

A Hierarchical Indicator System for Riverbank Collapse Risk Assessment: Methodology and Validation in the Jingjiang Reach, Middle Yangtze River

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Abstract. Riverbank collapse is a recurrent hazard in alluvial rivers, driven by complex interactions between flow, sediment, bank materials, and human activities. Quantitative stability assessment remains challenging due to the multiplicity of influencing factors and their nonlinear couplings. This paper develops a hierarchical indicator system for bank stability evaluation. Following six selection criteria (scientific validity, discriminatory power, comprehensiveness, dynamic adaptability, mixed-method quantification, and operational feasibility), we establish a three-tier framework consisting of a target layer, an attribute layer, and an indicator layer. Six characteristic indicators are selected: current bank slope condition, bank geological composition, revetment integrity, near-bank flow dynamics, near-bank bed scour, and slope ratio change. These are grouped under three attributes – present stability state, controlling factors and evolutionary process. Scoring rules and a weight allocation scheme are derived from long-term observations in the Jingjiang Reach of the Middle Yangtze River. The overall stability score is then partitioned into three risk levels. Using topographic and hydrological data from 2020, the method is applied to 167.78 km of typical bank sections. Validation against actual collapse events recorded in 2021 demonstrates good predictive capability, with the majority of high risk sections either experiencing collapse or being identified as requiring urgent protection. The proposed system offers a practical and transparent tool for bank collapse early warning and river management.

Keywords: bank collapse; hierarchical indicator system; stability assessment; Jingjiang Reach; Middle Yangtze River.

1. Introduction

In the Middle Yangtze River, particularly the Jingjiang Reach, the operation of the Three Gorges Project and other upstream cascades has led to a drastic reduction in sediment load, triggering intensified channel incision and frequent bank erosion. These processes not only alter river morphology but also increase flood control risks and threaten riparian infrastructure. Timely assessment of bank stability and early warning of potential collapses are therefore essential for moving from post-disaster response to proactive risk mitigation.

Numerous studies have attempted to model bank stability using force-equilibrium approaches. Thorne and Tovey highlighted the balance between driving and resisting forces in composite riverbanks [1]. Osman and Thorne proposed the critical shear strength concept and established the Osman-Thorne model, which later evolved into the widely used BSTEM (Bank Stability and Toe Erosion Model) [2]. Subsequent applications of BSTEM in the Jingjiang Reach include Zong et al. [3], Wang et al. [4], and Wang et al. [5]. Meanwhile, Xia et al. [6] and Deng et al. [7] developed two-dimensional models based on field sampling and in-situ tests. Although these physically-based models offer clear mechanistic insights, they typically rely on simplifying assumptions and consider only a limited subset of controlling factors, which limits their predictive accuracy under complex field conditions.

To complement these approaches, this paper presents a hierarchical indicator system that integrates multiple factors into a composite stability score. The system is designed to be data-driven, easy to implement with available field data, and capable of capturing both the current state and the evolutionary trend of a bank slope. The methodology is established using historical data from the Jingjiang Reach and validated against recent collapse events.

2. Hierarchical Evaluation Framework

2.1 Three-Layer Framework Architecture

Because bank stability is controlled by numerous factors with intricate interactions, no single index can fully represent the overall condition. A set of indicators must be selected from multiple dimensions (e.g., bank morphology, hydraulic forcing, human interventions) following these principles: scientific validity, discriminatory power, comprehensive coverage, dynamic adaptability, mixed-method quantification and Operational feasibility.

The proposed evaluation system comprises three hierarchical layers:

Target layer: The overall goal is to produce a quantitative stability score that supports early warning and management decisions.

Attribute layer: Three attributes are defined – (i) current stability status, representing the integrated outcome of all past and present processes; (ii) stability influencing factors, which include river boundary conditions (geology and revetment) and hydrodynamic conditions (near-bank flow characteristics); (iii) stability change process, capturing the cumulative effects of bed scour and slope steepening.

Indicator layer: Six specific indicators are nested under these three attributes, as detailed below.

2.2 Description of Individual Indicators

(1) Current bank slope status (current stability status attribute)

Ongoing or recent bank collapse provides the most direct and integrated evidence of instability. If a bank section is actively retreating, it indicates that all necessary conditions for failure have been met, regardless of whether the primary cause is weak bank material, strong flow, or other factors. This indicator is treated as a “black-box” synthesis of all active mechanisms.

(2) Bank slope geological condition (river boundary conditions attribute)

Different geological materials confer different erosion resistance. Rock banks are the most resistant, while sandy banks are the weakest. Composite banks (e.g., a cohesive upper layer overlying a sandy lower layer, which is typical in the Middle Yangtze River) exhibit intermediate behavior that also depends on layer thickness and elevation. Seepage and groundwater outflow are also considered.

(3) Revetment completeness (river boundary conditions attribute)

The presence and condition of bank protection works (including both above-water slope protection and underwater toe protection) significantly enhance erosion resistance. Historical data from the Jingjiang Reach show that among 29.0 km of total bank collapse in 2019, 88.0% occurred on natural (unprotected) banks and only 12.0% on protected banks [8], underscoring the importance of this factor.

(4) Hydrodynamic characteristics (hydrodynamic conditions attribute)

The proximity of the main current to the bank, the persistence of flow impingement, and the overall stability of the local river regime are key hydraulic controls. Banks subjected to sustained direct impingement experience higher shear stresses and are more prone to collapse.

(5) Scouring nearshore riverbed (stability change process attribute)

Bed scour near the bank lowers the toe elevation, increases bank height and steepness, and reduces passive resistance. The degree of recent and cumulative scour is used as an indicator.

(6) Changes nearshore slope ratio (stability change process attribute)

The slope ratio (height to horizontal distance) directly influences gravitational stability. Based on statistical analysis of measured data in the middle and lower Yangtze River, Tang et al. [9] suggested that stable slope ratios lie in the range of 0.23 – 0.45, and when the ratio exceeds 0.5, the probability of collapse increases markedly.

2.3 Complete Indicator System

The resulting indicator system comprises one target, three attributes, and six characteristic indicators, as illustrated in Figure 1.

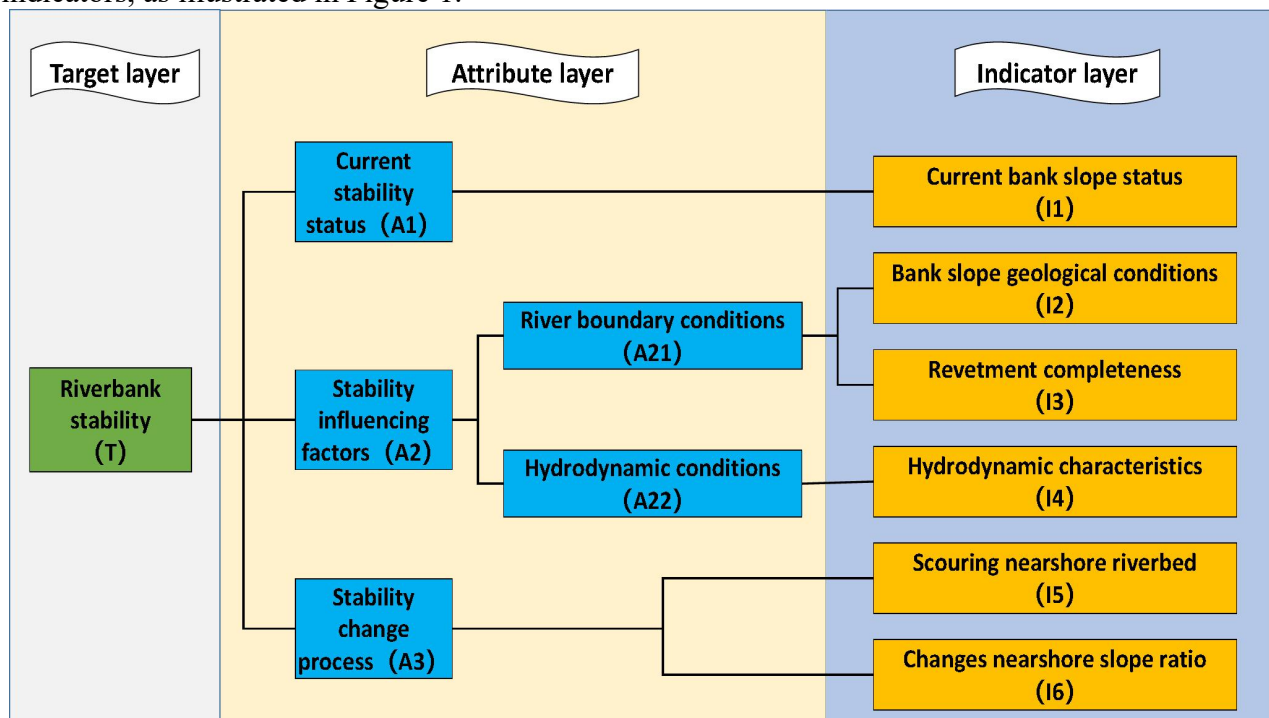


Fig. 1 Riverbank stability evaluation indicator system

3. Scoring and Weighting Protocol

The scoring rules and weight allocation were determined through iterative comparison of evaluation results with actual bank collapse records collected in the Jingjiang Reach since 2007.

3.1 Scoring Criteria for Each Indicator

Each indicator is scored on a scale where higher scores denote more stable conditions.

I_1 (current bank slope condition, 0 – 100): Based on the form (natural or protected bank), scale (small/medium/large), and severity (mild/moderate/severe) of recent collapses. No collapse in the past three years gives $I_1 = 100$.

I_2 (bank slope geological condition, 0 – 100): Higher scores for rock or well-consolidated clay banks, lower scores for loose sand or composite banks with seepage. Rock banks can be directly classified as stable without further scoring.

I_3 (revetment completeness, 0 – 100): Weighted combination of above-water protection (30%) and underwater toe protection (70%). Older works with poor integrity reduce the score; natural banks receive $I_3 = 0$.

I_4 (hydrodynamic characteristics, 0 – 100): Determined by local regime stability, flow impingement intensity and duration, and thalweg proximity. More severe or persistent impingement yields lower I_4 .

I_5 (Scouring nearshore riverbed, 0 – 50): $I_5 = 50$ for accreting beds; decreases with increasing scour depth.

I_6 (Changes nearshore slope ratio, 0 – 50): Decreases with steeper slopes.

3.2 Aggregation to Attribute Scores and Overall Stability Score

River boundary conditions attribute (A_{21}) is taken as the maximum of I_2 and I_3 , because effective revetment can compensate for poor natural geology:

$$A_{21} = \max(I_2, I_3)$$

Stability influencing factors attribute (A_2) then combines A_{21} (70%) and A_{22} (30%):

$$A_2 = 0.7 \times A_{21} + 0.3 \times A_{22} = 0.7 \times A_{21} + 0.3 \times I_4$$

Stability change process attribute (A_3) is the sum of I_5 and I_6 , reflecting the synergistic effect of concurrent scour and steepening:

$$A_3 = I_5 + I_6$$

Overall stability score (T) is a weighted average of the three attribute values (current stability status $A_1 = I_1$, stability influencing factors A_2 , stability change process A_3), with weights 40%, 30%, and 30% respectively (Table 1):

$$T = 0.4 \times A_1 + 0.3 \times A_2 + 0.3 \times A_3$$

Table 1. summarizes the weight distribution

Attribute	Current stability status	Stability influencing factors		Stability change process
Sub-component	-	River boundary conditions	Hydrodynamic conditions	-
Weight in T	40%	30%×70%=21%	30%×70%=9%	30%

3.3 Risk Level Classification

Three risk levels are defined based on the overall score T, as presented in Table 2.

Table 2. Classification of risk levels for bank collapse

Level of bank collapse risk	Range of T	Note
Blue	80~100	no immediate threat of bank collapse
Orange	60~79	potential hazards exist but collapse unlikely in the near future
Red	<60	serious hazards present, high probability of near-future collapse

4. Case Study: Jingjiang Reach, Middle Yangtze River

4.1 Study Area and Data

The Jingjiang Reach (Figure 2), with a total length of approximately 165.6 km, was selected for method validation. Using measured topographic, hydrological, and revetment data from 2006 to 2020, the stability of typical bank sections totaling 167.78 km is evaluated. The year 2020 was used as the baseline for assessment, and the predicted risk levels were subsequently compared against actual collapse events observed in 2021.

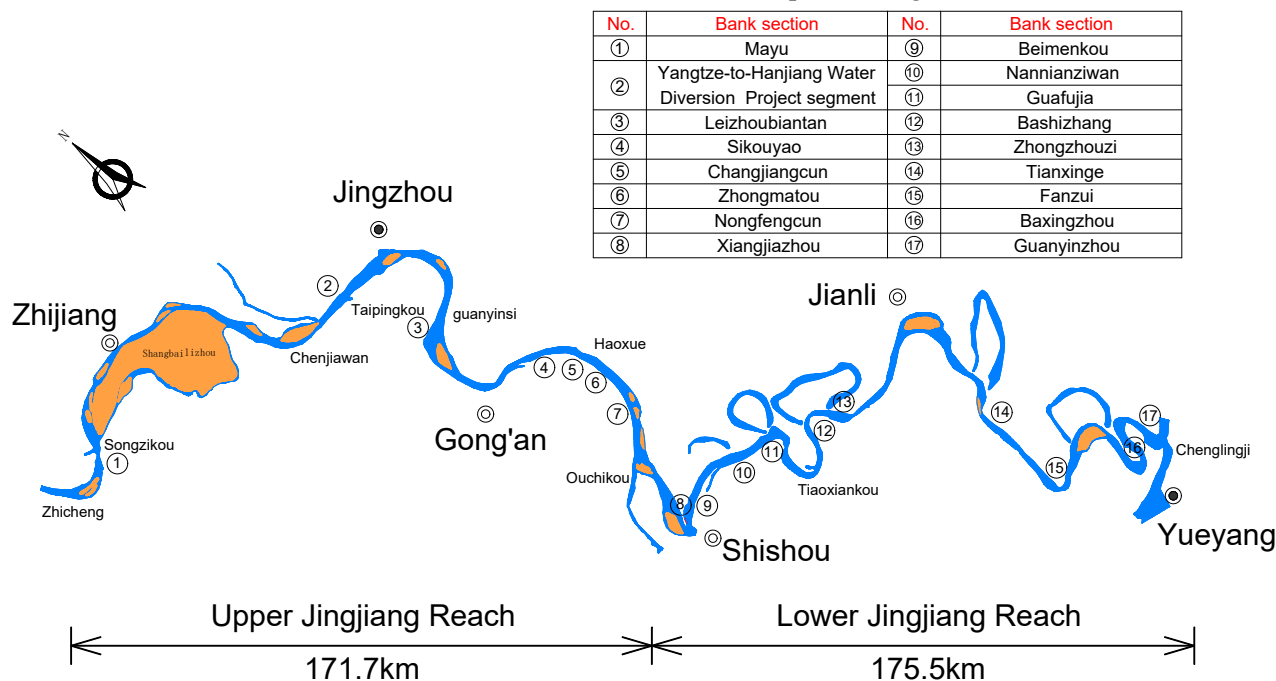


Fig. 2 River regime of the study reach

4.2 Stability Evaluation Results

The evaluation results indicate that the lengths of bank sections classified as blue, orange, and red risk levels are 90.36 km, 59.59 km, and 17.83 km, respectively. The red risk sections are presented in Table 3.

Table 3. Red risk bank sections in typical reaches of the Jingjiang Reach, Middle Yangtze River

River Reach	Evaluated Bank Section		Chainage Range	Length(m)
Upper Jingjiang	Mayu		Y1+560~Y2+600	1040
	Qing'anErshengzhou		6+500~4+400	2100
	Leizhoubiantan		0+000~1+100	1100
	Nanwuzhou	Sikouyao	40+900~40+370	530
		Changjiangcun	37+120~35+600	1520
Lower Jingjiang	Zhongmatou		35+000~33+000	2000
	Xiangjiazhou		23+900~21+450	2450
	Zhongzhouzi		7+120~7+420	300
	Beimenkou		9+000~11+000	2000
	Baxingzhou		2+400~4+630	2230
	Guanjinzhou	Upper Segment	564+860~563+020	1840
		Lower Segment	561+940~561+220	720
Totle length			17830	

4.3 Validation Against 2021 Observed Collapses

Table 4 summarizes the actual bankline conditions observed in 2021 for the evaluated sections. Comparing Table 3 with Table 4 reveals the following:

Most red risk sections (e.g., Mayu, Leizhou Biantan, Sikouyao, Changjiangcun, Zhongmatou, Baxingzhou, lower Guanjinzhou) indeed experienced either continued progression of previous collapses or new failure events in 2021, confirming the predictive skill of the method.

Several red risk sections (e.g., Qing'an Ershengzhou, Beimenkou, upper Guanjinzhou) did not collapse in 2021 because emergency protection works were implemented on those sections during

that year. This demonstrates that the evaluation successfully identified high-risk zones that would have collapsed without intervention – a key feature for proactive management.

Other red risk sections (e.g., the Yangtze-to-Hanjiang diversion project segment, Nongfengcun, Zhongzhouzi, Nannianziwan, Guafujia, Bashizhang, Tianxing, Fanzui) were previously collapsed but untreated; the red classification correctly flagged their persistent instability.

Overall, the agreement between predicted risk levels and observed outcomes is good, indicating that the proposed hierarchical indicator system is reliable for practical bank stability assessment.

Table 4. Bankline Conditions within the Evaluated Reaches for the Year 2021

Evaluated Bank Section	Chainage Range	Length (m)	Collapse Characteristics	Notes
Mayu	Y1+560~Y2+600	1040	Medium-scale, mild collapse on natural bank slope	Progression of previous year's collapse
Yangtze-to-Hanjiang Water Diversion Project segment	4+900~4+700	200	Small-scale, mild collapse on natural bank slope	Untreated collapse from previous year
	3+200~2+500	700	Small-scale, mild collapse on natural bank slope	Untreated collapse from previous year
Leizhoubiantan	0+000~1+100	1100	Large-scale, moderate collapse on natural bank slope	Progression of previous year's collapse
Sikouyao	40+900~40+370	530	Large-scale, mild collapse on natural bank slope	Progression of previous year's collapse
	40+370~39+700	670	Large-scale, mild collapse on natural bank slope	Untreated collapse from previous year
Changjiangcun	38+000~37+120	880	Large-scale, mild collapse on natural bank slope	Untreated collapse from previous year
	37+120~35+600	1520	Large-scale, moderate collapse on natural bank slope	Progression of previous year's collapse
Zhongmatou	35+000~33+000	2000	Large-scale, mild collapse on natural bank slope	Progression of previous year's collapse
Nongfengcun	27+800~24+000	3800	Small-scale, mild collapse on protected slope	Untreated collapse from previous year
Xiangjiazhou	23+900~23+150	750	Large-scale, severe collapse on protected slope	Progression of previous year's collapse
	23+150~21+450	1700	Large-scale, moderate collapse on natural bank slope	Progression of previous year's collapse
Zhongzhouzi	7+120~7+420	300	Medium-scale, moderate collapse on natural bank slope	Untreated collapse from previous year
Nannianziwan	1+600~2+200	600	Medium-scale, mild collapse on natural bank slope	Untreated collapse from previous year
	2+200~3+500	1300	Medium-scale, severe collapse on natural bank slope	Untreated collapse from previous year
Guafujia	5+800~7+300	1500	Large-scale, moderate collapse on natural bank slope	Untreated collapse from previous year
Bashizhang	520+000~519+200	800	Medium-scale, mild collapse on natural bank slope	Untreated collapse from previous year
Tianxing	40+900~40+600	300	Medium-scale, mild collapse on protected slope	Untreated collapse from previous year
Fanzui	23+200~20+000	3200	Large-scale, moderate collapse on natural bank slope	Untreated collapse from previous year
Baxingzhou	2+400~4+630	2230	Large-scale, moderate collapse on natural bank slope	Progression of previous year's collapse
Lower Guanyinzhou	561+940~561+220	720	Large-scale, moderate collapse on natural bank slope	Progression of previous year's collapse

5. Conclusions

This study has developed and validated a hierarchical indicator system for riverbank stability assessment. Six characteristic indicators are selected: current bank slope status, bank slope geological condition, revetment completeness, hydrodynamic characteristics, scouring nearshore riverbed, and changes nearshore slope ratio. These indicators are organized into a three-attribute framework comprising current stability status, stability influencing factors, stability change process. Based on long-term field data from the Jingjiang Reach, detailed scoring criteria for each indicator and a transparent weight allocation scheme are established. Application of the method to 167.78 km of bank sections in the Jingjiang Reach using 2020 data, with validation against actual collapses observed in 2021, shows that the predicted red risk zones correspond well to the locations of observed failures. Where protection works prevented collapse, the high risk prediction remains justified, demonstrating the value of the method for proactive management. The proposed system is therefore considered to be basically reliable and operationally useful.

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References

- [1] Thorne C R, Tovey N K. Stability of composite river banks. *Earth Surface Processes and Landforms*, 1981, 6(6): 469-484.
- [2] Osman A M, Thorne C R. Riverbank stability Analysis. I:Theory. *Journal of Hydraulic Engineering*, 1988, 114(2):134-150.
- [3] Zong Q L, Xia J Q, Deng C Y, et al. Modeling of the Composite Bank Failure Process Using BSTEM. *Journal of Sichuan University(Engineering Science Edition)*, 2013, (3):69-78.
- [4] Wang B, Yao S M, Yue H Y. Stability analysis for typical riverbank slope in the middle reach of Yangtze River by BSTEM. *Journal Yangtze River Scientific Research Institute*, 2014, 31(1):1-7.
- [5] Wang J, Zong Q L, Yue H Y, et al. Influence of dry-wet alternation condition on mechanical properties of riverbank soil for typical sections in Jingjiang Reach of Yangtze River. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2019, 35(2): 144-152.
- [6] Xia J Q, Zong Q L, Deng S S, et al. Recent adjustment in reach-scale bankfull channel geometry of the Jingjiang Reach owing to human activities. *Science China Technological Sciences*, 2014, 57(8): 1490-1499.
- [7] Deng S S, Xia J Q, Li J, et al. Influence of the variation of in-channel water levels on the riverbank stability in the Upper Jingjiang Reach. *Shuili Xuebao*, 2015, 46(7): 844-852.
- [8] Deng C Y, Li L Y, Guo C, et al. Study on Riverbank Stability Assessment Method and Its Application in the Jingjiang Reach in the Middle Yangtze River. 24th IAHR-APD CONGRESS, Wuhan, China, October 14-17,2024.
- [9] Tang J W, Deng J Y, You X Y, et al. Forecast Method for Bank Collapse in Middle and Lower Yangtze River. *Advanced Engineering Sciences*, 2012, 44(1): 75-81.