

Article

Research on Landslide Tsunamis in High and Steep Canyon Areas: A Case Study of the Laowuchang Landslide in the Shuibuya Reservoir

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Abstract

Landslides occurring on reservoir banks in steep, high-gradient canyon areas pose a significant risk of surge disasters when they slide into the water. This can endanger the lives and property of downstream residents and damage coastal infrastructure. Therefore, researching the formation mechanisms, disaster evolution, and risk assessment of the landslide-surge disaster chain in such areas is essential. This paper takes the Laowuchang landslide in the Shuibuya Reservoir area of the Qingjiang River, China, as its research object. Using GeoStudio 2018 software, it evaluates the landslide's stability under varying reservoir water levels and rainfall conditions. For potential unstable scenarios identified, a full-chain numerical simulation of the landslide–tsunami disaster was conducted based on the Tsunami Squares method, with a focus on analyzing the wave characteristics during generation, propagation, and run-up processes. Furthermore, the paper assesses the risk of landslide–tsunami disasters in the Laowuchang landslide area. The research findings indicate that: (1) Under the long-term continuous river incision, limestone of the Triassic Daye Formation slides along weak interlayers, inducing large-scale collapses. Subsequently, part of the landslide mass is transported by water, while most accumulates in the near-shore area of the Qingjiang River, ultimately shaping the present morphology of the landslide. (2) The Laowuchang landslide is stable under static water levels of 375 m and 400 m, with corresponding safety factors of 1.137 and 1.167, respectively. Under combined static water level and heavy rainfall conditions, the slope stability decreases significantly, with safety factors of 1.034 and 1.064, respectively. Under reservoir drawdown conditions, the slope tends to be unstable, with a safety factor of 1.047. (3) Numerical simulation results indicate that if the Laowuchang landslide fails into water by the speed of 12 m/s and with a volume of 2 million m³, the maximum initial wave height can reach 15.9 m. The tsunami's affected range spans 10 km upstream and downstream from the landslide mass, with four houses and one substation within a 2 km up and downstream falling into high-risk areas. If abnormal increases in landslide displacement occur, relocation and risk avoidance measures should be implemented. The findings of this study provide a scientific basis for the prevention and response to landslide–tsunami disasters in similar high and steep canyon terrains.



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Keywords: landslide; numerical simulation; stability analysis; risk assessment; landslide–tsunami disasters

1. Introduction

High and steep canyon regions are typically featured by rugged topography, steep bank slopes, and frequent landslide occurrences. When reservoir bank failures enter water, they can readily generate violent impulse waves, forming a typical “landslide–water entry–surge” disaster chain that poses severe threats to downstream residential areas and riverside infrastructure. Due to the suddenness of such events and their complex evolutionary processes, investigating the generation mechanisms and propagation characteristics of landslide-induced surges in high and steep canyon areas is of great engineering significance.

Existing studies have mainly explored the evolution process of landslide-induced surges using physical model tests and numerical simulations. Due to their intuitiveness and repeatability, physical experiments have become an important means to study the generation and propagation characteristics of surge waves. Noshin S [1] used GeoStudio to analyze the stability and seepage characteristics of four flood-control embankments in Muzaffargarh, Pakistan. The study identified piping-induced instability risks in several embankment sections and proposed corresponding reinforcement measures. Wu Yuhang et al. [2] carried out three-dimensional experiments on surge waves generated by blocky and granular landslides under mountainous river terrain conditions. By adopting orthogonal experimental design and multivariate nonlinear regression, they established empirical formulas for the initial maximum wave amplitude and its propagation attenuation, and verified the models using multiple landslide cases. Uribe [3] explored the influences of landslide geometry, velocity and aspect ratio, and revealed a power-law relationship between submarine landslide velocity and wave impact height. Wang Yue [4] conducted experiments on rigid blocks sliding along a gentle underwater slope to analyze the formation mechanism of submarine landslide surges. Results showed that the initial wave trough was larger than the wave crest, and prediction formulas for the maximum trough and crest heights were derived. Brizuela [5] systematically investigated submarine landslide surges in lacustrine environments and their internal response mechanisms, demonstrating that water depth, bottom topography, water temperature and sediment concentration gradients exert significant influences on wave propagation. Won M. et al. [6] further combined the limit equilibrium method with SVM, RF and XGBoost models for slope stability evaluation. It was found that the XGBoost model exhibited the best performance, and the slope ratio (v/h), slope height (H) and cohesion (c) significantly affected the safety factor and the position of the slip surface. Wu et al. [7] conducted physical model tests on granular landslide-generated waves to examine the effects of slide volume, impact velocity, and water depth on surge characteristics. Their results indicate that fully submerged slides generate larger primary wave amplitudes. Based on the relationship between the unit-width volume ratio R and Froude number Fr , a waveform boundary equation was derived, and a prediction model for the maximum wave amplitude using R was further proposed.

Benefiting from high efficiency and flexibility, numerical simulations have also emerged as an important tool for studying landslide-induced surges. Y. Zhang [8] conducted 14 numerical experiments using the Tsunami Squares method to investigate the influence of reservoir geometry on the propagation characteristics of landslide-generated waves. J. Wang [9] proposed an analytical hydrodynamic model for surge waves that con-

siders the water–soil interaction process. Shi Q. C. et al. [10] established a soil–water coupled model based on Smoothed Particle Hydrodynamics (SPH) and applied it to the Huangtian landslide case; the numerical results agreed well with field measurements. Zafar M. N. [11] combined high-resolution seismic surveys, bathymetric data, and a two-dimensional depth-averaged nonlinear shallow water model to reproduce a submarine landslide event in Lake Aiguebelette, France, with the simulated maximum wave amplitude reaching 3.6 m.

Overall, existing studies have systematically elucidated the generation mechanisms and propagation patterns of landslide-induced surges through experimental and numerical methods. These studies have clarified the fundamental relationships between landslide kinematic parameters and wave responses, providing a theoretical basis for understanding disaster mechanisms and formulating engineering mitigation strategies. Based on these findings, further investigations that consider the topographic conditions of high and steep canyon regions and the dynamic characteristics of landslides will help to deepen our understanding of the evolutionary processes of landslide-induced surges.

2. Basic Overview of the Landslide Area

2.1. The Geographical Location and Environmental Setting of the Landslide

The Laowuchang Landslide is situated on the southern bank of the Qingjiang Shuibuya Reservoir in Jingyang Town, Hubei Province, Hubei Province, (Figure 1), approximately 30 km upstream of the Shuibuya Water Control Project. Regionally, the landslide lies within the nearly east–west-trending folded mountains of the southwestern Hubeian extension of the northeastern Yunnan–Guizhou Plateau. This area features tectonic erosion landforms and low-to-moderate altitude mountains. The Qingjiang River flows eastward through the landslide area, with a vertical cutting depth of over 1000 m; the river valley is generally symmetric on both sides, and the valley slopes exhibit a stepped morphology.



Figure 1. Location Maps of the Laowuchang Landslide Area: (a) Location within Hubei Province, China; (b) location within Jingyang Town, Hubei Province; (c) topographic map of the steep canyon region.

Since the Shuibuya Reservoir (Qingjiang River) began impoundment in 2007, its water level has reached 400 m. The river here is ~900 m wide and 160 m deep, a key year-round navigable waterway that flows eastward across the Laowuchang Landslide's front edge. In a normal hydrological year (average precipitation), the reservoir water level typically drops from 400 m to 375 m during the flood-to-drought transition period, with a fluctuation range of ~25 m. The riverbed elevation is ~240 m, forming a 160 m-high exposed face at the landslide's front edge. Combined with the reservoir water level decline, these conditions favor landslide initiation.

The study area has a humid, rainy climate, with an average annual precipitation of 1375.6 mm. Historical records show: the maximum annual rainfall reached 2200.4 mm (1983), the maximum monthly rainfall was 630.1 mm (July 1983), and the maximum daily rainfall hit 178.2 mm (10 June 2017). Rainfall exhibits obvious seasonal variation, mostly concentrated in April–August. Based on 2002–2021 rainfall data, total precipitation in this period is 1184.5 mm, accounting for 71% of the annual total. Long-term data analysis reveals that June–August rainfall generally exceeds 450 mm, making up 23–25% of the annual rainfall. In contrast, winter rainfall (December–February) is relatively scarce, usually around 100 mm, which constitutes 5–9% of the annual total.

2.2. Basic Characteristics of the Landslide Body

The main sliding direction of the new Laowuchang landslide is slightly west of due north, approximately 0° . In plan view, it presents a tongue-shaped morphology (Figure 2), with a longitudinal length of 520 m, a width of 550 m, and a total area of about 0.1885 km². The main body of the landslide is located within Permian limestone, which has an overall relatively intact structure and gently inclined bedding planes. These bedding planes play a dominant role in the development of the sliding zone (Figure 3).



Figure 2. Plan View of the Laowuchang Landslide.

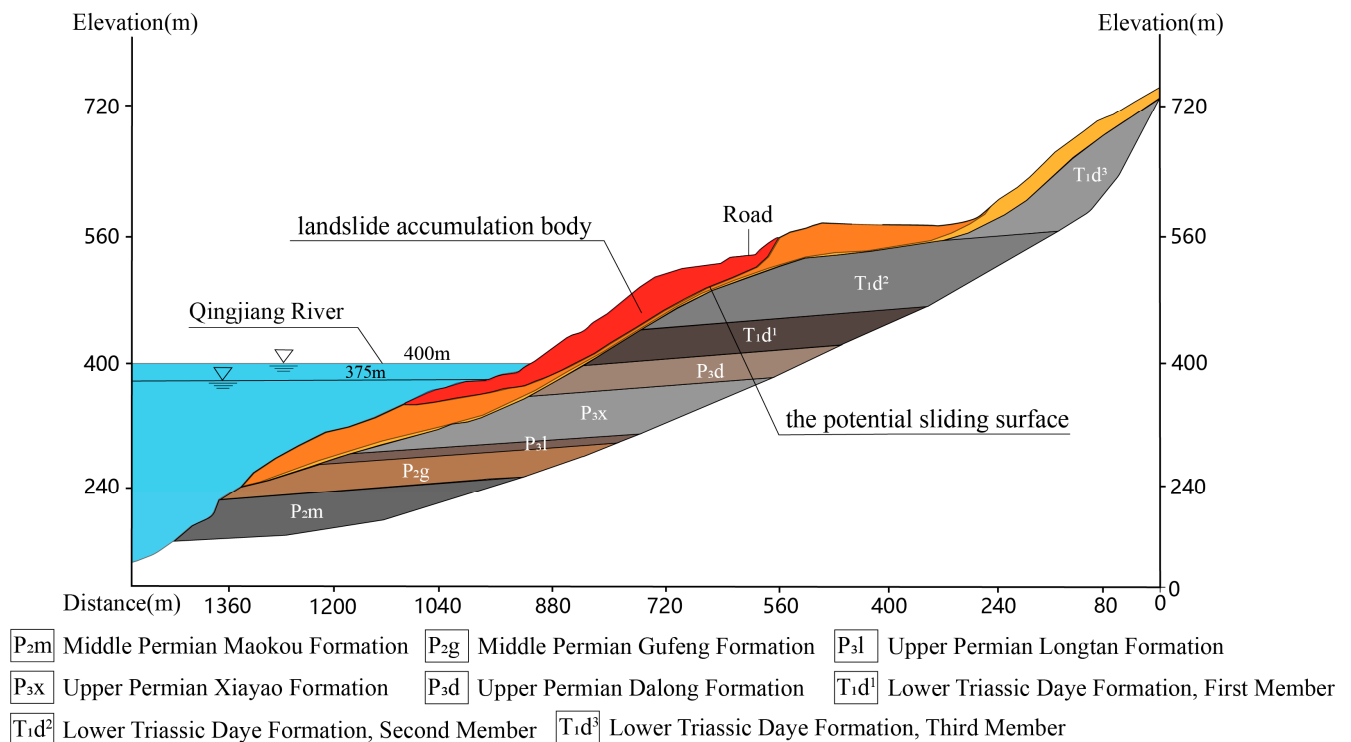


Figure 3. Cross-sectional diagram of the Laowuchang Landslide.

2.3. Mechanism of Landslide Formation

Through field investigations, the Laowuchang Landslide is found to be primarily controlled by a combination of factors, including topography, lithology, geological structure, and atmospheric precipitation. As indicated by previous data [12–15], during the late Middle Pleistocene (approximately 300,000–400,000 years ago), the continuous incision of the Qingjiang River cut through the Lower Triassic Daye Formation, exposing its front edge and thereby creating favorable conditions for landslide occurrence. The sliding process can be roughly divided into two stages, whose respective conditions are outlined as follows.

Stage 1 (Figure 4): The Qingjiang River cuts through the Lower Triassic Daye Formation, forming a steep, exposed rock face. Due to tectonic fragmentation, well-developed joints and fractures, and the softening of weak layers, the rock mass becomes fragmented and eventually collapses under gravity. The collapsed material is primarily composed of limestone blocks and gravel. As the river continues to incise, recurrent collapses occur; the accumulated material on the slope then becomes overloaded, triggering a landslide and thus transitioning to the next stage.

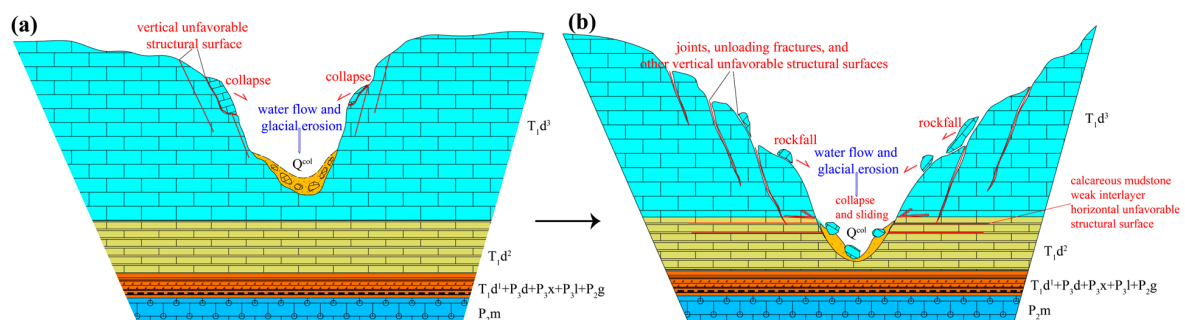


Figure 4. Schematic diagram of the first stage of the Laowuchang Landslide formation ((a) Middle to Late Pleistocene river movement; (b) intensification of river erosion during the Late Middle Pleistocene).

Stage 2 (Figure 5): After the landslide, the Qingjiang River continued to incise, initiating a phase of intense geological activity. Under gravitational forces, bedrock on the river-flanking peaks detached; successive collapses and landslides rapidly reshaped the topography, forming an initial “U”-shaped valley. As river incision deepened and penetrated the soft Permian layers, conditions for a new landslide were reactivated. Triassic limestone then collapsed along these weak layers, and the resulting deposits accumulated atop the Stage 1 landslide mass, triggering a second landslide event. A portion of this new landslide material was carried away by the river, while the remainder formed a potential landslide body. As the region transitioned from an active to a stable geological phase, the Qingjiang River continued to incise the medium-thick Permian limestone. Owing to the higher hardness of this rock, incision rates slowed, hydraulic action weakened, and overall geological activity diminished. During this period, debris flow deposits relieved pre-existing stress through processes such as landslides and thrusting, forming multi-level terraces with height differences of 20–80 m. Subsequently, geological events shifted to small-scale collapses and minor deformations, featuring reduced magnitude and extended time intervals.

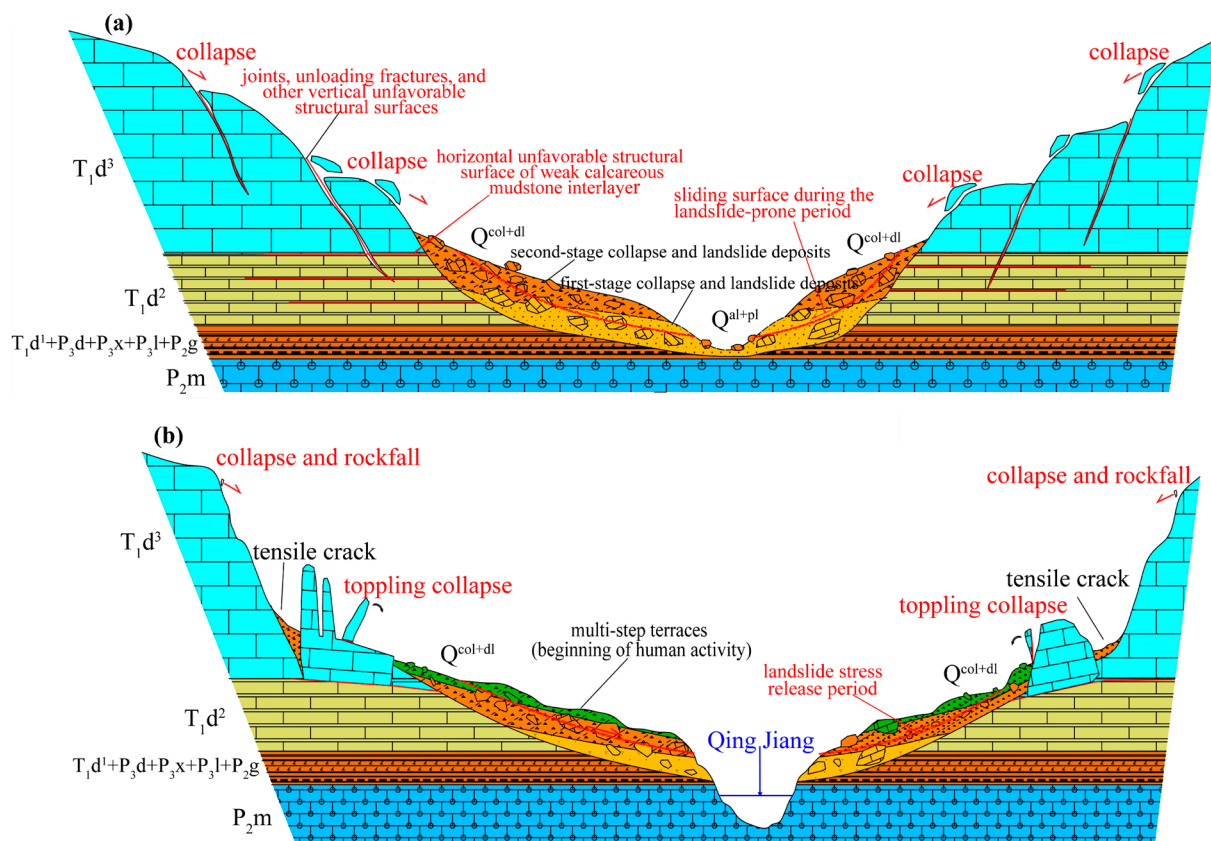


Figure 5. Schematic diagram of the second stage of formation ((a) Period of frequent geological events; (b) Transition from the period of frequent geological events to the stable period).

An analysis of the landslide’s sliding process divides the major landslide events in this area into two distinct stages.

Stage 1: Under river incision, limestone of the Triassic Daye Formation slides along weak interlayers, triggering a large-scale collapse.

Stage 2: The collapsed deposits, together with residual Triassic limestone, continue to release energy downslope, initiating a second landslide event. A small portion of the landslide mass is carried away by the river, while the majority remains and accumulates

in the near-shore reach of the Qingjiang River—forming the present topography of the Laowuchang Landslide.

Since the Quaternary, human activities have had minimal impact on the Qingjiang River's banks. The thick deposit layer has undergone creep deformation under gravity, occasionally releasing energy once deformation accumulates to a certain threshold. Over the past two decades, the most significant change has been the damming of the Qingjiang River for water storage: static water pressure and fluctuations in the drawdown zone affected the front of the original ancient landslide, triggering the formation of the Qingjiang Jingyang landslide group. Through overall translational movement, the landslide front advanced 50–200 m into the former river channel. When the front encroached below the river level, it formed a soil berm for support; lateral soil pressure on the deposit body gradually balanced out, and the landslide eventually evolved into its current state.

The present Laowuchang Landslide exhibits a tongue-shaped planar morphology (Figure 6), with a longitudinal length of 520 m, a width of 550 m, and a total area of approximately 0.1885 km². Its profile is step-like, and its three-dimensional shape is wedge-shaped. The elevation of the landslide's front edge (at the Qingjiang water level) is 360 m, while that of the rear edge is 560 m.

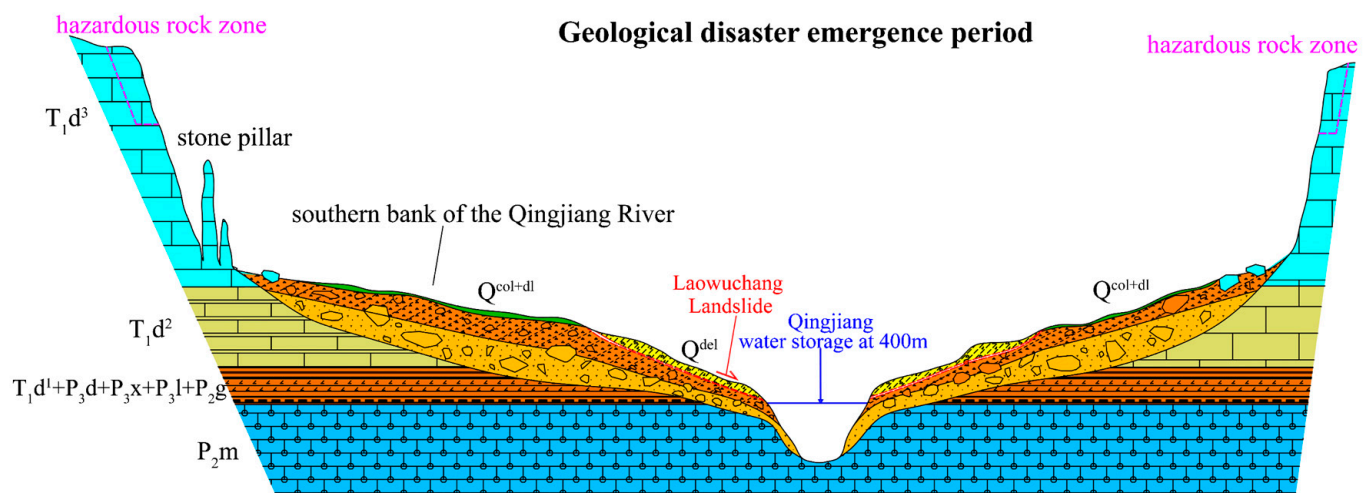


Figure 6. Current status of the Laowuchang Landslide after stabilization.

Landslide investigation data indicate that the landslide is generally thinner at the front and rear edges and thicker in the middle. Its thickness ranges from 36.0 to 50.5 m (average: 30 m), with a total volume of approximately $565.5 \times 10^4 \text{ m}^3$ —classifying it as a large-scale soil landslide.

At present, the Laowuchang Landslide no longer faces the risk of large-scale overall sliding. Only localized small-scale sliding and deformation occur along the riverbank, triggered by rainfall or human engineering activities. Additionally, a dangerous rock zone has formed on the steep back-slope cliffs; here, small-scale collapses and rockfalls are induced by factors such as rainfall.

2.4. Deformation Characteristics and Movement History

Since the impoundment of the Shuibuya Reservoir in 2007, the houses and ground on the landslide's rear platform have experienced varying degrees of deformation; localized bank collapses have also occurred at the landslide's front edge near the water surface. In April 2009, deformation intensified—primarily manifesting as cracks in the walls of houses on the landslide mass and ground fissures, with the most severe damage observed on the

eastern side. Local ground subsidence and horizontal displacements exceeding 5 cm were recorded during this period (Figure 7).

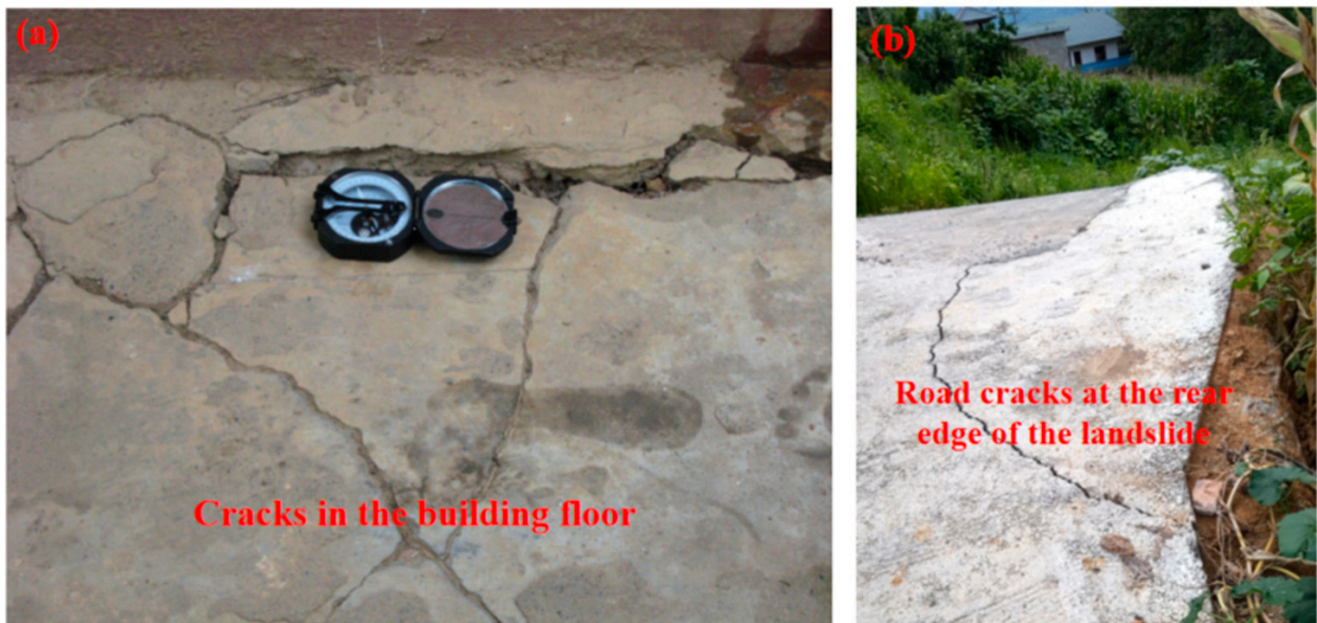


Figure 7. Actual photo of cracks in buildings and roads. (a) Photo of building cracks on the landslide; (b) Photo of road cracks.

During hydrological cycles in years with normal rainfall, the reservoir water level typically fluctuates between 400 m (flood season) and 375 m (dry season); frequent rumbling sounds have been detected beneath the landslide during these periods [16,17]. Such periodic water level fluctuations are one of the main triggering factors for geological hazards in the study area. Additionally, residential construction has increased slope sliding force via surface loading, while slope foot excavation, external filling, and road cutting have created numerous local steep, exposed faces—all of which have significantly undermined landslide stability.

Notably, if the landslide loses stability and collapses, its mass (volume: $565.5 \times 10^4 \text{ m}^3$) will slide rapidly into the Qingjiang River, potentially triggering a surge disaster in the reservoir area. This would threaten the safety of local residents and critical infrastructure, resulting in substantial social impacts.

3. Landslide Stability Analysis

3.1. Stability Scenarios and Landslide Parameters

After the Shuibuya Reservoir began impoundment, its water level fluctuated by 25 m, with a maximum of 400 m and a minimum of approximately 375 m. The stability of the Laowuchang Landslide is most likely influenced by reservoir water level changes and heavy rainfall—July sees the highest rainfall, with a historical maximum daily rainfall of 178.2 mm/d. Therefore, based on the most adverse scenario principle, this analysis aims to assess the landslide's stability under four scenarios: maximum water level, minimum water level, reservoir water level fluctuation, and extreme rainfall. For the fluctuation scenario, the water level decreases from 400 m to 375 m at a rate of 0.6 m/day. Given the frequent occurrence of extreme rainfall events this year (with daily rainfall exceeding historical records in many regions), the extreme rainfall is set to 200 mm/d, with a loading duration of 3 days. Five operational conditions are identified, as presented in Table 1.

Table 1. List of Selected Scenarios.

Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Static water level 375 m	Static water level 400 m	Static water level 375 m + extreme rainfall	Static water level 400 m +extreme rainfall	Water level dropping from 400 m to 375 m

The landslide mass of the Laowuchang Landslide is primarily composed of silty clay mixed with gravelly soil and blocky gravel mixed with soil. The corresponding geotechnical parameters [18] are presented in Table 2.

Table 2. Geotechnical Parameters.

Mechanical Parameters		Silty Clay Mixed with Fragmented Gravel	Blocky Gravel Mixed with Soil
Natural density (kN/m ³)		18.5	19.5
Saturated density (kN/m ³)		19.4	20.76
Natural shear strength	C (kPa)	36.77	9.86
	Φ (°)	16.8	27.5
Saturated shear strength	C (kPa)	31.8	3.75
	Φ (°)	13.7	22.5
Permeability coefficient (m/s)		1.35×10^{-7}	4.60×10^{-6}

3.2. Landslide Stability Calculation Methods

GeoStudio, a professional software developed by Geo-Slope International v2018, is widely used in universities and research institutions worldwide. Built on the theoretical framework of the limit equilibrium slice method, it enables stability analysis of geotechnical structures. By establishing a finite element numerical model, the software comprehensively accounts for key factors such as the soil mechanical properties of the landslide mass, groundwater flow, and external loads. It systematically analyzes the stress state of each slice, formulates force and moment balance equations, and thereby enables precise evaluation of slope stability [19].

For the Laowuchang Landslide model, the cell size is set to 10 m, with both quadrilateral and triangular element types incorporated. After discretization, the model yields 2044 nodes and 1767 elements in total.

3.3. Stability Analysis Results

To investigate the variation and patterns of the Laowuchang Landslide's safety factor under different scenarios, the SLOPE module was used to calculate the safety factor—based on unsaturated seepage analysis previously conducted with the SEEP module. The safety factors under the various scenarios are shown in Table 3.

Table 3. The stability factor of the Old House Yard landslide under various conditions.

Static Water Level 375 m	Static Water Level 400 m	Static Water Level 375 m + Extreme Rainfall	Static Water Level 400 m + Extreme Rainfall	Water Level Dropping from 400 m to 375 m
1.137	1.167	1.034	1.064	1.047

Taking the minimum stability factor (Fs) of the landslide—corresponding to the most critical slip surface under different reservoir water levels—as an example, the most critical slip surface is illustrated in Figure 8.

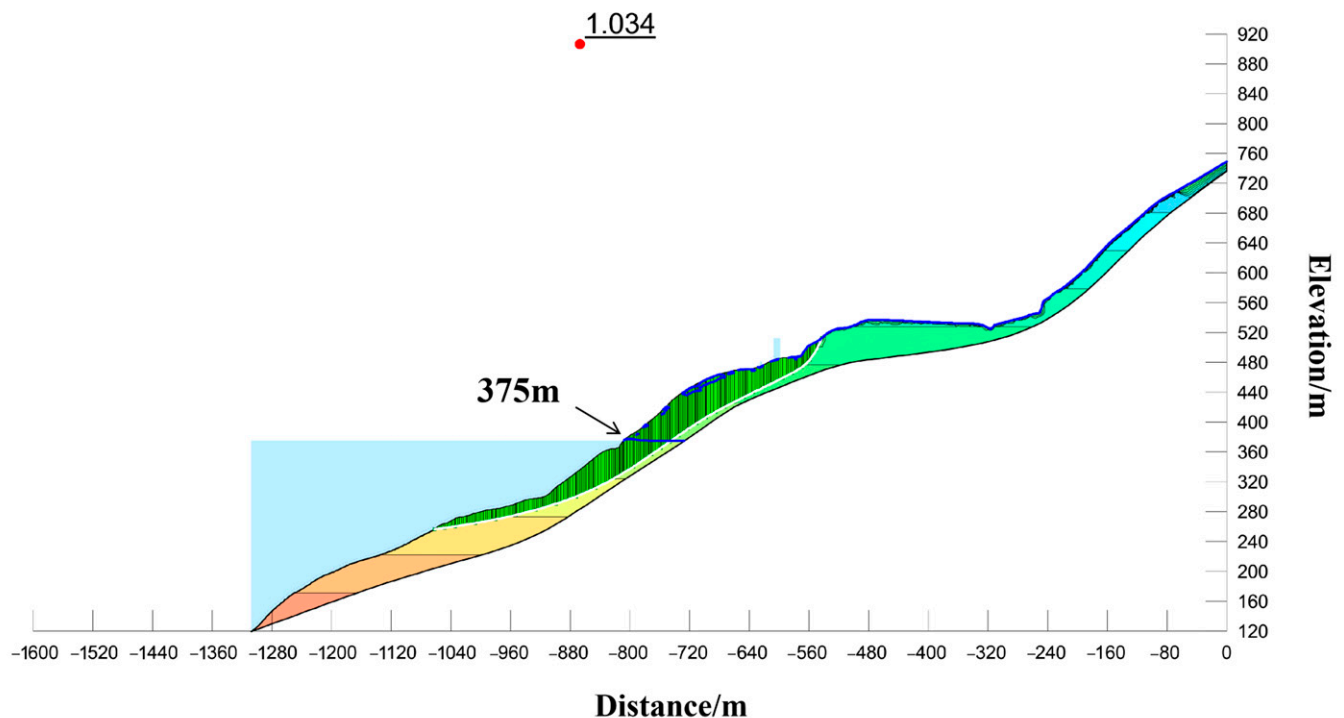


Figure 8. The diagram of the most critical slip surface.

Under Scenario 1 (static water level: 375 m), the landslide's safety factor is 1.137; under Scenario 2 (static water level: 400 m), it is 1.167. This indicates the landslide is stable under both static water conditions, with the safety factor increasing by 0.03 at the higher water level. The main reason is that the landslide material is silty clay interspersed with crushed stone, and this material has a low permeability coefficient. In the short term, water cannot penetrate it, so the effective stress on soil particles remains largely unchanged. Additionally, the landslide's front edge has a gentle slope; the rising reservoir water level provides effective toe support, generating a counterforce against sliding to enhance overall stability.

Under combined static water level and rainfall conditions, the landslide mass has a relatively low permeability coefficient. This limits rainwater infiltration volume; the infiltrated water increases soil weight, thereby reducing the landslide's overall stability. Specifically, the minimum stability factor (F_s) is 1.034 for Condition 3 and 1.064 for Condition 4.

With a static water level of 400 m as the initial condition, the soil below the phreatic line is in a saturated state. When the reservoir water level drops, groundwater flows toward the reservoir, generating a downward seepage force (dynamic water pressure) that impairs the landslide's stability. In contrast, during water level rise, increased pore water pressure reduces the soil's effective stress, while the water pressure at the landslide's front edge (toe) provides a stabilizing support effect. A comprehensive analysis of these two opposing effects shows that the stabilizing water pressure effect during rising water levels outweighs the buoyancy-induced destabilization, leading to an overall improvement in stability. However, after a complete cycle of reservoir water level fluctuations, the landslide's stability factor is lower than the initial value, due to the cumulative impact of groundwater level changes.

4. The Numerical Simulation of the Laowuchang Landslide Tsunami

The Laowuchang Landslide is located near the Qingjiang River. If it fails, a large volume of gravel and soil will slide into the water, triggering severe surge events that would cause significant damage to people, buildings, ships, and other infrastructure along

the riverbanks. Therefore, accurately simulating the landslide's water entry process and the subsequent surge propagation is of great significance for disaster prevention and mitigation in high-steep canyon areas.

4.1. Landslide Tsunami Prediction Methods

Tsunami Squares (TS), proposed by S. Ward and L. Xiao in 2015, is a new, intuitive, equation-free numerical simulation method suitable for modeling various fluid and quasi-fluid movements [20]. This method treats the simulated object as composed of countless tiny square blocks: during time iterations, it considers the forces acting on the object and the blocks' geometric characteristics and strictly adheres to mass and momentum conservation through grid movement, splitting, and reorganization (Figure 9). A key feature of TS is that it avoids solving differential equations throughout the dynamic simulation process—greatly improving simulation efficiency while maintaining accuracy. Thus, it can handle fine-scale simulations for small laboratory models and efficient simulations for large-scale objects at the actual ocean scale. Additionally, TS can account for various external driving forces such as gravity, wind pressure, air pressure, viscous resistance, friction and describe fluid dynamics processes for single-phase, multi-phase, multi-field, and multi-layer systems. For these reasons, TS is well-suited for large-scale simulations and widely applicable in fluid dynamics modeling.

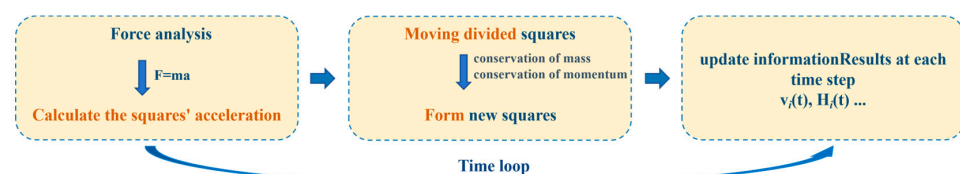


Figure 9. Tsunami Squares calculation process.

4.2. Landslide Instability Motion Simulation

4.2.1. Landslide Tsunami Simulation Study Scenarios

Key factors determining landslide tsunami characteristics include landslide mass volume, sliding velocity, and water depth [21–25]. The estimated volume of the Laowuchang Landslide is the specific value. Correspondingly, numerical simulations of the Laowuchang Landslide were performed under different combinations of sliding velocities and river channel depths. In consideration of the water level fluctuations of the Shuibuya Reservoir on the Qingjiang River, two representative water levels—W1 = 375 m and W2 = 400 m—were selected as the research scenarios for this study.

In the TS method, the movement parameters of the landslide are composed of gravity, basal friction, and dynamic friction. When the sliding velocity is low, the landslide movement is dominated by the basal friction coefficient (μ_b); when the velocity is high, it is dominated by the dynamic friction coefficient (μ_d). Different landslide velocities were determined by varying the basal friction coefficient, with two extreme values (0.01 and 0.1) selected for this study. By combining these two friction coefficient values with the aforementioned two water levels, four simulation conditions were obtained, as presented in Table 4.

Table 4. Analysis Scenario for Laowuchang Landslide Tsunami.

Scenario	μ_b	Water Level/m
V1W2	0.01	375
V1W2	0.01	400
V2W1	0.1	375
V2W2	0.1	400

4.2.2. Model Establishment

Using the digital elevation data of the Laowuchang area, combined with the landslide's boundary, thickness, and topographic data, a 3D topographic map of the study area was constructed via the Tsunami Squares (TS) method (Figure 10). Each pixel grid in the map has a side length of 10 m ($D_c = 10$).

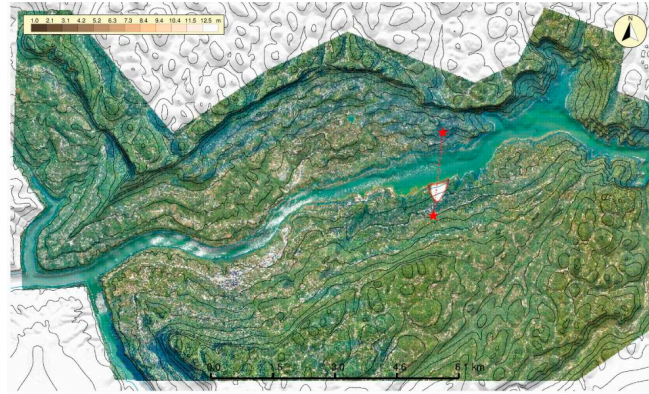


Figure 10. Laowuchang Landslide Area Map. The location of the two red stars labels the beginning and ending of the cross section view of landslide and river shown in Figure 11b.

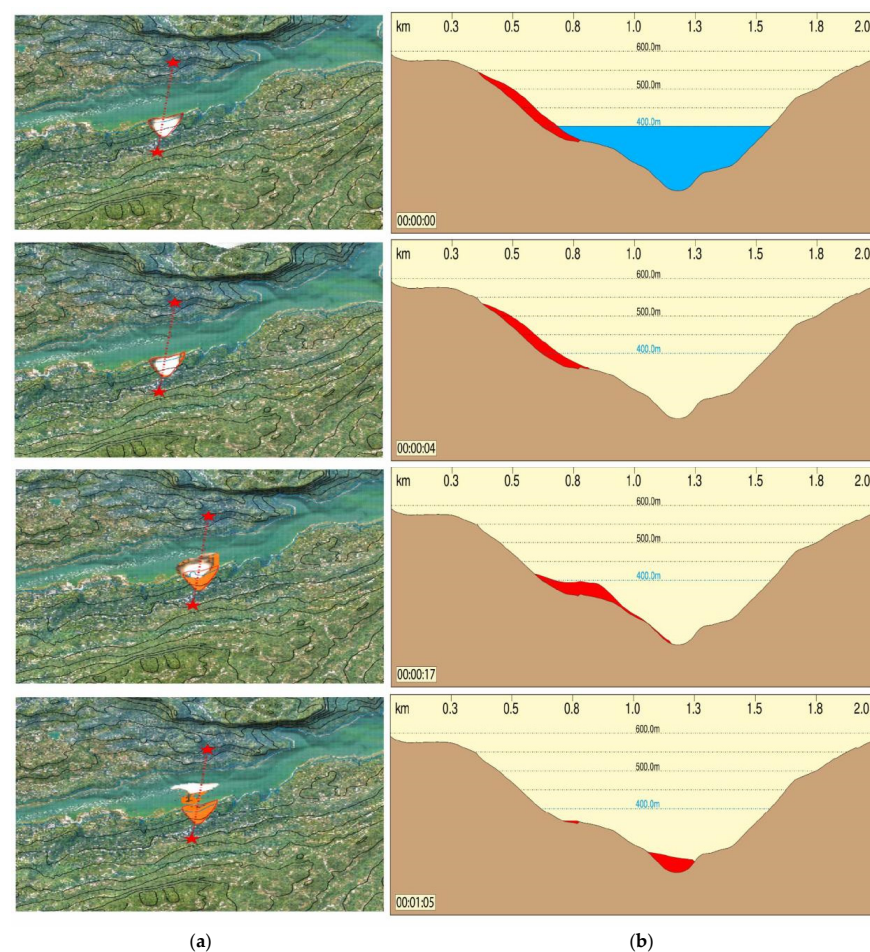


Figure 11. Profile of the motion evolution of the Laowuchang Landslide (V1W2). (a) Plan view of the landslide body movement; (b) cross-sectional view of the landslide body movement. The color change from brown to white on the landslide mass indicates the variation in the thickness of the landslide mass, where brown represents thinner areas and white represents thicker areas; orange indicates the sliding path of the landslide.

4.2.3. The Movement Process of the Landslide

Taking Working Condition V1W2 as an example, the entire movement process of the landslide is analyzed from both planar and cross-sectional motion characteristics, as illustrated in Figure 11. The landslide instability process exhibits typical progressive failure behavior: at the initial moment (0 s), the landslide mass remains stationary; as destabilization initiates (4 s), the mass starts to slide and deform under gravity, gradually moving downward, with integral sliding deformation as the main feature at this stage. As sliding continues to 17 s, the deformation range expands significantly, deformation intensifies, and displacement becomes prominent. By 65 s, the kinetic energy of the mass is exhausted and movement ceases. Under gravitational action, the collapsed material accumulates in low-lying areas, forming a typical fan-shaped deposit that settles on the water bottom.

4.2.4. Landslide Movement Velocity

Simulations were conducted for the four distinct working conditions, and the corresponding time-history curves of the landslide's average velocity were extracted, as presented in Figure 12. As observed from the figure, the landslide velocity generally exhibits a trend of initial increase followed by a decrease.

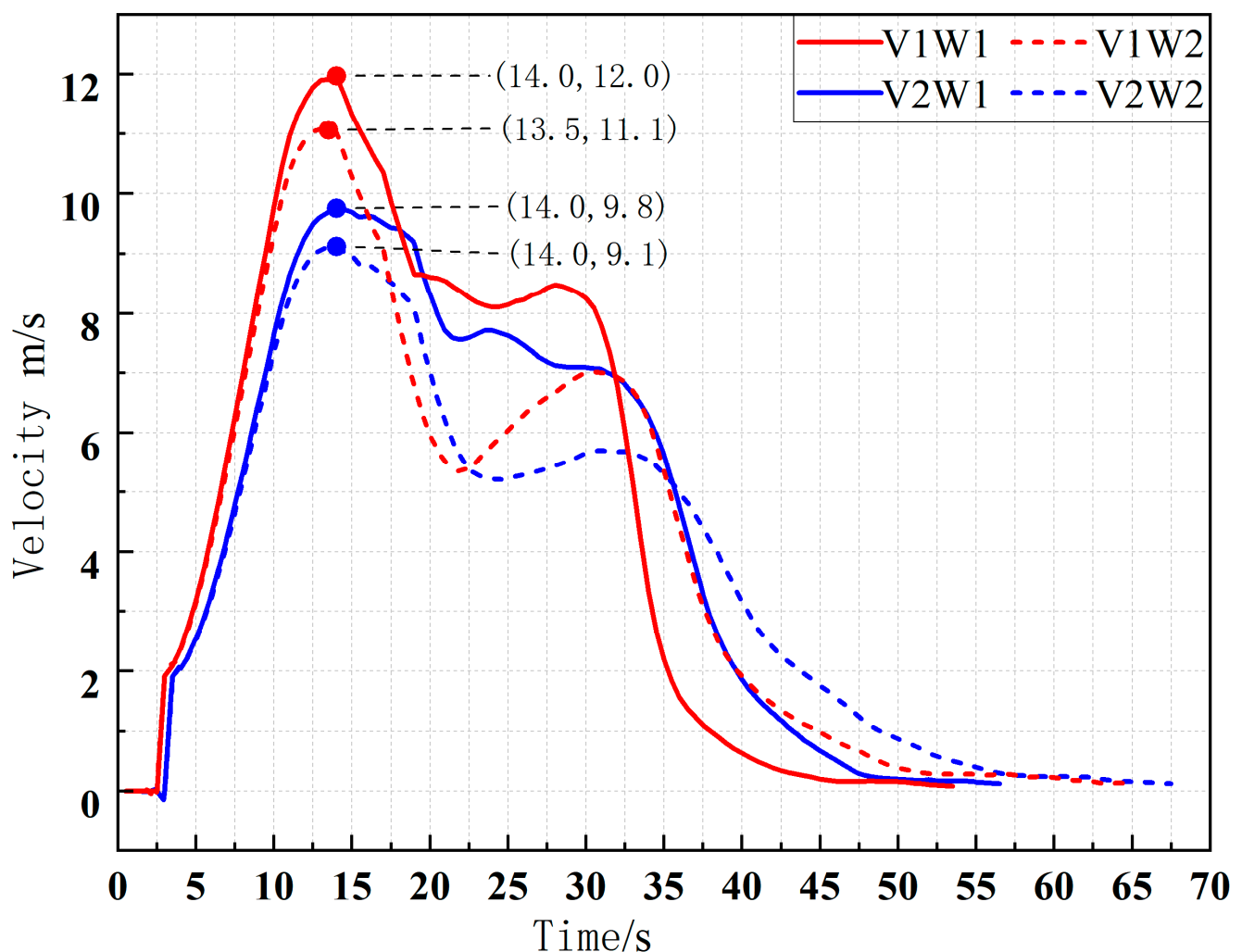


Figure 12. Time curve of the sliding mass velocity.

In the initial motion stage (i.e., within 10 s of the landslide starting to slide), the volume of the landslide submerged in water is relatively small, resulting in minimal water resistance. Thus, under the same water level conditions, the landslide velocity curves essentially overlap. As the submerged volume of the landslide continues to increase, the fluid resistance under the high water level (W2) becomes greater, leading to a smaller peak velocity of the landslide. When the landslide enters the deceleration phase (approximately 20–35 s), the velocity decreases noticeably but at a slow rate. Planar analysis indicates that this is mainly due to the gentle slope of the platform in the underwater terrain, which slows the velocity reduction rate. After 35 s, once the landslide crosses the platform and encounters a steep terrain drop, the velocity decreases rapidly, and the motion ceases upon reaching the valley.

Overall, when the base friction coefficient is 0.01, the landslide's peak velocity is 11.1 m/s under the high water level (W2) and 12 m/s under the low water level (W1), corresponding to a velocity difference of 0.9 m/s. When the base friction coefficient is 0.1, the peak velocity is 9.1 m/s under W2 and 9.8 m/s under W1, with a velocity difference of 0.7 m/s. These results indicate that the peak velocity is relatively higher under the low water level, though the difference from that under the high water level is not significant. In contrast, variations in the base friction coefficient exert a more pronounced influence on the peak velocity.

4.2.5. Tsunami Simulation Results

Cross-Sectional Wave Propagation

In high and steep canyon terrains, when landslides enter water, the generated tsunami waves are strongly constrained by narrow river channels, steep sidewalls, and complex topography. This constraint leads to amplified wave heights, concentrated energy, and intense wave reflections. Such wave aggregation can produce localized extremely high waves, posing greater disaster risks to downstream areas.

Taking Working Condition V1W2 as an example, the propagation of tsunami waves induced by the unstable Laowuchang Landslide (toward the opposite bank, upstream, and downstream) was calculated. Figure 13 illustrates the wave propagation and reflection patterns on the river channel cross-section of the main profile, under the conditions of a 400 m reservoir water level, 930 m river surface width, and 240 m maximum water depth. It also shows the evolution of landslide and water movement in the river channel at five time points: At 10 s, only a small portion of the landslide mass enters the water, lifting the water on the right side; at 20 s, most of the upper landslide mass collapses, forming a concave cavity at the water interface, while the wave gradually propagates to the opposite bank and approaches the shoreline; and at 50 s, the landslide movement nearly ceases, the wave reaches the opposite bank, and a reflected wave begins propagating back. By 900 s, the landslide movement stops completely, with the black curve representing the final wave peak values at each point on the water surface.

A comparison of the wave peak curves at 50 s and 900 s reveals that the uphill height of the first wave is not the maximum climbing height. Three characteristic points were selected on the cross-section: Point 1 (near the opposite bank), Point 2 (in the middle of the river channel), and Point 3 (close to the landslide's origin), with their specific locations shown in Figure 13. By analyzing the spatiotemporal evolution of cross-sectional wave propagation under high water level conditions in the high and steep canyon area, the wave height at each time step was recorded. This yielded the wave height time-history curves for these three points, as presented in Figure 14.

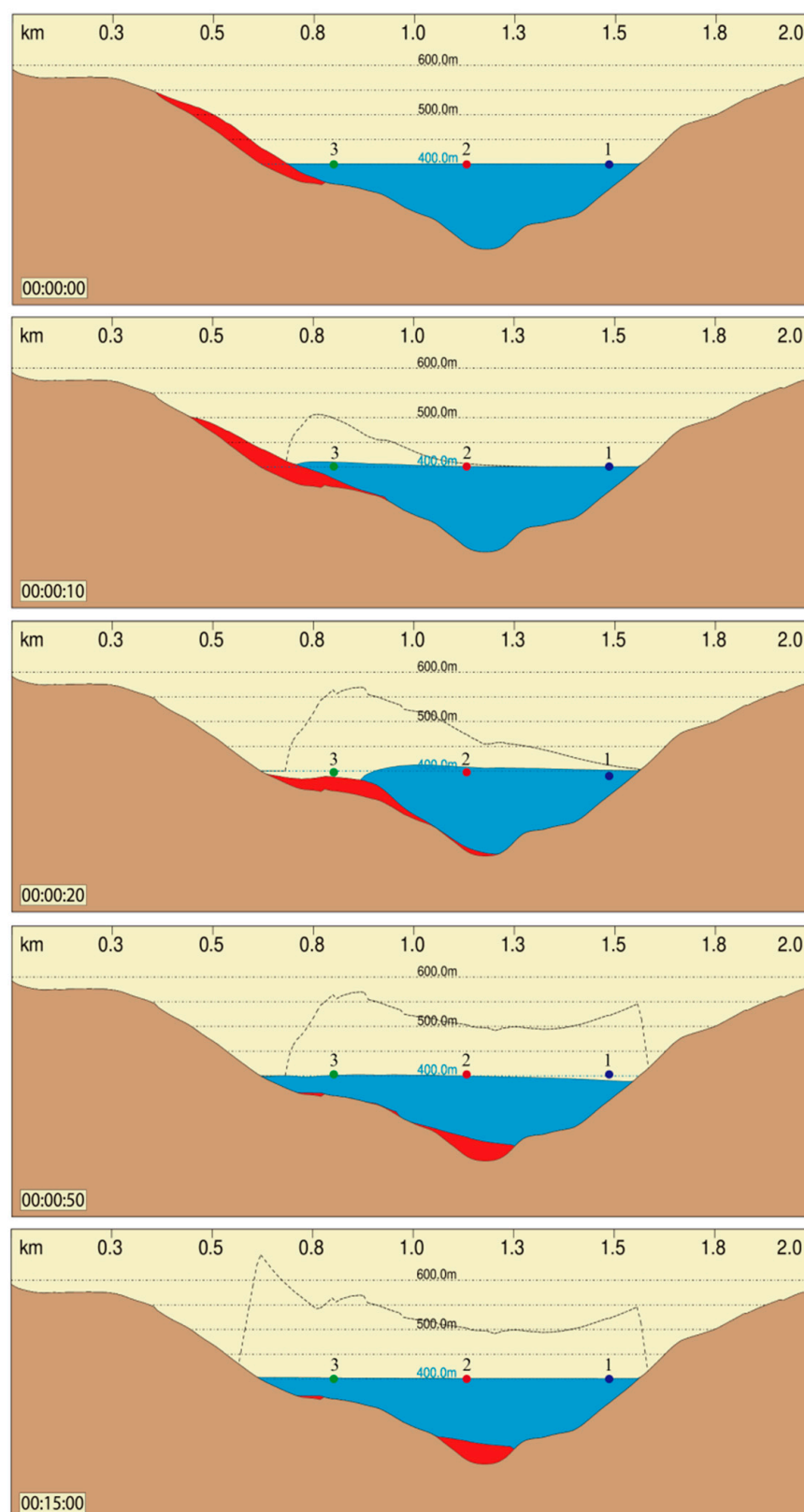


Figure 13. River channel cross-section wave propagation and reflection patterns on the main profile of the landslide at 0, 10, 20, 50, and 900 s. (The black solid line is formed by the peak values of the waves at each point on the water surface. To better display the wave peak patterns at various locations, the values of this curve are magnified by a factor of 10). Points 1, 2 and 3 are located near the landslide source, at the mid-channel and on the opposite bank of the river, re-spectively, for observing the wave height time-history variations at different positions of the river channel.

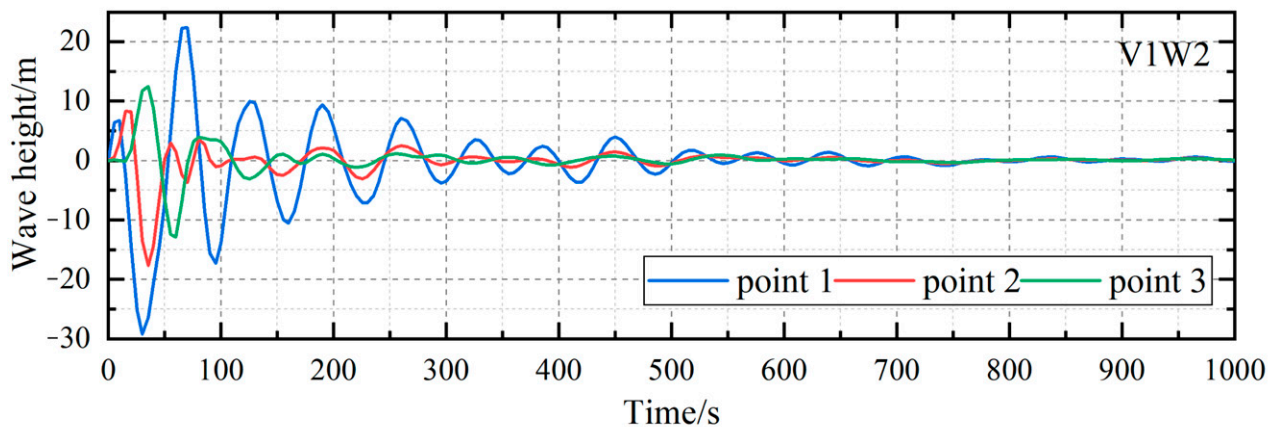


Figure 14. Oscillating wave trains corresponding to three locations on the river channel cross-section.

As observed from Figure 14, the first wave peak of each of the three wave trains is higher than the subsequent peaks. The 20 s interval between the first wave peaks of the blue and green curves corresponds to the wave propagation time from Point 3 (the landslide site) to Point 1 (the opposite bank); under high-water-level conditions, this propagation time extends to 40 s. The wave periods at Point 1 and Point 3 are both approximately 60 s, and their wave trains exhibit a distinct symmetrical trend: when the wave train at Point 1 reaches a peak, that at Point 3 is at a trough, and vice versa. In contrast, the wave train at Point 2 (located in the middle of the river channel) has a period of approximately 30 s—exactly half that of the wave trains at the two ends. These characteristics are consistent with the vibration pattern of standing waves.

Upstream and Downstream Propagating Waves and Climbing Waves

Simulations via the Tsunami Squares (TS) method show that landslide-induced tsunami waves propagate rapidly upstream and downstream along the Yangtze River, with an impact range of several kilometers. At 30 s after landslide destabilization, the water displaced by the landslide forms an arc-shaped flow that erodes the opposite bank slope, generating a maximum wave height of 15.5 m at this location. The wave maintains an overall arc shape, with a low center and high edges. By the 1st minute, after multiple reflections and refractions, the circular wave pattern dissipates, and the waves have propagated approximately 2 km both upstream and downstream. By the 8th minute, the waves continue to spread toward the opposite bank as well as upstream and downstream, with their range expanding steadily. By the 15th minute, climbing waves form along the slopes within the study area. During upstream and downstream propagation, the waves are constrained by the riverbanks, reflecting back and forth in the narrow channel until their energy is nearly exhausted and the water surface gradually calms (Figure 15).

We collected real-time simulation data of wave run-up heights along the riverbanks under four operating conditions, and the attenuation curves of wave height with distance are presented in Figure 16. As shown in the figure, the run-up wave heights on the landslide-affected bank are higher than those on the opposite bank. Both curves indicate that the wave heights on the two banks attenuate with increasing propagation distance: when the waves travel 2 km upstream and downstream, most of their energy has dissipated; beyond this range, the wave height changes slow down significantly, and the curves become gentler.

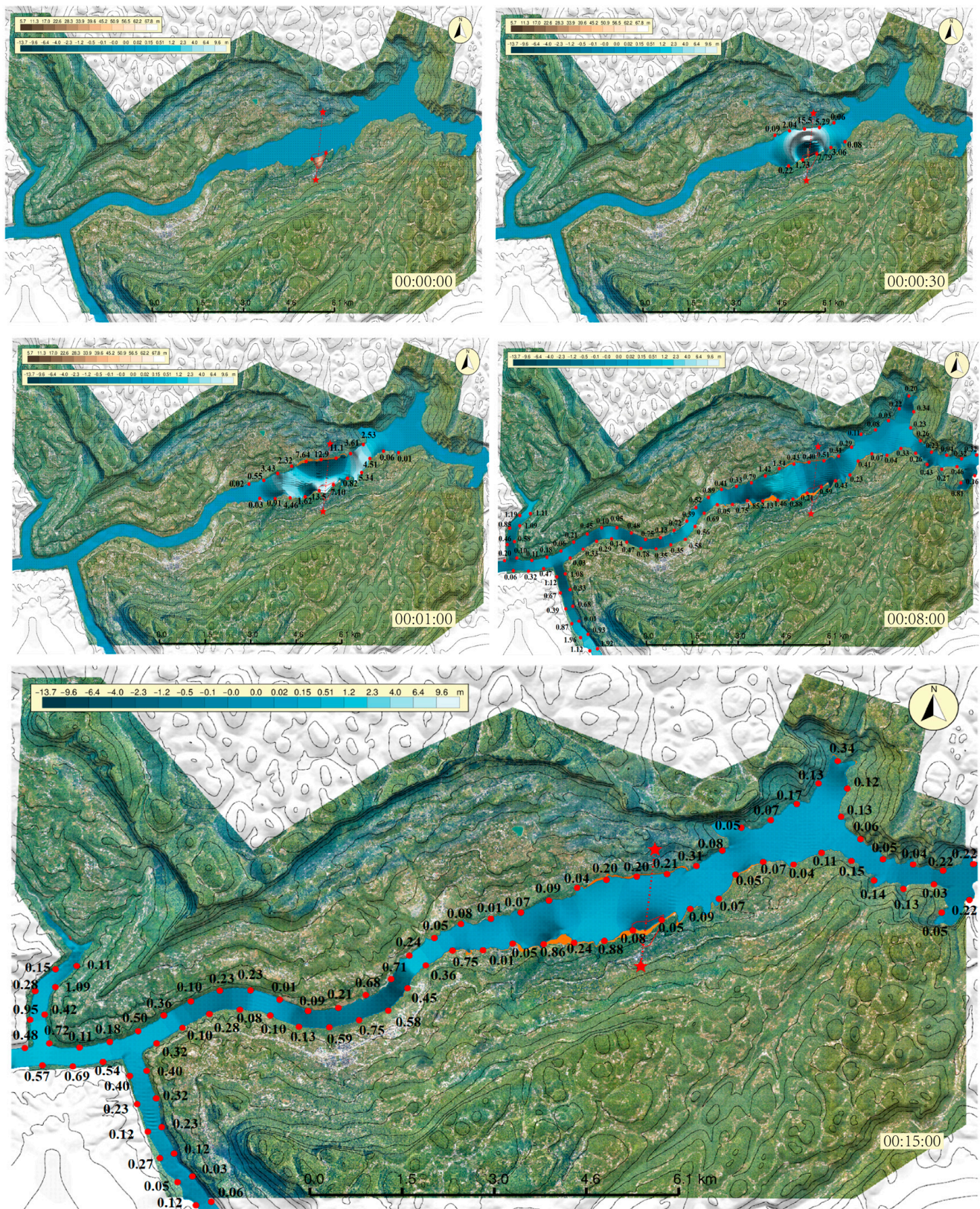


Figure 15. Propagation of tsunami waves caused by the landslide upstream and downstream. (The numbers indicate the runup wave height in meters, with a 500 m horizontal distance between each point. Red dots on the riverbank mark the positions of simulated climbing waves, and black numbers show their heights in meters. A wave height color legend is provided, and the simulated wave heights align with it).

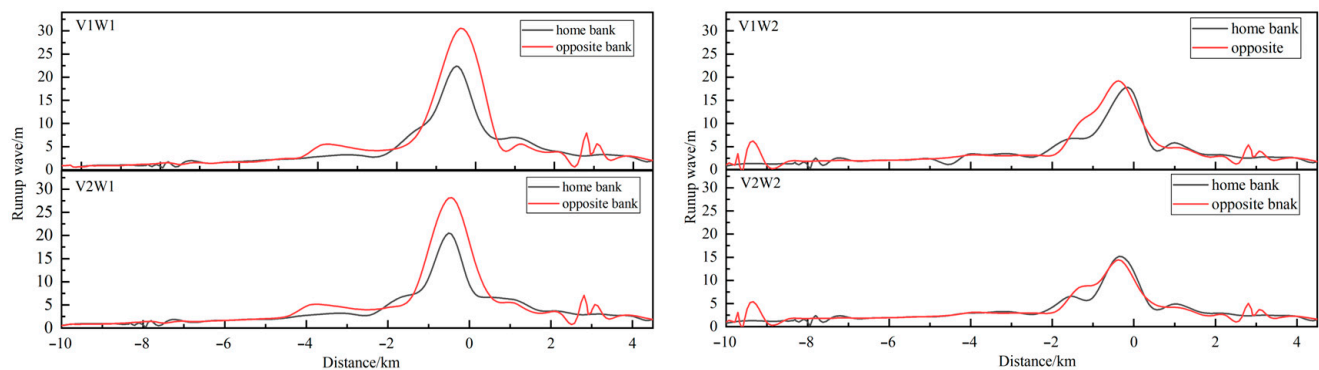


Figure 16. Attenuation curves of run-up wave height with propagation distance for the landslide-affected bank (blue solid line) and the opposite bank (orange solid line).

Neither of the two attenuation curves decreases strictly monotonically with distance; instead, both exhibit fluctuations, particularly within the 2 km upstream and downstream range. These variations are attributed to river morphology and bank slope characteristics. As waves propagate through the meandering, S-shaped channel, multiple interactions (including superposition and reflection) between positive and negative waves result in irregular attenuation. Additionally, the natural bank topography influences run-up heights across different regions: waves achieve higher run-ups in narrow tributaries or gullies, and similarly, in relatively narrow river sections compared to wider ones.

5. Risk Analysis of Surge Waves Induced by the Laowuchang Landslide

Based on the analysis of the landslide site topography and surge wave simulation results, the most unfavorable scenario (V1W2) was selected for surge wave risk analysis. Huang Bolin et al. [26] drawing on the Landslide Tsunami Hazard Risk Assessment Code and the Emergency Plan for Storm Surges, Tsunamis, and Sea Ice Disasters, classified tsunami intensity and warning levels according to the maximum amplitude range of landslide-induced waves: a maximum amplitude exceeding 2.0 m was defined as the red warning zone, 1.5–2.0 m as the orange warning zone, and 1.0–1.5 m as the yellow warning zone. In another classification system, Hu Lei [27] categorized tsunami intensity levels by the wave impacts on the receiving water body, specifically: very high (>2 m), high (1.5–2 m), moderate (1–1.5 m), medium (0.5–1 m), and low (<0.5 m).

Given the lack of established surge wave warning standards for China's river systems, this study formulated risk classification criteria with reference to the tsunami warning scheme issued by the State Oceanic Administration: surge wave heights of 0–1 m correspond to a blue warning, 1–2 m to a yellow warning, 2–3 m to an orange warning, and above 3 m to a red warning. By applying the aforementioned analysis method and warning standards, a surge wave risk warning map for the Laowuchang Landslide area was developed, with specific results presented in Figure 17.

The Laowuchang Landslide is located in a typical steep and narrow canyon, where geomorphology exerts a strong influence on the propagation and attenuation of surge waves. Analysis shows that the red warning zone is the highest-risk area. This zone is within 2 km upstream and downstream of the landslide, where the initial wave amplitude is large, and the landslide energy remains largely undissipated. Within the canyon, reflections and refractions at the riverbanks slow energy dissipation, forming concentrated high-wave-height zones. Adjacent to the red zone is the orange warning zone, which spans 1 km upstream and 1.5 km downstream. As surges spread outward, the canyon gradually widens. This widening expands the flow cross-section, disperses energy, and reduces wave heights, thus forming an extended yellow warning zone (3 km upstream and 4 km downstream).

The green warning zone mainly distributes in the downstream area and stretches 5 km; it represents the region where surges further disperse and stabilize. Landslide-induced surges affect various exposed elements, including individual houses, substations, road traffic, overhead power lines, communication towers, mines, and cemeteries. Among these elements, this study focuses on two key types: individual houses and substations.

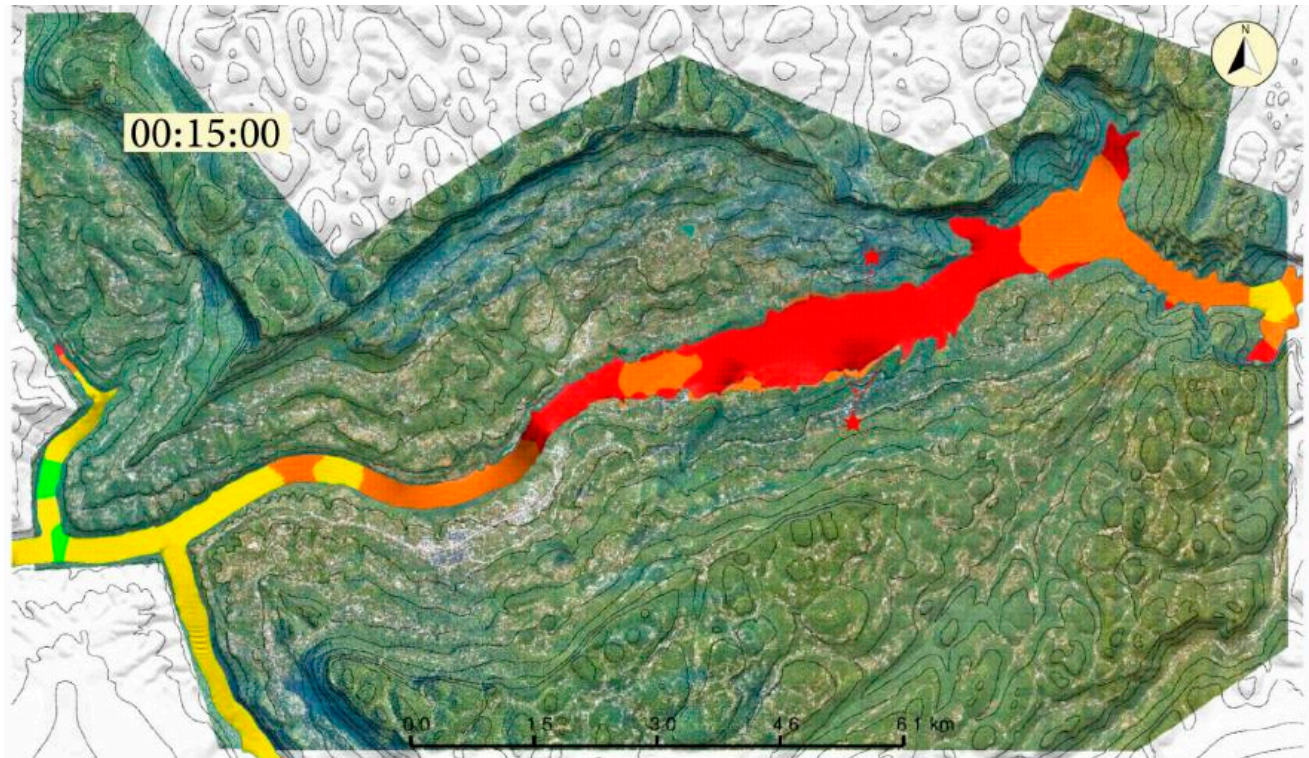


Figure 17. Landslide Surge Risk Map of Laowuchang. The blue area represents a surge height of less than 0.5 m, the green area a surge height of 0.5–1 m, the yellow area a surge height of 1–2 m, the orange area a surge height of 2–3 m, and the red area a surge height of more than 3 m.

The first category of exposed elements consists of individual houses. These are local residences that are densely scattered along the Qingjiang River, and their vulnerability directly affects residents' lives and property safety. The second category is substations. As the main power sources for the local community, substations are responsible for electricity transmission and distribution, and their normal functionality is critical to regional power supply. Thus, substations are designated as key exposed elements alongside those related to residents' safety.

The evaluation criterion adopts the relative elevation between the run-up wave height and the elevation of exposed elements. Specifically, if the elevation of an exposed element is lower than the run-up wave height, residents and the corresponding infrastructure face risks; if the elevation is higher, no adverse impact occurs. Exposed elements affected by surges are detailed in Table 5.

Table 5. Number of Exposed Elements Affected by Wave Height.

Exposed Elements	Number
House	4
Substation	1

The surge waves have affected four houses and one substation, which require relocation for risk mitigation.

6. Discussion

Landslide volume and impact velocity at water entry are two key factors governing the generation and evolution of landslide-induced surges. Accurately predicting post-failure landslide velocity remains a major challenge in current research on such surges. Although landslide volume can be estimated relatively reliably via engineering geological surveys and topographic reconstruction, whether the total failed volume exhibits a strict positive correlation with surge height is still unclear. This study, therefore, focuses on the relationships among impact velocity, failed volume, and surge height.

6.1. Discussion of Landslide Impact Velocity

Currently, common approaches for predicting post-failure landslide velocity mainly include empirical formula-based methods, analogy methods, and parameter-dependent prediction techniques. However, owing to the high complexity of landslide motion processes, each method has distinct applicability and inherent limitations. In practical research, multiple methods are therefore often integrated to constrain the reasonable range of landslide impact velocity.

Formula-based methods are generally derived from limit equilibrium theory or simplified dynamic models, in which post-failure landslide motion characteristics are estimated using key parameters such as shear strength parameters (c and ϕ) and friction coefficients (μ). These parameters are mostly obtained from static laboratory tests and cannot adequately reflect phenomena such as material fragmentation, phase transition, and dynamic mechanism variations during landslide motion [28]. Following overall instability, landslide behavior transitions from statically controlled to dynamically dominated, leading to inevitable deviations in velocities calculated using static parameters. Accordingly, formula-based methods are typically used only for qualitative analysis or as a supplementary reference in landslide velocity prediction.

The Dayantang [29], Magantang [30], Muzhuping [30], and Laowuchang landslides in the Qingjiang River basin exhibit similar regional settings and engineering geological conditions. Among these, Dayantang and Muzhuping are documented failed landslides, while Magantang and Laowuchang are currently stable. By comparing the motion parameters of Dayantang, Muzhuping, and Magantang (Table 6), engineering analogy is adopted to evaluate the rationality of the potential post-failure motion characteristics of the Laowuchang landslide, with a specific focus on its water-entry impact velocity.

Table 6. Statistics of Movement Parameters for the Dayantang, Muzhuping, and Magantang landslides.

Landslides	Landslide Volume ($\times 10^4 \text{ m}^3$)	Reservoir Area	Rock–Soil Mass	Maximum Impact Velocity (m/s)
Dayantang Landslide (occurred)	300	Shuibuya Reservoir (Qingjiang River)	Soil landslide	20
Muzhuping Landslide (occurred)	500	Shuibuya Reservoir (Qingjiang River)	Soil landslide	10
Magantang Landslide (potential)	2929.5	Shuibuya Reservoir (Qingjiang River)	Soil landslide	17.8

The maximum landslide velocity of the Laowuchang landslide under different scenarios ranges from 9.1 to 12.0 m/s. A comparison of kinematic characteristics among the failed and potential landslides in the Qingjiang River basin (including Dayantang, Muzhuping,

and Magantang) shows that their maximum velocities generally lie within approximately 10–20 m/s. The velocity of the Laowuchang landslide (9–12 m/s) thus falls within this empirical range, demonstrating its rationality from the perspective of engineering analogy.

6.2. Discussion of Landslide Volume and Surge Height

Data on the total failed volume, maximum impact velocity, and surge height of the Dayantang, Magantang, and Laowuchang landslides—all located in the Shuibuya Reservoir area of the Qingjiang River—were collected for comparative analysis, as summarized in Table 7.

Table 7. Motion and Surge Data of the Dayantang, Magantang, and Laowuchang Landslides.

	Landslid Volume ($\times 10^4 \text{ m}^3$)	Maximum Impact Velocity (m/s)	Maximum Surge Height at the Near Bank (m)	Maximum Surge Height at the Opposite Bank (m)
Dayantang Landslide	300	20	48.9	52.9
Magantang Landslide	2929.5	17.5	17.83	20.76
Laowuchang Landslide	565.5	12	22.32	30.58

As shown in Table 7, both the total volume and maximum impact velocity of the Magantang Landslide are higher than those of the Laowuchang Landslide. Nevertheless, its maximum surge heights at the near and opposite banks (17.83 m and 20.76 m, respectively) are lower than those of the Laowuchang Landslide (22.32 m and 30.58 m). This indicates that total landslide volume and maximum velocity are not the sole controlling factors for surge height.

The underlying reason is that, although the Magantang Landslide has a larger total volume, a considerable part of the sliding mass moves at relatively low velocity during the initial stage, contributing only limited kinetic energy to surge generation. The high-speed portion that actually enters the water and dominates surge formation accounts for only a small fraction of the total volume, leading to a lower overall surge height than that of the Laowuchang Landslide.

The Dayantang Landslide provides further support for this view: despite having the smallest total volume, nearly its entire mass accelerated to high velocity after failure. With both high velocity and an effective impacting volume, it generated the highest surge heights among the three.

These observations demonstrate that when evaluating the surge potential of a landslide, one should not depend solely on total volume or maximum impact velocity. A more reliable assessment requires comprehensive consideration of the failed volume, the high-speed water-entry fraction, and velocity distribution characteristics, to better estimate the potential magnitude and destructive power of the induced surge.

7. Conclusions

The Laowuchang Landslide is located in a typical deep canyon, where topographic features amplify the destructive potential of surges induced by the landslide upon entering water. Focusing on this landslide, this study systematically investigated the valley geomorphological evolution and related geological hazards in the Jingyang Town section of the Qingjiang River, and revealed the evolutionary process of local valley landforms. Using GeoStudio, the study analyzed the stability of the Laowuchang Landslide. For unstable slopes, numerical simulations of landslide-generated surges were conducted via

the Tsunami Squares method, with a focus on the landslide motion process, cross-sectional wave propagation, upstream and downstream surges, and run-up characteristics in the high-depth canyon. Finally, based on the simulation results, the study assessed the surge wave risks in the area. The main conclusions are as follows:

- (1) The geomorphological evolution of the Qingjiang Jingyang section can be divided into two stages. In the first stage, river downcutting caused the Triassic Daye Formation limestone to slide along weak interlayers, triggering large-scale collapses. In the second stage, the collapse debris or limestone further released energy along the slope, inducing landslides. While some of the landslide material was carried away by the river, the remaining material formed the present-day Laowuchang landslide landform.
- (2) Under static water levels in Condition one and Condition two, the slope remains stable. However, under Conditions three and four, heavy rainfall weakens the slope's stability, with the minimum safety factors reaching 1.034 and 1.064, respectively. Under Condition five, where reservoir water level fluctuations are considered, the safety factor decreases to 1.047, placing the slope in a potentially unstable state with a risk of failure.
- (3) Based on the wave simulation results, the red warning zone is concentrated within 2 km upstream and downstream of the landslide. The orange warning zone extends 1 km upstream and 1.5 km downstream from the red warning zone. The yellow warning zone extends 3 km upstream and 4 km downstream, while the green warning zone stretches approximately 5 km downstream. Within these warning zones, 4 houses and 1 substation are at risk, requiring relocation for safety and risk mitigation.

This study clarifies the geomorphological evolution mechanisms of the Qingjiang Jingyang section. The Laowuchang Landslide is assessed as potentially unstable, with a failure risk under reservoir water level fluctuations or heavy rainfall. Canyon topography amplifies wave heights, causing significant impacts; thus, the 4 residential buildings and 1 substation in the warning area are recommended for relocation. As a typical steep canyon-type landslide, research on its stability offers scientific insights into disaster mechanisms and preventive measures for canyon-type reservoir landslide hazards.

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