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Seismic Permanent Deformation and Stability Analysis of Tailings Dams Considering Liquefaction Effects

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Abstract: Taking the Jiutiaogou Tailings Pond as the research background, the time-history analysis method combined with the equivalent viscoelastic model are adopted to analyze the seismic performance of the tailings dam during the heightening and expansion process from three aspects: permanent deformation prediction, liquefaction potential, and overall stability. The numerical simulation results show that the liquefaction potential zone develops toward the shallow phreatic line area with the increase of dam height, forming a new weak zone; the residual deformation concentrates in the dam crest area, which affects the overall stability. It is suggested that comprehensive treatment measures combining construction process control and soil engineering improvement should be adopted to improve the dynamic overall stability of the heightened tailings dam.

Keywords: Tailings dam; Dynamic response; Liquefaction potential; Overall stability; Heightening and capacity expansion

1. Introduction

Tailings dams play a crucial role in mining by storing waste and preventing environ-mental contamination. Composed of granular materials and exposed to complex depositional conditions and prolonged dynamic loading, its stability is a major concern. Under seismic activity, dynamic responses often trigger increased deformation, elevated pore water pressure, material liquefaction, and potential overall failure, endangering both operational safety and the ecosystem [1]. Consequently, investigating the liquefaction mechanisms, and stability limits of tailings dams under earthquake conditions represents a key research focus in geotechnical engineering.

At present, research focuses on the deformation of tailings dams under dynamic conditions, the development of cumulative plastic strain in tailings sand under cyclic loading, dynamic constitutive relationships, the prediction of permanent displacement and the mechanism of effective stress loss of saturated tailings materials [2-4]. At the level of dynamic stability analysis and evaluation of tailings ponds, scholars [5~9] revealed the critical state and progressive failure process of dam slope instability.

Based on the engineering background of the Jiutiaogou Tailings Pond, this paper focuses on the dynamic stability problem of the tailings dam during the heightening and capacity expansion process, and studies the evolution laws of the effects of seismic action on the dam's dynamic response, liquefaction potential and overall stability at different heightening stages, aiming to provide theoretical basis and technical reference for the stepped heightening design and safety control of similar tailings dams.

2. Dynamic Stability Analysis Methods

2.1 Dynamic Time-History Analysis

The time-history analysis method was adopted for the dynamic analysis. Following the static simulation of the dam's formation, the earthquake event was introduced and its duration was discretized into 10 intervals. For each interval, the dynamic equilibrium equation was solved using the Wilson-θ step-by-step integration method with a time step of 0.02 seconds.

At the end of each dynamic interval, key parameters—including acceleration, dynamic stress, and dynamic strain—were computed. Empirical formulas were subsequently applied to derive residual strain and shear strain increments. The strain increments were then introduced as initial strains into a static analysis based on Biot's consolidation theory, which was performed to update the deformation and pore water pressure fields. The procedure cycled sequentially through all time intervals until the full earthquake duration was simulated.

The following two equations are used in the dynamic calculation to determine the dynamic shear modulus G and damping ratio λ:

$$G = \frac{k_2(\sigma_m)^{0.5}}{1 + k_1(\gamma_d)^{0.75}(\sigma_m)^{-0.5}} \tag{1}$$

$$\lambda = \lambda \frac{k_1(\gamma_d)^{0.75}(\sigma_m)^{-0.5}}{1 + k_1(\gamma_d)^{0.75}(\sigma_m)^{-0.5}}_{max} \tag{2}$$

Where$\sigma_m = \frac{1}{2}(\sigma_1 + \sigma_3)$, γ_d is the dynamic shear strain amplitude, k_1, k_2 are dynamic shear modulus parameters, and λ_{max} is the maximum damping ratio.

The empirical formulas are used to calculate residual volumetric strain increment and shear strain increment:

$$\Delta\varepsilon_v = c_1(\gamma_d)^{c_2} exp(-c_3R_f^2S_l^2)\frac{\Delta N_L}{1 + N_L} \tag{3}$$

$$\Delta\gamma_s = c_4(\gamma_d)^{c_5}R_f^2S_l\frac{\Delta N_L}{1 + N_L} \tag{4}$$

Where ΔNL and NL are the equivalent vibration count increment and its cumulative value, respectively C_1, C_2, C_3, C_4 and C_5 are calculation parameters derived from residual deformation tests, specifically from the relationship curves between axial strain and vibration count, and volumetric strain and vibration count under different stress states.

The seismic pore water pressure is calculated as follows:

$$\Delta u = K_u\Delta\varepsilon_v \tag{5}$$

$$K_u = k_uP_a\left(\frac{\sigma_m}{P_a}\right)^n \tag{6}$$

Where K_u is the rebound bulk modulus and k_u is the rebound modulus parameter.

2.2 Dynamic Stability Analysis

Dynamic finite element method for anti-sliding stability analysis is conducted using a stepwise search method based on static and dynamic calculations. This method performs dynamic stability calculations for the dam body at each moment during the earthquake. The safety factor is calculated using the formula:

$$F_s = \frac{\sum_1^n[(c'_d)_i l_i] + \sum_1^n[(\sigma^j + \sigma^d)_i l_i](tg\phi'_d)_i}{\sum_1^n[(\tau^{\ j} + \tau^d)_i l_i]} \tag{7}$$

Where $(c'_d)_i$ and $(\phi'_d)_i$ are the dynamic shear strength parameters of element i intersected by the sliding surface, and n is the total number of such elements. The length of the sliding arc within element i is l_i. The static normal and shear stresses on the sliding surface are σ^j and τ^j, respectively, while the corresponding dynamic stresses are σ^d and τ^d.

3. Dynamic Stability Analysis of the Tailings Dam

3.1 Finite Element Calculation Model

The studied tailings dam is situated in Yangba Village, Gansu Province, within a seismic zone with a peak ground acceleration of 0.20g. With a starter dam crest elevation of 1622.0 m and a final design elevation of 1672.0 m, the total dam height is 94 m, classifying the tailings pond as Grade III. Upon reaching the starter dam crest elevation, the embankment is raised using the upstream method at a 1:5.0 outer slope ratio. The foundation consists of gravelly soil, strongly weathered sandstone, moderately weathered sandstone, and slightly weathered sandstone.

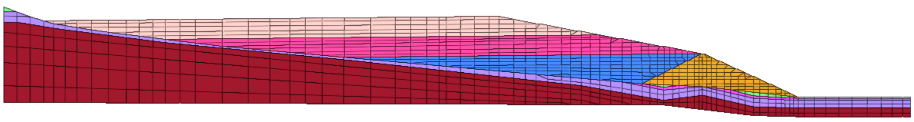


Figure 1: Element Mesh of the Tailings Pond Mode.

Table 1: Dynamic Calculation Parameters.

Material	k_2	λmax	k_1	n	c_1(%)	c_2	c_3	c_4(%)	c_5
Dam Rockfill	1300	0.22	22	0.44	0.62	0.57	0	6.7	0.77

3.2 Project Overview Finite Element Seismic Wave Input

The seismic design intensity for the area is degree VIII, corresponding to a peak ground acceleration of 0.20g. A synthetic seismic wave was generated for analysis, with the vertical acceleration set to 2/3 of the horizontal component. The wave, input at the bedrock level, has a total duration of 40 s and a time step of 0.02 s. The finite element mesh of the cross-section is shown in Figure 2.

a) Code-specified Design Response Spectrum b) Time-history Curve

Figure 2: Artificial Seismic Wave for Calculation.

4. Analysis of Numerical Simulation Results for Dynamic Stability

4.1 Project Overview Residual Deformation Analysis of the Tailings Pond

Figure 3 shows the permanent deformation distribution of the tailings dam at different stages. Calculation results show that the earthquake-induced deformation of the embankment dam is significant. For the final-stage embankment under normal operating conditions subjected to an earthquake, the maximum seismic settlement of the tailings dam is 36.0 cm, occurring at the dam crest. The maximum horizontal permanent displacement is 27.5 cm, occurring near the two-thirds height of the downstream face.

Horizontal Direction Vertical Direction

(a) Permanent Deformation for First-stage Embankment (cm)

Horizontal Direction Vertical Direction

(b) Permanent Deformation for Intermediate-stage Embankment

Horizontal Direction Vertical Direction

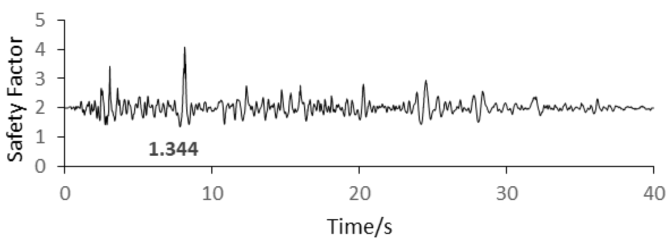
(c) Permanent Deformation for Final-stage Embankment

Figure 3: Permanent Deformation Distribution of the Tailings Embankment Dam (cm).

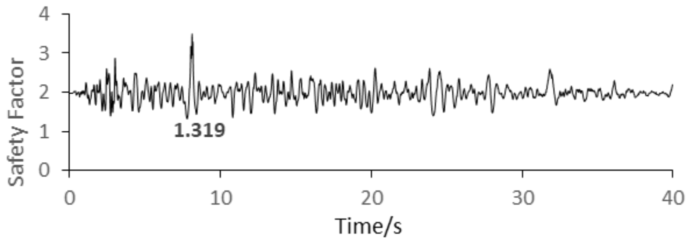
4.3 Stability Analysis of the Liquefaction Zone

Figure 5 presents the time-history of the anti-sliding stability safety factor for the downstream slope of the first-stage, intermediate-stage, and final-stage embankments under special operating conditions. The minimum stability safety factors for the downstream slopes of the first-stage, intermediate-stage, and final-stage embankments are 1.344, 1.319, and 1.287, respectively.

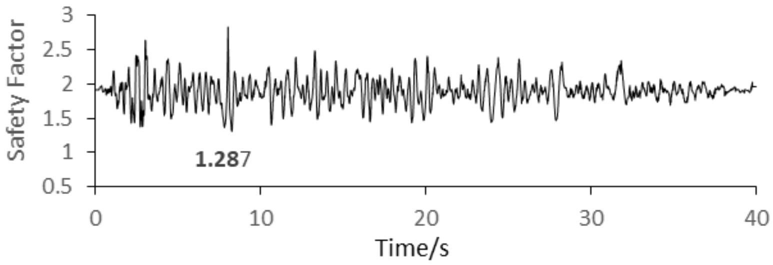
The minimum safety factors for the dam slopes are all greater than 1, indicating sufficient safety margin for slope stability. Figure 6 shows the locations of the most critical slip arcs for the dam slopes at final-stage stages.



(a) First-stage Embankment



(b) Intermediate-stage Embankment



(c) Final-stage Embankment

Figure 5: Time-history of Anti-sliding Stability Safety Factor for the Downstream Slope.

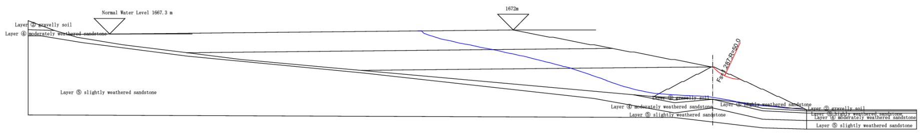


Figure 6: Locations of the Most Critical Slip Arcs for the Final-stage Embankment Dam Slope.

5. Conclusions

The cumulative seismic residual deformation is positively correlated with dam height, and its spatial distribution is concentrated in the dam crest region. This phenomenon highlights the dam crest area as a dynamic weak zone, necessitating enhanced construction quality control to prevent excessive deformation-induced cracking.

The spatial distribution of the liquefaction zone undergoes dynamic migration as the dam height increases, reflecting the relationship between pore water pressure accumulation and changes in soil confinement conditions. Close attention should be paid to the adverse effects of newly developed liquefaction zones on the overall stability of the dam.

Liquefaction zones are primarily distributed in areas of the embankment dam with shallow phreatic lines. A synergistic treatment approach combining compaction control, rate regulation, and soil improvement is recommended to increase material relative density. By suppressing liquefaction development, comprehensive dynamic stability of the dam body can be enhanced.

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