ISSN: 2688-8645

Investigation and Evaluation of Bank Slope Stability Along the Luoze River

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Abstract

The Loze River in Yiliang County exhibits significant geological hazards along its banks. This study investigates the geological environment of the river valley slopes from two perspectives: engineering geological conditions and slope structure. It summarizes the characteristics of geological hazard development. Finally, a multiple regression analysis method is employed to evaluate slope stability. By analyzing the statistical patterns between deformation instability phenomena and geological environmental conditions/ factors in existing river valley sections, a multiple regression prediction model is established to forecast slope stability in other river valley areas.

Keywords

Geological Engineering Environment; Slope Structure; Multiple Regression Analysis.

1. Introduction

Within Yiliang County, major transportation corridors (G352, S304, and the Yizhao Expressway), active key mines (Maoping Lead–Zinc Mine and Xiaofalu Coal Mine), as well as towns and villages are distributed along the banks of the Luoze River. Steep artificial cut slopes and cliff-edge housing are widespread. The riparian zone hosts relatively high densities of both permanent residents and transient populations, and human engineering activities are intense, including mining operations, road construction, cultivation on steep slopes, and slope cutting for housing development[1]. The river corridor is characterized by high relief and steep terrain, with slope gradients ranging from approximately 30° to 75°, and geological hazards are well developed. During the "9.07" earthquake in 2012, the Luoze River corridor constituted a severely affected area. Post-earthquake secondary geohazards exhibited the following characteristics: (1) they occurred predominantly within Carboniferous strata along the Luoze River and showed a positive correlation with seismic intensity; (2) they were mainly distributed on slopes with gradients of 20°–50°; and (3) they were densely concentrated within 500 m of roads and rivers, with occurrence frequency inversely related to the distance from these features. Over the past decade since the earthquake, collapses and landslides have continued to occur frequently in the region, causing substantial losses to lives and property[2]. Therefore, it is particularly important to conduct investigations and evaluations of slope stability along the Luoze River and to propose corresponding recommendations for risk management and control measures.

Based on the present field investigation, the river reach from Tangjiayanjiao in Luozehe Town to Zhongguankou in Jiaokui Town—an area characterized by dense infrastructure and population, concentrated settlements, and comparatively strong human engineering activities—was selected for stability assessment. The assessment scope primarily covers the first slope belt in this reach. It is generally a north–south-trending elongated zone extending along the river, with a total area of 88.23 km^2. The total length of the riverbank slopes on both the left and right banks of the main valley trunk stream is 81.27 km (Fig. 1).

2. Overview of the Engineering Geological Environmental Conditions of Valley Bank Slopes

The geomorphic types within the assessment area are dominated by tectonic–erosional middle- to high-mountain canyon landscapes. The Luozehe Town area in the southern part is characterized mainly by karst dissolution–erosional canyon landforms, whereas a small portion in the north comprises middle- to high-mountain canyon landforms with alternating tectonic–erosional and karst features. Stratigraphic units are relatively complete in the assessment area, accounting for approximately 65% of the total stratigraphic succession of the region. The principal exposed strata, from oldest to youngest, include the Silurian Sifengya Formation (S_2s) and Daluzhai Formation (S_2d); the Devonian Posongchong Formation (D_1ps) and Pojiao Formation (D_1P), Qingmen Formation (Dqm), Suotoushan Formation (D_2st), Hongyapo Formation (D_2hy), Qujing Formation (D_2q), and Zaijieshan Formation (D_3zj); the Devonian–Carboniferous Yanfang Formation (DCy); the Carboniferous Wanshoushan Formation (C_1w) and Huanglong Formation (Ch); the Permian Yangxin Formation (P_2y), Emeishan Formation (Pe), and Longtan Formation (P_3l); the Triassic Feixianguan Formation (T_1f), Jialingjiang Formation (Tj), Guanling Formation (T_2gl), and Xujiahe Formation (T_3x); the Jurassic Ziliujing Formation (J_1z), Shaximiao Formation (J_2^sx), and Suining Formation (J_2s); the Cretaceous Matoushan Formation (K_1m); and Quaternary (Q) residual–slope deposits and alluvial–pluvial deposits. The lithologic assemblage characteristics of each stratigraphic unit are summarized in Table 1. Structurally, the assessment area is located on the southwestern limb of the Yiliang Syncline, with northeast-trending faults developed to the south and north. Neotectonic activity is relatively strong. Most of the area lies within the VII and VIII seismic intensity zones of the "9.07" earthquake. Groundwater occurs mainly as pore water, fissure water, and karst water[3].

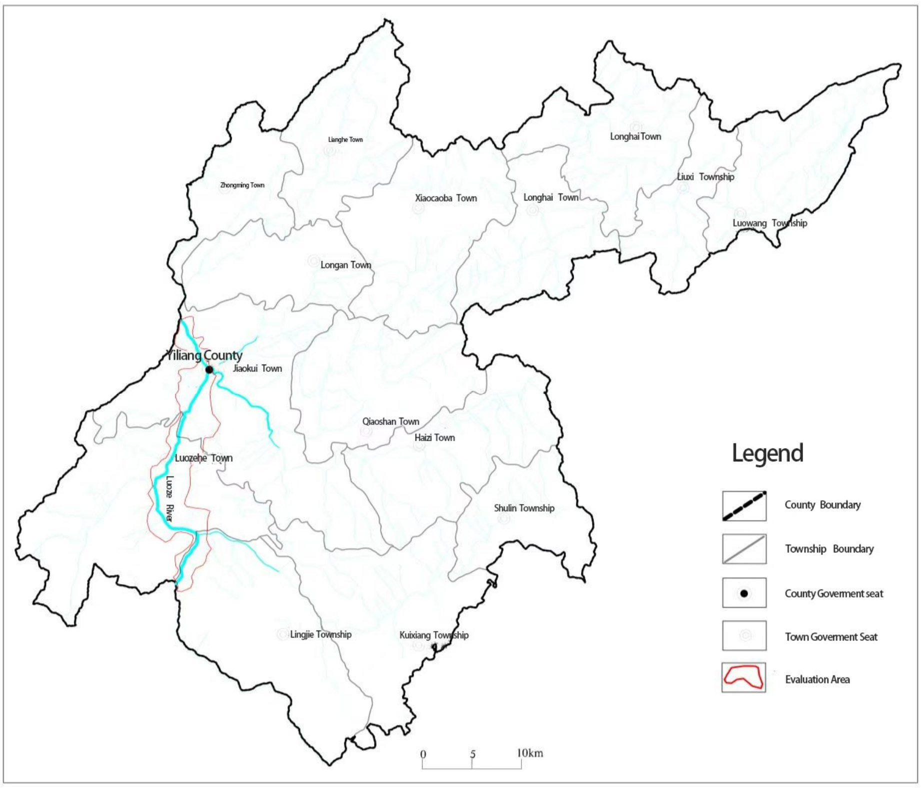

Figure 1. Map of the Slope Stability Assessment Area along the Luoze Riverbanks

ISSN: 2688-8645

3. Structural Types and Characteristics of Valley Bank Slopes

Bank-slope structure constitutes the fundamental condition controlling deformation and failure of riverbank slopes[4]. Variations in slope structure govern the type, frequency, and scale of deformation and failure. Therefore, elucidating the bank-slope structural characteristics within the assessment area is of critical importance for analyzing the developmental patterns, formation mechanisms, and stability of slope deformation and failures.Based on the field investigations conducted in this study—including verification of remote-sensing interpretations of geohazard sites, surveys of potential hazard points, and investigations of slope units—and from the perspective of geological bodies and their structural features, the bank-slope structures along the Luoze River valley within the assessment area were classified into seven types (Table 1). The classification was primarily determined by factors such as the types of rock–soil materials composing the slopes, structural and tectonic characteristics, bedding attitudes, and the relationship between strata orientation and slope strike. In total, 323 bank-slope sections were delineated. For each section, statistical analyses were performed on topographic characteristics, rock–soil material properties, and bank-slope structural features, thereby facilitating an understanding of the geological evolution of the slopes and providing a basis for subsequent stability analyses.

Table 1. Classification of Valley Bank-Slope Structural Types in the Assessment Area

No.	Bank Slope Type	Basis for Classification
1	Oblique-bedded layered bank slope	Bank slopes where the angle between the bedding dip direction and the slope aspect is 30°–60° or 120°–150°.
2	Dip-slope layered bank slope	Bank slopes where the angle between the bedding dip direction and the slope aspect is < 30°.
3	Transverse-bedded layered bank slope	Bank slopes where the angle between the bedding dip direction and the slope aspect is 60°–120°.
4	Anti-dip layered bank slope	Slope types where the angle between the bedding dip direction and the slope aspect is 150°–180°.
5	Sub-horizontal layered bank slope	Bank-slope types with bedding dip angles < 5°.
6	Massive-structured bank slope	Bank-slope types with bedding dip angles < 5°.
7	Colluvial (collapse–landslide) deposit bank slope	Bank slopes in relatively gentle belts near the valley floor, composed mainly of colluvial deposits derived from collapses and landslides.

Within the watershed, obliquely bedded (diagonally intersecting) layered bank slopes constitute the dominant structural type, with a total length of 20.32 km, accounting for 25% of all bank slopes. This is followed by anti-dip (reverse) slopes, with a total length of 17.88 km (22%); dip slopes (consequent slopes) total 13.82 km (17%); and loose-deposit bank slopes total 17.88 km (22%). Transverse layered bank slopes and igneous-rock bank slopes occur less frequently, with a combined length of 11.38 km, representing 14%.

Statistics on slope gradients indicate that bank slopes steeper than 40° predominate within the assessment area, with a total length of 38.20 km (47%). The next most common class comprises slopes of 30°–40°, totaling 19.51 km (24%). Slopes of 20°–30° and those gentler than 20° have lengths of 11.38 km and 12.19 km, accounting for 14% and 15%, respectively.

Across all bank slopes in the Luoze River valley, convex slopes have a total length of 22.76 km (28% of the total); concave slopes total 21.94 km (27%); straight slopes total 24.38 km (30%); and stepped slopes total 12.19 km (15%).

ISSN: 2688-8645

A statistical assessment of the engineering geological rock groups forming the bank slopes shows that all engineering geological rock groups recognized within Yiliang County are represented along the Luoze River banks. The bank slopes are composed of: unconsolidated deposits; thin- to medium-bedded hard clastic rock assemblages interbedded with weak layers; thin- to medium-bedded weak clastic rock assemblages; thick-bedded to massive hard, moderately karstified carbonate rock assemblages; medium- to thick-bedded hard, moderately karstified carbonate rock assemblages; and fractured, relatively soft, strongly weathered igneous rock assemblages (Table 2).

Table 2. Statistics of Engineering Geological Rock Groups of the Luoze River Bank Slopes

No.	Engineering geological rock groups constituting the bank slopes	Length of Bank-Slope Sections (km)	Percentage (%)
1	nconsolidated deposits	8.13	10
2	Thin- to medium-bedded hard clastic rock assemblage interbedded with weak layers	28.45	35
3	Thin- to medium-bedded weak clastic rock assemblage	12.19	15
4	Thick-bedded to massive hard, moderately karstified carbonate rock assemblage	24.38	30
5	Medium- to thick-bedded hard, moderately karstified carbonate rock assemblage	4.47	5.5
6	Fractured, relatively soft, strongly weathered igneous rock assemblage	3.66	4.5
Total		81.27	100

4. Development Characteristics of Geological Hazards

A total of 77 geological hazards and potential hazard sites were identified within the assessment area, accounting for 19% of the entire area. These include 46 landslides, 52 collapses/rockfalls, 3 debris flows, and 2 ground-surface collapses (sinkholes). In terms of size classification, 10 sites are of medium scale. Medium-to-large events are dominated by landslides; in addition, one debris-flow site and one ground-collapse site fall into the medium-to-large category. The remaining sites are small scale (67 in total), comprising 38 landslides, 25 collapses/rockfalls, 3 debris flows, and 1 ground-surface collapse (Table 3).

Table 3. Statistics of Geological Hazards and Potential Hazard Sites on Bank Slopes

Geological hazards and potential hazard sites Type	Scale			Total Scale
	Large	Medium	Small	
Landslide		8	38	46
Collaps		1	25	26
Debris flow			3	3
Ground collapseTotal		1	1	2
Total		10	67	77

5. Bank Slope Stability Assessment

A multivariate regression analysis method was employed for the bank-slope stability assessment. By statistically examining the relationships between observed deformation/instability phenomena of existing valley-bank slopes and the geological environmental conditions as well as governing factors, a multivariate regression predictive model was established to link influencing parameters with bank-slope deformation and instability, thereby enabling the prediction of stability for bank slopes in other reaches of the valley[5].

1. Classification of bank-slope stability. The stability of valley bank slopes depends on the degree of development, types, number, scale, and activity of geological hazards. In particular, landslides and collapses of medium scale and above, as well as gully-type debris flows, play a critical role in controlling bank-slope stability. Bank-slope deformation and instability are also constrained by topography and geomorphology, stratigraphic lithology, geological structures, and bank-slope structural conditions. Considering both the development of geological hazards and the relevant geological conditions, bank-slope stability was classified into four grades: high stability (A), relatively high stability (B), relatively low stability (C), and low stability (D).

2. Selection of assessment factors. Deformation and instability of bank slopes result from the combined effects of multiple factors. The engineering properties of the rock/soil materials, rock-mass structure, topography and geomorphology, and structural–tectonic assemblages constitute the fundamental conditions, whereas rainfall, earthquakes, and human engineering activities serve as triggering factors. The mechanisms by which these factors act during slope deformation and instability are complex. In accordance with the engineering geological characteristics of the Luoze River bank slopes, the following factors were selected for assessment: slope gradient, rock/soil type, bank-slope structural type, fluvial geological processes, degree of fault development, degree of joint/fracture development, structural-plane assemblages, development of geological hazards, human engineering activities, mean annual precipitation, and peak ground acceleration.

3. Model development. Multivariate regression analysis was adopted to construct a quantitative relationship between one dependent random variable and one or more independent variables. Through analysis and computation based on observed data, a regression model expressing the quantitative relationship between the dependent variable and the independent variable set was obtained.

4. Stability assessment procedure. The evaluation procedure for bank-slope stability along the Luoze River valley comprises the following steps: first, the valley bank slopes are segmented; second, stability for a subset of segments is qualitatively assessed to serve as known samples; third, multivariate regression analysis is performed to derive the functional relationship (i.e., regression equation) between bank-slope stability and the influencing factors; fourth, the regression equation and coefficients are subjected to significance testing. Once the regression coefficients are confirmed to be significant, the regression equation can be used to evaluate and predict the stability of other bank-slope segments.

Considering the controlling and influencing factors of bank-slope stability, and in combination with the engineering geological characteristics of the Luoze River valley, 11 factors—namely slope gradient, rock/soil type, bank-slope structural type, fluvial geological processes, degree of fault development, degree of joint/fracture development, structural-plane assemblages, development of geological hazards, human engineering activities, mean annual precipitation, and peak ground acceleration—were taken as independent variables, corresponding to (x_1, x_2, \ldots, x_{11}). Bank-slope stability was taken as the dependent variable (y), and a multivariate regression analysis was conducted for the stability assessment.

Because the variables in the observed samples differ in magnitude and units, appropriate data preprocessing is required to improve regression performance and to ensure comparability among variables. Therefore, all factors influencing valley bank-slope stability were transformed into dimensionless indices. In the data processing, the method adopted was to evaluate the stabilizing effect of each factor and classify its influence on bank-slope stability into four grades—favorable, moderate, unfavorable, and most unfavorable—assigned values of 1, 2, 3, and 4, respectively. The assignment criteria for each factor are provided in Table 4.

Table 4. Assessment Factors and Classification Criteria for Bank-Slope Stability

Factor	Discriminant indicator	Stability effect	Score
Topographic slope gradient	≤ 20°	Favorable	1
	20°–30°	Moderate	2
	30°–40°	Unfavorable	3
	≥ 40°	Most unfavorable	4
Rock/soil mass type	Thick-bedded to massive hard, moderately karstified carbonate rock assemblage; medium- to thick-bedded hard, moderately karstified carbonate rock assemblage	Favorable	1
	Thin- to medium-bedded hard clastic rock assemblage interbedded with weak layers	Moderate	2
	Thin- to medium-bedded weak clastic rock assemblage; fractured, relatively soft, strongly weathered igneous rock assemblage	Unfavorable	3
	Unconsolidated deposits	Most unfavorable	4
Bank-slope structural type	Anti-dip layered bank slope; transverse-bedded layered bank slope	Favorable	1
	Sub-horizontal layered bank slope	Moderate	2
	Oblique-bedded layered bank slope; massive-structured bank slope	Unfavorable	3
	Dip-slope layered bank slope; colluvial (collapse–landslide) deposit bank slope	Most unfavorable	4
Fluvial geological effect	Convex-bank slope	Favorable	1
	Straight bank slope	Moderate	2
	S-shaped bank slope	Unfavorable	3
	Concave-bank slope	Most unfavorable	4
Degree of fault development	Faults absent/undeveloped	Favorable	1
	Faults present nearby; rock-mass structure generally developed	Moderate	2
	Faults present within the area; rock-mass structure relatively poor	Unfavorable	3
	Faults present within the area with an evident fault breccia/fracture zone; rock-mass structure poor	Most unfavorable	4
Degree of joint/fracture development	Absent/undeveloped	Favorable	1
	Generally developed	Moderate	2
	Relatively well developed	Unfavorable	3

Following the above principles, each factor influencing valley bank-slope stability was processed accordingly. Fifty bank-slope sections were then selected, and their stability was individually judged from a qualitative perspective to serve as known samples. The stability grades were coded as follows: high stability = 1, relatively high stability = 2, relatively low stability = 3, and low stability = 4. Using the dataset from these 50 bank-slope sections, a multivariate regression analysis was conducted to establish a multivariate linear regression model. The linear correlation analysis indicated that (x_5) and (x_6) were linearly correlated; therefore, (x_5) was excluded. The resulting regression equation is:

$$y = 2.21 + 0.347x_1 - 0.334x_2 + 0.046x_3 + 0.053x_4 + 0.209x_6 - 0.006x_7 + 0.343x_8 - 0.004x_9 - 0.194x_{10} - 0.125x_{11}$$

Table 4. Continuation: Stability Evaluation Factors and Grading Criteria for Shore Slopes

	Well developed	Most unfavorable	4
Structural-plane assemblage	Unfavorable for the formation of landslides and collapses/rockfalls	Favorable	1
	Limited influence on the formation of landslides and collapses/rockfalls	Moderate	2
	Moderate influence on the formation of landslides and collapses/rockfalls	Unfavorable	3
	Favorable for the formation of landslides and collapses/rockfalls	Most unfavorable	4
Development of geological hazards	No hazard sites present	Favorable	1
	Sparse distribution; small scale	Moderate	2
	Moderate distribution; medium scale	Unfavorable	3
	Dense distribution; large scale; poor stability	Most unfavorable	4
Human engineering activities	Weak	Favorable	1
	Moderate	Moderate	2
	Relatively strong	Unfavorable	3
	Strong	Most unfavorable	4
Mean annual precipitation	≤ 1000 mm	Favorable	1
	1000–1100 mm	Moderate	2
	1100–1200 mm	Unfavorable	3
	≥ 1200 mm	Most unfavorable	4
Peak ground acceleration	0.05 g	Favorable	1
	0.10 g	Moderate	2
	0.15 g	Unfavorable	3
	0.20 g	Most unfavorable	4

significance test was performed for the derived regression equation. According to the ANOVA table of the regression model (Table 5), the regression performance is statistically significant.

Table 5. ANOVA (Analysis of Variance) Table for the Regression Model

Model	Sum of Squares	lf	Mean Square	F	Sig
22.337	10	2.234	12.843	0.000a	22.337
6.783	39	0.174			6.783
29.120	49				29.120

Therefore, the regression equation can be used to evaluate the stability of the 50 bank-slope sections. Specifically, when the predicted value ($\hat{y}$ < 1.5), the bank slope is classified as high stability; when ($\hat{y}$=1.5~2.5), it is classified as relatively high stability; when ($\hat{y}$=2.5~3.5), it is classified as relatively low stability; and when ($\hat{y}$>3.5), it is classified as low stability.

The evaluation results indicate that, among the 50 sample sections, only three samples were misclassified, whereas the stability classifications for all other sections were correct, yielding an overall accuracy of 94%, which demonstrates good predictive performance. On this basis, the above multivariate regression equation was applied to the 323 valley bank-slope sections within the Luoze River watershed to evaluate and predict their stability, producing the final stability assessment results for the Luoze River (Table 6).

The results show that there are 32 sections with high stability, with a total length of 9.94 km, accounting for 12.23% of the total bank-slope length; 63 sections with relatively high stability, totaling 15.64 km (19.24%); 120 sections with relatively low stability, totaling 29.62 km (36.45%); and 108 sections with low stability, totaling 26.07 km (32.08%).

Table 6. Statistical Summary of Bank-Slope Stability Assessment Results for the Luoze River

Category	High stability	Relatively high stability	Relatively low stability	Low stability
Number of bank-slope sections (No.)	32	63	120	108
Length of bank-slope sections (km)	9.94	15.64	29.62	26.07
Length proportion (%)	12.23	19.24	36.45	32.08

The poor stability of the valley bank slopes along the Luoze River is consistent with the area's fragile geological environmental conditions. In particular, in the Luoze River valley—especially the Tangjiayanjiao–Maoping reach—the terrain is steep and rugged, joints and fractures are well developed, and unfavorable combinations of structural discontinuities frequently induce bank-slope deformation and instability. Consequently, bank-slope stability in this reach is dominated by the low and relatively low classes. By contrast, bank slopes exhibiting relatively high or high stability are mainly distributed in the comparatively gentle and wider valley sections between Maoping and the Yiliang County segment of the Luoze River valley.

6. Recommendations for Risk Management and Control Measures

The bank slopes of the Luoze River valley are steep, with highly fractured rock-mass structures and a fragile geological environment, resulting in generally poor slope stability. Engineering construction activities can substantially disturb the existing topography and geomorphology, which is likely to trigger widespread bank-slope instability and consequently induce geological hazards such as landslides, collapses/rockfalls, and debris flows. In future large-scale development of the watershed, site selection and route alignment for engineering projects should, as far as practicable, avoid such high-risk reaches. Where avoidance is not feasible, appropriate mitigation measures should be implemented to minimize disturbance to these bank slopes, thereby reducing the risk of collapses/rockfalls, landslides, debris flows, and other related geohazards.

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