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Tailings Heterogeneity and Multi-Scenario Response of an Upstream Tailings Dam

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Abstract

Upstream tailings dams are highly vulnerable to instability under extreme rainfall and seismic loading, yet the mechanism by which depositional spatial heterogeneity governs dam responses and failure evolution under multiple scenarios remains insufficiently constrained. This study investigates a high-altitude canyon-type upstream tailings storage facility in western China using representative profiles, borehole sampling, laboratory testing, and GeoStudio-based numerical simulations. The results show that the deposited tailings become progressively finer from the dam front to the reservoir tail, while vertically they display a coarse-fine-coarse cyclic pattern, jointly forming a pronounced three-dimensional heterogeneous structure. This depositional heterogeneity is further translated into layered hydro-mechanical parameter zonation, characterized by relatively loose, more permeable, and lower-stiffness tailings in the shallow part, a compaction-transition zone in the middle part, and denser tailings with lower permeability, higher shear strength, and higher stiffness at depth. Under heavy rainfall, infiltration is preferentially concentrated in the shallow tailings, whereas the relatively low-permeability middle layers impede downward seepage, resulting in perched water, pore-pressure accumulation near the dam toe, and progressive reduction in effective stress and local shear resistance; consequently, the factor of safety decreases from 1.35 to 0.98. Under seismic loading, the combined influence of low stiffness in the shallow tailings, structural transitions in the middle-upper zone, and free-surface amplification promotes deformation localization in the crest and middle-upper deposited-tailings zone, leading to the development of potential sliding zones, a reduction in the factor of safety to 0.962, and a final permanent horizontal displacement of 18.2 mm at the highest downstream node of the dam crest. These findings demonstrate that tailings spatial heterogeneity is not merely a depositional feature, but the key internal factor governing seepage redistribution, deformation localization, and failure evolution of upstream tailings dams under different external disturbances.

Keywords

Spatial heterogeneity, Upstream tailings dam, Heavy rainfall, Seismic response, Failure evolution.

1 Introduction

Upstream tailings dams are prone to seepage redistribution, deformation localization, and stability deterioration under external disturbances such as heavy rainfall and earthquakes, and their failure is often accompanied by severe engineering damage and environmental risk. Previous studies have systematically examined the effects of dry beach length, drainage conditions, rainfall infiltration, and seismic input on tailings dam stability, and have shown that phreatic-line rise, pore-water-pressure accumulation, and dynamic amplification at the dam crest and in the shallow dam body are key processes governing instability (Wang et al., 2021; Han et al., 2023; Wang et al., 2017). However, most existing studies are still based on homogeneous bodies or simplified zoned bodies, with insufficient consideration given to the spatial heterogeneity formed during tailings deposition and the resulting stratified parameter differences. In particular, an integrated understanding of the stratigraphic correspondence among permeability, shear strength, and dynamic properties remains lacking. Taking a high-altitude canyon-type upstream tailings storage facility in western China as the study object, this study combines borehole investigation and in-situ sampling, laboratory testing, and GeoStudio numerical simulations to analyze the spatial differentiation and parameter zonation of tailings, and further to clarify their controlling effects on dam response and failure evolution under heavy-rainfall and seismic scenarios.

2 Study area and methods

2.1 Study area and dam structure

The study area is located in a high-altitude mining district in western China, where the tailings storage facility is situated within a typical mountain gully. The site is characterized by a south-high, north-low V-shaped topography with pronounced relief and belongs to a plateau temperate semi-arid monsoon climatic zone. The mean annual precipitation is 589.1 mm, with rainfall mainly concentrated from June to September; the multi-year maximum 1 h rainfall is 13.04 mm, the mean annual evaporation is 1893.1 mm, and the peak ground acceleration at the site is 0.15 g. As shown in Fig. 1, the tailings storage site exhibits a typical valley-type impoundment setting. The dam body consists of the initial dam, the compacted sand layer, the geomembrane-lined soil layer, and the deposited tailings within the impoundment. The deposited tailings can be divided vertically into five layers, namely Tailings soil 2-1 to Tailings soil 2-5, showing a distinct stratified depositional structure. The current tailings deposition elevation is approximately 4355.00 m, and the sub-dams have been raised to the nineteenth stage. Together, the dam structure and the stratified tailings provide the basis for the subsequent analysis of tailings spatial heterogeneity and the multi-scenario responses of the dam (Fig. 1).

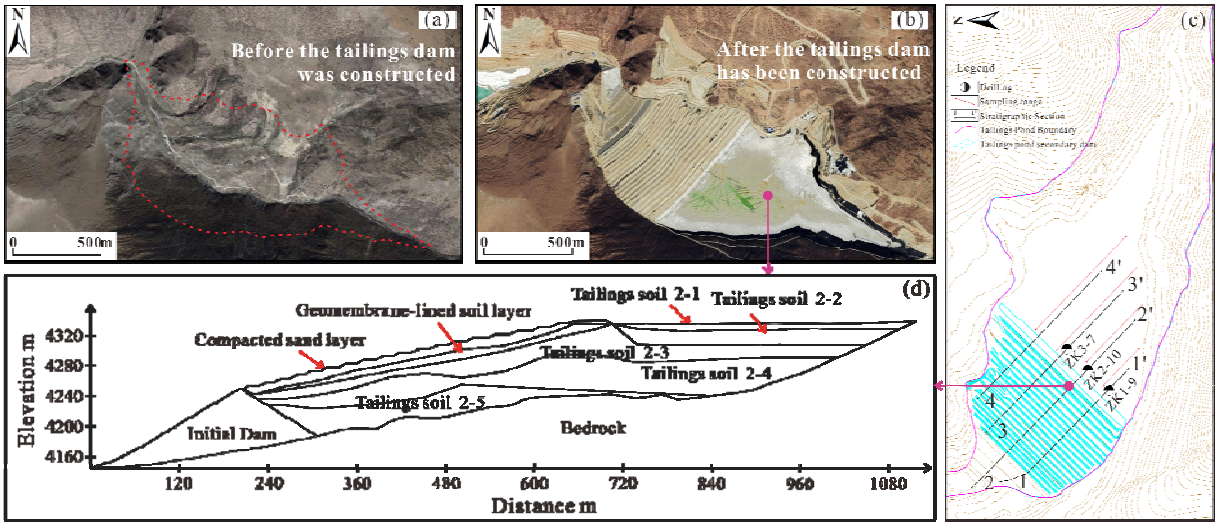


Fig. 1 Study area and representative longitudinal section of the upstream tailings dam.

2.2 Testing program and numerical modeling

To identify the spatial heterogeneity of tailings and its associated parameter zonation, borehole sampling and beach sampling were conducted along representative profiles, and conventional triaxial tests, cyclic triaxial tests, and permeability tests were carried out to obtain the shear-strength, dynamic, and permeability parameters of tailings in different layers. Considering the structural characteristics of

the dam and the borehole records, the central 2-2' section was selected as the representative calculation section. The SEEP/W, SLOPE/W, and QUAKE/W modules in GeoStudio were then employed to analyze the seepage, deformation, and stability responses of the dam under the normal operating, heavy-rainfall, and seismic scenarios. The scenario design in this study was intended primarily to clarify the controlling effect of tailings spatial heterogeneity on the multi-scenario responses and failure evolution of the dam. Accordingly, except for the normal operating condition, both the heavy-rainfall and seismic scenarios were analyzed under relatively unfavorable external disturbance conditions. The purpose was to compare seepage behavior, dynamic response, and stability evolution of the dam under extreme adverse conditions. Under the normal operating condition, the initial water table was defined according to the monitored groundwater level and the operating water level within the impoundment. Under the heavy-rainfall scenario, an equivalent rainfall infiltration boundary was applied to the upstream dam face and the surface of the deposited tailings, with a rainfall intensity of 13 mm/h and a duration of 24 h. Under the seismic scenario, a processed Wenchuan earthquake record was adopted and scaled to a peak ground acceleration of 0.30 g. The key hydro-mechanical parameters of each layer were determined by integrating laboratory test results with site investigation data, and were used to evaluate the controlling effect of tailings spatial heterogeneity on the multi-scenario responses and failure evolution of the dam. The representative numerical model and scenario settings are shown in Fig. 2, and the main parameters are listed in Table 1. To quantify the crest deformation under seismic loading, Point P was selected at the highest downstream node of the dam crest, and its horizontal displacement time history was extracted from the QUAKE/W results. After the seismic excitation ceased, a zero-acceleration segment was appended to capture the free-vibration decay, and the permanent displacement was determined as the final stabilized residual displacement.

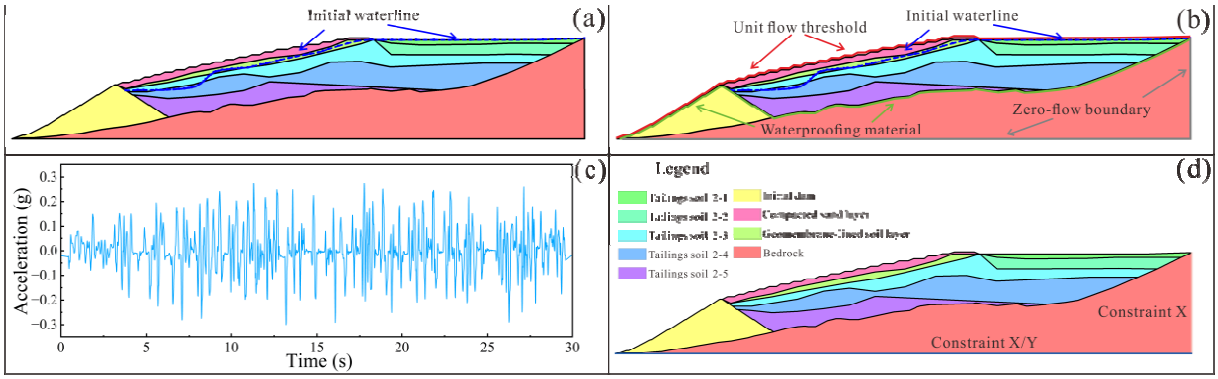


Fig. 2 Numerical model and scenario settings.

Table 1. Key hydro-mechanical parameters adopted in the numerical simulations.

Layer	c′ (kPa)	φ′ (°)	k (cm/s)	G_{max} (MPa)	Damping ratio (%)
Initial dam	28.0	36.0	1.60E-03	80	18
Compacted sand layer	0.0	26.0	1.38E-01	90	16
Geomembrane-lined soil layer	12.2	23.3	9.03E-05	60	20
Tailings soil 2-1	15.7	27.5	1.06E-04	65	23
Tailings soil 2-2	15.2	28.1	8.63E-05	75	21
Tailings soil 2-3	12.5	29.0	6.91E-05	90	18
Tailings soil 2-4	15.3	30.0	7.60E-05	125	16
Tailings soil 2-5	13.8	31.5	4.57E-05	135	14

3 Results and discussion

3.1 Tailings spatial heterogeneity and parameter zonation

The deposited tailings in the tailings storage facility exhibit pronounced spatial heterogeneity (Fig. 3). As indicated by the spatial differentiation pattern shown in Fig. 3 and the key parameters summarized in Table 1, the beach tailings generally become progressively finer from the dam front toward the reservoir tail, whereas the vertical profile displays a distinct coarse-fine-coarse depositional cyclicity, indicating marked differentiation in both the planar and vertical directions. Correspondingly, the hydro-mechanical properties of the tailings also show consistent zonation among different layers: the shallow tailings are generally characterized by a relatively high void ratio, strong permeability, and low dynamic stiffness; the middle layers exhibit a compaction-transition character; and the deep

tailings are characterized by relatively low permeability together with high strength and stiffness. In particular, the effective internal friction angle generally increases with burial depth, indicating that the particle skeleton of the deep tailings becomes denser and its shear resistance correspondingly stronger. These results demonstrate that tailings spatial heterogeneity is not merely a depositional feature, but is further translated into a layered hydro-mechanical parameter gradient that governs seepage, deformation, and stability within the dam, thereby forming the internal basis for the differentiated responses observed under multiple scenarios.

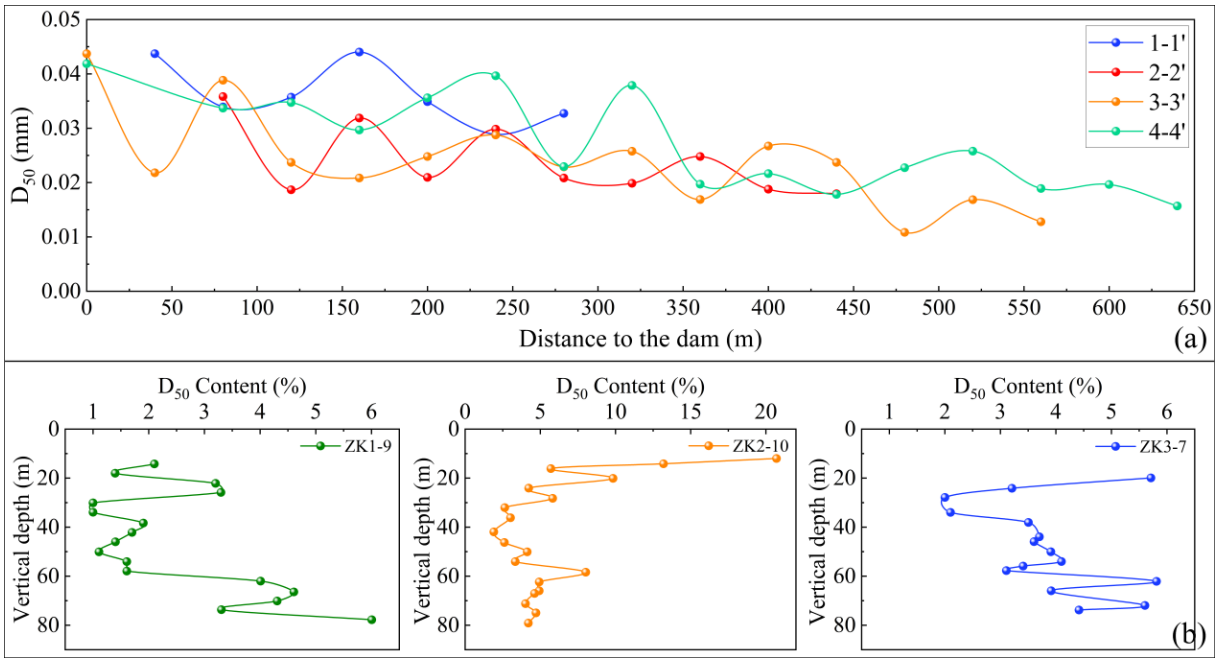


Fig. 3Tailings spatial heterogeneity and parameter zonation.

3.2 Heavy-rainfall-induced seepage and stability response

Under heavy rainfall, the seepage field within the dam changes markedly. As shown in Fig. 4a, with rainfall duration increasing from 0 h to 24 h, the phreatic line rises continuously in the shallow zone near the dam crest and around the dam toe, whereas changes in the middle and deeper parts of the dam remain relatively limited, indicating that rainfall infiltration is mainly concentrated in the surface and shallow tailings layers. This behavior is fundamentally attributed to the fact that the shallow tailings possess relatively high permeability and can therefore rapidly receive external water recharge, whereas the relatively low-permeability middle layers impede vertical seepage, thereby causing shallow perched water and pore-water-pressure concentration near the dam toe. As a result, dam stability decreases progressively with rainfall duration. As shown in Fig. 4b, the factor of safety declines gradually from 1.35 under the normal operating condition to 0.98 at 24 h. These results indicate that the deterioration of dam stability under rainfall is not caused simply by an increase in infiltration water input, but rather by the reorganization of rainfall disturbance into localized pore-pressure buildup and shear-strength degradation through the layered permeability contrast of the tailings. In other words, the weakening effect of rainfall on the dam follows a distinct evolutionary pathway of "shallow infiltration–middle-layer impediment–pore-pressure concentration near the dam toe–development of a potential slip surface."

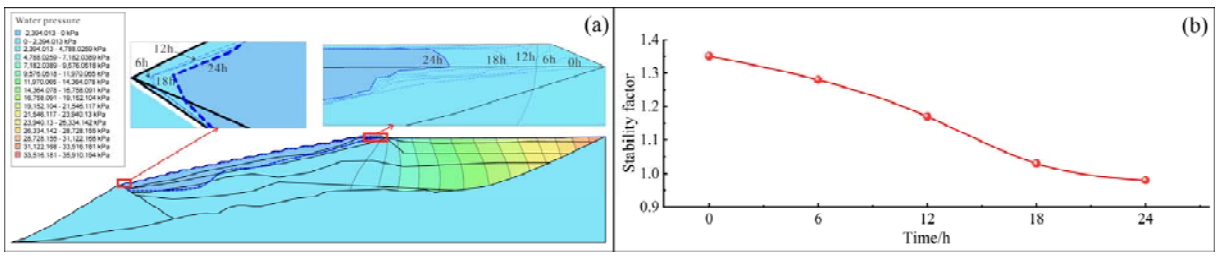


Fig. 4 Seepage-field evolution and stability response under the heavy-rainfall scenario.

3.3 Seismic displacement and stability response

Under the seismic scenario, dam deformation and stability reduction also exhibit pronounced spatial selectivity. As shown in Fig. 5a-c, the middle-upper deposited-tailings zone and the area near the dam crest constitute the principal zones of displacement concentration, and the horizontal displacement is markedly greater than the vertical displacement, indicating that the seismic response of the dam is dominated by the accumulation of horizontal deformation. This behavior is mainly attributed to the fact that the shallow tailings are relatively loose and of low stiffness, making them more susceptible to shear deformation under seismic inertial forces; meanwhile, the middle-upper part of the dam corresponds to a zone where stratigraphic transition and structural variation are more pronounced, so seismic disturbance is more readily transformed into localized deformation. Stability analysis further indicates that the factor of safety decreases from 1.35 under the normal condition to 0.962 under the seismic condition, and the potential sliding mass is mainly developed in the middle-upper deposited-tailings zone (Fig. 5e and f). In addition, the displacement time history of Point P, located at the highest downstream node of the dam crest, shows that the horizontal displacement gradually stabilizes after the seismic excitation ceases, with a final permanent displacement of 18.2 mm (Fig. 5d). These results demonstrate that tailings spatial heterogeneity controls the zones of displacement concentration, crest residual deformation, and the development of potential instability under seismic loading by governing contrasts in material stiffness and structural transition. The corresponding failure evolution can therefore be summarized as a process of "dynamic disturbance input–displacement localization in the crest and middle-upper zone–accumulation of permanent crest displacement–formation of a potential sliding zone."

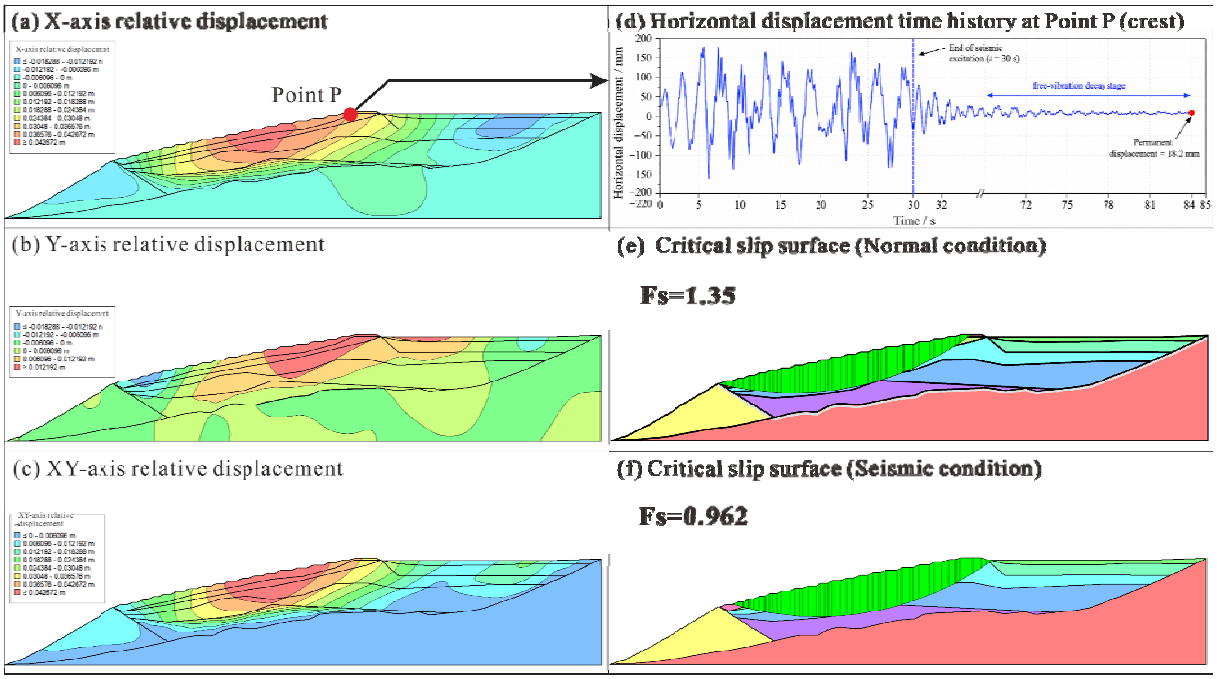


Fig. 5 Seismic displacement response, crest displacement time history, and stability analysis under the seismic scenario.

3.4 Discussion

The key significance of tailings spatial heterogeneity lies not in the depositional differences themselves, but in their further translation into a layered hydro-mechanical parameter gradient that governs dam response. The progressive grain-size reduction from the dam front toward the reservoir tail, together with the vertical coarse-fine-coarse depositional cyclicity, jointly gives rise to a spatial zonation characterized by a relatively loose shallow part, a transitional middle part, and a relatively dense deep part, which is further manifested as systematic differences in permeability, shear strength, and dynamic stiffness. For an upstream tailings dam, stability is controlled not primarily by the extreme value of any single parameter, but by the manner in which different parameters are combined and spatially distributed within the dam body. Previous studies have likewise shown that slope instability, seepage, and localized deformation commonly arise from the combined effects of internal material zonation and operating conditions (Otieno and Shukla, 2023; Williams, 2021). Accordingly, the layered parameter gradient identified in this study can be regarded as the internal basis for the differentiated responses of the dam under different external disturbances.

Differences in the physical and mechanical properties of Tailings soil at different layers lead directly to differences in their resistance to external disturbances. The shallow Tailings soil is generally characterized by a relatively high void ratio, relatively high permeability, and low dynamic stiffness, and its comparatively loose structure makes it the most sensitive to heavy-rainfall infiltration and seismic disturbance. The middle layers constitute a compaction-transition zone; their relatively low permeability makes them more likely to impede downward seepage during rainfall, whereas their structural transition characteristics make them a key zone for deformation transmission and concentration under seismic loading. By contrast, the deep Tailings soil is characterized by lower permeability, higher shear strength, and higher dynamic stiffness, with a denser structure and thus a relatively stronger resistance to external disturbances. In essence, the differences in dam response under different scenarios originate from the stratified contrasts in permeability, strength, and stiffness among different Tailings soil layers, as well as the resulting differences in disturbance resistance.

Although heavy rainfall and earthquakes represent different external triggering mechanisms, both are fundamentally governed by tailings spatial heterogeneity, albeit through different response pathways. Under the heavy-rainfall scenario, layered permeability contrast dominates the transmission of disturbance: the shallow high-permeability layers preferentially receive infiltration, whereas the relatively low-permeability middle layers impede downward seepage, making local pore-water-pressure accumulation more likely and further reducing effective stress and stability reserve (Theron et al., 2022; Du et al., 2024; Wu et al., 2025). Under the seismic scenario, by contrast, stiffness contrast and structural transition characteristics dominate the response mode: the shallow low-stiffness Tailings soil is more prone to dynamic deformation, and the middle transition zone more readily transforms such disturbance into localized displacement concentration. Previous studies have likewise shown that differences in cyclic response, permeability, and stiffness of tailings materials significantly influence displacement development and nonlinear deformation under seismic loading (Solans et al., 2023; Li et al., 2021). Therefore, heavy rainfall primarily affects dam stability through the pathway of "layered permeability contrast–pore-pressure accumulation–local strength degradation," whereas earthquakes mainly control dam failure evolution through the pathway of "stiffness contrast–deformation localization–formation of potential sliding zones." Taken together, the two scenarios indicate that tailings spatial heterogeneity is the key internal factor governing the zones of concentrated response and the failure pathways of the dam.

4 Conclusions

Taking an upstream tailings dam in western China as a case study, this study investigated the controlling effect of tailings spatial heterogeneity on the multi-scenario responses and failure evolution of the dam. The main conclusions are as follows:

(1) The deposited tailings exhibit pronounced spatial heterogeneity. The beach tailings generally become progressively finer from the dam front toward the reservoir tail, while the vertical profile displays a coarse-fine-coarse depositional cyclicity, together forming a parameter zonation characterized by a relatively loose shallow part, a transitional middle part, and a relatively dense deep part. This layered structure constitutes the internal basis for the differentiated responses of the dam under multiple scenarios. From an engineering perspective, tailings stratification should be delineated as finely as possible in conjunction with the discharge year, discharge sequence, and depositional process.

(2) Under the heavy-rainfall scenario, rainfall infiltration preferentially affects the dam surface and the shallow tailings layers, and, under the impediment of the relatively low-permeability middle layers, leads to shallow perched water and pore-pressure concentration near the dam toe, with the factor of safety decreasing from 1.35 to 0.98. The rainfall-induced response pathway can be summarized as "shallow infiltration–middle-layer impediment–pore-pressure accumulation–development of a slip surface."

(3) Under the seismic scenario, the middle-upper tailings zone and the area near the dam crest constitute the main zones of displacement concentration, while the potential sliding mass is primarily developed in the middle-upper deposited-tailings zone, with the factor of safety decreasing from 1.35

to 0.962. The horizontal displacement time history of Point P, located at the highest downstream node of the dam crest, further shows a final permanent displacement of 18.2 mm. The seismic response pathway can be summarized as "dynamic disturbance input–localized deformation concentration–accumulation of permanent crest displacement–formation of a potential sliding zone." The cyclic liquefaction behavior of tailings is a critical aspect of tailings dam stability analysis, and particular attention should be given to the accuracy of relevant laboratory testing and numerical simulation.

(4) Heavy rainfall and earthquakes represent different external disturbances, yet their effects on dam stability are both governed by tailings spatial heterogeneity. The former is mainly controlled by layered permeability contrasts, whereas the latter is primarily controlled by stiffness contrasts and structural transitions. Stability evaluation of tailings dams should therefore place emphasis on the acquisition of stratified parameters, the identification of dynamic properties, and the consistency of parameter assignment in numerical simulations.

References

Du C, Tao H, Yi F (2024) Seepage stability analysis of geogrid reinforced tailings dam. Scientific Reports 14:1814.

Han Y, Wang G, Zhang X, Zhao B (2023) Numerical simulation of seepage surface and analysis of phreatic line control from a fine-grained tailings high stacked dam under complicated geography conditions. Applied Sciences 13(23):12859.

Li Q, Ma G, Li P, Su Z (2021) Dynamic characteristics of tailings dam with geotextile tubes under seismic load. Reviews on Advanced Materials Science 60(1):599-614.

Otieno F, Shukla SK (2023) An insight into failure of iron ore mine tailings dams. International Journal of Mining, Reclamation and Environment 37(2):127-147.

Solans D, Kontoe S, Zdravković L (2023) Comparison of a tailings material and a natural sand in seismic site response analyses. Soil Dynamics and Earthquake Engineering 175:108269.

Theron C, Lorentz SA, Xu Y (2022) Rainfall-induced groundwater ridging and the Lisse effect on tailings storage facilities: A literature review. Journal of the Southern African Institute of Mining and Metallurgy 122(2):37-44.

Wang G, Hu B, Tian S, Ai M, Liu W, Kong X (2021) Seepage field characteristic and stability analysis of tailings dam under action of chemical solution. Scientific Reports 11:4073.

Wang G, Kang J, Du C, Tang Y, Kong X (2017) Study on tailings dam over-topping failure model test and break mechanism under the rainfall condition. TehničkiVjesnik 24(6):1897-1904.

Williams DJ (2021) Lessons from tailings dam failures—where to go from here? Minerals 11(8):853.

Wu W, Song Z, You Y, Peng R, Gan Y, Zhang B (2025) Pore water pressure and consolidation of tailing dams based on numerical simulation and similar modeling temporal and spatial distribution study. Scientific Reports 15:26122.