Modeling of the Effects of Secondary Flow on Bank Failure in a Curved Channel

DENG Chun-yan¹²*, XIA Jun-qiang², Yuan Yuan¹, Wang Min¹

¹River Department, Changjiang River Scientific Research Institute, Wuhan 430010, China;
²State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

* Corresponding Author: DENG Chun-yan; email: yaoye0121@163.com; phone: 13476119843

Abstract: The secondary flow is an important factor that affects the bank stabilization and morphological evolution in meandering reaches. In order to solve the problem of the bank failure in Upper Jingjiang River, the effect of the secondary flow on the river bank, the soil composition and mechanical properties were comprehensively considered, the Delft3D model and the BSTEM model were used to analyze the bank stability of the Upper Jingjiang River, and the process of bank failure was simulated. The simulation process is divided into two modes considering the secondary flow and not considering the secondary flow, and the results of the two models are compared and analyzed. The results indicated that, in both calculation modes, the bank collapse occurred during the periods of high water level and water level recession. Moreover, considering the secondary flow, the safety factor of the river bank decreases, the total collapse volume increases, and the bank shape after collapse is more in line with the actual situation.

1. Introduction

The Upper Jingjiang River has smooth river bend and obvious bifurcated characteristics, which is a typical microbent bifurcated river type. The entire river plane deforms little, but the main flow in the microbent bifurcated section oscillates frequently, and the dynamic state of partly river course is in constant changing [1, 2]. Since the 1990s, the upper Jing River is in stable state, but it has changed greatly near the microbent section of Shashi District and branch of protruding island. After 1998, due to erosion, Sanba Beach shrunk constantly. At the same time, the main line of the protruding island oscillated frequently and intensively. At the beginning of 2002, a massive bank collapse occurred in the Wencunjia, Upper Jingjiang River. The total length of the bank collapse was about 550m and the maximum collapse width was about 10m. At the beginning of 2005, because the collapse of the river bank was obvious in Wencunjia, it collapsed altogether again in the downstream part 300 meters from the previous collapse bank, with a total length of 300m and a collapse width of 10m [3, 4].

Due to the secondary flow at the bend, a loop circulation is formed on the cross-section, and the circulation often causes collapses at the bend. This phenomenon of bank collapse happens in the whole fluvial process. The bank collapses change the rivers, which is easy to trigger new bank collapses; hence it will lead to the deterioration of the river. For river sections with control requirements, it’s urgent to address the problem of bank collapse. In order to analyze the influence of secondary flow on
the process of bank collapse, this paper takes the Jing34 section in Shashi Reach as an example, and divides it into two calculation modes. One is to consider secondary flow, while the other is not to consider secondary flow, and Delft3D model and BSTEM model were used to simulate the long-time erosion and collapse process of the river bank.

2. Model

The research in this paper is mainly based on the previous research on the secondary flow of the bend, which was cited and found details in Literature [5]. This paper only briefly introduces the BSTEM model.

The BSTEM model is a model for calculating riverbank stability based on the EXCEL macro command [6]. There are three main methods for calculating the safety factor ($F_s$) of riverbank stability in BSTEM model, which are horizontal layer method, vertical slice method and cantilever shear collapse method. The first method was developed by Simon, equal to the wedge collapse model developed in 1998, which further improved the Osman-Thorne model developed by Osman et al. The second method was developed from the CONCEPTS model [6]. Based on the horizontal layer method, the third method is to set the angle of the collapse surface to 90° and then calculate the value of the safety factor ($F_s$). This paper adopts the third method, and the calculation formula of the safety factor $F_s$ is:

$$F_s = \frac{\sum_{i=1}^{I} \left( c_i L_i + (\mu_n - \mu_s) L_i \tan \phi_i' + \left[ P_i \sin \alpha - \mu_n u \right] \tan \phi_i \right)}{\sum_{i=1}^{I} \left( W_i - P_i \cos \alpha \right)}$$

(1)

In Equation (1), $I$ is the total number of layers of river bank collapse; $c_i$ is the effective cohesion of the i-th layer soil (kN/m²); $L_i$ is the length of collapse surface of the i-th layer soil (m); $u_n$ is pore gas pressure (kN/m²); $u_w$ is pore water pressure (kN/m²); $\phi_i'$ is the degree of increase (°) of apparent cohesive force of the i-th layer soil with increasing matrix suction; $P_i$ is applied by external water flow Hydrostatic pressure (kN/m²) of the i-th layer soil; $\phi_i$ is the effective internal friction angle (°) of the i-th layer soil; $W_i$ is the i-th layer soil weight (kN/m); $\alpha$ is the river bank slope (°); $\beta$ is the collapse surface angle (°).

The river bank collapse is mainly affected by the shear stress on the river bank soil. The calculation formula of shear stress ($\tau_f$) is:

$$\tau_f = \gamma_w R J$$

(2)

In Equation (2), $\tau_f$ is shear stress (N/m²); $\gamma_w$ is the severity of water(9.8kN/m³); $R$ is the hydraulic radius (m); $J$ is the water surface ratio drop.

This paper uses the BSTEM model to calculate the river bank stability. According to the calculation result of the safety factor $F_s$ of the stability of the riverbank, the riverbank is considered to be in a stable state when $F_s > 1.3$, while the riverbank is considered to be unstable and will collapse when $F_s \leq 1.3$.

It can be seen from Equation (2) that the effect of the secondary flow on the bank slope is mainly caused by the shear stress. In this paper, the Delft3D model is used to simulate the flow of the terrain measured in the Shashi Reach in November 2008, and the calculation results are embedded in the BSTEM model to simulate the collapse of the secondary bank.

3. Model simulation condition analysis

3.1 Simulated section

There are three bank sections in the Shashi Reach, namely Taipingkou Central Bar, Sanba Beach and Jinchengzhou Beach. The Jing34 section is located near the tail of the Taipingkou Central Bar (see in
Figure 1), which is in the shape of “W”. Over these years, the left bank is relatively stable, but the bank slope is slightly silted up; the right bank scours severely. Since 1996, this bank collapsed almost every year. From 1996 to 2010, the total collapse length of the bank was about 313m (see in Figure 2). The area has enlarged significantly. Because the left bank of the Jing34 section is relatively stable, and the right bank collapses severely, when it comes to the simulation of bank collapse, the right bank of the Jing34 section is selected as the initial calculation section.

Figure 2. Temporal changes in cross-sectional profiles at typical sections of Jing34.

3.2 Water level condition
According to the analysis in Literature [7], the characteristics of soil and near-shore current conditions of the upper Jing River bank show a periodic trend in a hydrological year, which makes the stability of river bank also change periodically. Therefore, this paper uses the hydrological year 2009 of the Jing34 section of the microbent section of Shashi District (December 16, 2008 to December 15, 2009) to study the influence of secondary flow on the bank collapse. In order to simplify the calculation of the river bank stability, the process of daily average water level in the hydrological year 2009 is divided into 11 periods of the average water level according to the trend of change (see in Table 2).

3.3 Riverbank soil mechanics
During the preliminary work, the site inspection and sampling were carried out in the section where river bank collapses particularly severely, and the indoor soil test was carried out on the sampled soil, so as to obtain the mechanical properties of each layer of the Jing34 section of the Shashi District section (see in Table 1).

| Thickness (m) | Soil sample     | Bulk density $\gamma$ (kN/m$^3$) | Shear strength $\phi$ (°) | $c$ (kN/m$^2$) |
|---------------|-----------------|----------------------------------|---------------------------|----------------|
| 16.42         | Unsaturated clay| 18.5                              | 27.8                      | 17.5           |
|               | Saturated clay  | 18.9                              | 25.1                      | 6.2            |
4. Analysis of the influence of secondary flow on bank collapse

4.1 The effect of secondary flow on safety factor

In the process of calculating the river bank stability through the model, the water flow strikes the river bank through the lateral force. Due to the characteristics of the binary structure of the Upper Jing River (upper cohesive soil layer, lower sand layer) \(^7,8\), the sand layer at the foot of the slope is eroded in the first place. As the shear stress of the nearshore water flow increases, the foot of the slope is scoured to a certain extent, then the upper clay soil layer will lose balance and collapse. Table 2 and Figure 3 show details of how the stability safety factor \(F_s\) of the Jing34 section changes in different periods when considering the impact of the secondary flow (denoted as mode A) and not considering the impact of the secondary flow (denoted as mode B) on the bank collapse during the hydrological year 2009.

In the hydrological year 2009, the water level followed the process of rising first and then falling. Before the water level reached the peak (period 6), the shear stress \(\tau_f\) of the nearshore water flow on the right bank of the Jing34 section was relatively small in both calculation modes, while the riverbank stability coefficient \(F_s\) was large. In mode A, \(F_s\) was 1.70–6.82, while in mode B, \(F_s\) was 1.79–8.12; both were greater than 1.3, and the bank was stable. Especially in the dry season, that is, in period 1, the water level of the Jing34 section was stable, the variation was about 30m, the value of \(F_s\) was above 6, and the river bank was highly stable. When coming to the point of whether considering the secondary flow angle or not, the horizontal shearing force was relatively large if the secondary flow was considered, which resulted in significant lateral scouring, and led to the riverbank stability safety factor \(F_s\) was 6.82) was significantly less than that of not considering the second flow \(F_s\) was 8.12).

Table 2. Calculation results of bank stability and bank collapse on the right side of the Jing34 section in 2009.

| Time period | Water level (m) | \(\tau_f\) (N/m²) | \(F_s\) | bank failure | Instability width (m) | Total earthwork (m³) |
|------------|----------------|------------------|--------|-------------|----------------------|---------------------|
|             |                | mode A | mode B | mode A | mode B | mode A | mode B | mode A | mode B | mode A | mode B | mode A | mode B |
| 1          | 29.97          | 2.57    | 2.19   | 6.82   | 8.12   | No     | No     | 0.00   | 0.00   | 62.73  | 58     |
| 2          | 31.17          | 3.21    | 2.75   | 2.95   | 3.14   | No     | No     | 0.00   | 0.00   | 13.62  | 23.6   |
| 3          | 34.31          | 4.91    | 4.10   | 1.70   | 1.79   | No     | No     | 0.00   | 0.00   | 27.44  | 19.77  |
| 4          | 34.33          | 4.74    | 3.84   | 2.26   | 1.99   | No     | No     | 0.00   | 0.00   | 5.37   | 8.2    |
| 5          | 37.19          | 4.93    | 3.87   | 3.15   | 3.25   | No     | No     | 0.00   | 0.00   | 8.6    | 7.55   |
| 6          | 39.55          | 5.06    | 3.94   | 4.06   | 4.08   | No     | No     | 0.00   | 0.00   | 8.83   | 7.39   |
| 7          | 37.72          | 5.27    | 4.05   | 3.17   | 3.20   | No     | No     | 0.00   | 0.00   | 9.54   | 6.95   |
| 8          | 34.35          | 5.20    | 4.12   | 1.02   | 1.02   | Yes    | Yes    | 0.84   | 0.73   | 149.41 | 141.45 |
| 9          | 31.47          | 3.44    | 2.70   | 2.50   | 2.63   | No     | No     | 0.00   | 0.00   | 16.96  | 13.3   |
| 10         | 30.99          | 2.83    | 2.15   | 0.66   | 0.77   | Yes    | Yes    | 10.15  | 8.48   | 234.35 | 217.47 |
| 11         | 29.75          | 1.91    | 1.38   | 1.48   | 2.14   | No     | No     | 0.00   | 0.00   | 21.31  | 13.58  |
| Sum        |                |         |        |        |        |         |        | 10.99  | 9.21   | 558.17 | 517.27 |

5.98 | Saturated sand | 8.1 | 35.1 | 0
During the process of the water level falling from the peak, the first collapse occurred in period 8. The collapse was in the flood period (including the period of 4~9, the total time was 5 months), which was in the Yangtze River flood season, when the flow was large, and the water level rose fast while it lasts in high level for a long time. The maximum flow through the Jing34 section was 32600m$^3$/s, the average flow was 17443m$^3$/s, and 9 days witnessed the water flowed at the speed of above 30000m$^3$/s. The highest water level was 39.72m and the average water level was 35.8m. At this stage, the shear stress of nearshore water flow further increased to a maximum of 5.27 N/m$^2$, which was much larger than the starting shear stress of the sand layer at the foot of the river bank. Therefore, the foot of the slope eroded the most during this period, and eventually lost balance, which occurred collapse for the first time. The safety factor $F_s$ of the river bank during the whole flood period was basically increasing first and then decreasing, and rebounding after the collapse. In the two calculation modes, the two slope safety factors $F_s$ differed slightly, with the maximum difference being only 0.02, and the slope safety factor $F_s$ was still relatively small when the secondary flow was considered.

A second collapse occurred during the retreat period, which happened in both of the two calculation modes. At this stage, due to the sharp drop in the water level in the river channel, the phreatic level in the river bank was lowered and the strength index of the soil body was also reduced. With the effect of shear stress of the nearshore water flow, the safety factor $F_s$ of the bank slope was reduced significantly. In the two calculation modes, the $F_s$ difference was larger than the rising period and the flood period, and the difference range was from 0.11 to 0.66. Furthermore, under the condition of mode A calculation, the safety factor $F_s$ was small.

It can be seen from the above analysis that after considering the secondary flow, the safety factor will be correspondingly reduced due to the influence of the river bank shear force; at the same time, the difference between the two safety factors is also related to the water level in the river channel. When the water level is low, the difference between the two is greater.

4.2 Influence of secondary flow on river bank erosion

In the two calculation modes, due to the shear stress of the water flow, the slope of the river bank is scoured to a certain degree at each period, which means the river bank has a certain degree of erosion in 11 periods. From viewpoint of the scouring of the riverbank unit length and the total soil volume of collapse in Jing34 section, under the condition of model A, the scouring and the total soil volume is 558.17m$^3$ in the hydrological year 2009, which was greater than the value under the condition of mode B (517.27m$^3$). From the time of bank collapse, the amount of erosion in the falling period (the second collapse period) was the largest, accounting for 45% of the total soil volume. The amount of
the flooding period (the first collapse period) ranked the second, accounting 36% for the total soil volume. Generally, when a collapse occurs, the effect of river bank erosion is more obvious after considering the secondary flow. The fact that whether considering the secondary flow only affects the total soil volume of erosion and collapse, but has no effect on the time and process of collapse.

### 4.3 Influence of secondary flow on bank slope morphology

The comparison of the bank slope stability analysis between the calculated results and the measured results is shown in Figure 4.

**Figure 4.** Comparisons between simulated and measured results of the right bank of the Jing34 section: (a) Mode A; (b) Mode B.

It can be seen from the figure that under the two calculation modes, the Jing34 section has collapsed twice in the hydrology year 2009. After the first collapse, the river bank slopes in Figure 3(a) and Figure 3(b) are basically in the same shape, with the difference in collapse width only being 0.11m; after the second collapse, the collapse width of the river bank in Figure 3(a) was significantly larger than that in Figure 3(b). After two collapses, the total widths of the river bank collapse were 10.9m and 9.21m respectively, while the measured collapse width in 2009 was 10.7m, and the relative errors were 2.7% and 13.9% respectively. This showed that, compared with the influence of secondary flow, after considering the secondary flow, the lateral shear stress became larger due to the influence of the secondary flow, which aggravated the scouring in the foot of the slope and led to a more severe collapse. The results of the simulation are more in line with the actual situation.

It should be pointed out that in the process of bank collapse simulation, the scouring at the foot of slope first occurred, and then the upper soil became unstable and collapsed. Because it’s complicated to calculate the soil accumulation at the foot of the slope, this value was not taken into consideration during this calculation process. Therefore, the accumulation of soil at the foot of the slope is encouraged to be considered in the course of further research.

### 5. Conclusion

In order to analyze the influence of secondary flow motion on the bank collapse, this paper studied the Jing34 section of microbent section in Shashi District, and the riverbank stability of this typical section in the hydrologic year 2009 was calculated by using Delft3D model and BSTEM model, and the main findings are as follows:

1. The stability of the river bank was calculated according to the average water level of the Jing34 section, and the bank collapse strength was analyzed. The results showed that the water level reached the peak value, especially in the dry season, and the water level passed through the peak of the drop process. Along with the occurrence of bank collapse, from the time of bank collapse, the bank collapse mainly occurred during the flood period and the falling period.

2. Under the two calculation modes, the safety factor, the amount of erosion and the new form...
after the collapse of the bank slope were different. When considering the secondary flow, the safety factor of the river bank reduced, and the total soil volume of the collapse increased. The shape of the bank slope after the collapse is more in line with the actual situation. It can be seen that the secondary flow has a significant impact on the collapse of the river bank.

Acknowledgements
This research was financially supported by the National Key R&D Program of China (2017YFC0405306, 2016YFC0402309, 2017YFC0405304), National Natural Science Foundation of China (Grant No. 51779014), the Special fund for basic scientific research business of central public research institutes (Grant No. CKSF2015049/HL).

References
[1] Huang W. D., Wang Z. Y. (2007) Fluvial process forecasting for the middle and lower reaches of the Yangtze River. J. Journal of Tsinghua University (Science and Technology), 47:2131-2134.
[2] Zhu L. L., Zhang W., Ge H. (2011) Evolution trend and causes of the typical braided middle Yangtze reach after Three Gorges reservoir impoundment. J. Journal of Hydroelectric Engineering, 30:106-113.
[3] Jingjiang Hydrology and Water Resources Survey Bureau(Changjiang Water Resources Commission). (2009) Investigation of bank collapse and analysis of riverbed evolution near key dangerous sections in Jingjiang River. Scientific Research Report, 75-79.
[4] Deng C. Y., Xia J. Q., Zong Q. L. (2013) Modeling the effects of secondary flow on the transport of flow and sediment in a slightly curved reach. J. Journal of Sediment Research, 5:29-36.
[5] Midgley TL, Fox GA, Heeren DM. (2012) Evaluation of the bank stability and toe erosion model (BSTEM) for predicting lateral retreat on composite streambanks[J]. Geomorphology, 145-146:107-114.
[6] Zong Q. L., Xia J. Q., Deng C. Y. (2013) Modeling of the Composite Bank Failure Process Using BSTEM. J. Journal of Sichuan University (Engineering Science Edition), 45:1-10.
[7] Yu W. C., Lu J. Y. (2008) Bank collapse and protection in the Yangtze River. China WaterPower Press, Beijing.
[8] Xia J. Q., Zong Q. L., Xu Q. X. (2013) Soil properties and erosion mechanisms of composite riverbanks in Lower Jingjiang Reach. J. Advances in Water Science, 24: 810-820.