximum swing amplitude of the stream power axis is at the top of the bend, but it swings gradually, so the erosion is most serious at the convex bank at the top of the bend. Because the sediment inflow from upstream of the Three Gorges Reservoir decreases greatly after impoundment, the sediment concentration of the current cannot meet the sediment carrying capacity of the current. In order to meet the sediment carrying capacity of the current, the current scours the riverbed. Consequently, the convex shore suffers cumulative erosion and the beach of convex shore keeps collapsing.

6. Conclusion
By analyzing the characteristics of water and sediment movement and riverbed evolution in the bend channel of the Tiaoguan-Laijiapu reach under the changing environment, the main conclusions are as follows:

(1) Before and after the construction of Three Gorges Reservoir, there is no significant change in the runoff. But the runoff process changed greatly in the downstream reach and the sediment inflow decreases significantly. The frequency change of flow level in different time periods is obvious, and the main manifestation is the reduction of large flow level and small flow level, while the middle water flow level increases. The radius and swing position of the stream power axis are closely related to the size of the flow. After the construction of Three Gorges Reservoir, the flow level of the middle water increases, and the position and action time of the stream power axis change, providing a dynamic condition for the cumulative erosion on the convex bank of the bend channel in the Tiaoguan-Laijiapu river section.

(2) The convex bank of the Tiaoguan-Laijiapu bend suffers cumulative erosion, the channel is scoured downward and the river channel is widened. Because of the different curvature radius and shape of the bend, convex bank at the upper section of the Tiaoguan bend is scoured more intensely and the section of the river changes from V-shape to W-shape; and the erosion of the convex bank at the top of Laijiapu bend is more intense, and the section of the reach is still V-shape.

(3) After impoundment of Three Gorges Reservoir, the sediment inflow decreases dramatically, and the sediment concentration of the flow is seriously sub-saturated, so scouring the riverbed to satisfy the sediment carrying capacity of the water flow. Therefore, the main factor of atypical evolution of the convex bank of the bend channel is the change of the upstream environment and the substantial reduction of the sediment inflow.

(4) Bend channel exists widely in many rivers with different shapes. The influence of curvature radius of bend channel on its stream power axis radius has not been found regularly, which is a direction of future research.

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