



Study on Recent Evolution and Influencing Factors of Sima Bend in the Yangzhong Reach of the Yangtze River

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Abstract. Meandering rivers are a common morphological feature in the middle and lower reaches of the Yangtze River. The apex of these bends has historically been a focus area for riverbank protection and channel management due to the impact of lateral flow impingement. With the operation of the Three Gorges Project and upstream cascade reservoirs, the middle and lower reaches of the Yangtze River have experienced long-term and extensive erosion, exacerbating the risk of bank failure in meandering rivers. This study focuses on the Sima Bend in the Yangzhong Reach of the lower Yangtze River, a well-known critical section characterized by severe meandering and intense bank collapse, where the river dynamics are complex, and management is particularly challenging. River evolution analysis indicates that, after the impoundment of the Three Gorges Reservoir, there has been a significant reduction in upstream sediment load, with an average sediment transport of only 129 Mt per year from 2003 to 2022. Significant floods occurred in the lower Yangtze River in 2016, 2017, and 2020, which further intensified the erosion of the Sima Bend. From 2011 to 2021, the general erosion depth reached 10~15 m, which threatened the safety of infrastructure and bank protection works. Numerical and physical model results indicate that during flood conditions, the river's main flow is significantly skewed towards the bank, with the impingement point located in the area of the left bank. Moreover, there is a pronounced secondary circulation in the vertical direction, which is the hydrodynamic reason for the continuous near-bank erosion in this area. The findings of this study provide technical support for flood control and the safe operation of water-related projects in meandering river sections.

Keywords: River evolution; River simulation; Meander flow; Sima Bend; Yangzhong reach of the Yangtze River

1 Introduction

Meandering rivers, as one of the fundamental river types, are the most widespread river forms in nature^[1]. These rivers are characterized by their sinuous contours and serpentine movement^[2], and their formation, development, and evolution are complex processes influenced by a variety of factors^[3]. Early on, Thomson^[4] explained the formation of meanders in alluvial plains, noting that sediment eroded from the concave bank of a meander travels downstream a considerable distance before depositing on the convex bank of another bend, rather than simply shifting from the concave to the convex bank within the same bend. In 1945, Friedkin^[5] analyzed the causes of meandering rivers, the sources, pathways, and deposition sites of sediments, and the role of sediments in bank collapse, concluding that riverbank erosion is the sole necessary condition for meander formation and that the meandering of an upstream channel propagates downstream, transforming a straight channel into a meandering one. Building on Friedkin's findings, Hooke^[6] argued that most researchers have overstated the importance of secondary flow in sediment transport in meandering rivers. He attributed the formation of meanders to sediment distribution in the channel rather than the effect of secondary flow, and he proposed that the equilibrium form of a river is not a straight channel but a meandering one. Qu Gang et al.^[7], through natural model experiments, found that during the formation and development of meandering rivers, the morphological elements of the channel are primarily determined by the conditions of water and sediment interaction. Within a certain range, when the cycle of water and sediment variation is shorter, with smaller inflow volumes and higher sediment concentrations, channels with greater sinuosity are more likely to form; conversely, when the inflow volume is larger, with overbank flow eroding floodplains, the resulting meandering channels tend towards a wider and shallower cross-sectional shape.

Due to the impact of lateral flow impingement, the apex of a meander has historically been a critical area for bank failure and channel management. Following the construction of the Three Gorges Dam and upstream mainstream and tributary reservoirs, the middle and lower reaches of the Yangtze River have undergone prolonged and extensive erosion due to "clear water release"^[8,9], exacerbating the risk of bank failure in meandering rivers. The Sima Bend, located in the upper section of the Yangzhong Reach of the lower Yangtze River, is one of the most severely affected meandering rivers in terms of bank failure^[10,11]. In recent years, studies on the Sima Bend have primarily focused on bank collapse issues^[12,13] and river channel management^[14]. However, relatively scant research has been conducted on the evolution characteristics of the Sima Bend and their influencing factors after the operation of the Three Gorges Reservoir. This study, focusing on the Sima Bend, systematically investigates the evolution characteristics and bank erosion mechanisms of typical meandering sections in the lower reaches of the Yangtze River after the construction of the Three Gorges Reservoir. It employs a combined approach of field data analysis, mathematical modeling, and physical model experiments. The research outcomes aim to fill the existing gap in understanding the evolution of the Sima Bend and its influencing factors post-reservoir operation, thereby providing a technical basis for flood control in meander sections and ensuring the safety of water-related engineering projects.

2 Study Area

The Sima Bend is located in the upper section of the left channel of Taipingzhou within the Yangzhong Reach of the lower Yangtze River, with a total length of approximately 14.7 km. The apex of the bend is at Sima River, extending from SanJiangying upstream to Gaogang Light Marker downstream, with Sima Town of Taixing City, Taizhou on the left bank, and Yangzhong City, Zhenjiang on the right bank (Figure 1). The Sima Bend is one of the most significantly curved and intensely collapsing sections in the lower Yangtze River, with a history of over 200 years of bank erosion. Historical records and investigations suggest that the bend formed in the late 18th century and began collapsing, having eroded 2.2 km northward and lost 13 km² of land. The former northern bank of the Yangtze River has since shifted to become the current southern bank, with the curvature radius decreasing from 13 km to 7.8 km. Since the founding of the People's Republic of China, 16,580 mu of arable land, 9,350 mu of river beach, 126 villages, 3,540 households, and 10,050 houses have been lost to erosion, with the highest intensity of bank collapse occurring near the apex at Sima Town. From the 1970s onwards, a series of spur dikes combined with revetment works were constructed, halting the overall retreat of the bankline, though major risks have persisted, and recent collapses have shifted towards the downstream area near Yangwan.

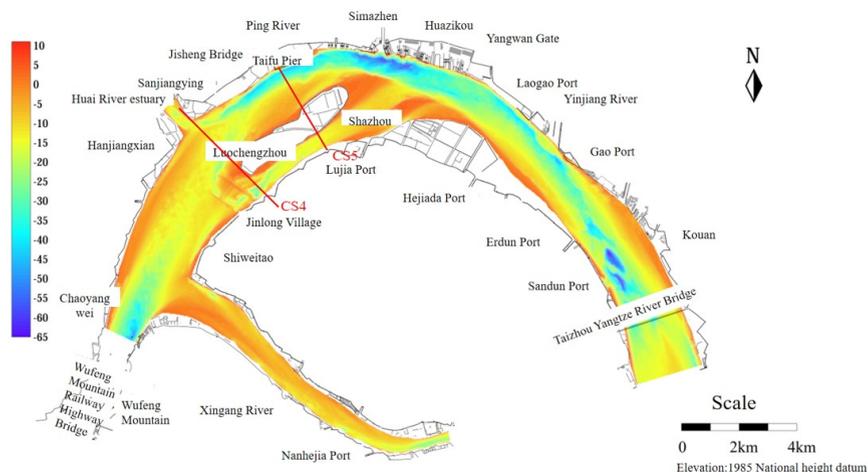


Fig. 1. Sima Bend in the Yangzhong Reach of the Yangtze River

Datong Station is the control hydrological station for water and sediment inflow in the lower Yangtze River. Based on data from 1950 to 2020, the average annual runoff at Datong Station is approximately 896.7 billion m³, with significant interannual variability, but no apparent long-term trend in the average runoff (Figure 2a). The annual average sediment transport at Datong Station is 350 million tons. In recent years, with the implementation of soil and water conservation projects and reservoir construction in the upper Yangtze River, sediment inflow has been decreasing. Sediment transport has shown a phased decrease, particularly after the impoundment of the Gezhouba and

Three Gorges projects. Between 1951 and 1985, the average annual sediment transport was 471 million tons; from 1986 to 2002, it averaged 339 million tons; and after the Three Gorges Reservoir impoundment in 2003, it dropped significantly, averaging 134 million tons between 2003 and 2020. Figures 2b and 2c compare the multi-year average monthly runoff and sediment transport before and after the impoundment of the Three Gorges Reservoir. The figures show that post-impoundment, the flood season flow has decreased, while the dry season flow has slightly increased. By 2020, compared to pre-impoundment levels, flood season flow had decreased by about 10%, while dry season flow increased by approximately 7%. However, the reduction in sediment transport during the flood season was significant, while the overall sediment transport during the dry season remained low. Post-impoundment, the annual sediment transport decreased significantly, from an average of 426 million tons before impoundment to 134 million tons, a reduction of 68.5%.

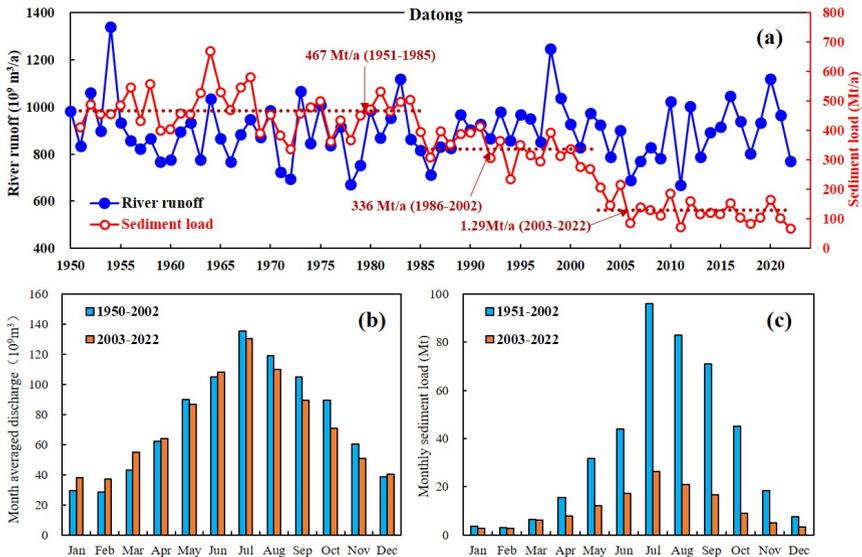


Fig. 2. Annual and Monthly Average Runoff and Sediment Transport at Datong Hydrological Station (Tidal limit) of the Yangtze River

3 Methodology

Analysis of field measurement data, mathematical model computations, and physical model experiments are the most common and direct research methods used to study river evolution characteristics, analyze influencing factors of river dynamic changes, and explore river evolution trends. This thesis employs all three research methods systematically to investigate the evolution characteristics of the Sima Bend and their influencing factors after the operation of the Three Gorges Reservoir.

3.1 Analysis of Recent Evolution Characteristics of the Sima Bend

Thalweg Line Changes. The main flow adheres to the left bank downstream from Sanjiangying, transitioning to the right bank near the exit at Gaogang Light Marker, moving along the left edge of Taipingzhou from Erduan Port to Bansha Weizi. Before 1981, the impact point of the thalweg in the transition section at the inlet was approximately 2.3 km upstream of Sanjiangying (the confluence of the Huai River with the Yangtze River). Due to the oscillation of the thalweg in the inlet section, the impact point had shifted downstream to about 1.2 km below the Huai River confluence by 1998. Since 2001, the position of the impact point has remained relatively stable, with minor oscillations in the thalweg line. As the Sima Bend continued to develop, the apex of the bend shifted downstream, indicating that bank collapse was progressing downstream. Consequently, the thalweg line from Dujiawei to Gaogang Light Marker also exhibited significant leftward shifts. Since the 1970s, following the implementation of regulation works such as spur dikes, submerged mattresses, and stone dumping, the bank collapse at Sima Bend has been preliminarily controlled, leading to a reduction in bank retreat and a deceleration in the downstream shift of the erosion center. However, the deep channel along the left bank continues to undergo erosion and deposition adjustments, with the thalweg line still showing some leftward migration. Between 1998 and 2016, the oscillation amplitude of the main flow line from Dujiawei to Gaogang Light Marker was within 250 meters. After the 2016 flood season, localized leftward thalweg shifts causing bank erosion were observed at the Sima River mouth, Huazikou, and Gaogang Light exit. The protruding tip of Gaogang Light has experienced erosion over many years, leading to a downstream shift of the thalweg impact point on the right bank from Erduan Port to near Sanduan Port (Figure 3).

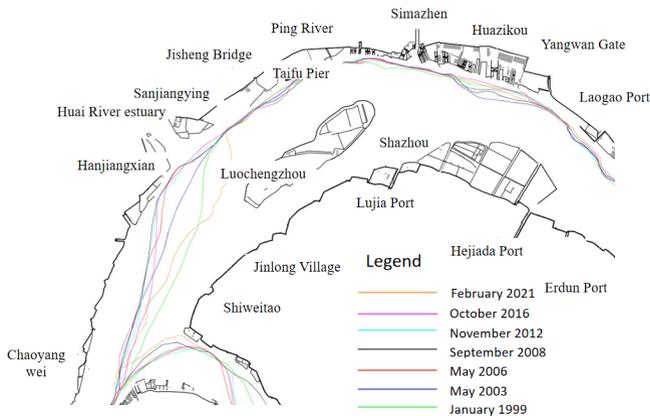


Fig. 3. Changes in Thalweg Line Over the Years

Deep Channel Changes. The -30m channel in the inlet section of the Sima Bend has shown a downward migration trend. In 1998, the -30m channel in the inlet section and the section from Dujiawei to Huazikou experienced scouring, resulting in a through-channel that expanded to the right. By 2006, the head of the -30m channel had

shifted downstream to Dujiawei. In 2015, the entire -30m channel from Dujiawei to Gaogang Light Marker was scoured through, and after the 2016 flood season, the channel further expanded, with its head moving upstream from Dujiawei to the vicinity of Sanjiangying, marking the largest extent recorded over the years. The downward and rightward expansion of the deep channel in the inlet section of the bend has facilitated the development of the right channel of Luochengzhou. The changes observed in 2021 were minimal compared to those in 2016 (Figure 4).

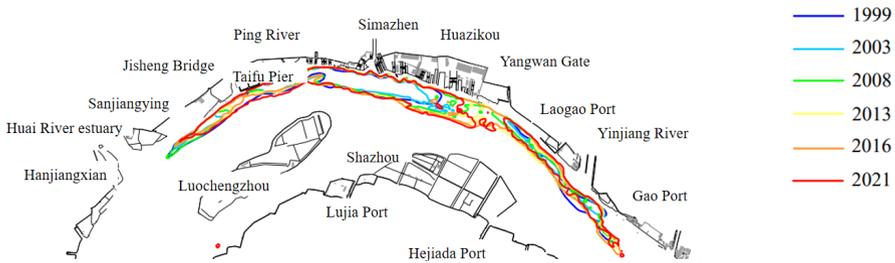


Fig. 4. Changes in the -30m Contour Line Over the Years

Erosion and Deposition Changes. Before the operation of the Three Gorges Project, significant scouring occurred in the inlet section of the Yangzhong Reach, around the shoals of Luochengzhou, and in the river sections from Yangwan Gate to the vicinity of Old Gaogang. Notable scouring also occurred on the concave bank of the Hanjiang Bend, with an average scour depth of about 5 to 7 meters, reaching over 8 meters in some areas. In contrast, sediment deposition occurred near the deep channel of the Sima Bend, with a maximum deposition depth of up to 13 meters (Figure 5).

From 2003 to 2008, following the completion and operation of the Three Gorges Project, significant scouring was observed in most areas, including the left and right channels of Luochengzhou, Sima Bend, and Old ngang, with an average scour depth of about 4 to 6 meters. Notably, significant scouring occurred in the left channel of Luochengzhou (Figure 6a). Between 2008 and 2013, sediment deposition occurred in the left channel of Luochengzhou, with deposition thickness generally not exceeding 5 meters. Apart from the aforementioned areas, the upper bend sections primarily experienced scouring, particularly in the right channel of Luochengzhou and the section from Huazikou to Gaogang, where scouring was significant (Figure 6b). From 2013 to 2016, scouring remained predominant in the study reach, with pronounced scouring observed on the concave side of the deep channel in Sima Bend and the concave side from the upstream end of Luochengzhou to Chaoyangwei. However, notable sediment deposition also occurred on the concave bank of the Hanjiang Bend (Figure 6c). From 2016 to 2021, after the major floods of 2016, 2017, and 2020 (with maximum flows at Datong reaching $70,700 \text{ m}^3/\text{s}$, $70,600 \text{ m}^3/\text{s}$, and $84,600 \text{ m}^3/\text{s}$, respectively), there was no significant change in sediment load compared to previous years. However, the significant bed-forming effect of these floods accelerated the recent downcutting of the river channel (Figure 6d). Consequently, 2021 saw more pronounced scouring compared to 2016, with significant erosion observed in the concave side of the Sima Bend, the tail of Luochengzhou, and the deep channel area of Old Gaogang. There was substantial

scouring on the left bank of the left channel of Luochengzhou, steepening the bankline further and threatening the stability and flood safety of the bank slopes along the channel. Meanwhile, extensive sediment deposition occurred on the shoals of Luochengzhou, likely due to the implementation of low-shoal protection measures at the head of Luochengzhou.

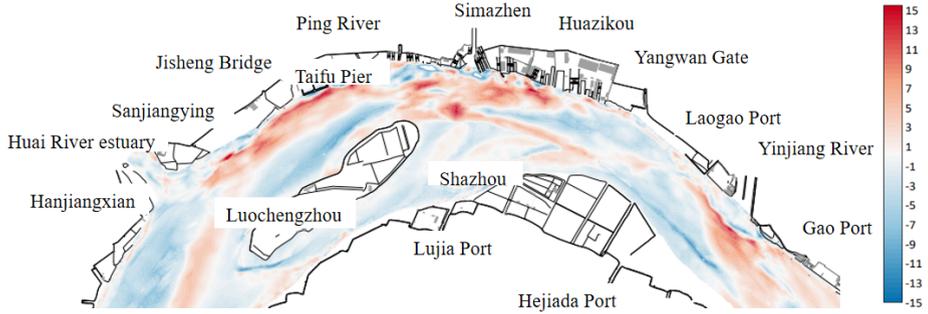


Fig. 5. Erosion and Deposition Changes in Sima Bend from 1999 to 2003

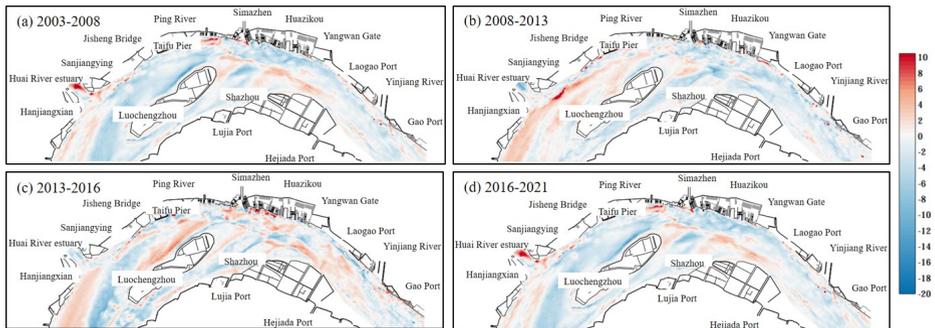


Fig. 6. Erosion and Deposition Changes in Sima Bend During Different Periods from 2003 to 2021

Changes in Typical Cross-Sections. The cross-section at the head of Luochengzhou (CS4) exhibits a "W" shape, with Luochengzhou dividing this cross-section into two channels, the left channel being the main one. From 1999 to 2003, the overall morphology of this cross-section showed little change. Between 2003 and 2006, the deepest points of both the left and right channels at the head of Luochengzhou experienced deepening, with the deepest points lowering by 4.4 meters and 8 meters, respectively. From 2006 to 2008, scouring continued in the left channel, with the scouring area expanding and an average deepening of 2 meters. The cross-sectional morphology in 2012 showed minor changes compared to 2008, with slight localized erosion and deposition. There was little difference between the cross-sectional shapes in 2016 and 2012; localized scouring occurred in both channels, with a deepening of about 4 meters. By 2019, both channels at this cross-section continued to develop, with the lowest point of the left channel deepening by approximately 3 meters, while the deepest point of the right

channel deepened by about 6 meters, indicating that the scouring intensity in the right channel was greater than in the left. From 1999 to 2021, the left channel showed minimal change, with slight localized erosion and deposition, while scouring continued in the right channel, deepening by approximately 5 meters at its deepest point (Figure 7).

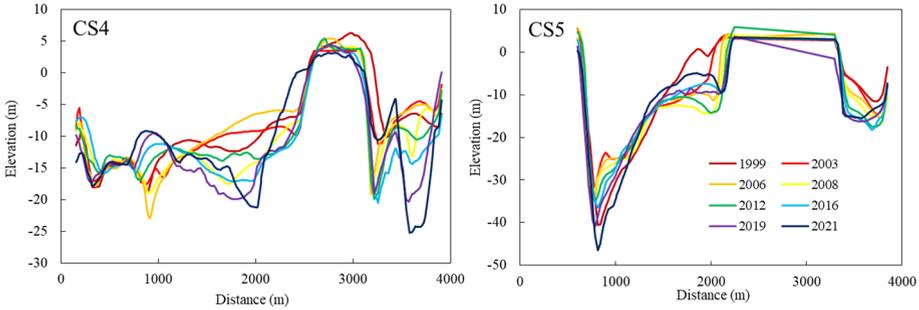


Fig. 7. Changes in Typical Cross-Sections Over the Years

The cross-section in the middle of Luochengzhou (CS5) displays a "V" shape with a deep channel skewed to the left for the left channel, and a shallow "U" shape for the right channel. From 1999 to 2003, as the upstream sediment supply decreased, this cross-section underwent continuous scouring, with an accumulated scour depth of about 12 meters. The right channel's morphology did not change significantly, and the depth at its deepest point remained relatively stable, though the scouring area gradually expanded, progressing towards the Luochengzhou side (Figure 7).

3.2 Flow Structure Simulation Analysis of the Sima Bend

Two-Dimensional Flow Numerical Simulation Analysis. To verify the conclusions regarding the recent downstream shift of the main flow impact point at the apex of the Sima Bend and the scouring locations in the river channel, a two-dimensional flow model was used to simulate the flow movement in the Wufengshan-Zhenjiang Xinglonggang section of the river. The results showed that after the flow passes through the left channel of Luochengzhou, the main flow closely adheres to the bank, particularly during both low-flow and flood-flow conditions. The main flow line is located within approximately 300 meters of the left bank, where the flow velocity is relatively high. This high velocity is the hydrodynamic reason for the continuous scouring of the riverbed in the left channel of Luochengzhou (Figure 8). The flow field diagrams indicate that the flow in the study reach is generally smooth, with no significant recirculation zones observed (Figure 9).

Local Physical Model Experiment Analysis of the Bend. To better understand the flow structure in the Sima Bend section, particularly within the left channel of Luochengzhou, this study conducted a physical model experiment. Based on the experiment's objectives and site conditions, a half-river model was selected. The simulated river reach extends from the confluence of the Huai River and the Yangtze River upstream to 2.69 km downstream of the Taifu Pier, with a total simulated length of approximately

7.74 km. Given the site conditions of the model and the past experience with lower Yangtze River models at our institute, a distorted model was used. The model scale was set at 1:250 horizontally and 1:125 vertically, with a distortion ratio of 2. The total length of the model was approximately 30.96 meters (Figure 10).

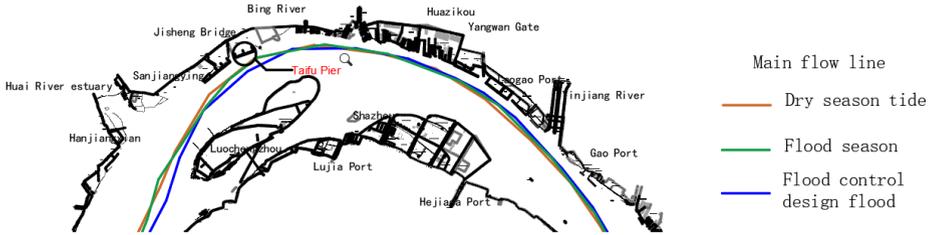


Fig. 8. Changes in Main Flow Line Under Different Conditions

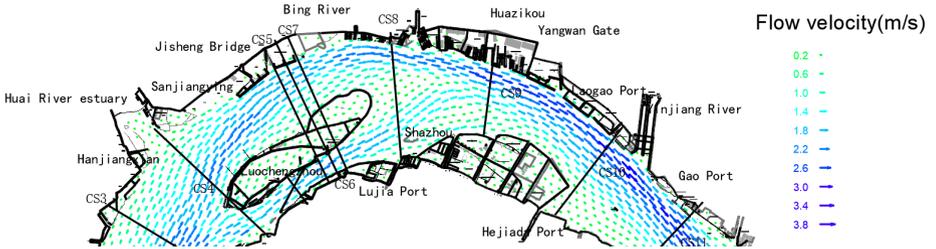


Fig. 9. Changes in Planar Flow Field Under Flood Control Design Condition

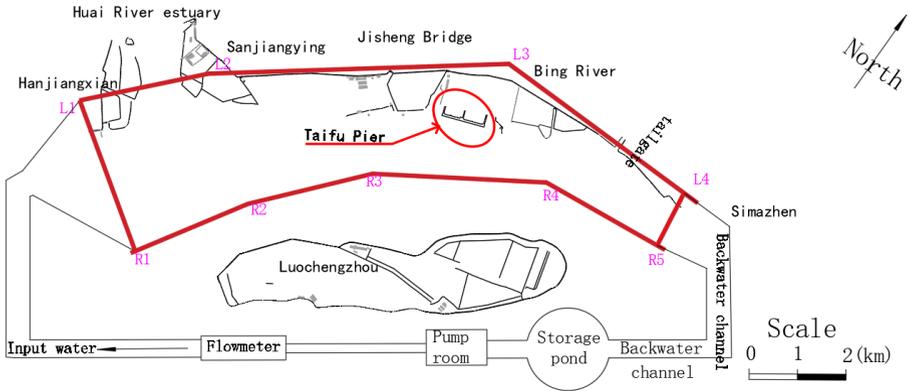


Fig. 10. Plan Layout of the Physical Model

The model experiment selected three scenarios as hydrological conditions for testing: the average flow during the spring tide in the dry season of 2021, the average flow during the spring tide in the flood season of 2021, and the flood control design flow of 85400 m³/s. Three water gauges and eight measurement cross-sections were set up to measure the cross-sectional flow velocity distribution. The results showed that as the

flow increased, the main flow line gradually shifted towards the right bank, and the curvature of the main flow line decreased with increasing flow (Figure 11). The effect of "small water turning, large water straightening" was evident. Under all three flow conditions, the impact point of the flow in the bend was consistently near the left channel of Luochengzhou, resulting in higher average flow velocities in this area compared to other regions. This higher velocity is the hydrodynamic reason for the continuous scouring of the riverbed in this area.

From the planar flow field simulation results, at cross-sections DM1 and DM2, the maximum value of the model's vertically averaged flow velocity was observed near the right bank of the model. For example, at cross-section DM1, the maximum flow velocity was exactly at the model's right boundary. Similarly, at cross-section DM2, the area of maximum flow velocity was also near the model's right boundary. At cross-section DM3, the maximum flow velocity was close to the model's left bank. At cross-section DM4, the location of the maximum flow velocity in the model corresponded to the actual river channel, approximately 400 meters from the left bank of the river. For cross-sections DM5 and DM6, the locations of maximum flow velocity in the model also corresponded to the actual river channel, being located approximately 360 meters and 300 meters from the left bank, respectively. These areas are precisely where the riverbed experiences the most intense scouring, with a maximum local scour depth of up to 15 meters over the past decade. After the flow passes through the bend apex and reaches cross-sections DM7 and DM8, the distance from the maximum flow velocity point to the left bank of the model remained unchanged (Figure 12).

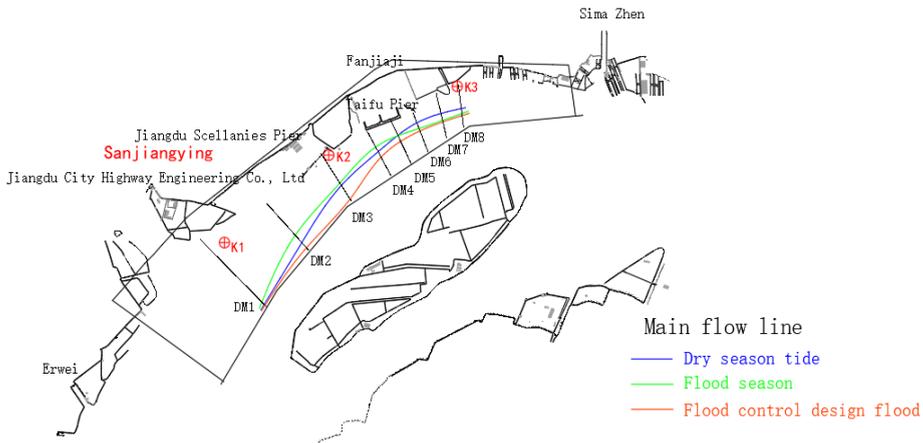


Fig. 11. Changes in Main Flow Line Under Three Scenarios

From the cross-sectional flow velocity distribution diagrams, it can be observed that at cross-sections DM1 to DM3, the maximum flow velocity is still relatively close to the right bank of the river. However, as the flow passes through the area where the pier is located (cross-sections DM4 to DM5), the zone of maximum flow velocity has shifted closer to the deep channel. The longitudinal flow velocity in this area is

inherently high, resulting in a strong scouring capability. However, due to the recent implementation of revetment works, the high-velocity flow is less likely to cause erosion along the banks. Consequently, the excess energy of the flow is instead discharged by further deepening the riverbed near the pier. Additionally, in this area, a more pronounced bend-induced secondary circulation has been observed: surface water flows from the convex bank towards the concave bank, while bottom water flows from the concave bank towards the convex bank. This flow characteristic promotes lateral sediment transport across the bend and exacerbates scouring in this area (Figure 13).

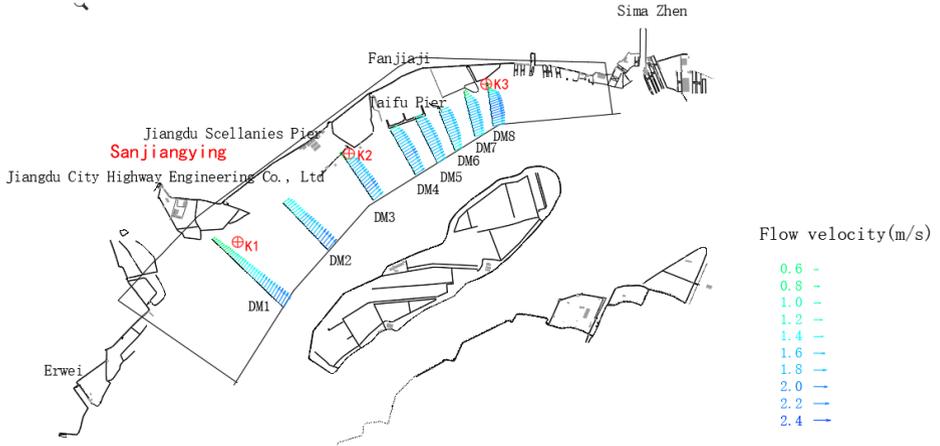


Fig. 12. Changes in Flow Velocity Distribution at Various Cross-Sections Under Different Flow Conditions

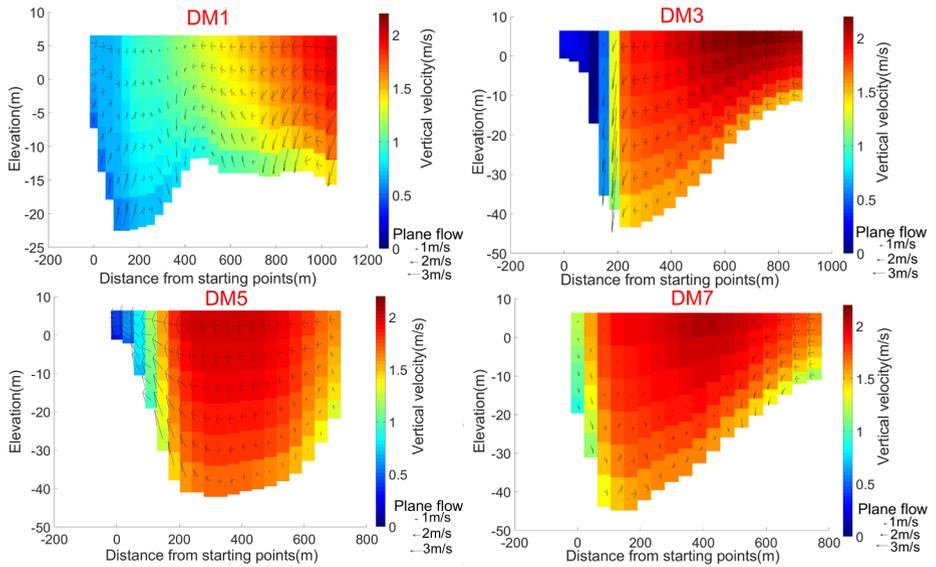


Fig. 13. Cross-Sectional Flow Velocity Distribution Under Condition 3

4 Discussion

Since the operation of the Three Gorges Project, the shoreline of the Sima Bend has remained relatively stable under the influence of regulation projects. However, the impact point at the apex of the bend and the scoured areas of the river channel have shifted downstream, and the bed scouring has intensified. Influenced by factors such as upstream river regime, water and sediment inflow, the impinging flow from the Wufengshan node, bend-induced secondary circulation, and boundary conditions, the concave bank of the river has experienced significant erosion. Meanwhile, corresponding sediment deposition has occurred along the convex bank shoals on the outer edges of Luochengzhou, sandbars, and the left edge of Taipingzhou. According to the erosion and deposition maps, from 1981 to 2003, significant scouring occurred along the main channel adjacent to the concave bank, with the scouring extending downstream from Jisheng Bridge to Gaogang Light Marker. The thalweg line shifted considerably to the left, with the greatest leftward shift occurring in the Pingjiang to Sima River mouth section, leading to frequent bank collapses in this segment. Since the 1970s, regulation works such as spur dikes, submerged mattresses, and stone dumping have been implemented at the Sima Bend, which have preliminarily controlled the bank collapse and reduced shoreline retreat.

Since the operation of the Three Gorges Project, local shoreline retreat has still been observed. As evidenced by the erosion and deposition maps from 2003 to 2019, the scouring along the left bank has moved downstream to below the Sima River mouth, with reduced intensity. Under the influence of revetment works, the overall changes in the position of the thalweg line and the left bank's planform have been minimal, and the shoreline is currently stable. However, in recent years, the apex of the Sima Bend has continued to migrate downstream, and the deep channel in the Sima Bend has deepened further, with a continuing trend of expansion.

5 Conclusions

(1) Since the impoundment of the Three Gorges Reservoir in 2003, the sediment transport has significantly decreased, with an average sediment load of 134 million tons per year from 2003 to 2020. Regarding water inflow conditions, after the impoundment of the Three Gorges Reservoir, the flood season flow decreased, while the dry season flow increased. By 2020, compared to pre-impoundment levels, flood season flow had decreased by about 10%, while dry season flow had increased by approximately 7%. The duration of medium flow conditions increased, enhancing bed-forming effects. Consequently, the significant reduction in sediment transport and the increased duration of medium flow conditions have led to a state of overall scouring in the study reach of the middle and lower Yangtze River (with some localized shoal deposition).

(2) During the years 2016, 2017, and 2020, after the impoundment of the Three Gorges Reservoir, the lower Yangtze River experienced consecutive major floods, while the sediment load remained relatively stable compared to previous years. The significant bed-forming effects of these large floods have accelerated recent riverbed

downcutting to some extent. As evidenced by the erosion and deposition maps and contour changes from 2016 to 2019, the shoreline of the Sima Bend is currently stable under the influence of revetment works. However, in recent years, the apex of the Sima Bend has continued to migrate downstream, and the deep channel in the Sima Bend has deepened further, with a continuing trend of expansion.

(3) The implementation of port channel regulation works at the lower Yangtze River mouth, the Luochengzhou protection project, and the second phase of the 12.5-meter deep water channel project below Nanjing (including the regulation of the Luochengzhou section) has restricted the development of the right channel of Luochengzhou and increased the hydrodynamic force in the left channel. This has contributed to the intensification of scouring in the left channel's riverbed in recent years.

(4) Recently, influenced by local river regime adjustments and major floods, the riverbed scouring on the left bank of Luochengzhou has continued to intensify, with scouring depths generally reaching 10 to 15 meters since 2011, posing a threat to the stability of the existing revetment works. However, following the implementation of revetment works along this shoreline (in 2023), the scouring of the riverbed in the Sima Bend section has been effectively controlled, and the current revetment effect is satisfactory.

This study systematically investigates the evolution characteristics of the Sima Bend and their influencing factors after the operation of the Three Gorges Reservoir, utilizing a combination of field data analysis, mathematical modeling, and physical model experiments. However, the research on the mechanism of river dynamic changes in the Sima Bend is currently limited to the hydrodynamic aspect, with the sediment movement characteristics yet to be clarified. In subsequent studies, water-sediment mathematical models or movable-bed physical model experiments should be employed to further explore the sediment movement characteristics and the mechanism of bank collapse in the Sima Bend.

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