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Safety Assessment of a Tailings Pond: A Case Study in China

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Abstract: Located in northwestern China, Qijiagou tailings pond is examined in this study. Since tailings pond is the fillings of tailings, physical properties of material in tailings pond are determined utilizing in-situ testing and laboratory experimentation. Geo-Slope software is employed to establish a simplified two-dimension model of the tailings pond and to analyze the seepage flow field. Static stability is evaluated with the limit equilibrium method while the equivalent linear method is applied to determine time-history response of the system. Calculated results reveal the dry beach length is reduced from 200m to 90m and the phreatic line rises by 2-3m in the design flood. Partial liquefaction occurs in the zone from water edge to the water reservoir tip while maximum liquefaction depth is approximately 15m under water level. The safety factor of tailings pond varies with seismic time process and the minimum safety factor is 1.5.

Keywords: *tailings pond, safety assessment, stability, dynamic response, liquefaction*

1. Introduction:

Rich in mineral resources, China generates 300 million tons of tailings waste from metal and nonmetal mines following extraction each year. Tailings waste is typically stored in ponds located behind the tailings dams which is a hydraulic fill dam consist of tailings deposit. A small portion of the tailings waste is utilized for underground filling or comprehensive utilization such as tailings reelection and reclamation; in addition tailings waste can also be used as building materials. Tailings ponds store waste from metal and nonmetal mines and are established by building a dam at the mouth of a valley or a compound in plain areas. The tailings dam is a periphery structure that includes a starter dam and embankment and is utilized for storing tailings waste and water. The starter dam may be an impermeable clay dam or a permeable heap stone dam for tailings storage in the initial stage of mining. The embankment is composed of tailings and has the same function as starter dam in the middle-late stages. Currently 12600 tailings ponds exist in China and store 7 billion tons of tailings waste from metal and nonmetal mines [1]. Tailings ponds are hazardous sources with harmful substance contents including heavy metal ions and chemicals. Catastrophic dam failure may potentially result in debris flow of tailings waste surging downstream and threatening financial loss, ecological damage and even bodily injury [2-4]. The first dam failure occurred in 1962 as a result of the steep slope and saturation at the Huogudu tailings pond, Yunnan Province, China. It is steep slope and saturated dam that is to be blamed. The accident resulted in 171 human deaths, 92 injuries and damage to 5.4 million square meters of farmlands. Another serious accident occurred in 2008 in Shanxi Province as a consequence of exceeding pond capacity with 281 deaths and 33 injuries resulting[5].Tailings ponds safety assessments for preventative actions are obviously vital as catastrophic consequences resulting from hidden dangers can be sudden and extensive.

2. Overview of Qijiagou Tailings Pond:

The Changba Lead-Zinc Mine, located in Cheng County in Gansu Province features a combined mining and processing capacity of 1.5 million tons annually. Qijiagou tailings pond operates as the primary depository for the tailings discharge of this mine.

2.1 Geological and Climate Conditions:

Qijiagou tailings pond (Fig. 1 and 2)is situated in southwestern portions of the Qinling Mountains where vegetation heavily covers steep terrain. Natural slope angle of the area is between 30°and 45° with surface strata consisting of quaternary overburden with a thickness of 1-3m and moderately weathered quartzite bedrock. The main gully of Qijiagou tailings pond is a symmetrical V-valley with the valley floor varying from 17-51m wide. The average gradient is 0.223, with a length of 1.39km and a catchment area of 1.176km^2. Additionally, the seismic magnitude is Ⅷ degree in this region.

The Cheng County region is characterized by a temperate continental climate with mild weather and moist air. Average numbers of annual rain days are 117 with an average annual rainfall of 727.7mm. Maximum daily rainfall quantity is 201.2 mm with an average maximum day rainfall quantity of 79 mm. The annual average temperature is 11.9℃ and maximum depth of frozen ground is 600mm.

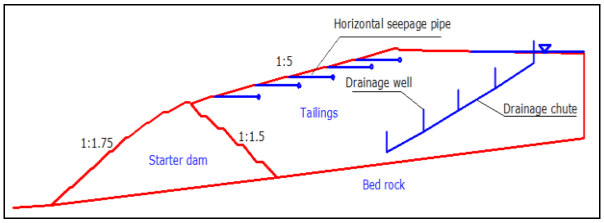


Fig. 1 *Section of Qijiagou tailings pond*

Fig. 2 *The plan of Qijiagou tailings pond (From Google Earth)*

2.2 Tailings Dam:

The Qijiagou tailings pond, tailings dam is composed of an embankment and permeable starter dam. The upstream embankment method characterized by embankment crest developing towards the upstream direction of starter dam, is applied for filling Qijiagou tailings pond. The tailings dam height is 135m with storage capacity reaching 18.6 million m3. The starter dam (Fig. 3) was built utilizing directional blasting and is a permeable rock-filled dam 80m in height with crest width of 4m.

The average slope ratio is 1:1.75 for free face and 1:1.5 for inner slope. The embankment (Fig. 4) is filled with tailings particles utilizing a hydraulic fill method and a multistage subdam system with 5m height differences between adjacent subdams. Average slope ratio is 1:5 for embankment with a flat slope surface covered by gravel soil. Reservoir water level in the tailings pond is 152m and the beach width from embankment crest to water boundary is 200m with a slope ratio of 1.0%.

Fig. 3 *Starter dam of Qijiagou tailings pond*

Fig. 4 *Embankment of Qijiagou tailings pond*

Table 1 Physical property of tailings particles

permeability coefficient K/cm·s^{-1}	min dry-density ρ_{min}/g·cm^{-3}	max dry-density ρ_{max}/g·cm^{-3}	plasticity index I_p/%	specific gravity G_s
5e-7	1..42	1.98	7.4	2.91

2.3 Properties of Tailings Particles:

Tailings ponds consist of tailings particles and water with properties of tailings particles contributing directly to pond stability. Characteristics of tailings particles were field tested utilizing the standard penetration test (Fig. 5) and laboratory tested utilizing the grain size analysis test(Fig. 6), density test, permeability test, and specific gravity test with results displayed in Table 1.

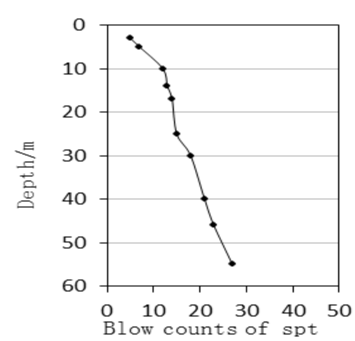


Fig. 5 *SPT test at different depths*

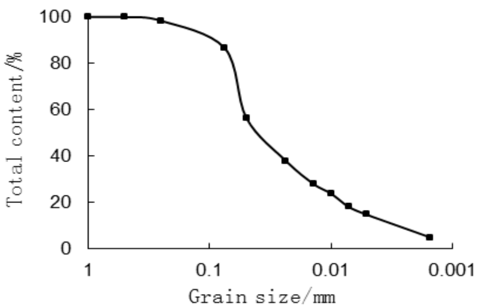


***Fig. 6** Grain size accumulation curve of tailings*

3. Safety Assessment of Tailings Ponds:

Tailings ponds are a fundamental component of mining infrastructure with locations typically near densely populated residential areas. Compromised dam structure, especially near populated zones, present potential for extraordinary consequences. Governmental monitoring related to tailings pond safety employs a series of measures to guarantee safe operations. Records provided by the United States Committee on Large Dams (USCOLD) and the United Nations Environment Programme (UNEP) in 2001 outlined 211 cases of tailings pond failure[6]. According to the survey records, the majority of accidents in tailings ponds resulted from flooding, earthquakes and slope instability [7]. The Chinese government, in response, has released the "Code for Design of Tailings Facilities" GB 50863-2013 for the unified management of tailings pond in China [8]. Calculation of flood control ability and slide-resisting stability are included in the code safety assessment. Flood control ability calculations are based on meteorological and hydrographic characteristics of the region and Qijiagou tailings pond flood drainage system. The stability calculation then has two components; static calculation and dynamic calculation, both based on analysis of the seepage field.

3.1 Flood Control Calculation:

Flood control calculations, based on the type and dimensions of the tailings pond flood releasing structure and a specific standard of design flood, determine flood control capacity. The standard of design flood depends on several factors with the frequency of flood control standard set at 0.2%. Factors also considered in design flood standards include; storage capacity, dam height, service life of tailings pond and conceivable hazard to the public and the ecological downstream environment.

3.1.1 Flood Calculation:

Maximal peak discharge of the tailings pond is calculated utilizing the simplified formula as follows:

$$Q_p = \frac{A(S_p F)^B}{(\frac{L}{mJ^{\frac{1}{3}}})^c} - D\mu F \quad (1)$$

The parameters are obtained from hydro-geological data of the tailings pond. Where Q_p is the design peak flood discharge rainfall intensity, m^3/s. S_p is the rainfall intensity rainfall intensity, mm/h. F is the catchment area of the reservoir, F=1.176km^2. L is the length of main channel in the reservoir, L=1.39km. m is convergence parameter of the reservoir, m=0.5. J is the slope of the reservoir, J= 0.223. μ is the average field infiltration rate during the period of rainfall, mm/h. A,B,C,D are factors to calculate maximum peak discharge, obtained by referencing the table.

$$\mu = (1-\alpha_{24})\frac{H_{24P}}{24} \quad (2)$$

$$H_{24P} = K_P \overline{H}_{24} \quad (3)$$

a_{24} is runoff coefficient for rainfall duration 24 hours, α_{24}=0.75.H_{24P} is the rainfall in 24 hours for frequency P. $\overline{H}_{24}$ is the average max annual rainfall, $\overline{H}_{24}$=79mm.K_P is the coefficient of modulus for frequency P,K_P=4.2.
In addition, total flood discharge is calculated according to the following formula:

$$W_{tP} = 1000\alpha_t H_{tP} F \quad (4)$$

Where W_{tP} is the total flood discharge during the period t for rainfall frequency P.

Fig. 7 represents the 500-year flood hydrograph and Table 2 illustrates the main parameters of flood calculation.

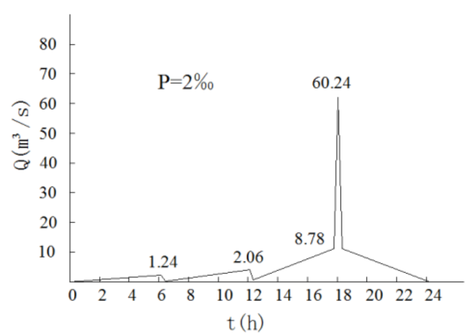


***Fig. 7** Flood hydrograph of design frequency P=2‰*

***Table 2** Calculation results of design flood*

Rainfall frequency	μ/mm.h^{-1}	S_p/mm.h^{-1}	Q_P/m^3.s^{-1}	H_{24P}/mm	W_{24P}/10^{4}m^3
p=2‰	3.456	105.68	46.57	331.8	29

3.1.2 Flood Routing

Tailings ponds provide two protective measures in flood control: flood storage and flood detention. Flood storage reduces peak flooding by impounding flood waters while flood detention operates by regulating dam capacity through pond water retention. When inflow is greater than discharge, a portion will be temporarily stored in the tailings pond and, following the peak flood, the tailings pond will be discharged gradually.

Tailings pond flood regulation capacity is determined according to the topographic map. When water level has slight discrepancy in elevation, the section of tailings pond can be treated as a trapezoid approximately, calculated by the following formula:

$$V=(S_1+S_2)\Delta H/2 \quad (5)$$

Where S_1 is the surface area of beginning water level and S_2 is the surface area of calculating water level. ΔH is the level difference between S_1 and S_2.

Flood routing is conducted based on the principle of water balance. In any period of time Δt the following formula is workable:

$$\frac{1}{2}(Q_s+Q_z)\Delta t-\frac{1}{2}(q_s+q_z)\Delta t=V_z-V_s \quad (6)$$

Where Q_s and Q_z represent the water amount that flows into the tailings pond at the beginning and end of the period time Δt, respectively, q_s and q_z represent the water amount that drained out of the tailings pond at the beginning and end of the time period, Δt, respectively. V_s and V_z denote the amount of water stored in the tailings pond at the beginning and end of the period, respectively.

According to the calculation, under condition of flood frequency P=2‰, Qijiagou tailings pond's reservoir capacity for flood control is 207,438 m^3 and the corresponding water level is 153.1m increasing 1.1m from 152m. The minimum free height is 1.9m with a beach width contraction from 200m to 90m. Calculations indicate the tailings pond's flood regulating ability satisfies the Chinese standard within the "Code for Design of Tailings Facilities".

3.2 Seepage Field Calculation

Stabililty of tailings pond slope is affected by seepage and is considered as a safety factor related to water pressure and dam height as interstitial flow occurs from a higher to a lower water head under water pressure **[9]**. The piezometric line represents constant water level in the cross section of a tailings pond and the phreatic line represents the steady seepage field. The phreatic line is also referred to as the tailings dam lifeline as the rise of groundwater level will lead to the increase of pore water pressure and ultimately to increased seepage force. A higher water level may increase instability and liquefaction possibilities of the tailings dam, thus the phreatic line consistently serves as a primary index in safety assessments for tailing ponds.

Fluid flow conforms to Darcy law in two-dimensional steady-state seepage field:

$$V_x=-K_x\frac{\partial H}{\partial x} \qquad V_y=-K_y\frac{\partial H}{\partial y} \quad (7)$$

Where, V_x, V_y represent seepage velocity in direction of x axis and y axis, respectively. K_x, K_y represent permeability coefficients in direction of x axis and y axis, respectively and H represents the hydraulic head.

Given the incompressibility of water and soil grains, the equation of continuity may be derived according to the Law of Conservation of Mass.

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial H}{\partial y}\right)+Q=0 \quad (8)$$

Where, Q is water gushing rate.

Hydraulic boundary condition:

$$H(x,y)|_{B1}=H_0(x,y) \quad K_n\frac{\partial H}{\partial n}|_{B2}=q(x,y) \quad (9)$$

Where n is the normal direction of the boundary. Formula (8) is the water head boundary condition and flux boundary condition, respectively.

Ground water flow in the Qijagou tailings pond is simulated utilizing Geo-Slope software. Calculating parameters from laboratory experiments are displayed in Table 1. Seepage field calculation results are illustrated by the following images under both normal conditions and flood conditions (Fig. 8 and 9). The phreatic line is approximately parallel to the slope in embankment while an abrupt decline occurs in the starter dam which is filled with rock and retains high permeabililty properties. The dry beach length will be reduced to 90m and the phreatic line will rise by 2-3 meters in flood.

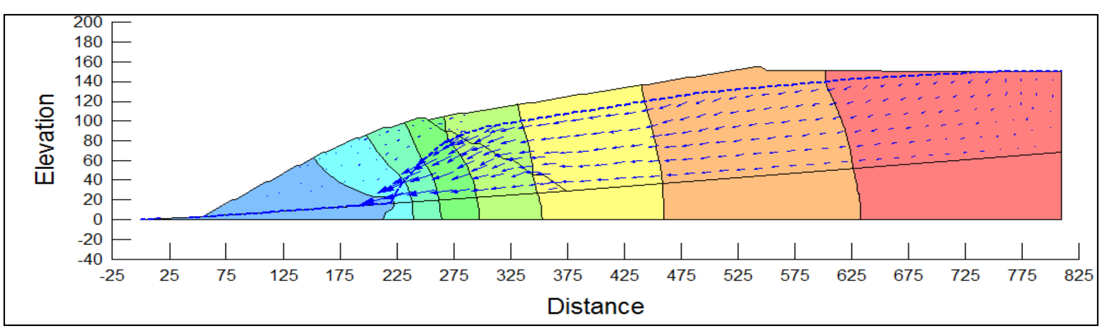


***Fig. 8** Seepage field of Qijiagou tailings pond in normal*

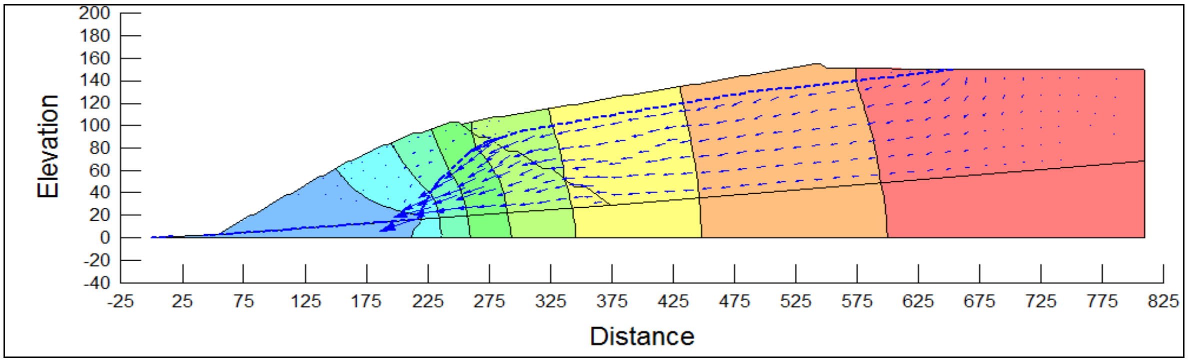


Fig. 9 *Seepage field of Qijiagou tailings pond in flood*

Table 3 *Mechanical properties of materials in Qijiagou tailings pond*

material	unit weight	saturated unit weight	permeability coefficient	cohesion	Angle of internal friction
	γ/KN·m^{-3}	γ_{sat}/KN·m^{-3}	K /m·s^{-1}	c'/kPa	ψ'/°
tailings	20.1	20	5.83E-6	28	5
starter dam	20.0	25	9.71E-3	35	70
bed rock	23.0	28	1.00E-11	40	500

Table 4 *Calculation results of static stability*

Working condition	slide surface location	safety factor	
		Bishop method	Swedish method
normal	starter dam	1.749	1.684
	embankment	2.737	2.521
flood	starter dam	1.749	1.684
	embankment	2.572	2.291

3.3 The Static Stability of Tailings Dam:

Analysis of the starter dam and embankment sites are conducted as tailings dam stability is calculated with the limit equilibrium theory which considers soil as a rigid body[10]. Simple Bishop and Sweden arc methods of limit equilibrium theory are applied to calculate the stability coefficients of slope. Soil property parameters are listed in Table 3 and safety factors are displayed in Table 4. Qijiagou tailings pond demonstrates sufficient stability under static conditions and the embankment safety factor is greater than the starter dam. A rise of the phreatic line will reduce security of the embankment while the safety factor of the starter dam remains unaffected as a result of a high permeability feature for the starter dam.

3.4 Dynamic Stability of Tailings Dam:

Basic seismic intensity is 8.0 degree in Qijiagou tailings pond area allowing for potential and serious earthquake hazards, thus analysis of seismic response and stability of the tailings pond is necessary[11]. When performing calculations, material characteristics especially constitutive relationship, must be known. The stress-strain relationship of tailings deposit typically features two characteristics: nonlinear and stagnant, described by two parameters: equivalent shear module G and equivalent damping ratio λ[12-13]. Tailings deposit materials are regarded as viscoelastic material in the equivalent-linear method for dynamic analysis of tailings pond, thus seismic response characteristics of tailings pond are studied utilizing the dynamic time-history method. Buildup and development of pore water pressure under dynamic load is a key factor in the deformation and strength behavior of soils. Growth of pore water pressure occurs with earthquake occurrence and when excess pore water pressure is equal to initial effective stress the soil will be liquefied[14-15].

The dynamic liquefaction resistance shear stress method is adopted as the criterion to determine whether the tailings deposit may be liquefied and in this method, seismic force and resistance of liquefaction are expressed as cyclic shear stresses. If seismic forces are greater than liquefaction resistance, excess pore water pressure will reach maximum value, leading to soil liquefaction[16]. Dynamic triaxial testing is conducted to determine the liquefaction resistance shear stress. Table 5 presents results of dynamic triaxial tests under confining pressure 100kPa. The number of cycles under earthquake intensity of Ⅷ is 30 based on Seed’s advice with the shear stress ratio of liquefaction at 0.285 for experimental results. Based on Mulilis’s research results, the experimental results should be corrected with a tailings’ shear stress ratio of liquefaction of 0.285*0.6=0.171, considering the differences between field and test conditions.

Table 5 *Results of cyclic triaxial tests*

dry density ρ_d/g·cm^{-3}	confining pressure σ_3/kPa	destruction cycles/*n*		
		12	20	30
1.70	100	0.355	0.316	0.285

A seismic acceleration time-history curve is required for dynamic response analyses, thus artificial seismic waves were utilized in this study[17]. The earthquake acceleration time-history curve is displayed in Fig. 10. Seismic forces act horizontally on the bottom of the tailings pond while the liquefaction zone occurs from the water edge to the water reservoir tip with a maximum liquefaction depth of approximately 15m under water level (Fig. 11). Minimum safety factor of the tailings pond is 1.5 (Fig. 12) and varies with the seismic time process.

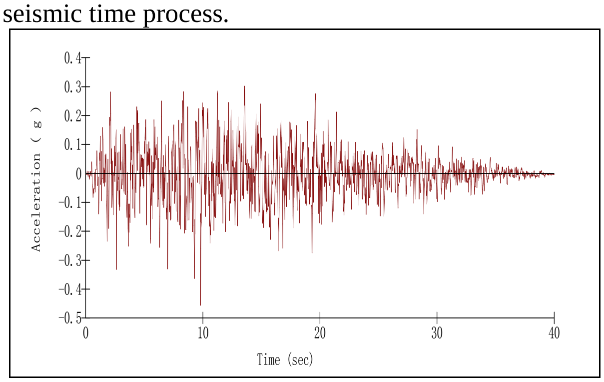
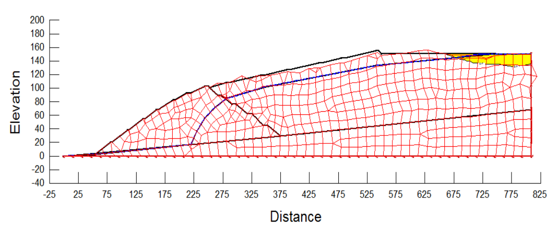
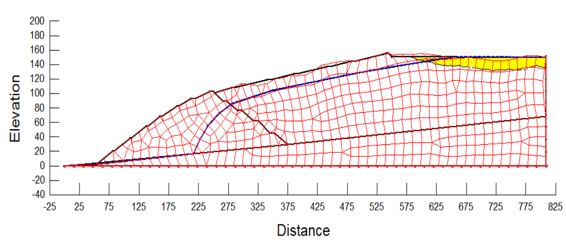


Fig. 10 *The acceleration-time curve obtained by artificial means*



(A) Normal working condition



(B) Flood working condition

Fig. 11 *The liquefaction area in different conditions*

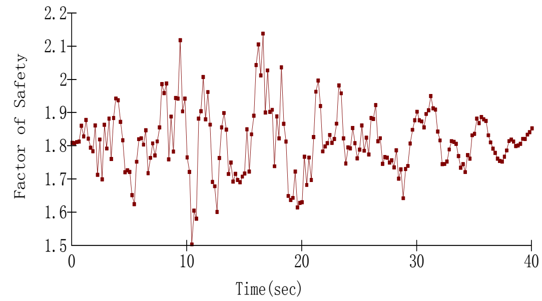


Fig. 12 *The time-history curve of safety factor*

4. Conclusion:

A safety assessment of Qijiagou tailings pond is conducted from four aspects in this study including, flood control calculation, seepage field calculation, the static stability of tailings dam and the dynamic stability of tailings dam. The analysis was conducted utilizing in-situ testing and laboratory experimentation. Dry beach length was determined, according to flood and seepage field calculations, to be reduced from 200m to 90m and the phreatic line determined to rise by 2-3m under 500-year flood conditions. Tailings pond safety requirements for stability can be met with a minimum safety factor of 1.684 for starter dam and 2.291 for embankment, both greater than minimum value 1.15 required by the “Code for Design of Tailings Facilities”. Qijiagou tailings pond is then considered stable under 500-year flood conditions. Under seismic action, liquefaction zones of the tailings pond is from water edge to the water reservoir tip while maximum liquefaction depth is approximately 15m under water level and minimum safety factor varies from 1.5 to 2.1with the seismic time process. Calculations then indicate Qijiagou tailings pond is safe whether under flood or seismic condition.

5. Acknowledgement:

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