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Using Numerical Simulation to Analyze the Stability of A Tailings Dam

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Abstract: ***In order to explore the influence of different strata on the stability of the tailings dam, this paper takes a tailings dam as the research object, uses the Bishop method and the Janebu method, and uses numerical simulation to study and analyze the stability of the tailings dam under three working conditions. The research results show that the tailings silt has the highest stability, the tailings medium sand is only relatively stable under normal working conditions, and the tailings fine sand, tailings sub-clay and tailings clay have poor stability.***

Keywords: Numerical Simulation, Tailings Formation, Dam Stability.

1. Introduction

Tailings ponds are places for stacking tailings. They are constructed by building dams to intercept valley mouths or enclosing land. They are man-made debris flow hazards. Once the dam body loses stability and collapses, it will not only damage the environment and cause property losses, but also endanger the lives of nearby residents. Therefore, the stability analysis of tailings ponds is of great significance, and many scholars have conducted relevant research. Liang Bing et al. proposed that the seepage field is the main influencing factor that induces the seepage stability of tailings dams. Strengthening the study of seepage stability of tailings dams is an important basis for ensuring the safety of tailings dams and is conducive to reducing the risk of tailings dam failure [1]. Deng Jinpeng et al., based on the numerical simulation of tailings pond failure and combined with the damage and sliding damage research in the field of debris flow, established a damage and sliding damage assessment model for downstream highway bridges caused by dam failure tailings and debris flow [2]. Tao Pengfei et al. conducted numerical simulation analysis of the current stability of closed tailings ponds to identify potential hazard sources of closed tailings ponds [3]. Chu Chengxin et al. used numerical calculation, flood control calculation, and debris flow warning value judgment model to establish a multi-hazard risk assessment system for tailings dams and carried out application [4]. Fu Botao et al. used GDEM-PDyna software based on the finite element and discrete element coupling method to construct a numerical model of debris flow fluid discharge evolution, carried out tailings dam breach evolution analysis, and dynamically simulated the movement law of mud and sand and the flooding range during the tailings dam breach [5]. Sun Hongchang et al. organically combined tailings dam stability and dam breach simulation, used FLAC3D to calculate the stability of tailings dams under three conditions: normal water level, flood level, and overtopping water level, and used Rhino and Fluent to establish the tailings dam and downstream fine terrain, and carried out research and analysis on the flow state of tailings dam breach water and sand at different times and different terrains [6]. Deng Hongwei et al. used 3Dmine and Midas/GTS software to establish a three-dimensional numerical model, and based on the seepage-stress coupling mechanism, studied the influence mechanism of dry beach length on the stability of tailings dam [7]. He Jinlong et al. used three different calculation methods in the limit equilibrium method: the Swedish arc method, the Bishop method and the Janbu method to calculate the stability of the tailings dam synchronously with the seepage [8].

This paper takes a tailings pond as the research object, uses the Seep/w module in Geostudio to analyze the seepage field, and then uses the Slope/w module combined with the limit equilibrium method to obtain the influence of different tailings strata on the stability coefficient of the dam under normal conditions, flood conditions, and special conditions (earthquake + flood).

2. Project Overview

The tailings pond is a valley-type tailings pond, which adopts upstream dam construction and is built in the downstream section of the valley. The initial dam of the tailings pond is a permeable rockfill body. The later sub-dam is gradually accumulated with the tailings production, forming an accumulation dam, and the dam is built by mechanical rolling method. The final accumulation elevation of the tailings pond is 180m, and the final dam height is 138m. It is a second-class tailings pond. The local rainfall season is from May to August, with an average annual rainfall of 1080mm. The seismic fortification intensity is VI, and the design basic earthquake acceleration is 0.05g.

3. Calculation Principle

3.1 Basic Theory of Stability Calculation

The stability assessment of tailings dams refers to the limit equilibrium method of slope calculation. The limit equilibrium theoretical methods involved in this article mainly include Bishop's method and Jane's method.

The most commonly used method is the simplified Bishop method. While meeting the basic assumptions, the simplified algorithm still has good calculation accuracy. The advantage of the Janbu method is that it can meet the two equilibrium conditions of force and moment, and is suitable for the stability analysis of sliding surfaces of any shape. The main difference between the above two sliding surface stability analysis methods is that they assume different shapes of sliding surfaces. The sliding surface shape of the Bishop method is an arc, while the sliding surface shape of the Janbu method can be any shape.

3.2 Matric Suction in Unsaturated Soils

Unsaturated soil is composed of soil particles and air and water filled between the particle skeletons. When soil particles and water interact, the soil particle matrix shows an affinity for water, that is, it absorbs water. In soil mechanics, this effect is called matrix suction, and the absorption effect of the solute in the solution on the soil water is called solute suction or seepage suction. Existing research results show that the solute suction in general soil is smaller than the matrix suction in terms of value and influence on the engineering properties of the soil, so the suction considered in soil mechanics generally refers to matrix suction.

3.3 Permeability Characteristics of Unsaturated Soil

The flow of water in the infiltration process of saturated soil obeys Darcy's law, and its permeability coefficient can be considered as a constant. When Darcy's law is applied to unsaturated soil, its permeability coefficient cannot be assumed to be a constant, but a function of the water content or matrix suction of the unsaturated soil. Generally, the permeability coefficient in unsaturated soil is affected by changes in both porosity and saturation. Generally, in the seepage analysis of unsaturated soil, it is assumed that the soil skeleton does not deform, so the pore volume in the soil can be considered to be unchanged or change very little, and the effect of pore volume on permeability coefficient can be ignored. At this time, the water content in the soil pores, or the saturation, is the main factor affecting the permeability coefficient.

The permeability coefficient of unsaturated soil can be determined directly or indirectly. Since direct measurement is often difficult to carry out, the indirect method is often used to calculate the permeability coefficient of unsaturated soil. Generally, the relationship curve between matrix suction and saturation or the soil-water characteristic curve is used to calculate the permeability coefficient.

3.4 Soil-water Characteristic Curve of Unsaturated Soil

The matrix suction or matrix potential of unsaturated soil is a function of soil water content. The relationship between soil water content (mass water content, volumetric water content or saturation) and matrix suction is defined as the soil-water characteristic curve. This curve reflects the relationship between the energy state of water in the soil and the amount of water in the soil under unsaturated conditions.

4. Numerical Modeling Solutions

4.1 Model Building

This paper mainly uses the Seep/w and Slope/w modules in Geostudio software to analyze the seepage characteristics and stability change characteristics of tailings dams.

The Seep/w module is mainly used to analyze steady-state and transient seepage problems. The user first defines the problem in the module, sets the grid properties, and inputs material parameters, soil-water characteristic curves, permeability coefficient functions, boundary conditions, rainfall parameters, etc. according to the problem. Finally, the seepage law is analyzed based on the change curves of volumetric water content, pore water pressure, etc. obtained by the software. The Slope/w module mainly analyzes the stability problems of different types of slopes based on the limit equilibrium theory. It can perform stability analysis based on the pore water pressure at each point, the seepage free surface, material parameters, etc. calculated by the Seep/w module [9].

Seep and Slope modules in Geostudio numerical software are used to simulate the seepage field under rainfall conditions and the corresponding stability analysis. The calculation process is shown in Figure 1.

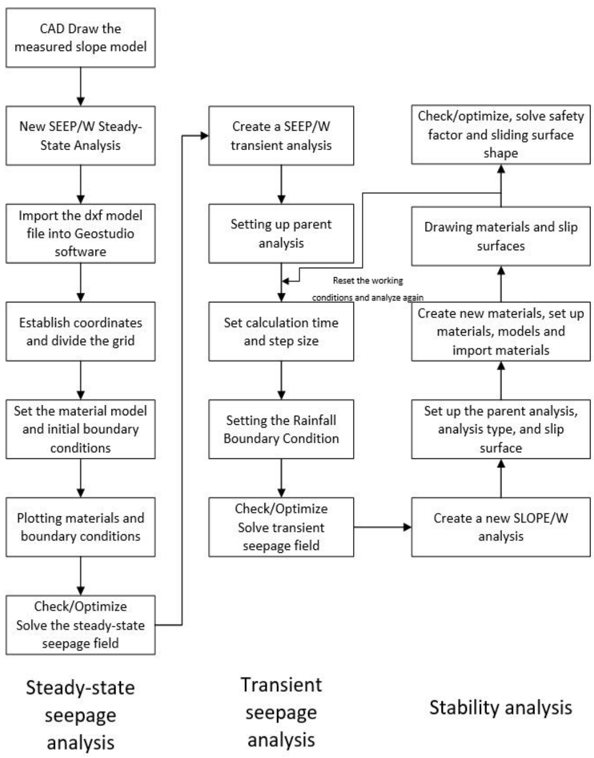

Figure 1: Calculation process

This paper takes the section of the study area with a net height of 160m, a length of 1650m, and a rockfill dam extending 45m downward as the research object, and draws the model section based on the key control points in the drilling data. To ensure the calculation accuracy, the unit size is relatively small, taking 1.0m. The soil layers in the tailings dam are tailings medium sand, tailings fine sand, tailings silt sand, tailings sub-clay, tailings clay, gravel soil and bedrock from top to bottom. The calculation model is shown in the Figure 1. Stability calculation parameters are shown in Table 1.

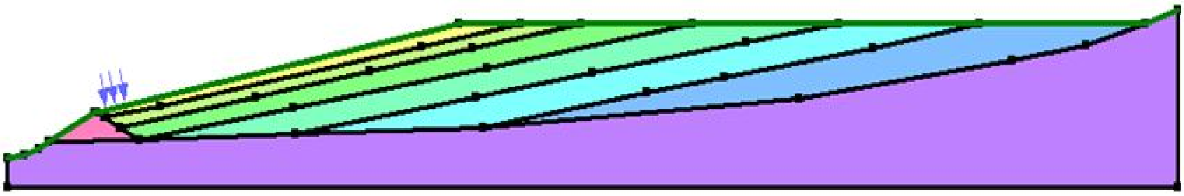

Figure 1: Tailings dam model

Table 1: Physical and Mechanical Indicators l of Original Soil Samples In Each Soil Layer

Soil layer	Layer number	Density	Natural bulk density	Saturated density	Shear strength (consolidation quick shear)			
			γ	γ sat	Natural state		Saturation	
			(KN/m³)	(KN/m³)	C (KPa)	φ (°)	C (KPa)	φ (°)
Rockfill dam	1	Dense	18	20	8	φ36	7	35
Gravel soil	2	Dense	19.7	22	15	28	11	24
Tailing Medium Sand	3	Slightly dense	19.7	22	0	30	0	26
Bedrock	4	—	22	24	18	38	16	35
Tailing Fine Sand	5	Loose	19	19.4	0	28	0	24
Tailing Silt Sand	6	Loose	18.5	18.8	4	25	1	22
Tailing Sub-clay	7	Flow Plasticity	18	18.5	8	20	6	14
Tailing Clay	8	Flow Plasticity	18	18.2	10	12	8	10

4.2 Working Conditions

This tailings dam is a secondary structure. When the Bishop method and Janbu method are used to calculate the minimum safety factor of the dam slope against sliding stability, the values are as follows according to the "Safety Design Code for Tailing Dams": 1.25 for normal operation; 1.15 for flood operation; and 1.05 for special operation. The stability of the tailings dam is studied and analyzed under three working conditions.

Normal working condition refers to the tailings pond operating under normal conditions, which is only affected by its own weight and the water in the tailings pond. Therefore, under normal working conditions, it is only necessary to calculate the infiltration line of the tailings pond during normal operation and the stability of the tailings pond body affected by its own weight.

Flood conditions refer to the impact of heavy rainfall on the reservoir area and the sudden increase in water level on the safe operation of the tailings pond based on normal conditions. The flood conditions refer to the impact of water level changes on the safe operation of the tailings pond based on the normal water level recorded in the reservoir area engineering survey report.

Special working conditions refer to the extreme conditions encountered during the operation of the tailings dam project. Here, the special working conditions are set to the stability of the tailings dam when it is simultaneously affected by earthquakes and floods.

5. Seepage Field Analysis

5.1 Treatment of Rainfall Intensity and Infiltration Intensity

Rainfall infiltration is an extremely complex process. On the one hand, rainfall itself is a process composed of many factors, such as rainfall intensity, rainfall duration, rainfall amount, rainfall type, etc. On the other hand, not all rainwater that falls on the surface can infiltrate into the soil. Part of the rainfall infiltrates into the ground through the surface, and a large part of it is lost as runoff on the surface.

According to the "Design Code for Tailings Facilities" (GB50863-2013), the instantaneous unit line method was used in this calculation, and the calculated 24-hour rainfall once in a thousand years was 402mm, and the peak flow Q was 23.16m3/s.

In this paper, the stability of soil under rainfall conditions is studied. The paper assumes that all rainfall infiltrates into the ground and uses rainfall intensity as the flow boundary water flow to calculate the infiltration rate. This assumption is used to conduct a preliminary finite element analysis of the stability of rainfall slopes.

5.2 Processing of Soil-Water Characteristic Curve and Permeability Coefficient Function

The soil layers in the tailings dam are mainly tailings medium sand, tailings fine sand, tailings silt sand, tailings sub-clay and tailings clay. When analyzing the seepage problem of saturated-unsaturated soil in seep/w, the water pressure properties of the soil are mainly considered. The selected material model is the saturated/unsaturated model. In the seep/w finite element analysis software, the sample function estimation method is used to estimate the functional relationship between the volumetric water content and the matrix suction by setting the saturated water content, that is, the soil-water characteristic curve. The soil-water characteristic curves of each soil layer are shown in the Figure 2.

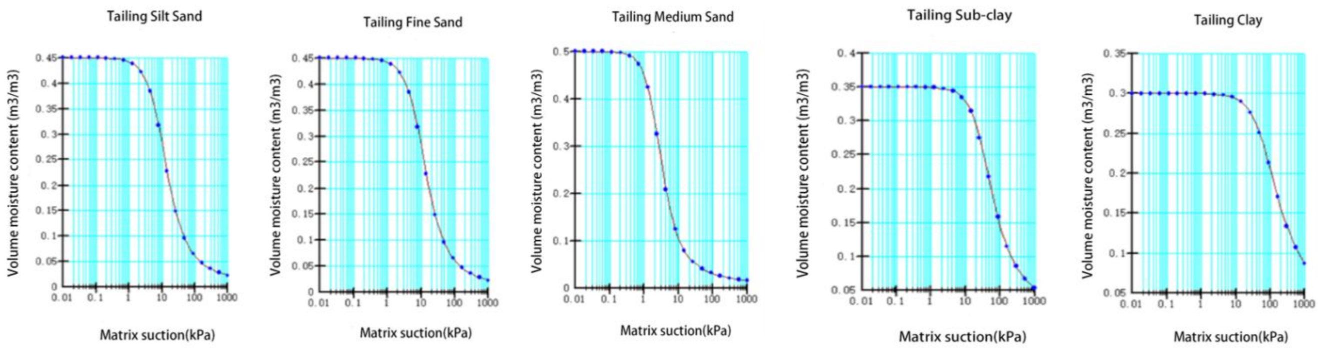

Figure 2: Soil and water characteristic curve

The permeability coefficient function is obtained from the soil-water characteristic curve. Seep/w finite element analysis software provides two calculation models to analyze and solve the permeability coefficient function of the soil-water characteristic curve. One is the Van Genuchten model and the other is the Fredlund and Xing model. This paper uses the Van Genuchten model to solve the analysis. When defining the permeability coefficient function, select the soil-water characteristic curve of the corresponding soil layer. The saturated permeability coefficient is provided by the measured data. The permeability coefficient function curves of each soil layer are shown in the Figure 3.

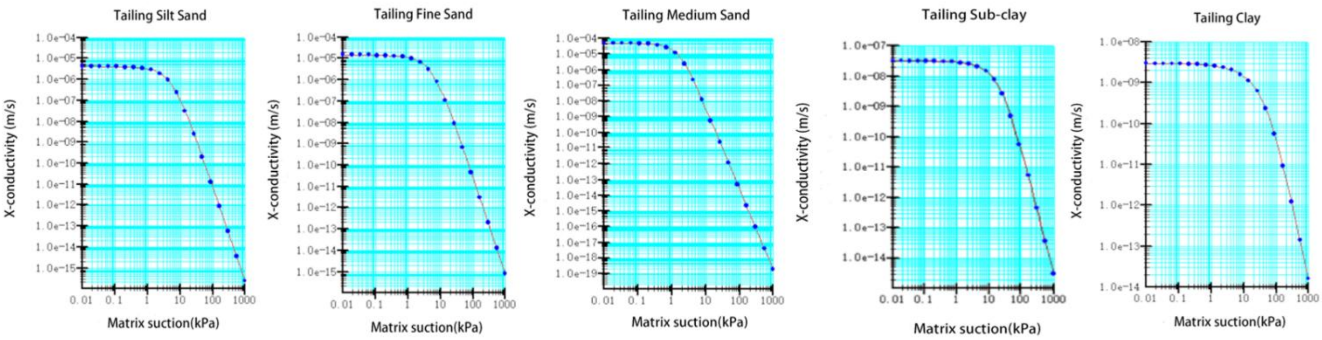

Figure 3: Permeability curve

5.3 Seepage Field Simulation

This dam is an earth-rock dam. During the analysis, it was considered that the dam was completely permeable. According to the design, drainage and flood discharge facilities were built on the foundation of the tailings pond. Its drainage system includes the initial dam drainage system and the accumulation dam slope drainage facilities. A cushion layer is set at the bottom of the upstream of the initial dam, and the accumulation dam is set up with a radial well plus a drainage pipe. The tailings pond adopts a flood discharge system of overflow tower-drainage pipe and dam shoulder interception ditch, and the No. 8 overflow tower in the reservoir is the main flood discharge facility.

Under natural working conditions, the materials of each part are assigned values on the established model, and the groundwater level is drawn according to the measured monitoring data. The bottom and right side of the model are impermeable boundaries, and the accumulation dam is a permeable boundary. Natural seepage simulation is carried out, the results are shown in Figure 4.

Under flood conditions, a certain total head boundary is set on the uppermost dam surface of the upstream dam body, and the free seepage surface is set on the outer surface of the dam body. After the setting is completed, the seepage analysis is carried out. The seepage calculation results are shown in Figure 5.

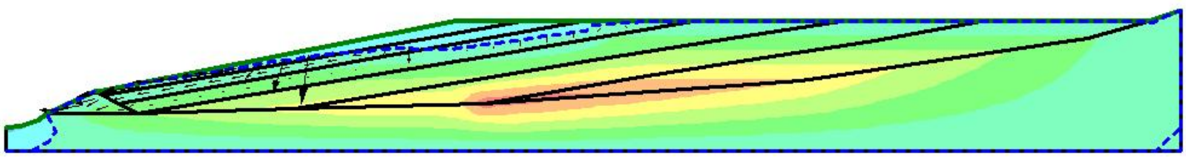

Figure 4: Pore water pressure distribution and seepage diagram under natural conditions

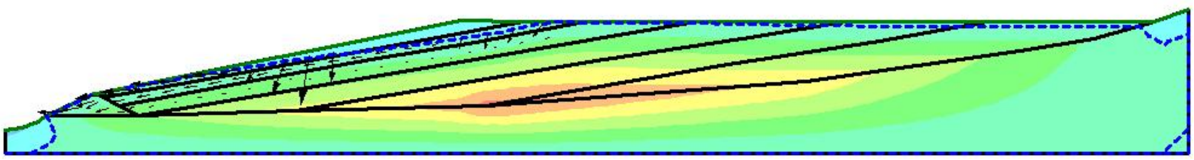

Figure 5: Pore water pressure distribution and seepage diagram under flood conditions

Based on the natural working conditions and flood working conditions, it can be seen that the pore water pressure is the largest at a depth of 100m below the top of the tailings dam. As the flood water level rises, the pore water pressure gradually increases, the pore water pressure in the bedrock is the smallest, and the water in the tailings dam is discharged along the slope to the rockfill dam. The infiltration water flow density at the rockfill dam is the largest. Therefore, the tailings dam is most susceptible to seepage damage near the rockfill dam.

6. Stability Analysis

6.1 Composite Formation Stability Calculation

The cohesion and internal friction angle of each soil layer under saturated conditions are selected as stability analysis parameters below the groundwater level, and the cohesion and internal friction angle of the natural state are selected above the groundwater level. Values are assigned to each soil layer, and after seepage analysis is performed using the seep/w module, stability calculations are performed under three working conditions.

1) Natural conditions

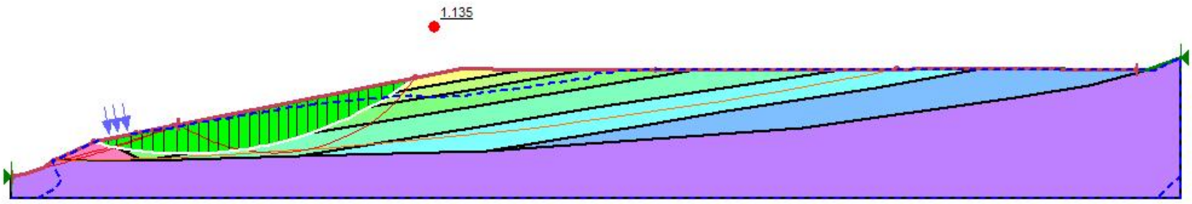

Figure 6: Stability of Bishop tailings dam under natural conditions

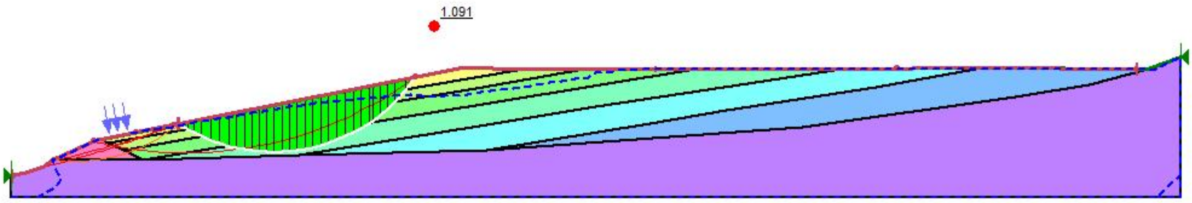

Figure 7: Stability of Janbu tailings dam under natural conditions

Under natural working conditions, the groundwater level of the tailings dam is stable, steady-state seepage occurs in the slope, and the pore water pressure remains constant. Figures 6 and 7 calculate the stability of the tailings dam according to the Bishop method and the Janbu method respectively. The critical sliding surface passes through the tailings medium sand, tailings fine sand and tailings silt sand, and the stability coefficients are 1.135 and 1.091 respectively, which are lower than the standard values and may cause instability and failure.

2) Flood conditions

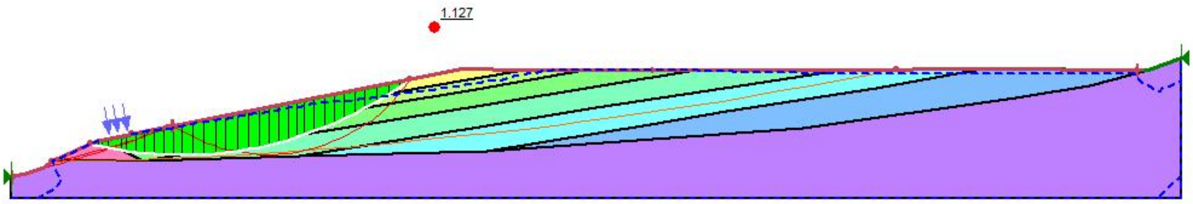

Figure 8: Stability of Bishop tailings dam under flood conditions

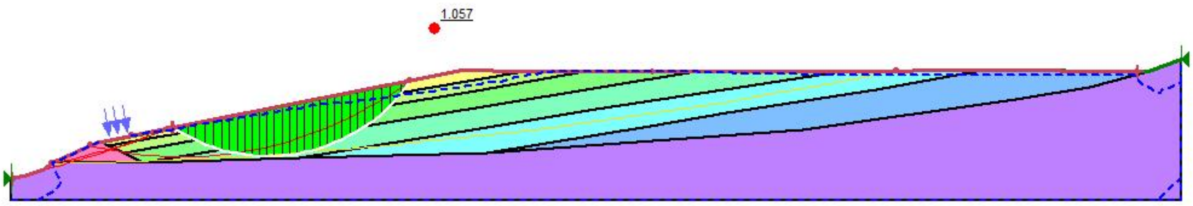

Figure 9: Stability of Janbu tailings dam under flood conditions

Under flood conditions, the groundwater level rises, the water content of the surface layer gradually increases, the pore water pressure increases, and the matrix suction decreases accordingly. Figures 8 and 9 calculate the stability of the tailings dam according to the Bishop method and the Janbu method respectively. The critical sliding surface passes through the tailings medium sand, tailings fine sand and tailings silt sand. The stability coefficients are 1.127 and 1.057 respectively, which are slightly lower than the stability coefficients under natural conditions and lower than the standard values. Instability and failure may occur.

3) Special working conditions

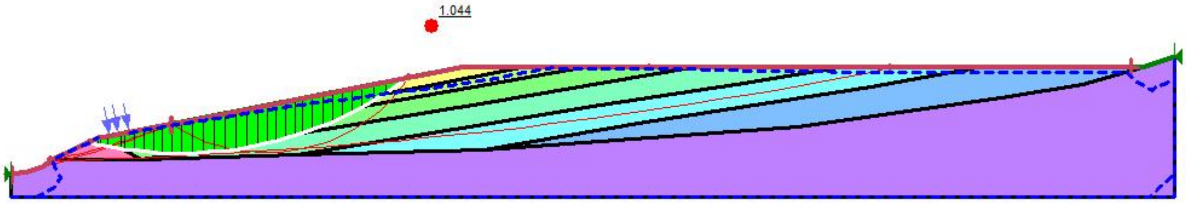

Figure 10: Stability of Bishop tailings dam under special conditions

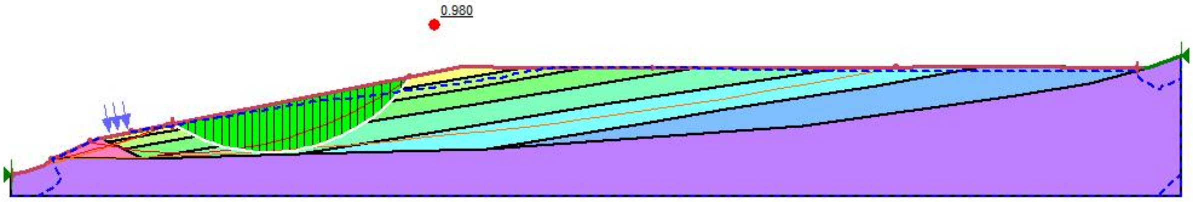

Figure 11: Stability of Janbu tailings dam under special conditions

The special working condition (flood + earthquake) is to add 0.05g earthquake acceleration to the flood working condition. The seepage path remains almost unchanged, but the tailings dam is more prone to instability under the horizontal earthquake acceleration. Figures 10 and 11 calculate the stability of the tailings dam according to the Bishop method and the Janbu method, respectively. The stability coefficients are 1.044 and 0.980, respectively, which are lower than the standard values and may cause instability and failure.

6.2 Single Formation Stability Calculation

When the tailings dam contains a single stratum (medium tailings sand, fine tailings sand, silt tailings sand, sub-clay tailings and clay tailings), the stability of the tailings dam under natural conditions, flood conditions and special conditions is calculated respectively. Taking silt tailings sand as an example, the calculation results are shown in Figures 12 and 13.

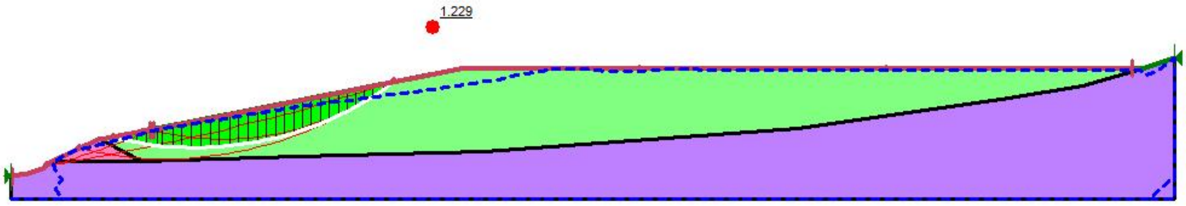

Figure 12: Stability of Bishop tailings silt sand under special working conditions

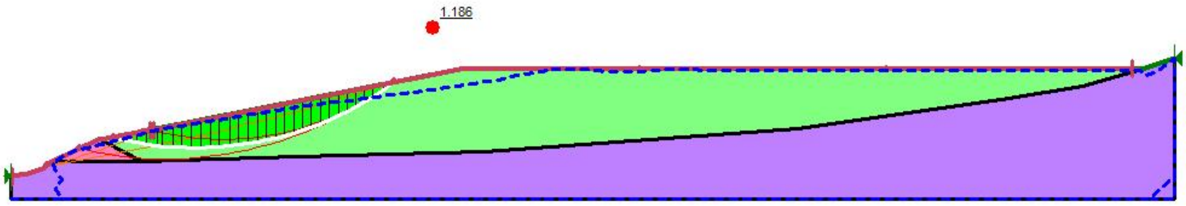

Figure 13: Stability of Janbu tailings silt sand under special working conditions

In the Figure, when the tailings dam is filled with tailings sand, under special working conditions, its cohesion is 1kpa, the internal friction angle is 22°, the tailings sand permeability coefficient is large, the pore water pressure dissipates quickly, and the stability coefficients are 1.229 and 1.186 respectively, which meet the design requirements.

According to this method, the safety factor of each working condition of the remaining soil layer is calculated respectively. The calculation results are shown in Table 2.

Table 2: Safety factor under different working conditions in a single formation

Strata	Operational status	Safety Factor(Fs)		
		Bishop Method	Janbu Method	Standard value
Tailing Medium Sand	Natural	1.269	1.266	1.25
	Flood	1.040	1.036	1.15
	Special	0.996	0.992	1.05
Tailing Fine Sand	Natural	1.216	1.212	1.25
	Flood	1.065	1.060	1.15
	Special	1.019	1.014	1.05
Tailing Silt Sand	Natural	1.335	1.290	1.25
	Flood	1.312	1.266	1.15
	Special	1.229	1.186	1.05
Tailing Sub-clay	Natural	0.854	0.826	1.25
	Flood	0.841	0.813	1.15
	Special	0.788	0.761	1.05
Tailing Clay	Natural	0.631	0.611	1.25
	Flood	0.630	0.609	1.15
	Special	0.590	0.571	1.05

As can be seen from the Table 2, the tailing silt sand has the highest stability and meets the specification requirements under the three working conditions; the tailing medium sand meets the specification requirements under natural working conditions, but does not meet the specification requirements under flood and special working conditions; the tailing fine sand, tailing sub-clay and tailing clay have poor stability and do not meet the specification requirements under the three working conditions, and the safety factors of tailing sub-clay and tailing clay are less than 1, which is in an unstable state. The reason is that tailing sub-clay and tailing clay have large disturbances, low cohesion and internal friction angle, and much lower shear strength than naturally deposited tailing clay and tailing sub-clay.

7. Conclusion

This paper takes Chengmendong tailings dam as the research object, introduces the basic characteristics of unsaturated soil, analyzes the saturated-unsaturated soil mechanical characteristics of tailings medium sand, tailings fine sand, tailings silt sand, tailings clay and tailings sub-clay, and obtains the soil-water characteristic curve and permeability characteristic curve of each soil layer. Through the seepage field analysis, the stability of different strata under natural conditions, flood conditions and special conditions is solved, and the main conclusions are as follows:

1) Rainfall infiltration causes the pore water pressure in the unsaturated soil to rise, and the matrix suction decreases or is lost, resulting in a decrease in the shear strength of the unsaturated soil, which in turn affects the stability of the slope and reduces its safety factor.

2) Under flood conditions, the seepage field flows downward along the slope, the density of seepage water flow is the largest at the rockfill dam, and the tailings dam is most susceptible to seepage damage near the rockfill dam.

3) The stability safety factors of the three working conditions in the composite strata are low and do not meet the standard design conditions. In addition, under special working conditions, the safety factor obtained by the Janbu method is less than 1, and the tailings dam will become unstable and collapse.

4) In the single formation stability analysis, tailing silt sand has the highest stability, followed by tailing medium sand, and tailing fine sand, tailing sub-clay and tailing clay have poor stability. Tailing sub-clay and tailing clay have large disturbance, low cohesion and internal friction angle, and much lower shear strength than naturally deposited tailing clay and tailing sub-clay.

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