ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

Two-Dimensional Limit Equilibrium Analysis of Tailings Dam Stability under Rainfall-Seismic Coupling

Xiang Lu[1], Mingxing Lu[1,a,*], Zhenyang Diao[2]

[1]*College of Emergency Technology and Management, University of Emergency Management, Sanhe, 065201, China*
[2]*Shandong Zhengyuan Environmental Technology Co., Ltd., Jinan, 250013,China*
[a] *lumingxing@cidp.edu.cn*
**Corresponding author*

Abstract: *Rainfall infiltration and earthquake loading are two important external factors affecting the stability of tailings dams, and their sequential action may significantly reduce the stability reserve of a dam slope. In this study, a representative cross-section of a valley-type tailings dam was established in GeoStudio, and SEEP/W-SLOPE/W coupling was used to evaluate the dam under initial, rainfall, earthquake and rainfall-seismic coupled conditions. The Morgenstern-Price method was selected because it satisfies both force and moment equilibrium and is applicable to non-circular slip surfaces. The results show that the initial factor of safety is 1.486. Under rainfall, the factor of safety decreases with increasing rainfall intensity, reaching 1.453 for the local daily maximum rainfall of 151.4 mm/d. Under earthquake loading, the safety factor decreases from 1.423 to 1.317 as the horizontal seismic coefficient increases from 0.017 to 0.10. The coupled condition is the most unfavorable case, with the factor of safety decreasing to 1.273, but still higher than the specification threshold of 1.15. The analysis clarifies the evolution of pore-water pressure, the decrease in stability reserve and the shallow migration of the critical slip surface under coupled rainfall and seismic loading.*

Keywords: *Tailings Dam, Limit Equilibrium Method, GeoStudio, Rainfall Infiltration, Seismic Stability, Coupled Condition*

1. Introduction

Tailings dams are key facilities for mine production and are also major hazard sources. Historical accident statistics show that rainfall infiltration and earthquakes are two important triggers of tailings dam instability [1,2]. For upstream tailings dams with loose and layered materials, rainfall may raise the phreatic line, reduce matric suction and increase pore-water pressure, while earthquake loading introduces additional inertia force and may accelerate deformation or liquefaction-related weakening [3-5]. The seepage-strength relationship is commonly interpreted through unsaturated soil strength theory and hydraulic conductivity functions [11,12].

This study takes a second-class valley-type tailings reservoir in Chengde, Hebei Province as the engineering background. The total dam height is about 187 m, and the dam body consists of an initial dam, tailing medium sand, tailing fine sand, tailing silt and foundation rock. The stability evaluation follows the safety-factor framework used in tailings facility design and related GeoStudio-based tailings dam studies [13]. The purpose of this paper is to establish a two-dimensional seepage-stability calculation procedure, quantify the effects of rainfall and earthquake loading, and identify the most unfavorable slip-surface evolution under coupled conditions.

2. Materials and Methods

2.1 Project Section and Model Geometry

A representative cross-section was selected for two-dimensional analysis. The model includes the initial dam, layered tailings, reservoir terrain and bedrock. The model length is 1213 m, the maximum

ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

model height is 343 m and the dam height is about 186 m. The cross-section and generalized geometry are shown in Figures 1 and 2.

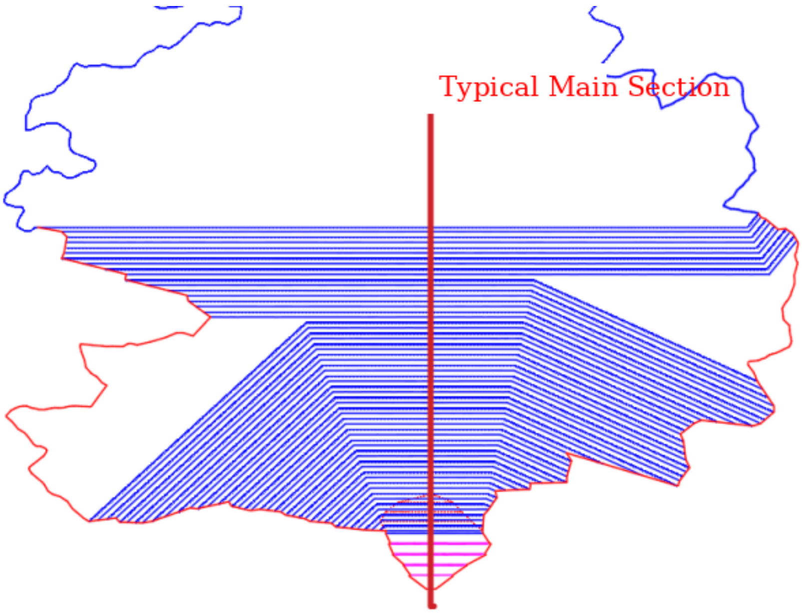


Figure 1: Location of the representative cross-section.

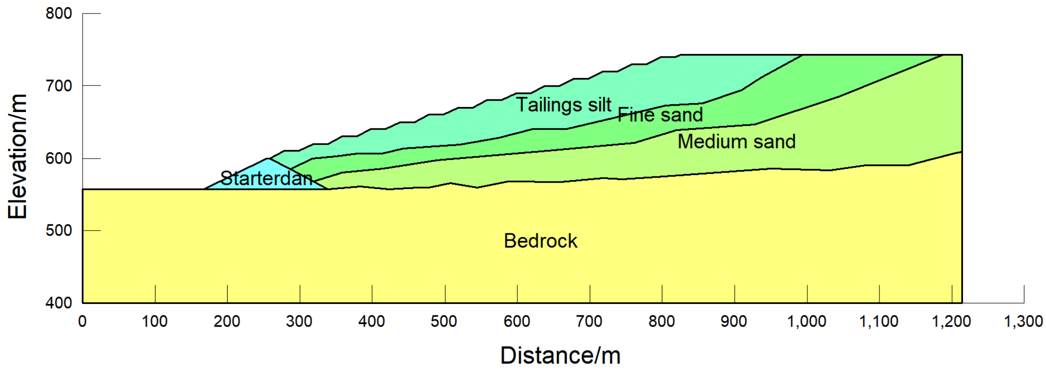


Figure 2: Geometric model of the main section.

2.2 Coupled Seepage-Stability Calculation

The two-dimensional analysis was conducted using SEEP/W and SLOPE/W in GeoStudio. SEEP/W was used to obtain the steady and transient pore-water pressure fields under rainfall, and the calculated seepage field was imported into SLOPE/W for stability calculation [6]. The upstream reservoir level was set as a head boundary, the downstream slope was set as a potential seepage face, and the bottom boundary was impermeable. The boundary arrangement is shown in Figure 3.

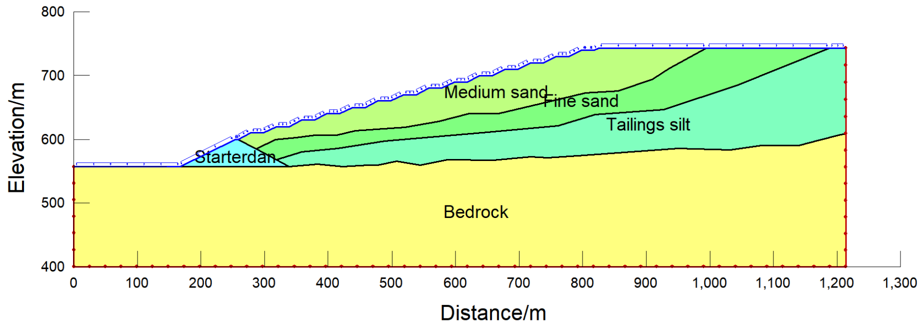


Figure 3: Boundary conditions used in the two-dimensional model.

ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

The Morgenstern-Price method was used as the main limit equilibrium method. Compared with simplified methods, it satisfies both force equilibrium and moment equilibrium, and it can handle circular or non-circular critical slip surfaces [9,10]. For earthquake cases, the pseudo-static method was adopted by introducing horizontal and vertical seismic coefficients into the strip forces. This setting provides a clear and reproducible basis for evaluating the minimum safety-factor trend under different loading conditions. Table 1 summarizes the calculation conditions.

Table 1: Calculation conditions for the limit equilibrium analysis.

Case	Type	Rainfall condition	Earthquake condition	Purpose
L-1	Initial	None	None	Initial stability
L-2	Rainfall	Local daily maximum rainfall	None	Rainfall effect
L-3	Earthquake	None	Design earthquake	Seismic effect
L-4	Coupled	Local daily maximum rainfall	Design earthquake	Combined effect

3. Results

3.1 Initial Stability

For the initial condition, the minimum factor of safety is 1.486. The critical slip surface passes through the lower part of the dam body, and the calculated safety factor is higher than the required value for the corresponding operation condition. This result indicates that the dam has sufficient stability reserve before rainfall or earthquake loading. Figure 4 shows the corresponding factor of safety and critical slip surface.

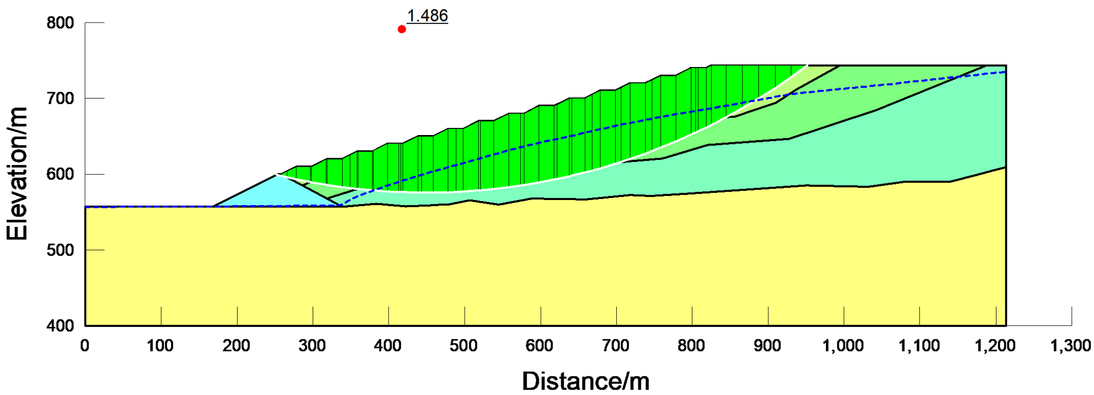


Figure 4: Factor of safety and critical slip surface under the initial condition.

3.2 Rainfall Condition

The pore-water pressure results show a clear transition from negative pore pressure near the upper dam body to positive pore pressure near the lower impoundment area. With increasing rainfall intensity, matric suction decreases, the negative pore-pressure zone shrinks and the phreatic line rises. These responses directly weaken the shear strength of unsaturated tailings and promote the upward migration of the potential slip surface. Figure 5 shows the pore-water pressure contours, and Table 2 summarizes the corresponding factors of safety.

ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

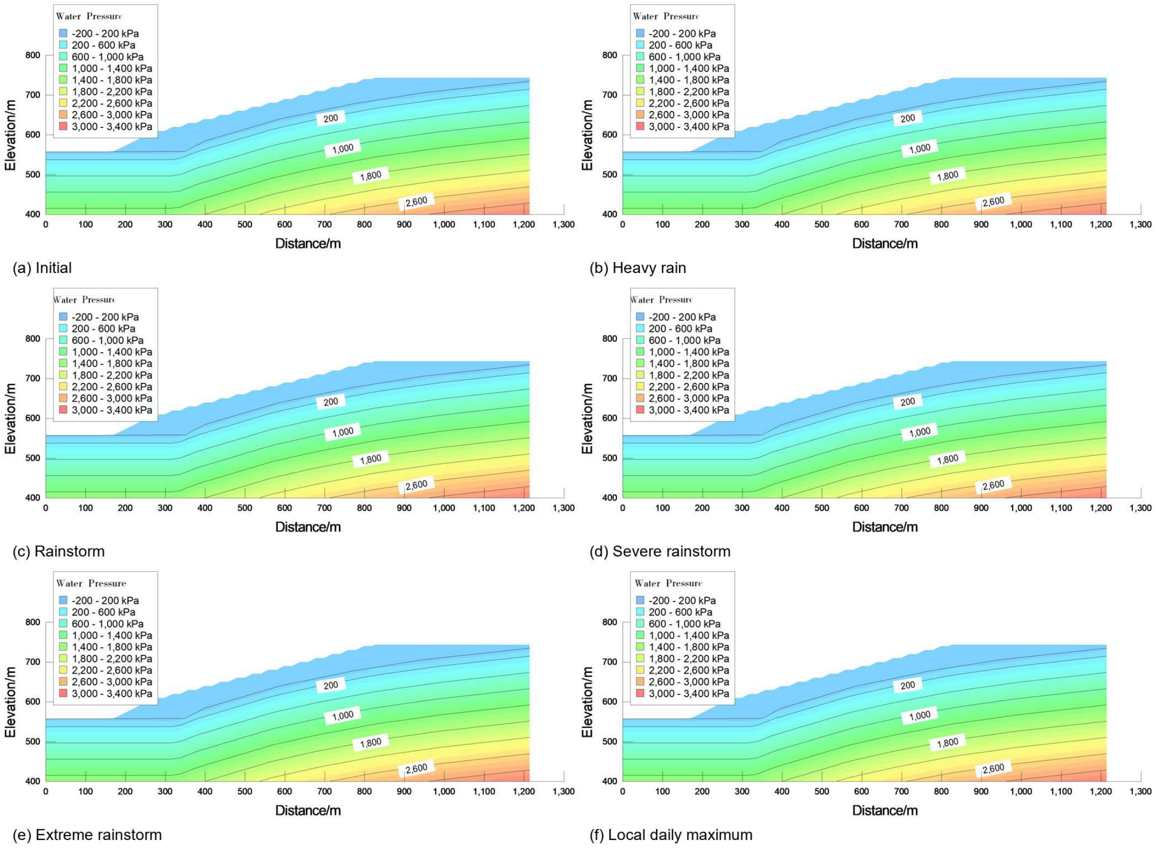


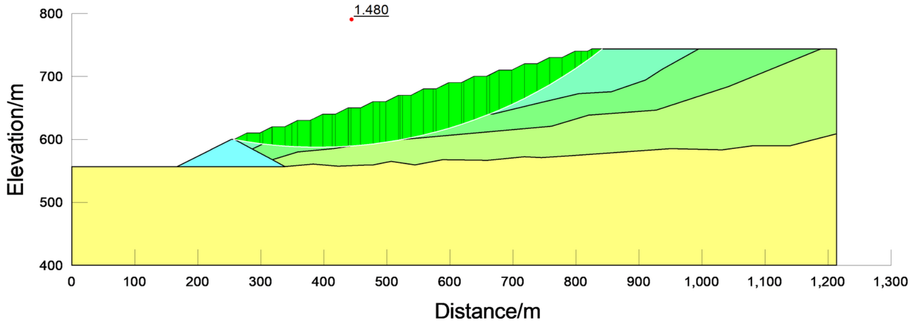
Figure 5: Pore-water pressure contours under different rainfall intensities.

Table 2: Factors of safety under different rainfall intensities.

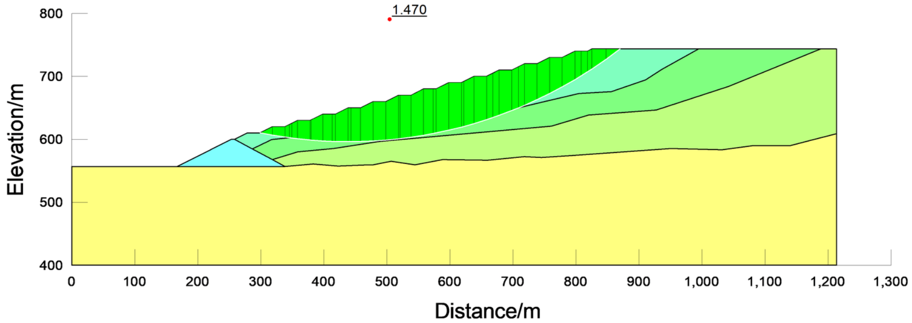
Case	Rainfall intensity (mm/d)	Duration (d)	Method	Initial Fs	Post-rainfall Fs
R-1	25	1	Morgenstern-Price	1.486	1.480
R-2	50	1	Morgenstern-Price	1.486	1.470
R-3	100	1	Morgenstern-Price	1.486	1.464
R-4	250	1	Morgenstern-Price	1.486	1.443
R-5	151.4	1	Morgenstern-Price	1.486	1.453

As rainfall intensity increases from 25 mm/d to 250 mm/d, the factor of safety decreases from 1.480 to 1.443. For the local daily maximum rainfall of 151.4 mm/d, the factor of safety is 1.453. The calculated values remain above the allowable safety factor, but the decreasing trend demonstrates that rainfall infiltration is a significant weakening factor. Figures 6 and 7 show the corresponding critical slip surfaces and time-history curves, respectively.

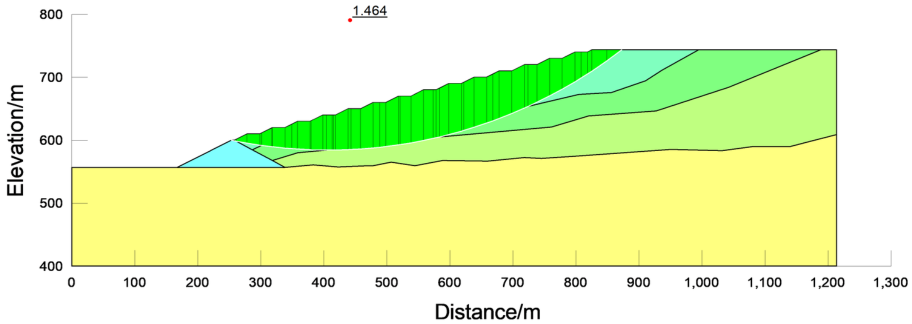
ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114



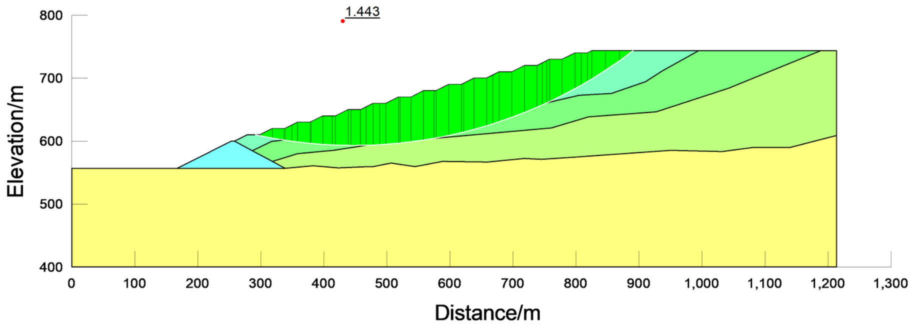
(a) Initial



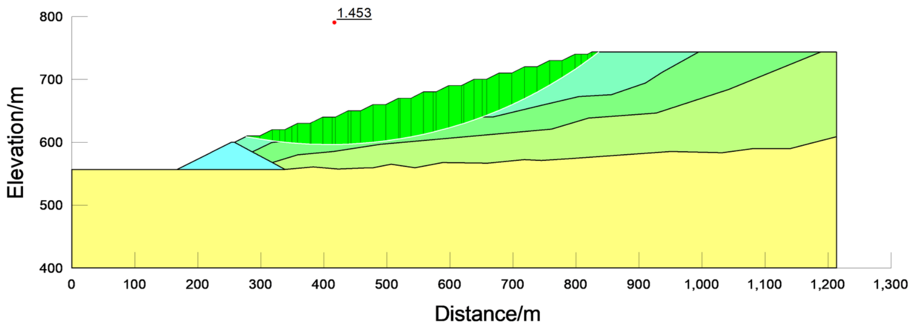
(b) 25 mm/d



(c) 50 mm/d



(d) 100 mm/d



(e) 151.4-250 mm/d

Figure 6: Critical slip surfaces under rainfall conditions.

ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

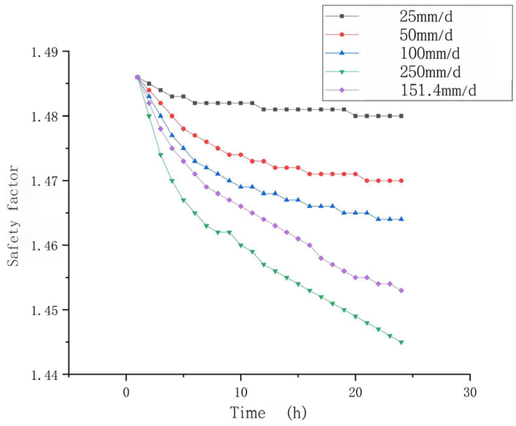


Figure 7: Time-history curves of factors of safety under rainfall conditions.

3.3 Earthquake Condition

According to the seismic design parameters of the project site, three seismic levels were considered. The horizontal seismic coefficients were 0.017, 0.05 and 0.10 for frequent, design and rare earthquakes, respectively. The limit equilibrium results show that the safety factor decreases as the seismic coefficient increases. Table 3 summarizes the calculated results, while Figures 8 and 9 show the critical slip surfaces and the relationship between seismic coefficient and factor of safety, respectively.

Table 3: Factors of safety under earthquake conditions.

Case	Earthquake input	Horizontal seismic coefficient	Factor of safety	Slip surface change	Evaluation
G-1	Frequent earthquake	0.017	1.423	Almost unchanged	Stable
G-2	Design earthquake	0.05	1.388	Slightly shallower	Stable
G-3	Rare earthquake	0.10	1.317	Obviously shallower	Stable

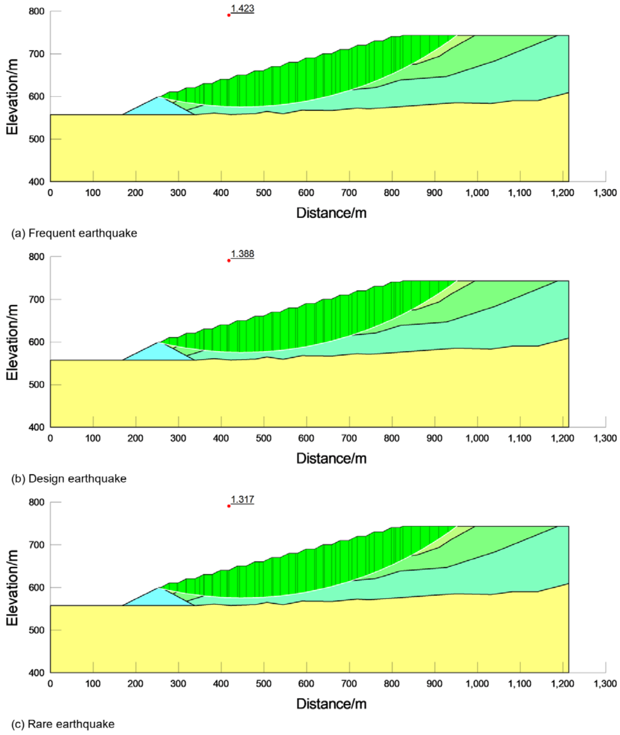


Figure 8: Critical slip surfaces under different earthquake levels.

ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

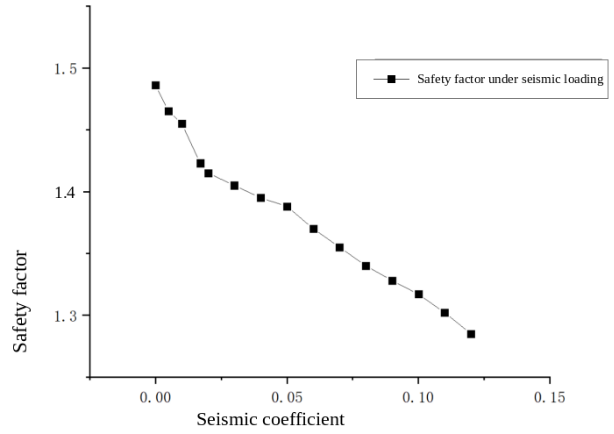


Figure 9: Relationship between seismic coefficient and factor of safety.

The factor of safety decreases from 1.423 to 1.317 as the seismic level increases. Meanwhile, the critical slip surface migrates from a deeper circular surface to a shallower surface, indicating that the shallow dam slope becomes more sensitive under stronger inertia force.

3.4 Rainfall-Seismic Coupled Condition

The coupled case was designed as local daily maximum rainfall followed by the design earthquake. The pore-water pressure field at t = 24 h was imported from SEEP/W into SLOPE/W, and a horizontal seismic coefficient of 0.05 was applied. This sequential procedure represents the weakening of the initial hydraulic and stress states before earthquake loading. Table 4 summarizes the factors of safety under the static, single-action and coupled conditions.

Table 4: Factors of safety under single and coupled conditions.

Case	Condition	Factor of safety	Reduction from initial	Reduction from rainfall	Reduction from earthquake
C-0	Static	1.486	-	-	-
R-5	Rainfall only	1.453	2.22%	-	-
G-2	Earthquake only	1.388	6.60%	-	-
C-1	Rainfall-seismic coupling	1.273	14.33%	12.39%	8.29%

The coupled factor of safety is 1.273, which is substantially lower than the rainfall-only and earthquake-only values. The decrease relative to the initial condition reaches 14.33%. This indicates that rainfall and earthquake loading do not act as two isolated factors; rainfall first raises pore-water pressure and reduces effective stress, then the earthquake force mobilizes a shallower and weaker sliding zone. Figure 10 shows the critical slip surface under the rainfall-seismic coupled condition.

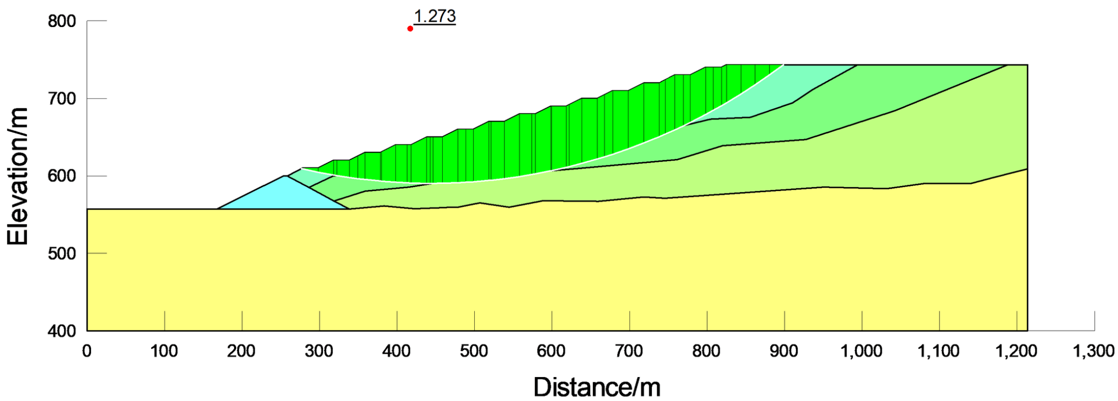


Figure 10: Critical slip surface under the rainfall-seismic coupled condition.

ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

4. Discussion

The two-dimensional limit equilibrium results show a consistent stability degradation path from the initial condition to the coupled condition. Rainfall mainly acts by increasing pore-water pressure, reducing matric suction and weakening the shear resistance along the potential slip surface. Earthquake loading mainly acts by adding horizontal inertia force, which increases the driving component of the sliding mass. When rainfall and earthquake loading occur sequentially, the rainfall-modified pore-pressure field becomes the initial condition for the seismic calculation, so the sliding surface is more likely to migrate toward the shallow saturated zone.

The coupled condition does not simply equal the sum of the rainfall-only and earthquake-only responses. The rainfall-only safety factor is 1.453 and the design-earthquake safety factor is 1.388, while the coupled safety factor decreases to 1.273. This result indicates that the hydraulic weakening caused by rainfall amplifies the influence of seismic inertia force. From an engineering perspective, the slope remains stable because the calculated safety factor is higher than the specification threshold of 1.15, but the stability reserve is markedly reduced and should be treated as the key condition for monitoring and risk control.

The critical slip-surface evolution also supports this interpretation. Under the initial condition, the slip surface is relatively deep and mainly controlled by the overall dam geometry. With rainfall, the slip surface moves upward as the phreatic line rises. With stronger earthquake loading, the slip surface becomes shallower because the upper dam body is more sensitive to inertia force. Under the coupled condition, the slip surface is concentrated near the rainfall-influenced shallow zone, showing that pore-pressure redistribution and pseudo-static seismic force jointly control the most unfavorable sliding mechanism.

5. Conclusions

A two-dimensional GeoStudio model was established for the representative section of the tailings dam. The Morgenstern-Price method was selected to evaluate initial, rainfall, earthquake and rainfall-seismic coupled conditions.

Rainfall infiltration reduces the factor of safety by raising pore-water pressure and reducing matric suction. The post-rainfall factor of safety decreases to 1.453 under the local daily maximum rainfall of 151.4 mm/d.

Earthquake loading produces a stronger reduction in safety factor than rainfall alone. Under the design earthquake, the factor of safety is 1.388; under the rare earthquake, it decreases to 1.317.

The rainfall-seismic coupled condition is the most unfavorable case. The factor of safety decreases to 1.273, and the critical slip surface migrates toward a shallower zone near the rainfall-influenced phreatic surface.

The two-dimensional analysis shows that rainfall-induced pore-pressure redistribution and pseudo-static seismic force jointly control the shallow migration of the critical slip surface. The coupled condition should therefore be used as the key condition for safety monitoring and risk prevention.

References

[1] ICOLD. Tailings Dams: Risk of Dangerous Occurrences: Lessons Learnt from Practical Experiences[M]. New York: United Nations Publications, 2001.
[2] AZAM S, LI Q. Tailings dam failures: A review of the last one hundred years[J]. Geotechnical News, 2010, 28(4): 50-53.
[3] XU W Y, ZHOU W J, YAN L. Research progress on seepage stability of rainfall-induced accumulation landslides[J]. Advances in Science and Technology of Water Resources, 2020, 40(04): 87-94.
[4] WU L Z, SELVADURAI A P S, ZHANG L M, et al. Poro-mechanical coupling influences on potential for rainfall-induced shallow landslides in unsaturated soils[J]. Advances in Water Resources, 2016, 98: 114-121.
[5] KRAMER S L. Geotechnical Earthquake Engineering[M]. Upper Saddle River: Prentice Hall, 1996.
[6] GEO-SLOPE International Ltd. Seepage Modeling with SEEP/W: An Engineering Methodology[M]. Calgary: GEO-SLOPE International Ltd., 2012.

ISSN 2663-1563 Vol. 8, Issue 1: 112-120, DOI: 10.25236/AJAGE.2026.080114

[7] MORGENSTERN N R, PRICE V E. The analysis of the stability of general slip surfaces[J]. Geotechnique, 1965, 15(1): 79-93.

[8] DUNCAN J M, WRIGHT S G. Soil Strength and Slope Stability[M]. 2nd ed. Hoboken: John Wiley & Sons, 2014.

[9] FREDLUND D G, MORGENSTERN N R, WIDGER R A. The shear strength of unsaturated soils[J]. Canadian Geotechnical Journal, 1978, 15(3): 313-321.

[10] VAN GENUCHTEN M T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils[J]. Soil Science Society of America Journal, 1980, 44(5): 892-898.

[11] China Nonferrous Metals Industry Association. GB 50863-2013 Code for Design of Tailings Facilities[S]. Beijing: China Planning Press, 2013.

[12] OZCAN N T, ULUSAY R, ISIL N S. A study on geotechnical characterization and stability of downstream slope of a tailings dam to improve its storage capacity (Turkey)[J]. Environmental Earth Sciences, 2013, 69(6): 1871-1890.

[13] JIA Y J. Stability study of tailings dam based on GeoStudio[J]. Shanxi Metallurgy, 2023, 46(4): 112-115.