Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-8, Issue-5, May 2026
DOI: 10.53469/jrse.2026.08(05).05

Study on Development Characteristics and Movement Process Numerical Simulation of the slumping deposit above Haojiping Tunnel Entrance

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Abstract: ***The stability of railway tunnel entrance slopes directly affects construction and operational safety. Taking the slumping deposit above the entrance of Haojiping Tunnel on the Shanghai–Kunming High-Speed Railway as the research object, the development characteristics of the mass and the damage to existing protective measures were identified through field investigation. The three-dimensional movement process following potential failure was simulated using DAN3D software, and the slope stability under different rainfall conditions was analyzed using GeoStudio software. Targeted prevention and control recommendations are proposed. DAN3D simulations indicate that after failure, the mass movement lasts approximately 40 s, with a maximum horizontal travel distance of 78.1 m and a maximum velocity of 14.5 m/s. The maximum accumulation thickness reaches 1.3 m, posing a threat to the railway line at the tunnel entrance. GeoStudio calculations reveal a stability factor of 1.110 under natural conditions, corresponding to a basically stable state. Under a cumulative rainfall of 270 mm over three days, the factor decreases to 1.013 (under-stable state), and under an extreme rainfall of 360 mm over three days, it drops to 0.953 (unstable state). This confirms that short-duration intense rainfall is the primary trigger for potential failure of the creeping landslide mass. Based on the analysis, it is recommended to install additional passive protective nets, strengthen deformation monitoring, and regularly clear drainage facilities to ensure railway operational safety. The research findings can provide a theoretical basis for the operation and maintenance of railway tunnels in the hilly and mountainous regions of South China.***

Keywords: Creep-slidings, Tunnel entrance slope, DAN3D, GeoStudio, Stability analysis, Prevention and control measures.

1. Introduction

In South China, mountainous and hilly terrains are extensively distributed, with complex geological structures, abundant rainfall, and frequent rainstorms. With the continuous densification of the railway network in Hunan Province, especially in the mountainous areas of western and southern Hunan, railway alignments inevitably traverse complex geological environments. Consequently, the stability of entrance and exit slopes of tunnels has become increasingly prominent [1–4]. The widely distributed residual and colluvial deposits and completely to highly weathered rock masses in this region experience significant reductions in mechanical strength under sustained rainfall and rainstorm conditions, which can readily induce geological hazards such as slumping and landslides, posing serious threats to the construction and operational safety of railway tunnels [5].

In recent years, extensive research on tunnel–slope interactions has been conducted both domestically and internationally. Zhou Wenjiao systematically investigated the failure modes and mechanisms of tunnels under landslide–tunnel interaction, proposed six typical tunnel failure modes, and revealed the consistency between the spatiotemporal distribution of tunnel deformation and landslide deformation [1]. Sun et al. examined the development characteristics of collapses in loess vertical slopes and their effects on adjacent tunnels [6]. Chen Long et al. employed GeoStudio to evaluate the stability of landslide deposits under rainstorm and seismic conditions and used DAN3D to predict the potential impact area of landslides [7]. In terms of numerical simulation, DAN3D, as a numerical model for three-dimensional terrain-based dynamic analysis of rapid flow slides, debris flows, and avalanches, has been widely applied to landslide runout simulation and hazard assessment [8–9]. GeoStudio software has also been extensively utilized in seepage field analysis and slope stability evaluation under rainfall conditions [10–11], with studies indicating that slope safety factors decrease with prolonged rainfall duration under long-term continuous rainfall [12]. Currently, research on slumping deposits at railway tunnel entrances tends to focus on individual aspects, whereas integrated studies that systematically combine the characterization of slumping deposit development, assessment of existing mitigation measures, runout process simulation, and stability analysis under rainfall conditions remain scarce. Taking the slumping deposit above a railway tunnel entrance as an engineering case, and based on detailed field investigations to ascertain the development characteristics of the slumping deposit and the damage status of existing prevention measures, this study comprehensively applies two numerical simulation methods, DAN3D and GeoStudio, to conduct analyses from two dimensions: the runout process following failure of the slumping deposit and its stability under varying rainfall conditions. Targeted comprehensive remediation recommendations are then proposed, with the aim of providing reference for similar engineering projects.

2. Overview

2.1 Project Overview

The Haojiping Tunnel of the Shanghai–Kunming High-Speed Railway is located approximately 440 m north of Haojiping Yao Ethnic Township, Zhongfang County, Huaihua City, Hunan Province, with the tunnel entrance at mileage K1369+580. The site lies within a medium-to-low mountainous landform region characterized by significant topographic relief. The upper slope extends approximately 50 m in length, 45 m in width, and 15 m in height, with a slope aspect of 72° and a gradient ranging from approximately 20° to 40°. The micro-topography is defined by steep slopes.

A slumping deposit has developed above the tunnel entrance, measuring approximately 20 m in longitudinal length, 30 m in transverse width, and with an average thickness of about 5 m, resulting in a total volume of approximately 3×10^4 m³, which is of considerable scale. The slumping deposit is predominantly composed of residual and colluvial silty clay mixed with gravels, exhibiting a loose structure and poor mechanical properties. The region receives abundant precipitation, with an annual rainfall ranging from 1200 to 1600 mm, concentrated between April and August and accounting for 70% of the total annual rainfall. Frequent rainstorms significantly influence the stability of the slope.

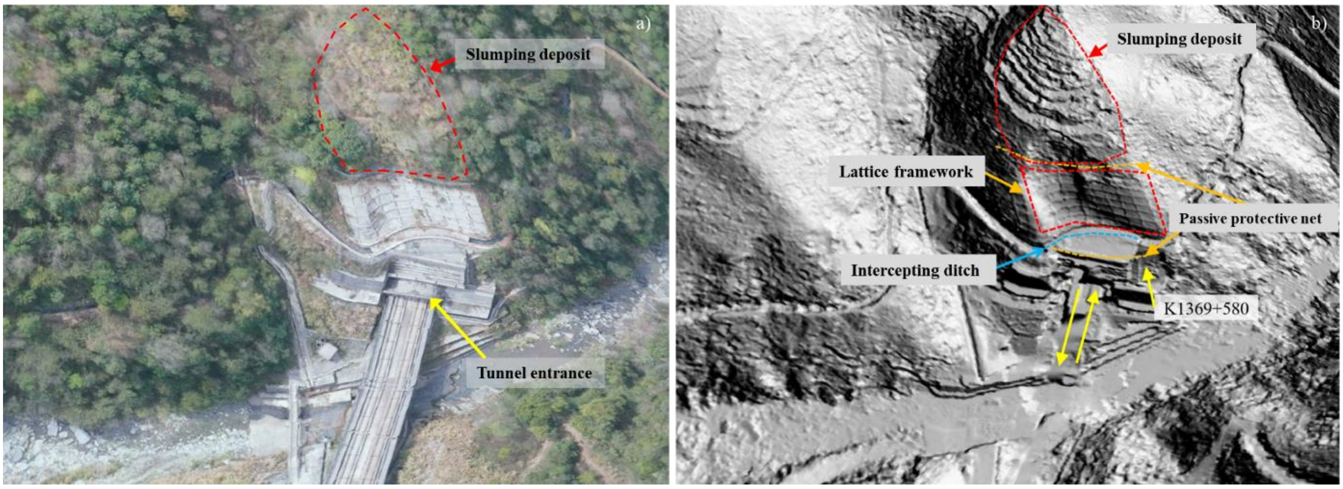


Figure 1: Orthophoto and hillshade map of the slumping deposit area above the Haojiping Tunnel entrance

2.2 Development Characteristics

1) Morphological characteristics. The slumping deposit exhibits a tongue-shaped or irregular distribution in plan view, with high surface vegetation coverage. Arc-shaped tension cracks, ranging from 5 to 20 cm in width, are visible at the rear scarp. The middle slope surface is undulating, displaying multiple stepped platforms, while the front edge appears bulging with localized collapse features.

2) Material and structural characteristics. The slumping deposit consists primarily of silty clay mixed with gravels, with gravel content ranging from approximately 40% to 60% and particle sizes generally between 2 and 15 cm. The deposit is loosely structured, highly porous, and exhibits relatively high permeability. The underlying bedrock is composed of sandy slate of the Lower Sinian Nantuo Tillite Formation.

3) Deformation characteristics. Investigations reveal that the slumping deposit is currently in a creep deformation stage. Multiple tension and shear cracks are visible on the slope surface. Deformation is concentrated mainly in the middle and upper parts of the deposit and intensifies significantly during the rainy season, indicating that rainfall is the primary factor triggering further deformation of the slumping deposit.

4) Hydrogeological characteristics. Groundwater within the slumping deposit primarily consists of pore water in loose materials and fissure water in bedrock, recharged by atmospheric precipitation. The depth to the groundwater table varies considerably, rising markedly during the rainy season, which adversely affects the stability of the slumping deposit.

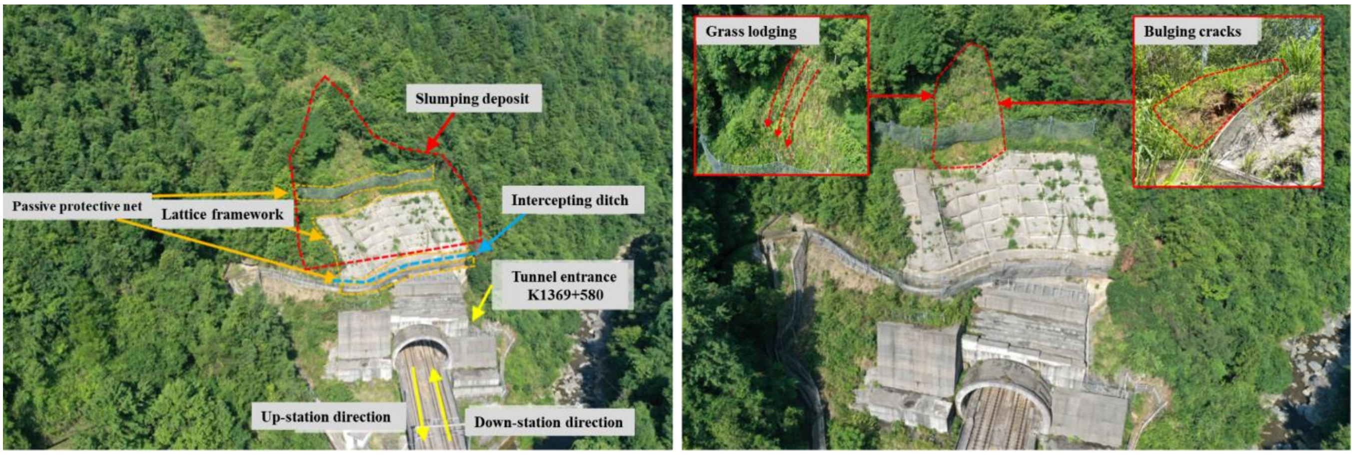


Figure 2: Aerial image of the slumping deposit and protective measures

2.3 Development Trend of the Slumping Deposit and Damage Status of Protective Measures

Field investigations indicate that the slumping deposit has exhibited distinct deformation traces over the past three years. Vegetation coverage on the surface of the slumping deposit is notably lower than in surrounding areas, with significant lodging of grasses. Bulging cracks are observable at the front edge (Figure 2). From the hillshade map with vegetation filtered out, the boundary of the slumping area is clearly discernible, appearing as a distinct tonal and textural transition zone in the imagery, which intuitively reflects differences in material composition and spatial morphology between the slumping deposit and the adjacent stable hillslope. The slope surface is arcuate and steep, favoring sliding of the slumping deposit. The rough surface texture of the deposit indicates poor geotechnical stability and susceptibility to slumping under the influence of gravity and external forces.

A lattice framework slope protection, approximately 40 m long, 20 m wide, and covering an area of about 800 m², is installed above the tunnel exit. A passive protective net, approximately 35 m long and 4 m high, is deployed at the slope toe; following slumping deformation, wire breakage has been observed. Another passive protective net, approximately 40 m long and 4 m high, is installed at the mid-slope, showing signs of deformation. An intercepting ditch is located on the middle slope, with no gravel accumulation observed within it.

3. DAN3D Runout Process Simulation

3.1 Model Establishment and Parameter Selection

DAN3D (Dynamic Analysis in Three Dimensions), developed by Canadian scholar Hungr [13], is a dynamic analysis software based on continuum mechanics. Employing a depth-integrated method in the Lagrangian coordinate system, it effectively simulates the entire motion process of rapid geohazards such as landslides and debris flows. Based on three-dimensional terrain data and appropriate rheological models and parameters, the software simulates the velocity, travel distance, deposition thickness, and impact area of the sliding mass.

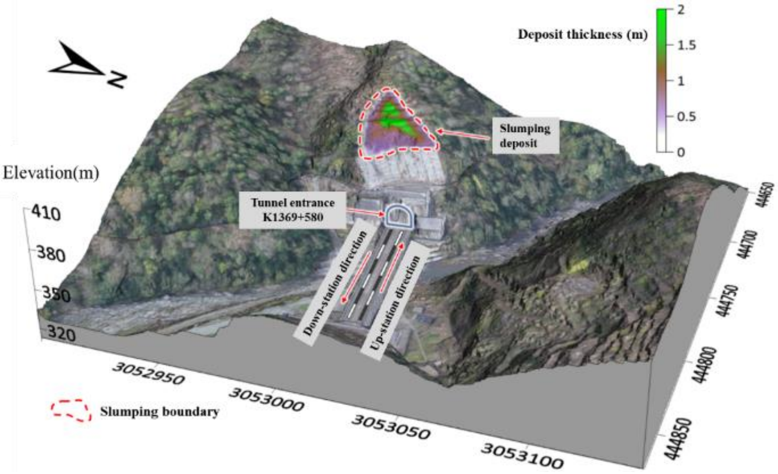


Figure 3: Digital elevation model of the slumping deposit area

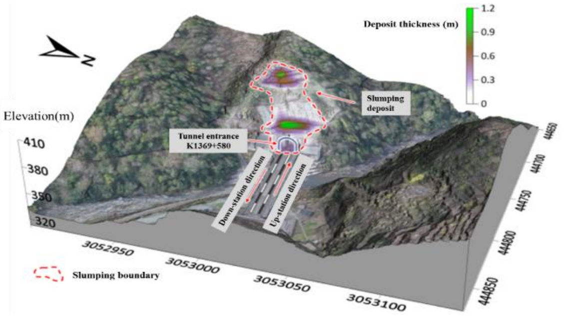
Table 1: Simulation parameters

Parameter	Unit weight (kN/m³)	Friction coefficient μ	Turbulence coefficient ξ (m/s²)	Internal friction angle (°)	Rheological model
Value	20.1	0.16	360	13.5	Voellmy

For the slumping deposit, based on existing data and field investigation results, parameters including unit weight, friction coefficient, turbulence coefficient, and internal friction angle of the slope material are presented in Table 1. The Voellmy rheological model was selected. A model of the study area was constructed using elevation information of the slope (Figure 3), and a sliding mass model was built incorporating borehole data. Surfer software was used to convert the model into ASCII grid data files, which were subsequently imported into DAN3D for slope simulation calculations.

3.2 Numerical Simulation Results

The simulated runout process of the slope using DAN3D is illustrated in Figure 5. Simulation results indicate that following failure, the motion of the slope mass lasted approximately 40 s, achieving a maximum horizontal travel distance of about 78.1 m and a vertical drop of approximately 47.2 m. Upon detachment, the debris moved from west to east, passed over the lower lattice framework slope protection, and accumulated on the platform above the tunnel entrance, with a portion of the debris continuing downward to reach the railway line and gully. The final affected area of the slope movement is approximately 4572.6 m², with a maximum deposit thickness of 1.3 m.



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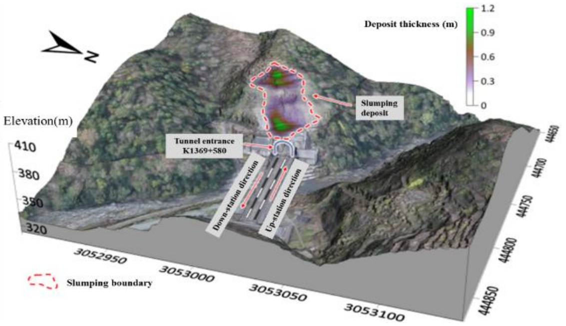

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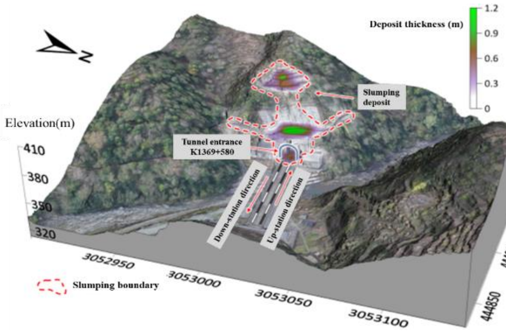

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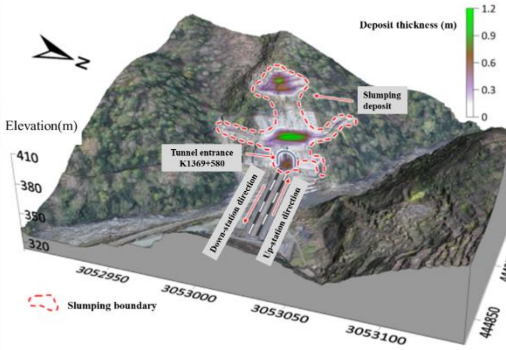
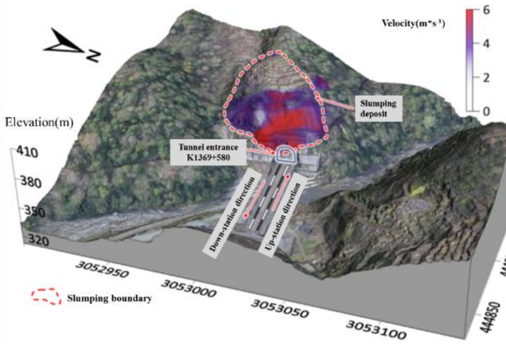


(d) t=40s

Figure 4: Simulation results of slumping runout deposition distribution



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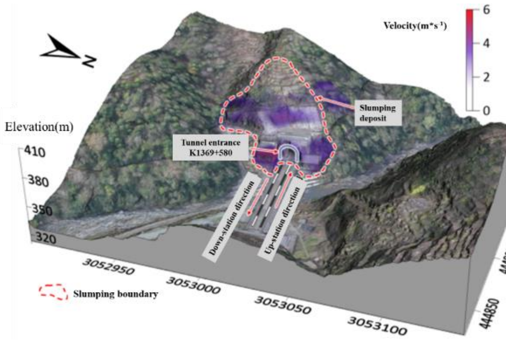

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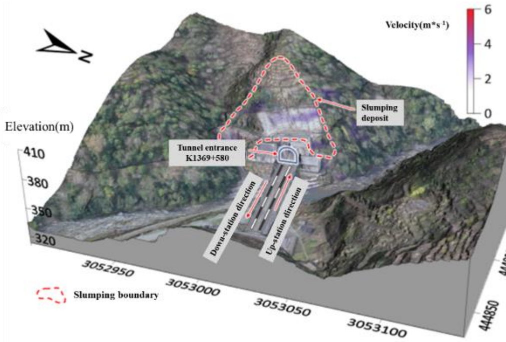
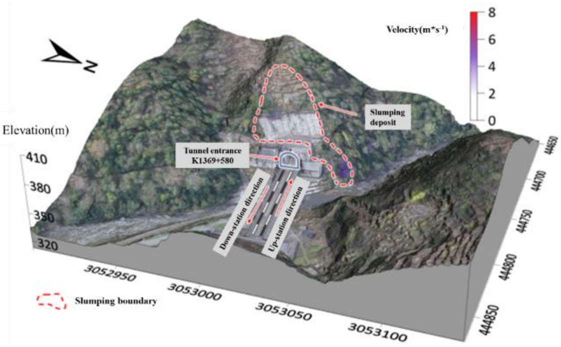


(c) t=20s



(d) t=40s

Figure 5: Simulation results of slumping runout velocity distribution

The distribution of deposit thickness and velocity during slope movement are shown in Figures 4 and 5, respectively. At approximately 5 s after initiation, the debris was primarily located at the lower lattice framework slope protection position, exhibiting steep gradients and relatively high velocities; at this stage, the velocity of the main debris mass exceeded 10 m/s, and the maximum deposit thickness was about 1.1 m. By simulation time 10 s, a portion of the debris had reached the platform above the tunnel entrance and began accumulating, while a small amount of debris continued moving along the hillside adjacent to the tunnel entrance, maintaining a nearly constant velocity of approximately 5 m/s. By simulation time 20 s, the vast majority of the debris had essentially ceased moving, forming a deposit with a maximum thickness exceeding 1.2 m above the tunnel entrance, with debris velocities predominantly in the range of 0–2 m/s. By simulation time 40 s, almost all debris on the slope had come to rest, accumulating on the platform above the tunnel entrance and on the railway line at the tunnel entrance. The maximum deposit thickness, approximately 1.3 m, occurred on the platform above the tunnel entrance, while the deposit thickness on the railway line at the tunnel entrance was about 0.8 m.

3.3 Analysis of Slumping Deposit Motion Parameters

The variation of maximum debris velocity over time during slope movement is presented in Figure 6.

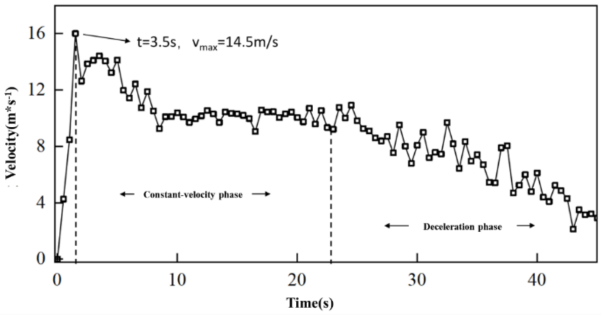


Figure 6: Maximum velocity–time curve of the slumping deposit debris

The figure shows that following failure, the velocity of the debris increased rapidly, reaching a maximum value of 14.5 m/s at simulation time 3.5 s. Subsequently, after a slight decrease, the velocity exhibited an overall trend of uniform motion, decreasing to approximately 10 m/s between 3.5 s and 23 s and then remaining constant. After 23 s, the main portion of the debris essentially stopped moving, while localized debris maintained low velocities that gradually diminished. By simulation time 40 s, the maximum velocity had dropped below 2 m/s, and slope movement had largely ceased.

4. Stability Analysis of the Slumping Deposit

4.1 Computational Model

The finite element simulation software GeoStudio was employed to analyze the stability of the slumping deposit. Based on the engineering geological conditions and macroscopic deformation characteristics of the slump, the main sliding profile was selected as the computational profile to represent the overall stability development trend. The sliding mass was considered as silty clay, the sliding bed as sandy slate of the Lower Sinian Nantuo Tillite Formation, and the sliding zone as the contact interface between the slumping deposit and the underlying bedrock. Since the geotechnical properties of the contact zone approximate those of the overlying sliding mass material, and considering that shear zones typically do not fully coalesce prior to complete failure and their shear strength parameters lie between peak and residual values due to strain softening, a distinct sliding zone was not separately modeled. The simulation scenarios were designed primarily to consider the influence of sustained rainfall on the stability of the landslide, as detailed in Table 2.

Table 2: Scenarios for slumping stability analysis

Scenario	Description
Scenario 1	Natural conditions
Scenario 2	Rainfall: 270 mm accumulated over 3 days
Scenario 3	Extreme rainfall: 360 mm accumulated over 3 days

In the SEEP/W module of GeoStudio, available mesh element types include triangles, quadrilaterals, and rectangles. The model in this study was constructed strictly following finite element requirements, employing both triangular and quadrilateral elements for mesh discretization. Theoretically, finer meshes yield more accurate results; however, increasing the number of elements correspondingly increases computational cost and time. Balancing result accuracy, computation time, and boundary condition application, a 1 m mesh size was adopted for the two-dimensional model of the slumping deposit, resulting in a total of 4,433 elements and 4,556 nodes, as shown in Figure 7.

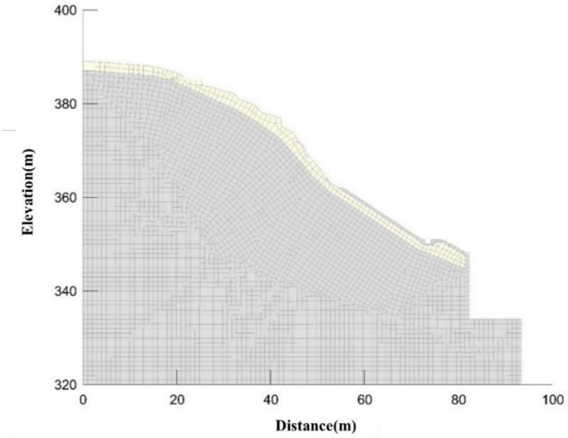


Figure 7: Computational model for slumping deposit stability analysis

4.2 Computational Parameters

Key parameters for GeoStudio calculations include saturated volumetric water content, friction angle, and cohesion. As this is a soil landslide, the sliding mass is treated as silty clay, the sliding bed as sandy slate of the Lower Sinian Nantuo Tillite Formation, and the sliding zone as the contact interface between the slumping deposit and the underlying bedrock; therefore, simulation parameters focus primarily on the sliding mass properties. Parameters were derived from existing geotechnical investigation data of the hazard area and adjacent regions, as presented in Table 3.

When simulating the seepage field using the SEEP/W module, the permeability coefficient and volumetric water content of the sliding mass are functions of pore water pressure within the slope. When saturated, the permeability coefficient and volumetric water content are constant, saturated values. In the unsaturated state, empirical values were used to define these parameters. This simulation adopted saturated parameters and the Van Genuchten empirical curve to determine volumetric water content and permeability coefficient under unsaturated conditions, as shown in Figure 8.

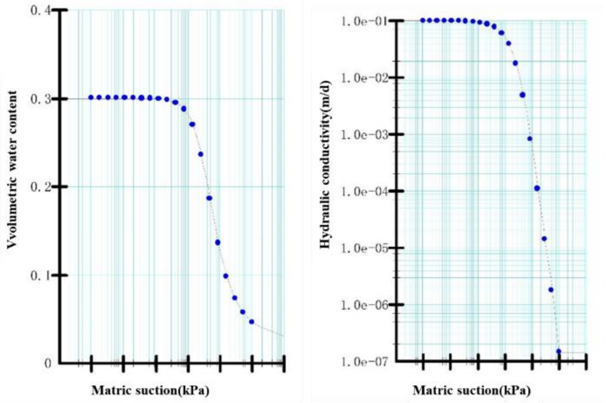


Figure 8: Volumetric water content function and permeability coefficient function of the slumping deposit

Table 3: Parameters for stability calculation

Material	Unit weight γ (kN/m³)	Internal friction angle φ (°)	Cohesion c (kPa)
Sliding mass (natural)	20.1	13.5	22.5
Sliding mass (saturated)	21.1	13.0	20.0

4.3 Calculation Results

Calculation results are presented in Table 4. Under natural conditions without rainfall (Scenario 1), the stability of the slumping deposit is highest, with a factor of safety (FoS) of 1.110, indicating a basically stable state. Under Scenario 2 (270 mm accumulated rainfall over 3 days), the factor of safety decreases to 1.013, corresponding to an understable state. Under the extreme rainfall scenario (Scenario 3, 360 mm accumulated rainfall over 3 days), the factor of safety reaches a minimum value of 0.953, indicating an unstable state.

Table 4: Calculated factors of safety

Scenario	Scenario 1	Scenario 2	Scenario 3
Factor of safety	1.110	1.013	0.953

5. Risk Assessment and Remediation Recommendations for the Slumping Deposit

Field investigations indicate that the slope is relatively steep, composed of silty clay mixed with gravels with low strength, lacks overhead cover, and is subjected to repeated rainfall erosion and direct solar radiation over many years, which can lead to soil softening and loosening. Additionally, repeated construction activities during tunnel operation and maintenance may disturb the slumping deposit, potentially altering the in-situ stress state and thereby reducing slope stability. Under long-term effects and intense rainfall, the unit weight of the rock and soil mass may increase while strength decreases, leading to increased driving forces and reduced resisting forces, potentially triggering slumping that threatens the railway line at the tunnel exit.

Numerical simulation results show that following failure, the deposition process of the slumping deposit would bury the railway line at the tunnel entrance. Stability calculations indicate that the slumping deposit is in an understable state under rainfall conditions and an unstable state under extreme rainfall conditions. The region where the tunnel entrance is located experiences a humid climate with frequent short-duration intense rainfall events. Therefore, there exists a possibility that the slumping deposit may undergo failure induced by short-duration heavy rainfall, posing a threat to the railway infrastructure.

Existing protective measures generally meet safety requirements; however, field investigations have revealed localized deformation and wire breakage in the passive protective net. Based on the development characteristics of the slumping deposit, the damage status of existing prevention measures, and the numerical simulation results, it is recommended to install an additional passive protective net above the tunnel entrance and to strengthen deformation monitoring of the slumping deposit. To mitigate severe rainfall infiltration, drainage ditches should be periodically desilted to ensure that drainage measures remain unobstructed and effective.

6. Conclusions

1) The slumping deposit has a total volume of approximately 3×10^4 m^3, which is of considerable scale. It is predominantly composed of residual and colluvial silty clay mixed with gravels, exhibiting a loose structure and poor mechanical properties. The deposit is currently in a creep deformation stage.

2) According to DAN3D numerical simulation results, the runout process following failure of the slumping deposit lasts approximately 40 s, with a maximum horizontal travel distance of about 78.1 m and a vertical drop of approximately 47.2 m. The maximum velocity varies with time, exhibiting a rapid increase—constant velocity—deceleration pattern, reaching a peak velocity of 14.5 m/s.

3) GeoStudio stability calculations show that under natural conditions without rainfall, the factor of safety is 1.110, indicating a basically stable state. Under 270 mm accumulated rainfall over 3 days, the factor of safety is 1.013, indicating an understable state. Under the extreme rainfall scenario of 360 mm accumulated rainfall over 3 days, the factor of safety reaches a minimum of 0.953, indicating an unstable state. Therefore, short-duration intense rainfall is a critical triggering factor for failure of this slumping deposit.

4) Field investigations indicate that under the influence of operational maintenance activities and repeated rainfall, the slumping deposit poses a risk of instability, which could potentially bury the railway line at the tunnel entrance and threaten railway operational safety.

5) Existing protective measures generally satisfy safety requirements; however, localized deformation and wire breakage have been observed in the passive protective net. Based on the development characteristics of the slumping deposit, remediation measures including the addition of a passive protective net, enhanced deformation monitoring, and periodic desilting of drainage ditches are proposed.

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