Study on the Stretching Mechanism of the lower Reach of the Distribution Estuary of Alluvial River after Lateral bypass flow-Taking Jingjiang Reach of the Yangtze River as an Example

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Abstract: After diversion, alluvial rivers tend to widen in local areas downstream of diversion ports. The flow is dispersed and the main stream changes in a year are complex, which has a great impact on flood control, navigation and water intake. Taking the Jingjiang reach in the middle reaches of the Yangtze River as an example, according to its historical development, this paper describes the variation of the river regime in the downstream of the diversion ports. Based on the analysis of a large number of measured water and sediment data and the boundary conditions of Jingjiang reach, the characteristics of flow movement in the diversion port reach are studied by combining the solid model test. It is found that after river diversion, the distributary morphology of water flows along the river section changes, and the mainstream develops from concentration to dispersion, and the flow of river diversion will change with the variation of channel flow. Generally speaking, in dry season, because of the small diversion volume, the main stream downstream of the diversion port is far from the diversion port, while in flood season, the diversion volume increases, and the main stream affected by the suction of the diversion port is often close to the diversion port, which causes frequent changes of the main stream downstream of the diversion port in the year. In addition, when the mainstream develops from centralization to dispersion, the riverbank will be eroded by water flow, and the mechanical properties of the riverbank soil will change, and the riverbank gradually loses stability and subsequently collapses. The main reason for the widening in the lower reaches of the diversion estuary is a comprehensive effect due to the changes of the distributary morphology and the main stream position caused by the diversion and the geological conditions of the channel.

1. Introduction

For a long time, the evolution of Jingjiang River has been concerned by many scholars. There are several diversion ports in Jingjiang reach. The water and sediment in the main stream of Jingjiang reach distribute into Dongting lake by diversion port, while Dongting lake enters into the Yangtze River through Xiang, Zi, Yuan and Li rivers in Chenglingji [1,2]. Therefore, the diversion port of Jingjiang reach is an important link between Dongting lake and the Yangtze River. It not only has an important impact on the water and sediment conditions of Dongting lake, but also plays an important role in the evolution of the river bed downstream of the diversion port [3,4]. The relationship between the river and the lake is very complex. In recent years, researchers have found that the evolution of the
lower reaches of the diversion port is intense, which has a great negative impact on channel regulation, flood control and disaster reduction. Although many scholars have done some research on the river bed evolution in the lower reaches of the diversion port after water flow and sediment diversion, there is no comprehensive study on the internal mechanism of channel widening in the lower reaches of the diversion port. In this paper, the mechanism of channel widening in the lower reaches of the diversion ports of Jingjiang River are studied, which can provide reference for flood control and disaster reduction, river regulation and channel improvement in Jingjiang River, and also has an important reference value for the study of other similar river sections.

2. Historical evolution of the distribution estuary section of Jingjiang river

2.1. Summary of the historical evolution of Jingjiang reach

The development of the ancient Yangtze River began at the end of the Tertiary and continued to the Himalayan period. The rising of the Qinghai-Tibet Plateau has changed the circulation situation in the lower atmosphere. As the establishment of the monsoon belt in eastern China, the climate in most areas of the Yangtze River basin has changed from drought and heat to warmth and humidity, with abundant precipitation. Under these conditions and such terrain, the runoff in the basin increases, and the function of river bed-building is greatly enhanced, resulting in the formation of a unified and coherent Yangtze River [5]. According to the $^{14}$C dating of drilling samples, the age of the formation of the ancient Jingjiang river is about 40000 years ago [6]. From the Pre-Qin Dynasty to the present, the diversion of Jingjiang River had been changing constantly. There were three branches of Jingjiang River in the Pre-Qin Dynasty. Among them, Xia Shui flowed eastward and Qianjiang Longwan entered Yun-meng lakes and Yongshui from the south branch of Shashi city to the southeast to the present Shagang area injects Yun-meng lakes. Another branch joins with Hanshui to enter Yun-meng lakes north of Shashi city. During the Han, Jin, Southern and Northern Dynasties, according to the annotation of Shuijingzhu of Lidaoyuan, there were 24 distributors of Jingjiang River in the Eastern Jin and Southern Dynasties, and 16 distributors under Chenglingji. During the Tang and Song Dynasties, Yun-meng lakes disintegrated, and after the Song and Yuan Dynasties, Jingjiang hole became thirteen holes of nine holes and during the Yuan and Ming Dynasties, Jingjiang main road began to build its own bed. From Qing Dynasty to modern times, there were four distributaries in the south of Jingjiang River. From ancient to modern, they were Tiaoxiankou, Taiping Kou, Ouchikou and Songzikou, respectively. In 1958, the Tiaoxiankou was gradually abandoned. Since modern times, the main characteristics of the historical evolution of the lower Jingjiang River were as follows: bend concave bank collapse, convex shore beach silt long, when the bend develops to a certain shape, in the event of a larger flood year, it was easy to occur bend bypassing and shoal cutting or natural cutting-off bend. After the bend was cut and straightened, the river course developed into a new bend, which caused great changes in the river regime downstream. The regulation of sediment transport and riverbed erosion and siltation in the upper Jingjiang River was basically balanced by the middle of the 20th century due to the construction of dykes on both sides of the upper Jingjiang River, the blockage of caves, the formation of Songzikou, Taipingkou and Ouchikou diversion channels. The plane shape and beach pattern of the upper Jingjiang River were basically unchanged. The displacement of the main stream, the ebb and flow of the beach and the alternation of the main branches were frequent. The main characteristics of the river evolution were the collapse of concave bank in the bend, the long siltation of the salient bank and the possible cut-off of the current into a river center or a river center beach. The position of main branches in bends with central bar was relatively stable for a long time, such as Guansandbar, Dongshi sandbar, Jiangkou sandbar, Huojian sandbar and Mayang sandbar. Only the main branches of Sanba beach, Jincheng sandbar and Tuqi sandbar have alternated. The historical Changes of Jingjiang River is shown in Figure 1.
2.2. Formation and historical change of the three Jingjiang estuaries

Due to the long-term interaction between water flow and riverbed, Jingjiang reach evolved into four distributaries in modern times. Water and sediment in the main stream converged into Dongting lake through the four rivers and into the Yangtze River from Dongting lake in Chenglingji, forming a complex river-lake relationship. Taipingkou is the entrance of Hudu River into the lake. Hudu River was formed in Renzong period of Northern Song Dynasty (1023-1063). It had been shrunk and dredged many times in history. Ouchikou is the entrance of the Ouchihe River into the lake. It was built during the Song and Ming Dynasties. In the 39th year of Jiajing (1560), Ouchikou was formed. Songzikou is the entrance of Songzi River into the lake. Nine years after Tongzhi reign of Qing Dynasty (1870), Songzikou River burst and formed Songzikou. The variation of maximum diversion volume in each diversion port is shown in Table 1 (the figures in brackets in the table are statistical years). From the analysis of Table 1, it can be seen that since the formation of the four diversions in Jingjiang River, the maximum diversion volume of each diversion port has been decreasing continuously since the 1930s. Historically, due to the great influence of diversion on the river course, the lower reaches of the diversion estuary evolved dramatically and the river course widened continuously. In modern times, with the construction of Jingjiang revetment project, the trend of widening has been alleviated, and the channel changes in the lower reaches of the diversion estuary are shown in Figure 2.
a. Historic changes of rivers near Songzikou

b. Historic changes of rivers near Taipingkou
2.3. Characteristics of river regime changes in the downstream of the diversion port

After the formation of the diversion estuary, the water and sediment conditions had changed. The process of flow factors such as discharge, gradient, velocity and sediment carrying capacity in the lower reaches of the diversion estuary adapting to the riverbed also changed comparing with that in the upper reaches of the diversion estuary [7]. The river regime in the lower reaches of the diversion estuary has been adjusted one after another, mainly manifesting in the widening of the channel in the lower reaches of the diversion estuary (Table 2), the increase of bending degree of river bends, shallow shoals or river centers were formed in the river course, and the mainstream line swung frequently, forming multi-channel development. Recently, due to the implementation of the revetment project of the upper Jingjiang River, the changes of the riverbank have been controlled [8]. However, in the lower reaches of the diversion estuary, the mainstream swings greatly, and the river regime still appears to be adjusted. When the diversion estuary is located on the convex bank of the river, the sediment deposition at the entrance is serious due to the circulation movement of the bend channel, resulting in the decrease of the diversion, which has a relatively small impact on the evolution of the downstream river; when the diversion estuary is located on the concave bank of the river, the sediment deposition at the entrance is less. As a result, there are more diversions, which have a relatively large impact on the evolution of the lower reaches of the river. Figure 3 shows the Jingjiang River regime.

Table 1. Variation of maximum diversion volume in each diversion port in a year

| Year and Maximum Flow (m$^3$/s) | Diversion port | Songzikou | Taipingkou | Ouchikou |
|---------------------------------|----------------|-----------|------------|----------|
| 1938 | 12300 | 4150 (1926) | 18900 (1937) |
| 1954 | 10180 | 3240 (1948) | 14800 (1954) |
| 2017 | 2410 | 730 (2017) | 720 (2017) |
Table 2. Channel width at upstream and downstream locations of diversion estuary

| Section | D2   | D3   | D5   | J12   |
|---------|------|------|------|-------|
| Songzikou | 998.7 | 1292 | 2319.5 | 2006.7 |

| Section | J30 | J31 | J32 | J33 |
|---------|-----|-----|-----|-----|
| Taipingkou | | | | |
| River width (m) | 1355 | 1397 | 1541 | 1565 |

| Section | J84 | J85 | J89 | J90 |
|---------|-----|-----|-----|-----|
| Ouchikou | | | | |
| River width (m) | 990.4 | 1172 | 1397 | 2441 |

Figure 3. Location diagram of three ports

2.4. Recent evolution characteristics of the river section near the diversion estuary

The reach near Songzikou is located at the upper end of the upper Jingjiang River. It is the transitional section from the sandy pebble channel downstream of the Three Gorges Reservoir to the sandy channel. There is a slight bend of Lujia River near the reach and a moraine dam at the centre of Lujia River in the channel. Before the impoundment of the Three Gorges Reservoir, from 1986 to 2002, the main stream of the Songzikou had been washed out, and there was some siltation at the port. The sediment in the Lujia River was silted up, and the maximum siltation thickness was close to 10m. After the impoundment of the Three Gorges Reservoir, from 2002 to 2016, the nearby reach showed the trend of scouring downward cutting [9]. Near the Songzikou, the downward cutting range of the riverbed was more than 10 m. The intensity of sediment scouring in Lujia reach was great and the moraine dam in the middle of the river was slightly silted.

The reach near Taipingkou is located in the middle section of the upper Jingjiang River, which belongs to the slightly curved braided reach. There are many beaches nearby, such as the Taipingkou beach, Sanba beach, Jinchengzhou and Lalinzhou. The north branch of Hudu river had been seriously...
silted up. From 2002 to 2016 after impoundment of the Three Gorges Reservoir, the reach was affected by incoming water and sediment. It was characterized by beach erosion and deep channel siltation, mainly scouring. Most of the silted areas before impoundment of the Three Gorges Reservoir turned to scouring and the scouring areas still basically maintained the trend of scouring. Frequent oscillation of the main stream in the river, mutual fluctuation of the beach and the alternation of the rise and fall of the branching channels were the main characteristics of the river changes near the Taipingkou.

The reach near the Ouchikou is located at the tail of the upper Jingjiang River and the beginning of the lower Jingjiang River. The upper reaches of the Ouchikou are relatively straight, and widening gradually near the Ouchikou. The lower reaches of the Ouchikou are Shishou bend section. Before impoundment of the Three Gorges Reservoir, there was a slight scouring in 1995-2003. After impoundment of the Three Gorges Reservoir, there was a strong scouring in 2003-2016, with a scouring amount of $4.42 \times 10^6$ m$^3$. From 2016 to 2017, there was a slight scouring amount of $4.9 \times 10^5$ m$^3$. From 1987 to 2002, before impoundment of the Three Gorges Reservoir, the lower reaches of the estuary were generally silted up, and the change of scouring and silting thickness was mainly concentrated in the bend section. Among them, at the near shore of Shishou city, the sediment deposited continuously. Because of the influence of human activities and the change of water and sediment condition in the upstream, the maximum thickness of sediment deposits was about 30m, and the maximum scouring depth was about 25m. In addition, there were obvious scouring and silting near Tianxingzhou. From 2002 to 2016, the lower reaches of the Three Gorges Reservoir were affected by incoming water and sediment, which showed that beach scouring and deep channel siltation, mainly scouring. The most varied scouring depth was still in the vicinity of Shishou city, with the maximum scouring depth of about 22m. After the impoundment of the Three Gorges Reservoir, the scouring intensity of the channel was further increased, and the beach body on the convex bank of the bend was also in the scouring state [10]. Deep changes before and after the construction of the Ouchikou section as shown in Figure 4.

In summary, the upstream channel of the diversion estuary basically develops in a straight and slightly curved way. After diversion, the channel widens, sediment falls and silts in the channel, gradually forming the river-centre continents. The channel develops in a branching way. Under natural conditions, the boundary conditions are poor in scouring resistance, and the channel develops in a wide and shallow direction. In recent decades, after boundary protection, the scouring resistance has increased, the river widening is alleviated, the change of river pattern is relatively stable.

![Figure 4](image_url). Deep changes before and after the construction of the Ouchikou section
3. Water and sediment conditions in diversion estuary reach

3.1. Flow conditions

Since the 1950s, the Jingjiang reach has experienced major water conservancy events, such as the cutting of the lower Jingjiang River, the construction of the Gezhou dam and the Three Gorges Reservoir in the upper reaches. These projects have exerted varying degrees of influence on the water flow and sediment diversion of the three Jingjiang estuaries. In order to analyze and study the rule of water flow and sediment diversion in three estuaries, this paper divides the 60 years since 1956 into five periods according to the major water conservancy activities of human beings. The first stage is 1956-1966 (The period before the bend of lower Jingjiang River was cut); the second stage is 1967-1972 (The Cutting Period of Zhongzhouzi, Shangchewan and Shatanzi in lower Jingjiang reach); the third stage is 1973-1980 (The Period from the cut-off of lower Jingjiang River to the closure of Gezhou dam); the fourth stage is 1981-2002 (The Period from the closure of Gezhou dam to the Pre-impoundment of the Three Gorges Reservoir). The fifth stage: after 2003 (after the Three Gorges Reservoir impoundment operation). The flow and sediment of the three diversion estuaries are mainly from the upper reaches of the Yangtze River. These flow and sediment mainly converge into Dongting lake from may to october. The flow and sediment in this period accounted for more than 90% of the total flow in the whole year. According to the observation data of five control stations at the entrance of three diversion estuaries (Table 3), since 1956, the diversion attenuation speed of the three diversion estuaries is the fastest in the lower Jingjiang River cutting period and the later period of cutting, and the diversion attenuation amplitude of the Ouchikou is the largest (the diversion ratio of the third stage of the Ouchikou is only 40% of the first stage), while that of the Songzikou and Taipingkou is in a continuous slow atrophy.

| Period       | Zhicheng | Songzikou | Taipingkou | Ouchikou | Total of three terms |
|--------------|----------|-----------|------------|----------|----------------------|
|              | Σ Split ratio (%) | Σ Split ratio (%) | Σ Split ratio (%) | Σ Fractional flow Split ratio (%) |
| 1956~1966    | 4525     | 485.2     | 209.7      | 4.6      | 636.8                | 1332 | 29.4 |
| 1967~1972    | 4302     | 445.4     | 185.7      | 4.3      | 390.2                | 1022 | 23.8 |
| 1973~1980    | 4441     | 427.5     | 159.9      | 3.6      | 246.9                | 834.6 | 18.8 |
| 1981~2002    | 4441     | 370.8     | 132        | 3        | 182.5                | 685.3 | 15.4 |
| 2003~2017    | 4146     | 290.1     | 83.87      | 2        | 105.9                | 479.8 | 11.4 |

Note: No measured discharge and sediment transport data are found in Zhicheng from 1956 to 1991. The sediment inflow from water and sediment inflow are superimposed by Yichang and Changyang hydrological station in the same period.

3.2. Sediment conditions

Table 4 shows the changes of the amount and ratio of sediment distribution of the three branches in each period from 1956 to 2017. Statistical results show that the average annual sediment inflow in Zhicheng during the fifth stage decreased by 92.2% compared with that in the first stage from 1956 to 2017, while the total sediment distribution in the three estuaries decreased from 19600 ×10^4 t in the first stage to 870 ×10^4 t in the fifth stage, with a decrease of 95.6%. In the four stages before the impoundment operation of Three Gorges Reservoir, the sediment distribution ratios of Songzikou,
Taipingkou and Ouchikou all decreased during the time period, among which the Ouchikou decreased greatly. During the cutting period of lower Jingjiang River and before the closure of Gezhou dam, the amount and ration of sediment diversion at the Ouchikou decreased rapidly. Since the operation of the Three Gorges Reservoir in 2003, the sediment diversion ratio of Songzikou and Ouchikou has increased compared with the fourth stage except that of Taipingkou, and the increase of the sediment distribution ratio of Songzikou and Ouchikou is larger than that of the fourth stage. Among them, Songzikou increases greatly.

Table 4. Statistical tables of sediment yield and sediment diversion ratio in each period of three estuaries unit: 10⁴t

| Period       | Zhicheng | Songzikou | Taipingkou | Ouchikou | Total of three terms |
|--------------|----------|-----------|------------|----------|---------------------|
|              | Σ Sediment diversion ratio (%) | Σ Sediment diversion ratio (%) | Σ Sediment diversion amount (%) | Σ Fractional flow | Sediment diversion ratio (%) |
| 1956~1966    | 55300    | 5350      | 9.7        | 2400     | 11800               | 21.3 | 19600 | 35.4 |
| 1967~1972    | 50400    | 4850      | 9.6        | 2130     | 7220                | 14.3 | 14200 | 28.2 |
| 1973~1980    | 51200    | 4710      | 9.2        | 1940     | 4430                | 8.7  | 11100 | 21.7 |
| 1981~2002    | 46400    | 4150      | 8.9        | 1530     | 2980                | 6.4  | 8660  | 18.7 |
| 2003~2017    | 4340     | 462.3     | 10.7       | 121      | 284.6               | 6.6  | 870   | 20   |

4. Boundary conditions of divergent estuary reaches

4.1. Boundary material composition

The section from Zhicheng to Jiangkou is the transition from low hilly area to alluvial plain area. Because the two sides are mostly controlled by low mountains and hills, the riverbanks are relatively stable. The river bed overburden is mainly composed of sand, gravel and pebble, and the average thickness is about 20-25m. The underlying layer is bedrock. Most of the beaches are covered by gravel and pebble, and there are also coarse and medium sand falling and silting. Most of the banks from Jiangkou to Ouchikou are alluvial plains, as well as lake terraces, denuded hills and river terraces and floodplains. The riverbank is composed of pebbles, sand and clayey soil. The lower pebble roof inclines downstream with a slope of about 0.2%. The middle sand roof has a lower elevation and is generally below the low water level. The lower Jingjiang River begins at the Ouchikou and part of its right bank is hilly terrace, which has relatively strong anti-scouring ability; 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 composition of riparian soil in Jingjiang reach can be roughly divided into two types, namely, three-layer structure and two-phase structure. The structure of Zhicheng to Jiaoziyuan is roughly three layers, in which the structure above Songzikou is composed of three layers of soil-gravel-rock, and the structure below Songzikou is composed of three layers of soil-sand-gravel. Jiaoziyuan is mainly composed of two-phase structure, which is bounded by the Ouchikou. In the channel above the Ouchikou, the upper cohesive soil layer is relatively thick (generally 7-17m) and mainly consists of silty loam with clay and sandy loam. In the channel above the Ouchikou, the upper cohesive soil layer thickness decreases and the scouring resistance decreases. In summary, the impact resistance from the upstream to the downstream showed a weakening trend. The two-phase structure of the upper Jingjiang reach is significantly different from that of the lower Jingjiang reach, as shown in Figure 5.
4.2. Mechanical properties of boundary structures

The mechanical characteristics of the river bed boundary conditions are mainly related to the composition of the material of the river bank boundary, the shape of the river bend, the ratio of the river bank slope and the flow intensity acting on the river bank. The material of riverbank is different, the cohesive force, the angle of friction repose and the angle of internal friction are different. Table 5 is the physical index of the material of riverbank at the typical position of Jingjiang reach. The pressure of riverbank soil and flow resistance are different due to the different geometry of river bend and slope ratio. Under the force of water flow, the riverbank is eroded and the slope foot is washed deep. In addition, the leakage and piping caused by the difference between river water level and underground water level lead to the thinning of cushion layer, which leads to the loss or reduction of supporting force of soil on the upper riverbank, and finally causes riverbank collapse. In summary, the analysis of the mechanical characteristics of the river bank boundary can be summed up as hydrodynamic analysis and soil mechanics analysis. Combining hydrodynamic analysis with soil mechanics analysis on the basis of mechanics mechanism analysis is an ideal method to study the characteristics of river boundary and river bed evolution. When the riverbank collapses, the relevant mechanical parameters and flow conditions of riverbank soil will change accordingly. Therefore, the analysis of its coupling mechanism is the key to study the mechanical characteristics of riverbed boundary and riverbed evolution.

Songzikou and Taipingkou are located in the upper Jingjiang reach. The two banks are mainly of dual structure, with the upper layer of sticky soil and the lower layer of non-sticky soil. The upper layer of cohesive soil is 7-17m thick, and the lower layer of non-cohesive soil is 3-10m thick, and the roof elevation of lower layer is generally below the high-water level. The whole river bank slope is relatively large. Under the action of water flow, cracks first appear on the top of the river bank, and the upper material gradually slides down along the arc or plane forming a collapse pit. The Ouchikou is located at the beginning of the lower Jingjiang River. The upper part of the lower Jingjiang River bank is composed of clay. The soil layer is thinner, about 5 m thick, and the lower part is composed of sand. The soil layer is thicker, usually more than 30 m. Sandy soil is weak in scouring resistance. Under the action of water flow, the lower layer of sandy soil is eroded forming steep bank and high slope, resulting in collapse around the axis. Before 1990, there was no large-scale revetment project in the Jingjiang River. After the diversion of the three estuaries, the lower reaches of the estuary continued to collapse and the channel gradually widened. This indicates that, under the action of water flow, the difference of soil material, shape of river bend and slope ratio of bank will lead to the difference of force, direction and collapse mode of bank soil. Based on the analysis of the mechanical properties of
the materials along the banks of Jingjiang River, it is found that although there are different ways of bank collapse between the upper and lower Jingjiang rivers, the banks collapses under the action of water flow, which provides a precondition for channel widening.

Table 5. Physical indicators of the bank material of the Jingjiang River

| Reach         | Layering     | Name of soil sample | Physical Indicators | Shear strength |
|---------------|--------------|----------------------|---------------------|----------------|
|               |              |                      | Wet density (t * m⁻³) | Water content (ω) | Void ratio (e) | Saturation (S/a) | Dry density (p_d * t * m⁻³) | Cohesive force (c) | Internal friction angle (Ψ) |
| Upper Jingjiang River | The first layer | Sandy silt | 1.49 | 15.3 | — | — | 1.3 | — | — |
|               | The second layer | Low liquid limit clay | 1.89 | 29 | — | — | 1.46 | 18.9 | 31 |
|               | The third layer | Sandy silt | 1.629 | 25 | — | — | 1.3 | — | — |
| lower Jingjiang River | The upper layer | Low liquid limit clay | 1.86 | 32.9 | 0.934 | 95.2 | 1.4 | 9.3 | 31 |
|               | The lower layer | Fine-grained sandy soil | 1.44 | 6.2 | — | — | 1.36 | — | — |

5. Experimental study on flow characteristics of diversion estuary reach

In order to study the velocity distribution of the upper and lower sections of the diversion estuary in detail, the fixed-bed test was carried out in the Yangtze River Flood Control Model Hall of the Jianghu Regulation Laboratory of the Ministry of Water Resources. The horizontal scale of the model is 1:400, and the vertical scale is 1:100. The model satisfies the conditions of geometric similarity and flow movement similarity.

5.1. Model test condition

According to the content of the experiment research and the need of the tail gate control of the model, the scope of the model test of upper Jingjiang is about 200 km from Zhicheng to Beinianziwan. The initial topography of the model adopt the 1:10000 underwater and shore topography of the upper Jingjiang River measured in October 2002. The test inlet flow is controlled by the sum of the measured flow in Shashi, Songzikou and Taipingkou. The downstream water level control station is Shishou gauging station. The three diversion control stations are five hydrological stations located in Xinjiangkou, Shadaoguan, Mituo Temple, Kangjiagang and Guanjiapu respectively. The test conditions are shown in Table 6 and the test arrangement at the diversion port is shown in Figure 6.

Table 6. Fixed bed test conditions

| Shashi Flow (m³/s) | 5500 | 12500 | 32000 | 50000 |
| Songzikou diversion Flow (m³/s) | 20 | 700 | 4040 | 8700 |
| Ouchikoukou diversion Flow (m³/s) | 0 | 250 | 1340 | 2800 |
| Taipingkoukou diversion Flow (m³/s) | 0 | 240 | 2090 | 6150 |
| Model Inlet Flow (m³/s) | 5520 | 13450 | 37380 | 61500 |
5.2. Distribution of cross-section velocity in upstream and downstream reach of diversion estuary

In the fixed-bed model test, the velocity of the typical sections on the upper and lower reach of the diversion estuary was measured. At three locations of Songzikou, Taipingkou and Lotus Pond Kou, six typical sections of D2 and J12, J30 and J33, J84 and J85 are selected for comparison (Figure 7, 8, 9). From the analysis of the velocity distribution in the upstream and downstream of Songzikou, Taipingkou and Ouchikou in (Figure 7, 8, 9). It can be seen that the mainstream develops from single concentration to bifurcation and flatness in the process of widening from narrow to wide, and its position gradually wobbles to both sides of the strait. The mainstream position varies under different flow conditions, which is gradually developing towards the shore from upstream to downstream of the diversion estuary with the increase of flow level. This phenomenon may be caused by the attraction of the diversion port to the mainstream. This change in the mainstream leads to an increase in the near-shore velocity, which leads to a gradual increase in the sediment carrying capacity of the near-shore flow, and a gradual enhancement of the erosion capacity, which eventually leads to the gradual erosion and collapse of the riverbank.
Figure 7. Flow velocity distribution of the upper and lower sections of Songzikou
Figure 8. Flow velocity distribution of the upper and lower sections of Taipingkou
6. Stretching mechanism of lower distributary channel

Generally, the effects of lateral channel stretching can be divided into two categories: alluvial effects caused by water and sediment movement, including channel collapse caused by water erosion and channel widening caused by Non-water and sediment movement, including channel collapse, seepage, piping, wind wave and sand removal. In the upstream of the diversion estuary, the main stream is concentrated, and after the diversion estuary, the main stream is dispersed and fragmented. With the increase of flow, the main stream gradually swings to both sides of the river, and the bank is scoured. In Songzikou, Taipingkou and Ouchikou reach, the two banks are mainly dualistic structures, which consists of clay, non-clay and sandy soils of different thicknesses. Riverbank soils are different in composition, and their mechanical characteristics are different when they begin to move under the action of certain factors. Generally speaking, for clay riverbanks, they are subjected to the thrust, uplift force, effective gravity and intergranular cohesion of the water flow acting on the bank wall. For non-cohesive riverbanks, the effect of intergranular cohesion can be neglected, and the scouring force of the water flow is the main driving force to start the material of riverbanks. When the riparian soil collapses caused by piping, seepage, wind and wave, the main factors affecting the process of riparian
collapse are related to the physical properties of riparian soil, which are also affected by water and sediment conditions. Riverbank collapse and widening is the result of the joint influence of water and sediment conditions and physical characteristics of riparian soil. The main reason for the widening of the lower reaches of the diversion estuary is the change of water and sediment conditions caused by the diversion of the diversion estuary. After the flow passes through the diversion port, the mainstream is dispersed and flattened, and the shear stress caused by water flow on the surface soil of the river bank is increased, which is ultimately greater than the shear resistance of the soil along the river bank. In addition, Under the combined action of piping, seepage and wind wave, the riparian soil starts and gradually collapses and widens. The gradient of the channel expresses the slope of the potential energy consumed by the water flow in overcoming resistance, transporting sediment and shaping the river bed. Generally speaking, river diversion will reduce the gradient of the upper reaches and increase the gradient of the lower reaches, which will intensify with the increase of river diversion. After the diversion of the Jingjiang River, the gradient of the lower reaches of the diversion estuary decreases compared with that of the upper reaches of the diversion estuary. As the specific drop of river decreases, the velocity decreases, the main flow oscillates, and the river plane changes dramatically. Under natural conditions, the river boundary is unprotected, and the flow follows the principle of minimum energy consumption. The riverbed on both sides of the river is gradually scoured and the riverbed. In recent decades, with the gradual decrease of the separated discharge of the three diversion estuaries, the downstream channel gradient decreases slowly, and with the change of the boundary conditions of the channel, the trend of channel widening has been alleviated.

7. Conclusion

The following conclusions are drawn by analyzing the flow conditions and boundary conditions in the section of Jingjiang branch:

1) With the development of the Yangtze River, the diversion estuary of Jingjiang reach have gradually decreased from ancient to present. After the impoundment of the Three Gorges Reservoir, the amount of water and sediment separated by the three diversion estuaries have gradually decreased.

2) In the Songzikou and Taipingkou reach, the two banks are mainly of binary structure, with the upper clay layer and the lower non-clay layer. The upper part of the Ouchikou reach bank is clay group, the soil layer is thinner, the lower part is sandy soil, and the soil layer is thicker. Scouring can occur on both banks of the three river sections under the action of current, but the erosion resistance of Ouchikou is worse compared with the physical indexes of bank materials in each diversion estuary section.

3) The change of flow conditions in the lower reaches of the diversion estuary, combining with seepage, piping and wind waves, is the main reason for the erosion, collapse and widening of the lower reaches of the diversion estuary. Therefore, the river widening is affected by both hydrodynamic and soil mechanics conditions.

4) The method of hydrodynamics-soil mechanics is used to study the intrinsic mechanism of river channel widening, which can be used to analyze the mechanism of river bank erosion and collapse. This method is suitable for both non-viscous and viscous riverbanks. In the related research, how the sediment moving in the river channel and how the bed sand and suspended sediment are transformed are still not fully explained, which is still the direction of future research.

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