Disaster Characteristics of Tailings Dam Failure in Xinjiang High-Cold Region and Bridge Risk Assessment Postprint

Authors: Zhang Yuqi, Wang Yuandi, Zhao Xiaoyan, Cui Wenrong, Long Ruixin, Jialiang Wang

Date: 2025-07-22T00:00:00+00:00

Abstract

In recent years, rapid mineral resource development in China's alpine regions has led to a surge in tailings disposal demand. The complex geological and climatic conditions, coupled with frequent natural disasters, have made tailings dam failure mode prediction and risk assessment a critical technical challenge requiring urgent breakthroughs. This study investigates a tailings dam in an alpine region of Xinjiang and a downstream bridge, determines water source discharge by integrating glacier meltwater-rainfall-debris flow confluence conditions, simulates the tailings dam failure process using the HEC-RAS system, systematically summarizes the movement characteristics, variation patterns, and impact ranges of failure flows under different operating conditions, and accordingly delineates hazard zones while evaluating the impact effects and scour depth of failure flows on bridges. The results indicate that: (1) elevation and topography are the dominant factors controlling failure flow movement characteristics; (2) total tailings discharge volume is positively correlated with peak failure flow rate, flow velocity, and flow depth; (3) the failure process exhibits suddenness and high-energy characteristics with short peak flow duration; (4) bridge damage from failure flows is primarily manifested as pier impact and scour. Provided that bridge clearance meets code requirements, it is recommended that overall impact pressure, block stone impact pressure, and scour depth be adopted as core indicators for bridge risk assessment. This research can provide theoretical support for tailings dam failure disaster prevention and resilient bridge engineering design in alpine regions.

Full Text

2. Project Overview

With the development of mineral resources in western China, the demand for disposal of large quantities of mining waste has become increasingly prominent. The number of tailings ponds in alpine regions such as Xinjiang has grown rapidly, and their engineering safety and stability have become critical geological issues constraining regional sustainable development. Globally, over 35,000 tailings ponds exist, with alpine region tailings ponds accounting for approximately 15-20% of the total. Since systematic record-keeping began in 1915, more than 300 major tailings pond breach accidents have occurred worldwide, with alpine region tailings pond accidents comprising about 10% of the global total. The risk of tailings facility failure under extreme environmental conditions is increasing year by year [2]. Currently, research on tailings pond disasters in high-altitude cold regions is severely lacking, making the rational deduction of tailings pond failure modes and assessment of dam-break risk important engineering problems that urgently need to be addressed in these areas.

Tailings ponds often store large quantities of saturated mining waste, and after a breach, the outflow typically forms a high-velocity slurry flow that is a solid-liquid mixture. This characteristic shows high similarity to debris flows, as the breach fluid essentially constitutes a solid-liquid coupling system with rheological properties. Both transport media are water, entraining large amounts of solid particles (tailings sand or natural debris) to form solid-liquid mixed flows with high velocity and substantial impact force. Consequently, many scholars have referenced debris flow kinematic characteristics in tailings movement simulations [4]. In studies of tailings pond breach processes and risk assessment, complete replication of actual evolution patterns is often constrained by limited conditions, a limitation that can be better addressed through numerical simulation methods. In research on dam-break dynamic processes, tailings movement simulations often reference debris flow analysis. Based on real topographic data, hydrodynamic models in numerical simulation (such as FLO2D, DAN3D) and Smoothed Particle Hydrodynamics (SPH) methods can accurately predict debris flow velocity, impact force, and affected range [7]. However, a systematic risk assessment framework for alpine region tailings ponds has not yet been established.

This study focuses on an alpine tailings pond in Xinjiang and a proposed downstream bridge. Based on topographic parameters of the study area, the HEC-RAS analysis system is employed to simulate the tailings pond breach process, obtaining kinematic characteristics and affected ranges of breach fluids under different scenarios. According to the breach simulation results, hazard levels are classified for different scenarios, and the distribution characteristics of total impact force and boulder impact force from breach fluids on the bridge are obtained. This research can provide references for tailings dam failure assessment and bridge risk evaluation in alpine regions.

The study area is located within the Kunlun-Karakoram Mountains, featuring a high mountain to extremely high mountain broad-valley landform with typical inland alpine and plateau arid-cold climate characteristics. The bedrock strata consist primarily of the Bayan Har Group upper formation (TB3) sandstone-quartz schist composite strata, with thickness ranging from 5.0 to 50.0 m. The tectonic unit belongs to the Songpan-Garzê fold system (VII) Dahongliutan miogeosynclinal fold belt (VII2), with significant regional tectonic activity. The peak ground acceleration is 0.2g, the characteristic period is 0.45 s, and the seismic fortification intensity is VIII. According to meteorological station statistics, June to August constitute the high-temperature season with daytime temperatures reaching 22.7°C, while September to May of the following year is the low-temperature season with minimum temperatures dropping to -35.2°C. The area experiences cold weather with an annual precipitation of only 202.8 mm, mostly concentrated from June to August. The hydrological system is primarily fed by seasonal snow and ice melt, with low development of surface water and groundwater.

The tailings pond is a valley-type facility covering an area of 1.5 km^2, with a catchment area of 74.5 km^2, operating elevation of 4516–4570 m, total dam height of 46.0 m, and total storage capacity of 1390\$×10^{4}\$ m^3, classified as a Class III pond. Its ancillary facilities consist of the tailings pond area, tailings dam, in-pond flood discharge facilities, and upstream flood interception and discharge facilities. The tailings dam employs a one-time construction method in two phases: initial dam and final dam. The proposed bridge passes through the "U" -shaped valley mouth downstream of the tailings pond, with a total length of 899.34 m, span arrangement of 27\$×\$32 m, and maximum pier height of approximately 47.3 m. The distance from the tailings pond to the bridge location is 2.05 km. The planar and sectional location relationships of the study area are shown in Figure 1 [Figure 1: see original paper] and Figure 2 [Figure 2: see original paper].

3.1 Parameter Determination

Parameters required for tailings dam breach assessment mainly include initial dam elevation (z_0), storage capacity, water level elevation (Hr), weir overflow coefficient, breach parameters, channel Manning coefficient, and tailings characteristics. The initial dam elevation is selected as the final dam crest elevation (4570 m). The tailings dam is a concrete gravity dam with a weir overflow coefficient of 2.8. Breach parameters are divided into initial breach parameters and breach expansion parameters. The initial breach bottom width (B_0) can be calculated from the initiation flow velocity (Vc) and inflow rate (q). The initial breach angle/side slope (β_0) can be taken as the natural angle of repose. Breach expansion coefficients (m_1, m_2) can be automatically obtained through the built-in interpolation algorithm in the program. Field investigations indicate no vegetation cover on the downstream surface of the tailings dam with flat terrain, so a Manning coefficient n of 0.06 is selected. According to existing design data, 79% of the full tailings particles are smaller than 0.074 mm, the tailings slurry mass concentration is 65%, and the dry tailings density is 2.62 t/m^3. The calculation parameters are listed in Table 1 .

Water sources for alpine region tailings ponds mainly consist of rainstorms and glacial meltwater runoff, with potential upstream debris flow convergence under extreme conditions. Integrating the characteristics of rainstorms, glaciers, and debris flows yields the peak flood discharges shown in Table 2 .

3.2 Working Condition Selection

Breach volume is a critical parameter for tailings dam failure disaster analysis. The breach volume for this numerical simulation is determined considering two dam slope instability failure modes: accumulation dam breach above the most dangerous sliding surface under final dam conditions (seismic condition) and flood overtopping breach.

This study first employs Geostudio software to analyze the stability of the tailings pond under seismic conditions, using the material above the sliding surface as the breach volume for the seismic scenario. Three breach modes are selected for simulation: seismic condition, 1/3 flood overtopping breach, and full flood overtopping breach, as classified in Table 3 . The mass fraction of discharged tailings sand after breach cannot be obtained experimentally; therefore, the design-specified tailings slurry mass concentration of 65% is adopted for this simulation.

4.1 Breach Cross-section Flow Characteristics

The temporal variation of breach cross-section flow under different dam failure conditions is shown in Figure 3 [Figure 3: see original paper]. Overall, the flow changes for Scenarios 1 through 3 demonstrate a pattern of rapid rise to peak followed by rapid decay, with short peak flow duration, indicating the breach process features abruptness and high-energy release characteristics. Peak flows at the breach occur at 20, 25, 15, and 25 minutes after breach initiation, with maximum flows of 4473.65 m^3/s, 2550 m^3/s, 8564.24 m^3/s, 4500 m^3/s, 2568.2 m^3/s, and 8550 m^3/s respectively.

4.2 Breach Fluid Velocity Characteristics

The velocity distribution during breach fluid movement for Scenarios 1 through 3 is shown in Figure 4 [Figure 4: see original paper]. The tailings pond contains substantial material and water sources, and the enormous energy released during instantaneous dam failure is rapidly converted to fluid kinetic energy, causing flow velocities to remain at peak values exceeding 10 m/s during the initial breach stage (0–40 minutes). Thereafter, velocities gradually decrease, approaching zero by approximately 240 minutes after breach. For all three scenarios, breach fluids reach the proposed bridge alignment area within a short time after dam failure: approximately 18 minutes for Scenario 1, 22 minutes for Scenario 2, and 16 minutes for Scenario 3. Comparison of velocity changes across scenarios reveals that larger breach volumes correspond to shorter acceleration phases and faster velocity decline after peaking. The maximum velocities for Scenarios 1 through 3 are 11.2 m/s, 9.3 m/s, and 12.1 m/s respectively.

The flow depth distribution during the entire breach process is shown in Figure 5 [Figure 5: see original paper]. Approximately 60 minutes after breach, the accumulation range of breach material no longer changes. Breach volume and topography significantly influence flow depth—larger breach volumes and narrower flow terrain result in greater flow depths.

5.1 Tailings Pond Dam Breach Debris Flow Hazard Zoning

The flow depth distribution during breach fluid movement for Scenarios 1 through 3 is shown in Figure 5. The breach fluid exhibits distinct stage characteristics in flow depth: during the initiation stage (0-10 min), no obvious flow depth distribution forms; during the development stage (10-20 min), the debris flow approaches the proposed bridge alignment with significantly increased flow depths at all locations, exceeding 10 m maximum and covering the entire valley mouth; after 40 minutes, the dissipation stage begins with gradual flow depth decay at all locations, with relatively large flow depths remaining only in river channels.

The bridge location downstream of the tailings pond has an elevation of 4465 m, seismic acceleration of 0.2g, total length of 895.474 m, maximum pier height of 43 m, average pier height of 33.4 m, and is designed with steel-concrete composite girders. The design deck elevation is 4590 m. Simulation results indicate a maximum debris flow depth of 10 m, and the bridge clearance height meets requirements.

The hazard degree of breach debris flow is expressed as:

$$H = \frac{\rho v^2 h}{2}$$

where H is hazard degree, ρ is debris flow density (kg/m^3), v is debris flow velocity (m/s), and h is debris flow depth (m).

Substituting calculation results into the formula and performing normalization, the natural breaks method is used to classify debris flow kinetic energy, dividing affected areas into four hazard levels: very low, low, medium, and high.

As shown in Figure 6 [Figure 6: see original paper], in Scenario 1, 435.7 m on the left side of the proposed bridge alignment lies within the risk zone, with a high-risk area length of 55.95 m and medium-risk area length of 35.78 m. In Scenario 2, 199.7 m on the left side lies within the risk zone, with high-risk and medium-risk area lengths of 49.51 m and 24.29 m respectively. In Scenario 3, 544.93 m on the left side lies within the risk zone, with high-risk area length of 48.87 m and medium-risk area length of 53.85 m.

The pier shape coefficient is taken as 1.0. The calculation method for large boulder impact force in breach fluid references the impact force formula for piers in the "Specification for Investigation of Debris Flow Disaster Prevention Engineering (Trial)" (T/CAGHP 006-2018):

where F is boulder impact force (N), γ is kinetic energy reduction coefficient (taken as $\gamma = 0.3$ for circular-end frontal impact), V is boulder velocity (m/s), C_1 and C_2 are elastic deformation coefficients (taken as $C_1 + C_2 = 0.005$ for boulders and piers), and W is boulder mass (kg).

According to dam material requirements, a 0.5 m diameter sphere is used for large boulder impact force calculations. With an average boulder density of 2650 kg/m^3, the boulder mass is approximately 173.5 kg. The final calculated distribution of total debris flow impact force and boulder impact force along the proposed bridge alignment for breach Scenarios 1-3 is shown in Figure 7 [Figure 7: see original paper].

5.2 Bridge Engineering Risk Assessment

The vulnerability of the proposed bridge engineering under debris flow action is simultaneously influenced by the bridge failure mode, debris flow characteristics, and bridge parameters. According to tailings pond design data, 79% of full tailings particles are smaller than 0.074 mm, indicating high clay content in the solid material forming the breach fluid. The total impact pressure calculation method references the empirical formula in the "Specification for Investigation of Debris Flow Disaster Prevention Engineering (Trial)" (T/CAGHP 006-2018):

where δ is total debris flow impact pressure (Pa), γ_c is debris flow unit weight (kN/m^3), v is debris flow velocity (m/s), α is the angle between the structure surface and debris flow impact pressure (°), and λ is structure shape coefficient.

The maximum debris flow impact pressures for breach Scenarios 1-3 are 79.21 kPa, 46.21 kPa, and 117.44 kPa respectively, with maximum boulder impact forces of 37.99 kN, 29.02 kN, and 46.27 kN.

The empirical formula for debris flow scour depth calculation in the specification is:

where H_B is local scour depth (m), P is scour coefficient (taken as 1 per specification), H_c is debris flow depth (m), K is debris flow average velocity increase coefficient (taken as 2.016 for 65% mass fraction per specification), V_c is debris flow velocity (m/s), V_H is non-scouring velocity for soil (taken as 1.5 m/s based on field investigation), and n is a coefficient related to bank plane shape (taken as 1/4). The maximum scour depth under full storage conditions is 2.65 m (Table 4).

Conclusions

Based on a tailings pond and proposed bridge project in an alpine region of Xinjiang, this study employs the HEC-RAS system to simulate the tailings pond breach process, investigates the movement process of breach fluid, performs hazard zoning of the breach area, and conducts risk assessment of the downstream bridge. The following conclusions are obtained:

(1) Elevation and topography are the primary controlling factors influencing breach fluid kinematic characteristics. The "narrow-pipe effect" produced by U-shaped valley terrain in alpine regions constrains fluid diffusion, causing rapid increases in breach fluid velocity. Water source analysis for alpine region dam breaches should consider combined effects of rainstorms, glacial meltwater, and debris flows.

(2) Total tailings discharge volume is positively correlated with breach peak discharge, flow velocity, and flow depth. The breach process exhibits abruptness and high-energy characteristics with short peak flow duration. Under full storage capacity breach conditions, debris flow velocity reaches a maximum of 12.1 m/s during transport, with maximum flow depth reaching 10 m. At the proposed bridge alignment, maximum velocity is 8.82 m/s and maximum flow depth is 7.787 m.

(3) Under full tailings pond breach conditions, 535.79 m on the left side of the proposed bridge alignment lies within the risk zone, with 43.3 m passing through high-risk areas and 48.66 m through medium-risk areas.

(4) Damage to bridges from breach fluid mainly manifests as pier impact and scour. Provided the bridge clearance meets code requirements, it is recommended that total pier impact pressure, boulder impact pressure, and scour depth be adopted as core indicators for bridge risk assessment.

References

[2] Bowker L N, Chambers D M. In the dark shadow of the supercycle tailings failure risk & public liability reach all time highs[J]. Environments, 2017, 4(4): 75-76.

[3] Zhang Jiarong, Liu Jianlin. Statistical analysis and causation study of tailings dam failures and leaks in China[J]. China Molybdenum Industry, 2019, 43(04): 10-14.

[4] Duan Weiqiang, Cui Shixin. Analysis and research on safety evaluation methods for a certain upstream tailings dam[J]. Geology and Exploration, 2014, 50(4): 783-788.

[5] Zhang Chao, Yang Chunhe, Kong Lingwei. Study on mechanical properties and stability analysis of tailings sand from a copper mine[J]. Rock and Soil Mechanics, 2003, 24(5): 858-862.

[6] Wu T, Qin J. Experimental study of a tailings impoundment failure overtopping[J]. Mine Water Environment, 2018, 37(2): 272-280.

[7] Pudasaini, Shiva P. Hajra, Sayonita Ghosh, Kandel, Santosh, et al. Analytical solutions to a nonlinear diffusion-advection equation[J]. Zeitschrift Angewandte Mathematik und Physik, 2018, 69 (6): 1-20.

[8] Ruan Dexiu, Hu Jianhua, Zhou Keping, et al. Simulation of tailings dam failure disaster based on coupling of FLO(2D) and 3DMine[J]. China Safety Science Journal, 2012, 22(08): 150-156.

[9] Lin Shuiquan. Study on overtopping failure process and post-failure impact of tailings dam based on SPH method[D]. Kunming University of Science and Technology.

[10] Guangjin Wang, Sen Tian, Bin Hu, et al. Evolution pattern of tailings flow from dam failure and the buffering effect of debris blocking dams[J]. Water, 2019, 11(11): 2388.

Note: Figure translations are in progress. See original paper for figures.