Numerical Analysis of Stability of Tailings Dam in Cold Region under Freeze-Thaw Cycle

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Abstract: The reasonable design and treatment of tailings dams in cold region is an important embodiment of the implementation of China's strategy for sustainable development. The stability of tailings dams undergoing freeze-thaw(F-T) cycle is a key issue in minerals resource development in cold region. At present, the stability evaluation of tailings dam under an established state is mostly carried out to judge whether the dam is unstable or not, but the dynamic development law that can reasonably describe the stability of tailings dam has not been obtained. Based on FLAC3D, combined with the heat conduction theory considering the ice-water phase transition, the elastic-plastic constitutive model and the strength reduction method, a numerical analysis platform for the stability of tailings dams in cold region under the F-T cycle is established. The numerical simulation calculation under three operating conditions is carried out to obtain the variation rule of the thaw depth of the dam with time under different operating conditions and the SF of the dam under different F-T cycle. As the stress-strain state and safety factor of tailings materials are analyzed in real time, the development law and internal mechanism of the SF of tailings dam under the F-T cycle are identified.

Keywords: Frozen Soil; Tailing Dam; Freeze-Thaw Cycle; Safety Factor

1. Introduction

With about one-fourth of its land area covered by permafrost, China is the third-largest country in the world. Mineral resources are abundant in cold regions. In recent years, the scale of national development and utilization of mineral resources has gradually increased, accompanied by the production of a large number of tailings dams. Tailings is a kind of special soil, which is produced by ore dressing operation. The dam body formed by tailing accumulation is called tailing dam. Unlike tailings dams in general areas, tailings dams in cold regions are subject to the effects of F-T cycles, i.e., the void ratio, strength, compression modulus, and other physical and mechanical parameters of the tailings change under the action of F-T cycles, which affects the stability of tailings dams [1-3].

Engineers and academics have invested a lot of time and effort into studying the stability of tailings dams in conventional regions, and have obtained relatively mature tailings treatment methods. Shen et al. [4] studied the influence of tailings classification particle size selection on the safety and stability of tailings ponds, and clarified the technical path to obtain a scientific and reasonable tailings classification particle size value. Bhanbhro, R et al. [5]conducted triaxial tests on the different depths tailings of the dam. The results showed that depth had little effect on the strength and stiffness of tailings. Dedring, T et al. [6] proposed an empirical model for risk assessment that incorporates tailings-specific planimetric area regression and allows for risk assessment of dams by providing information on residents and buildings in the area affected by the dam.

Academics have also conducted some studies on tailings in cold regions. Liu et al. [7]conducted triaxial CU shear tests on tailings soils at Yunnan-Guizhou Plateau . It has been found that when the number of F-T cycles are increased, the mechanical properties of the tailing soil such as peak shear strength and elastic modulus decrease significantly. Zhang et al. [8]conducted undrained and unconsolidated tests on tailing sand under different initial conditions by using a high-low temperature alternatively changing testing-box and the strain controlled tri-axial apparatus. Under the same moisture content, the cohesion decreases with the number of F-T cycles and then stabilizes ,while the internal friction angle changes in the opposite direction. The effects of different number of F-T cycles on the physical and mechanical properties of tailings in cold regions were investigated by indoor F-T cycles by Ai, et al. [9] The open group specimens showed higher shear strength, cohesion, and internal friction angle with increasing cycles, while the sealed group specimens showed the opposite. Jin et al.[10]conducted the down-scale tailings dam model tests on a self-designed device under different freezing temperatures (-5,-25,-45 ℃).The test results show that: the internal stress of the dam increases with decrease of freezing temperature; the stress growth rate in the early stage of F-T cycle at each key position is higher than that at the other stages. The pore water pressure in the dam decreases with decrease of freezing temperature. The variation range, periodicity and regularity of pore pressure increases with the position depth of the dam.

There have been some studies on tailings dams in cold regions that have examined changes in physical and mechanical parameters under the action of F-T cycles, and mainly on the stability evaluation of dams under established thawing conditions or on the calculation of the critical conditions for keeping the dams stable under various operating conditions according to specific formulas, but in fact, the stability of the dam essentially changes dynamically with the continuous thawing of the permafrost layer before the dam destabilization damage occurs. Previous studies cannot reasonably describe the dynamic development process of the SF, so it is necessary to establish a theoretical method that can dynamically describe the development law of tailings dam stability during the thawing process. Therefore, based on FLAC3D , this study studies the development law of dam deformation and strength by establishing a numerical analysis platform for the stability of tailings dams in cold regions under F-T cycle, and then reasonably analyzes the influence of F-T cycle on the stability of tailings dams. This is of great importance for the management of tailings dams in cold regions and the prevention of dam failure disasters.

2. Stability Analysis Theory of Tailings Dam under F-T Cycle

A numerical analysis platform for the stability of tailings dams in cold regions is developed using the heat conduction theory, the elastoplastic constitutive model and the strength reduction method. To simplify the problem, the heat conduction equation considering the ice-water phase transition is used in this numerical simulation to determine the thawing and freezing zone of the dam and to derive the thawing depth under different operating conditions.

$$-h_{i'i}+h_v+\rho c\frac{\partial T}{\partial t}(h_i=-\lambda T_{'i}) \quad (1)$$

$$c=\begin{cases} c_u & (T>T_p) \\ c_f+\dfrac{c_u-c_f}{T_p-T_b}(T-T_b)+\dfrac{L}{1+W}\dfrac{\delta W_i}{\delta T} & (T_b\le T\le T_p) \\ c_f & (T\le T_b) \end{cases} \quad (2)$$

$$\lambda=\begin{cases} \lambda_u & (T>T_p) \\ \lambda_f+\dfrac{\lambda_u-\lambda_f}{T_p-T_b}(T-T_b) & (T_b\le T\le T_p) \\ \lambda_f & (T\le T_b) \end{cases} \quad (3)$$

where h_v is the fluid heat source(W/m3) and c is the equivalent specific heat ($J/kg{\cdot}°C$) considering the phase change. In Eq. (2), the way of taking equivalent specific heat c and the thermal conductivity λ are given, where cu is the specific heat of the thawed soil, cf is the specific heat of the frozen soil, λ_u and λ_f is the thermal conductivity of the thawed and frozen soil, respectively, L is the latent heat of phase change of water (J/kg), W and Wi is the total water content and ice content of the frozen soil, respectively, Tp and Tb is the upper and lower boundary temperature values of the phase change zone of the frozen soil, respectively.

The behavior of thawing area tailings is modeled using an elastoplastic constitutive model that combines an elastic stress-strain relationship with the Mohr-Coulomb plastic yield criterion. Initially, the stress-strain relationship in the elastic phase of the tailings is described using the general Hook's law. However, as the dam gradually thaws, it becomes destabilized and vulnerable to damage once the stress reaches a specific threshold. At this point, the critical state of the dam transitioning from elastic to plastic deformation is determined using the Mohr-Coulomb plastic yield criterion.

The strength reduction method is to reduce the shear strength indices of tailings with a reduction coefficient, as shown in Formula (4) and Formula (5), and then replace the reduced c and ϕ into the formula for calculation, and judge whether the dam reaches the limit equilibrium state according to the SF; Keep calculating until the tailings reaches the ultimate equilibrium state, and then the discount factor will equal the overall SF for thawed-frozen dams. The specific expression of the strength reduction method is shown in the following equation:

$$c' = c/F_S \tag{4}$$

$$\tan\phi' = \tan\phi/F_S \tag{5}$$

$$\tau_{f'} = c' + \sigma\tan\phi' \tag{6}$$

The tailings' initial cohesion and internal friction angle are represented by c' and ϕ', respectively. Additionally, the reduced cohesion and internal friction angle of the tailings are denoted as c' and ϕ'.The shearing strength after reduction is indicated by $\tau_{f'}$, and the reduction factor for each iteration is represented by F_S. The initial value of the reduction factor is obtained to be small enough to ensure that it is an almost elastic state to begin with. Then, with increasing values, the reduced shear strength index gradually decreases until F_S increases to a certain value, the actual shear stress of soil is exactly equal to the reduced shear strength index, and the dam is in a state of ultimate equilibrium, F_S is the SF of the post-thawed dam, and then the stability of the thawed tailings is judged by the SF.

The stability analysis of tailings dams in cold regions under F-T cycles, as discussed above, utilizes the thermo-mechanical coupling numerical analysis platform of FLAC3D. The thawing area of the dam is first determined through the heat conduction equation and then assessed for stability using the Mohr-Coulomb plastic yield criterion embedded in FLAC3D, utilizing the strength reduction method. The migration and percolation of water in surface tailings are not taken into account when studying the stability development of tailings dams during the F-T process.

3. Numerical Modeling

3.1 Calculating Parameter

To account for the effects of varying tailings densities and temperature boundary conditions on dam stability under F-T cycles, three distinct operating conditions were chosen for numerical simulation, as outlined in Table 1.

After undergoing F-T cycles, tailings dams have frozen, thawed, and F-T zones within the dam. In the frozen zone, the mechanical properties of the frozen soil are similar to that of a rigid body, so for ease of calculation, the mechanical parameters in this area are significantly higher than those in the thawed zone of the dam. For the convenience of calculation, the mechanical parameters of the F-T zone and the thawed zone are considered the same. The mechanical parameter indicators of the soil layer in the thawed zone after 10 F-T cycles are generally used as the basis for engineering design. The calculated mechanical parameter indicators are shown in Table 2.

Table 1. Three Operating Conditions Schematic Table

Operating conditions	Tailings primary dam				Tailings fill dam			
	Density/kg·m^{-3}	T_0/°C	1	α/°C·a^{-1}	Density/kg·m^{-3}	T_0/°C	1	α/°C·a^{-1}
1	2.20	2.0	18	0.02	2	2.0	18	0.02
2	1.80	2.0	18	0.02	1.65	2.0	18	0.02
3	2.20	2.0	18	0.02	2	9.5	20	0.02

Table 2. Mechanical Parameters of Frozen and Thawed Tailings

Stratum	Density/g·cm^{-3}		Cohesion/kPa		Internal friction angle/°		Bulk modulus /kPa		Shear modulus /kPa	
	Frozen	Thawed	Frozen	Thawed	Frozen	Thawed	Frozen	Thawed	Frozen	Thawed
Block stone	2.25	2.25	7000	15	30	5	5e^5	0.80e4	5e5	1.40e4
Silt	2.02	2.02	7000	5	30	20	5e^5	0.36e4	5e5	0.22e4
Silty clay	1.96	1.96	7000	6	30	19	5e^5	0.21e4	5e5	0.13e4

3.2 Boundary Conditions

Based on field measurement data in the permafrost region of the Qinghai-Tibet Plateau[11], The upper boundary temperature conditions of the model follow a sinusoidal pattern. The formula can be expressed as:

$$T = T_0 + \alpha t + l\sin\left(2\pi\frac{t}{365} + n\pi\right) \tag{7}$$

where, T_0 is the mean annual temperature and taken as 2.04℃ for the numerical analysis model of tailings dam; The amplitude l is set to 10.64, while α represents the annual warming rate of the earth's surface (0.02℃/year), with an initial phase of π/2. The boundaries on both sides of the model are defined as adiabatic, but the influence of geodesic heat flow on slope temperature is taken into consideration. [12], Apply a heat flux of 0.02 W/m2 to the lower boundary of the model. The left and right front and rear boundaries of the dam model are adiabatic.

Based on the above parameters and boundary conditions, the tailings dam model is established. The initial dam is made up of block stones, the height is 10m, and the upstream slope ratio and downstream slope ratio are both 1: 1. The width of the slope is 5m, the accumulation dam is formed by the accumulation of tailings and divided into two layers, which are silt and silty clay respectively. The dam height is 40m, and the upstream slope ratio is 1:1.5. In this numerical simulation, only the thawing deformation of the dam under the influence of dead-weight was taken into account. As a result, the bottom boundary of the model was fixed in all directions when calculating the initial stress field of the dam, with a displacement of 0 along the x direction on both sides of the boundary. The top boundary was left unconstrained. Since the majority of soil deformation occurs in the thawing area, the boundaries on both sides of this zone are fixed when using the Mohr-Coulomb criterion for calculation, while the boundaries on both sides of the frozen zone are considered free. See Figure 1 for the established model.

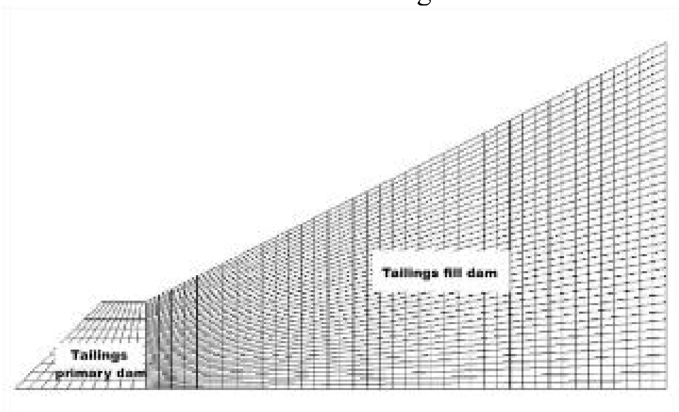
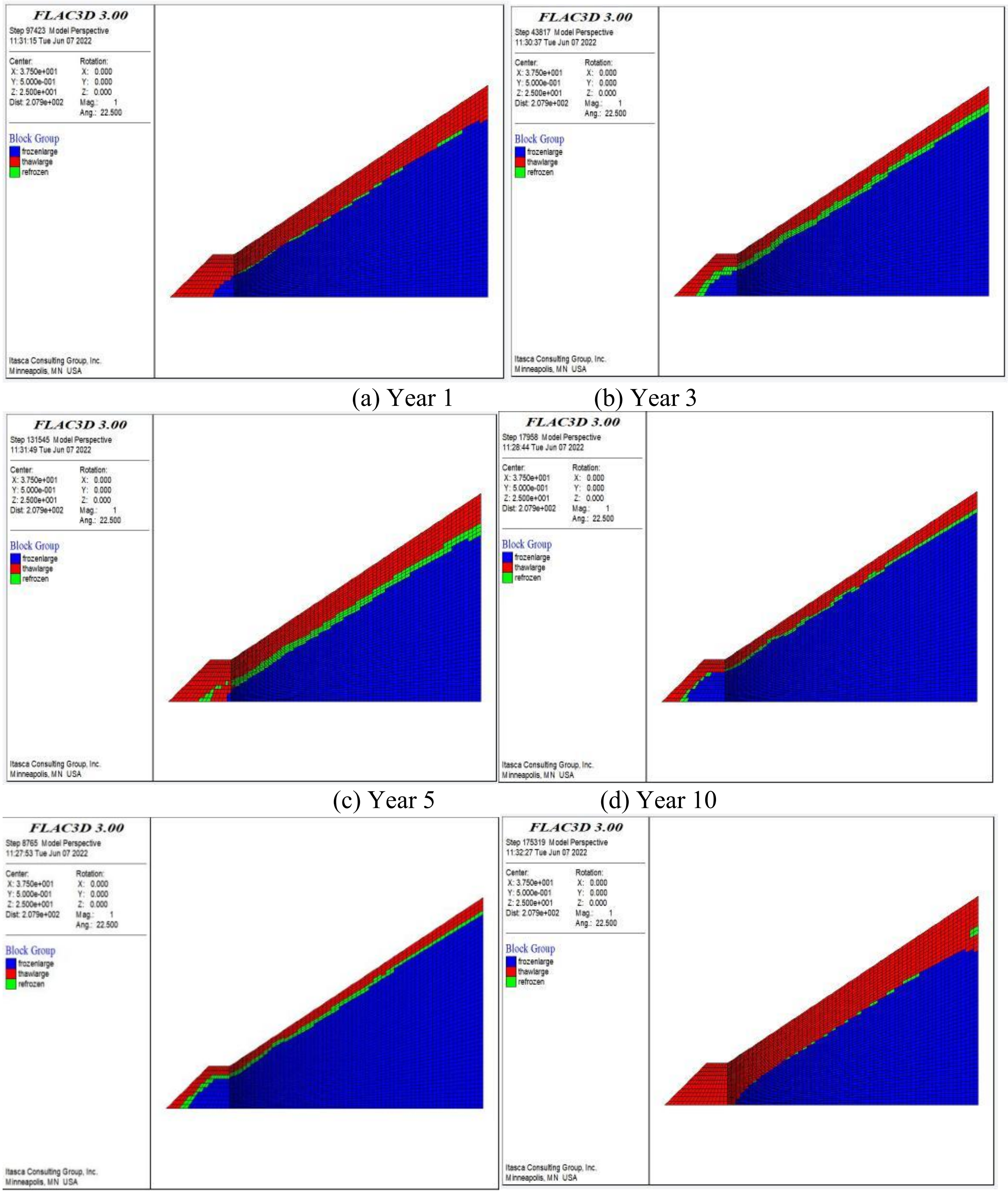


Figure 1. Numerical Analysis Model of Tailings Dam

4. Results

4.1 Variation in Thaw Depth of Tailing Dam During Thawing

The thawing depth of the tailings dam in different operating conditions and different years was obtained by using the self-programmed FISH language in FLAC3D for thermology field calculation. Under different operating conditions, the thawing depth of the dam after F-T cycles in different years was calculated by rewriting the program data, and the thawing depth diagram of the dam in different years was obtained by inputting corresponding instructions. FIG. 2(a) shows the thawing depth diagram of the dam during a year of F-T cycles under working condition 1. It can be seen from the diagram that the thawing area is above the dam with a depth of about 3m, and there is a part of F-T transition area between the freezing area and the thawing area. With the increase of the years of F-T cycle, the thawing depth of the dam gradually increases. After three years of thawing, the depth of the thawing area of the dam is about 5m, and after five years of thawing, the depth of the dam is about 6m. The thawing depth of the dam changes steadily with the increasing time of F-T cycle.



(a) Year 1 (b) Year 3

(c) Year 5 (d) Year 10

(e) Year 15 (f) Year 20

Figure 2. Thawing Depth Diagram of Different Years Under Operating Condition 1

Under operating condition 2, the thawing depth of the dam after 1, 3, 5, 10, 20 and 30 years of F-T cycle was calculated by rewriting the program , and the variation diagram of the thawing depth was drawn. From the figure, it can be seen that there are three stages in the variation of thawing depth with F-T cycle time. The first stage is the period of rapid growth, as shown in FIG. 3. From the beginning of F-T cycle to 20 years later, the thawing depth deepens rapidly, and the increase rate of the thawing depth is about 2m/ year. The second stage is a slow growth period, from 20 years to 50 years, the thawing depth in this stage still deepens with the increase of F-T time, but the increase rate has an obvious decreasing trend compared with the first stage, the thawing depth increase rate is about 1m/year. The third stage is the stable period, in which the thawing depth does not change with the increase of time and is stable at 35m. The variation of thawing depth with the time of F-T cycle under the operating condition 3 is similar to that under the operating condition 2.

As shown in FIG. 3, a comparative analysis of the line chart of thawing depth under operating condition 1 and operating condition 2 shows that the overall change trend of the two charts is the same, but the thawing depth under the same time is different. For example, the thawing depth of the dam after a year of F-T cycle under operating condition 1 is 4m, while that under operating condition 2 is 6m. The thawing depth of the tailings dam after five years of F-T cycle under operating condition 1 is 6m, and that under operating condition 2 is 14m. It shows that under the same F-T years and the same temperature boundary conditions, the thawing depth of the tailings dam is different under different geological conditions. The thawing depth of the tailings dam formed by the accumulation of lower density tailings is greater than that of the tailings dam formed by the accumulation of high density tailings.

A comparative analysis of the line chart of thawing depth under operating condition 1 and operating condition 3 shows that under the same F-T year and the same soil condition, the thawing depth of tailings dams is different under different temperature boundary conditions. The thawing depth of tailings dams with higher temperature is greater than that of tailings dams with higher density and lower temperature.

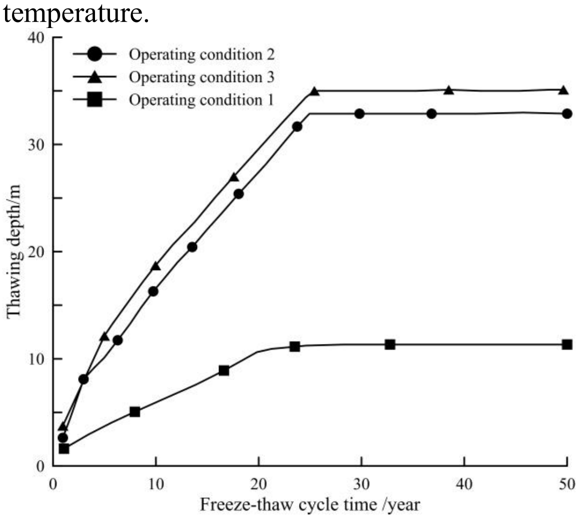


Figure 3. Comparison of Thawing Depth Under Different Operating Condition.

4.2 Variation in SF of Tailing Dam During Thawing

After the thermal field calculation is completed, the self-programmed program is used to analyze the stability of tailings dam in cold region. Table 3 shows the SFs of tailings dams with different F-T cycle under operating condition 1. As can be seen from the data in the table, the SF decreases dynamically with the development of time.

Table 3. SF of Tailings Dam

Time/ year	1	2	4	5	10	15	20	30	40	50
SF	1.414	1.313	1.180	1.133	1.023	0.945	0.914	0.711	0.617	0.617

Figure 4 shows the change of SF with freeze-thaw cycle time according to Table 3, from which we can see that the SF of the tailings dam decreases with the increase of F-T cycle time, where the F-T time from the first to the tenth year, the SF of the tailings dam is always greater than 1, the tailings dam is in a stable state, When the tailing dam is thawed for 10 to 15 years (about 12 years), the SF of the tailings dam always decreases. After 12 years of thawing, the SF of the tailings dam is less than 1 and the dam is destabilized. As can be seen directly from Figure 4, the SF of tailings dam experienced two stages of sharp decline and stable change over time. Two representative thawing years were selected in these two stages of the line chart, and the thawing years in which the variation trend of the SF changed during the transition period of these two different stages were found to study the influence of the development of the TF and the PSL on the dynamic development of the SF.

The plastic slip line(PSL) is the section at the place of maximum shear stress in the tailings dam, and the TF is the interface between frozen soil and thawed soil obtained by thermal calculation. FIG. 5(a) shows the relationship between the thawing front(TF) and the PSL in the first year of thawing. At this time, the SF of the tailings dam is 1.414. It can be seen from the line chart that the PSL is higher than the TF, and the dam is in a stable state. When the dam is thawed to the tenth year, the SF is 1.023; when it is thawed to the fifteenth year, the SF is 0.945. During this period, the dam gradually changes from a stable state to a limit equilibrium state, and finally becomes unstable and fails. At this stage, the thawing front coincides with the plastic slip surface, the dam will be destabilized along the PSL. After 40 years of thawing, the thawing depth deepens, the TF and the PSL no longer coincide, and the failure will occur in the thawing area where the soil strength parameter is small.

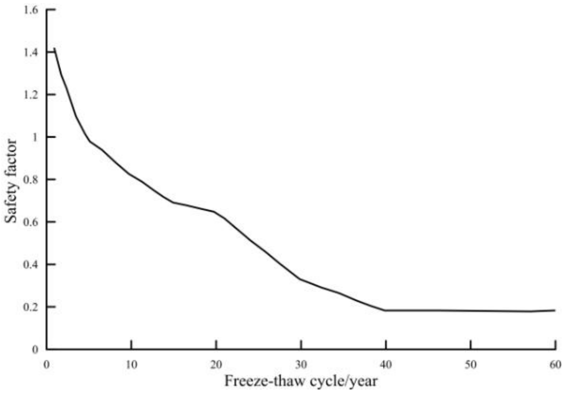
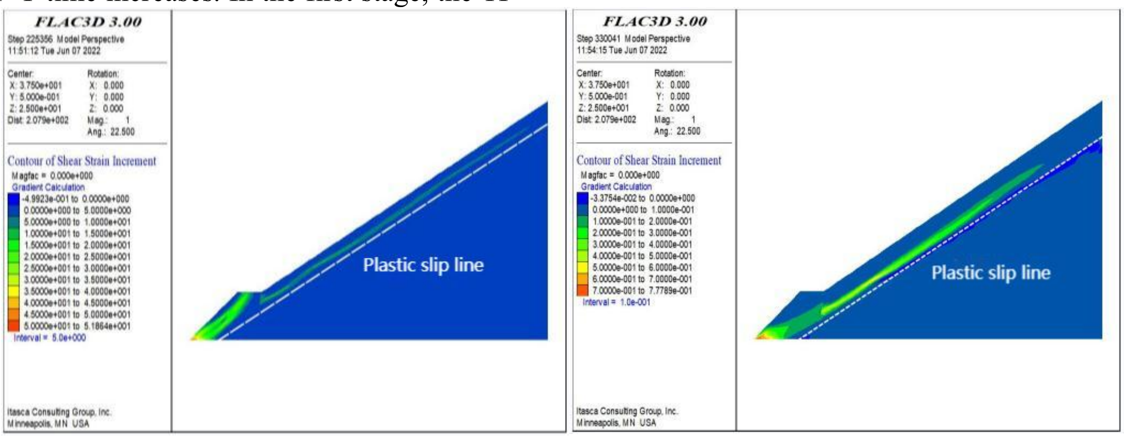


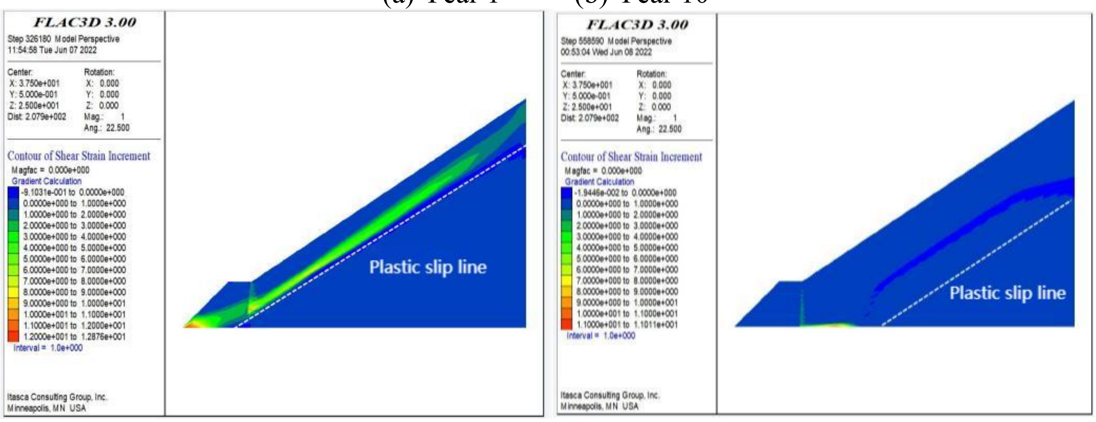
Figure 4. Variation line chart of SF at different F-T cycle years.

In summary, the relationship between TF and PSL of the tailings dam undergoes three stages as F-T time increases. In the first stage, the TF and PSL both move downwards as F-T cycle time increases, resulting in a decrease in SF as the TF remains below the plastic slip surface. The depth of TF stabilizes over time, while the PSL continues to descend and the SF gradually decreases. In the third stage, the depth of TF remains constant, the position of PSL stabilizes, and SF remains unchanged.

The SF of thawed tailings dam changes dynamically with the development of time, and its change goes through two stages of first decreasing and then keeping constant. With the gradual downward movement of the TF, the SF also decreases, and the TF always coincides with the PSL at this stage. When the TF of the dam continues to deepen and the position of the PSL remains unchanged, the SF of the slope remains constant, and the stability of the dam follows the instability law of the conventional soil slope.



(a) Year 1 (b) Year 10



(c) Year 15 (d) Year 20

Figure 5. Positional relation between TF and PSL at Different Time.

5. Conclusions

In this paper, the influence of F-T cycle on the stability of tailings dam in cold region and the mechanism of its stability change is studied. A numerical analysis platform is established which can dynamically analyze the dynamic development law of the stability of tailings dam during the thawing process. By calculating the SF of the thawed dam, the development law and internal mechanism of the SF over time are analyzed, and the following conclusions are obtained:

(1) In terms of the thawing depth of tailings dam, the higher the temperature of the dam is, the deeper the thawing depth will be, and the lower the density of tailings is, the deeper the thawing depth will be when the slope and soil conditions remain unchanged.

(2) The SF of tailings dam changes dynamically with the development of time, which goes through two stages of first decreasing and then keeping constant. With the gradual downward movement of the TF, the SF also decreases, and the TF always coincides with the PSL at this stage. When the TF of the dam continues to deepen and the position of the PSL remains unchanged, the SF of the slope remains constant, and the stability of the dam follows the instability law of the conventional soil slope.

(3) The ultimate purpose of studying the stability of tailings dam is to serve disaster prevention and reduction and engineering construction. Through the research and analysis of the stability of tailings dam in cold regions, the dynamic development law and internal mechanism of the SF of tailings dam are obtained, which is of great significance to the design, management of tailings in cold regions and the implementation of China's strategy for sustainable development.

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