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Superiority of Filtered Tailings Storage Facility to Conventional Tailings Impoundment in Southern Rainy Regions of China

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Abstract: In order to evaluate the superiority of a filtered tailings storage facility (FTSF) to conventional tailings impoundment in the southern rainy regions of China (SRRC), the tailings slurry leakage and pollution accident occurring at the wet tailings dam (WTD) of Yinshan were analyzed, the properties of the tailings were tested in a laboratory, and the possibility of tailings liquefaction was evaluated. Comparisons of the slope stabilities of the filtered tailings dam (FTD) and WTD in normal operation, flood, continuous rainfall, and earthquake situations were simulated using the Slide software. The results show that the FTD has less chance of seepage, lower failure probability, and limited potential destructiveness than the WTD with average slope safety factors of 2.120 for normal operation, 1.919 for flooding, 1.204 for continuous rainfall, and 1.724 for a magnitude-6.0 earthquake. The disaster chain model of the WTD of Yinshan belongs to the bursting and slippage chain. As the most safe and effective active prevention measure, the FTSF has the advantages of saving water, protecting the environment, improving its stability in flood and rainfall situations, and reducing the dam failure probability and potential losses, which is greatly applicable to the SRRC.

Keywords: FTSF; conventional tailings impoundment; SRRC; slope stability analysis; disaster chain; chain-cutting disaster mitigation

1. Introduction

The main purpose of a tailings dam is to contain the tailings slurry, which may contain several types of toxic substances and pose a risk to the nearby population and environment [1]. According to statistical data, China has constructed more than 11,000 conventional tailings impoundments using the upstream method [2]. Although easy to operate with a low initial cost, upstream tailings dams are inherently less stable than dams constructed using other methods. Because of their high amounts of sands and fines, the tailings are susceptible to liquefaction, and the failure of these dams can be disastrous for people, property, and the surrounding environment. The upstream method of dam construction has resulted in the highest number of dam failure accidents in the southern rainy regions of China (SRRC) [3]. For example, on 21 September 2010, a failure occurred in the Gaoqiling tailings dam located in the Guangdong province after a heavy rainfall brought by the typhoon Fanapi, causing 22 deaths and losses of 460 million CNY [4]. Several failure examples and their consequences are listed in Table 1.

Table 1. Failure examples of upstream tailings dams in the southern rainy regions of China (SRRC).

Failure Date	Name	Province	Failure Consequences
26 September 1962	Huogudu dam, Yunan Tin Group Co.	Yunnan	171 killed, 20 million CNY losses
13 July 1997	Longjiaoshan, Daye Nonferrous Metals Co.	Hubei	28 killed, 55 million CNY losses
18 October 2000	Dachang, Nandan Tin Mine	Guangxi	28 killed, 34 million CNY losses
25 November 2009	Yinshan Mine, Jiangxi Copper Co.	Jiangxi	Leakage 30,000 m^3, pollution sweep 3 km
21 September 2010	Gaoqiling dam, Zijin Mining Co.	Guangdong	22 killed, 460 million CNY losses

It was demonstrated that the disposal technology of paste tailings and filtered tailings are ideal solutions for ensuring the safety of a tailings dam and dealing with serious tailings pollution on the surface [5,6]. Brackebusch [7] described the production of paste tailings and highlighted the environmental and economic benefits of using the disposal of paste tailings at the New Jersey mill in Kellogg, ID. Fourie [8] reflected hvon whether the thirteen potential benefits attributed to the paste and thickened tailings have been realized using a grading system. Power et al. [9] detailed the technological process and economic advantages of dry stacking over traditional methods in bauxite residue issues. Davies [10] provided practical guidelines for the design and development of filtered dry stack tailings facilities based upon the successful conceptualization, design, and operating experience at a number of these facilities.

Figure 1 shows the continuum of the water contents available for tailings management [11]. Although safer than a traditional upstream tailings dam, the water content in paste tailings is still higher than 25%. With a high water influx under strong rainfall conditions, the free water surface of a paste tailings dam will increase rapidly to a very high and dangerous level, increasing the susceptibility of the tailings to liquefaction and leading to a high dam failure possibility [12].

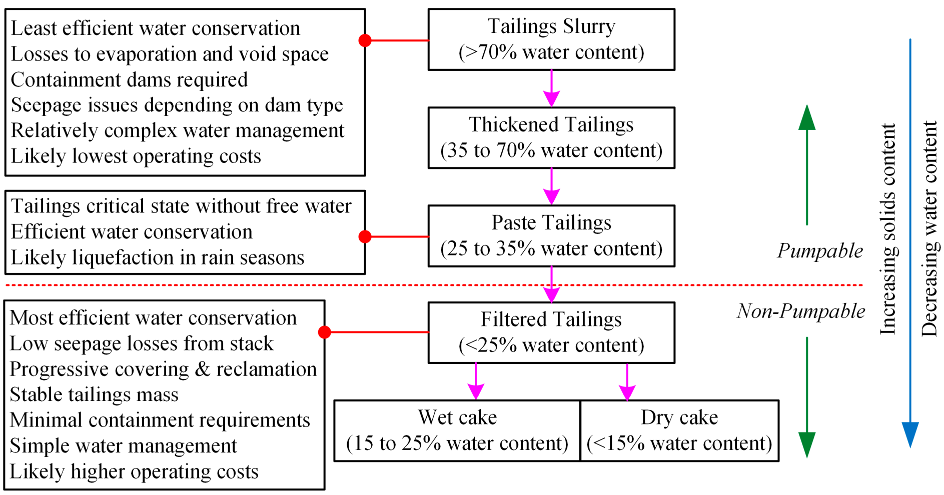


Figure 1. Continuum of water contents available for tailings management.

With the advances in dewatering technologies over the past few decades, the development of large-capacity vacuum and pressure filter technology has presented an opportunity for storing tailings in an unsaturated state rather than as a conventional slurry or in the "paste-like" consistency associated with thickened tailings [10,13]. As a new tailings treatment method, the water content in filtered tailings is usually less than 25%. In the filtered tailings disposal technology (FTDT), deep-cone thickeners or vacuum or pressure filters are widely used so that the tailings can then be stacked. This saves water, which potentially reduces the impact on the environment in terms of reductions in the potential seepage rates and space used, leaves the tailings in a dense and stable arrangement, and eliminates the long-term dangers that dams leave after mining is finished [14].

However, large tailings production in wet terrain cannot be feasibly handled and placed according to the Tailings and Mine Waste Conference of 2015 that was held in Vancouver, BC, Canada [15].

Using filtered tailings in these conditions can result in high risks to the people downstream [14]. To solve this problem, the Chinese government has enacted the "Safety technical regulations for the tailings discharge of dry", in which it was formalized that there must be a dam to store the filtered tailings, especially in SRRC. By storing the filtered tailings instead of the tailings slurry in a dam, the filtered tailings storage facility (FTSF) has been the safest and most environmentally friendly tailings disposal method in SRRC. For example, the FTSF of Zhenyuan Mine, which is located 100 km north of the broken Huogudu tailings dam, has better dam stability, larger effective storage capacity, and longer service life than its previous tailings impoundment [16].

A disaster chain is defined as a sequence of unfortunate events, each of which is the main cause of the next episode event, and has been widely used in disaster analysis for earthquakes, floods, and mining [17]. Peng et al. [18] found that mining groundwater, land subsidence and earth fissures occur in a sequence and constitute a disaster chain with respect to urban hazards in Xi'an. Gao et al. [19] analyzed the disaster chains induced by mining and proposed a series of prevention measures according to the chain-cutting disaster mitigation technology.

In this study, the 30,000 m^3 tailings slurry leakage and pollution accident occurring at the wet tailings dam (WTD) of Yinshan were analyzed, and the possibility of tailings liquefaction was evaluated. Slide software simulations were used to compare the slope stabilities of the filtered tailings dam (FTD) and WTD in normal operation, flood, continuous rainfall, and earthquake situations. The disaster chain model of the WTD of Yinshan was constructed, and the mechanism of the FTDT for disaster mitigation was analyzed on the basis of chain-cutting disaster mitigation technology.

2. Accident Analysis and Liquefaction Evaluation

2.1. Accident Analysis of the WTD of Yinshan

The WTD of Yinshan is located approximately 3 km north of Dexing, Jiangxi Province, China. The third-class dam was constructed using the upstream method in a U-shaped valley (Figure 2). It has a height of 75 m, a total storage capacity of 28.97 million m^3, and a service life of 15 years. A 20-m-tall starter dike was built of locally available waste rocks containing a significant amount of granite. With an 8-m-wide crest, the upstream and downstream slope ratios of the starter dikes are both 1:2. Gravelly sandy silt and coarse copper mine tailings were excavated for the construction of the sub dikes. With an average outside slope ratio of 1:5, the height of the sub dike is 5 m, and the crest is 2 m wide. According to the design, there are a total of 11 sub dikes, and the elevation of the dam crest is +140 m.

(**a**) (**b**)

Figure 2. The WTD of Yinshan: (**a**) satellite imagery; (**b**) scene photograph.

Located in the SRRC, this region has a typical subtropical monsoon climate with a high average annual rainfall of 1870 mm, and there are more than 100 rainy days and 60 thunderstorm days annually in Dexing. Lightning strikes, which are always accompanied with strong rainfall, cause destructive effects on the tailings on-line detection system. Owing to the low mass concentration of the tailings slurry from Yinshan, there is a water surface area of 1.37 km^2 in the WTD. With a high water influx after a strong thunderstorm in 2009, the free water surface increased rapidly to a high and dangerous level, leading to a leakage accident of 30,000 m^3 of tailings slurry that swept downstream more than 3 km.

2.2. Evaluation of Tailings Liquefaction

The bedrock, consisting of moderately to slightly weathered granite, was assumed to be strong rock. The RQD of the borehole cores is more than 90, and the rock quality is excellent. The starter dike is composed primarily of broken stones that were derived from the surficial waste rocks around the embankment and roller compacted during construction. The tailings, however, are the primary construction material comprising the sub dikes. Gravelly sandy silt, which was derived from the residual surficial soil, was also used as a construction material covering the sub dikes and then for revegetation.

The grain size distribution curves for the sandy silt and copper tailings are depicted in Figure 3. As seen in the figure, the average particle size of the tailings of Yinshan is only 42 µm, and more than 65% of the content is smaller than 74 µm, which is in the range of fine sand. According to the liquefiable soil ranges given by Tsuchida [20], the tailings are susceptible to liquefaction.

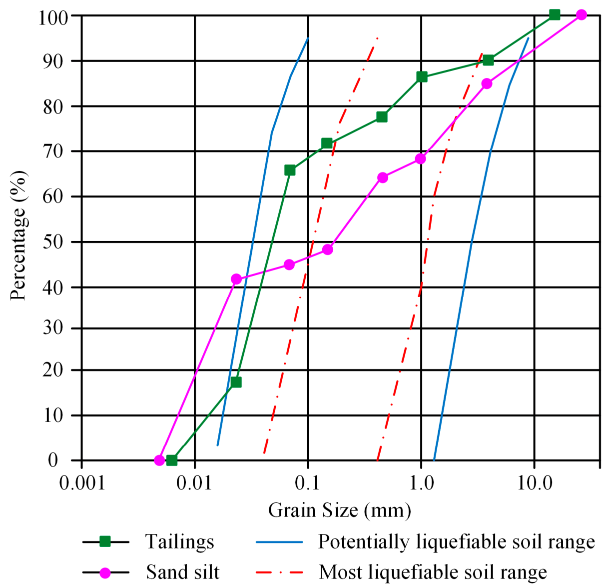


Figure 3. Grain size distribution curves for the gravelly-sandy silt and tailings of Yinshan.

3. Slope Stability Analysis

Slide is a slope stability software program with a built-in finite-element groundwater seepage analysis for steady-state or transient conditions [21]. Flows, pressures, and gradients are calculated on the basis of user-defined hydraulic boundary conditions. A seepage analysis is fully integrated with the slope stability analysis or can be used as a standalone module [22]. According to the tailings properties of Yinshan, Slide was used to simulate the slope stability of a FTD and a WTD in normal operation, flood, continuous rainfall, and earthquake situations.

3.1. Dam Section and Tailings Properties

A cross section of the WTD of Yinshan is shown in Figure 4. When the tailings slurry is discharged in the dam at a certain velocity, a fan-shaped overflow area, for which the throat is a starting point, will appear on the dry beach [23]. Coarse particles in the overflow area will settle first. Considering that the tailings in Yinshan are fine, the main component on the dry beach is fine sand tailings with an average particle size of 1.0 mm. A higher slurry velocity will result in finer tailings, and the tailings will be carried further. Silty sand tailings with an average particle size of 0.074 mm will be transported further in the transition area before settling. Tailings that are transported to the water-accumulated area will diffuse quickly in the water. Silty soil tailings with an average particle size of 0.037 mm will settle quickly in the water, while the ultrafine clay-sized tailings will settle slowly at the center of the water-accumulated area.

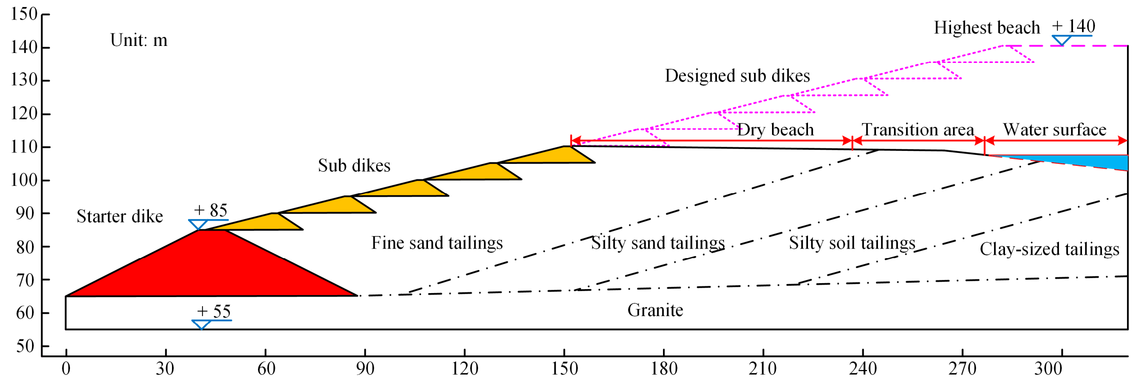


Figure 4. Cross section of the WTD of Yinshan.

The properties of the main materials mentioned above are listed in Table 2. The samples for laboratory analysis were obtained from borehole cores from the site. The strength parameters of the various soils, for both normal operations and earthquake situations, were measured using the 3-triaxial compression experiment. Since dynamic loadings can make more damage to dam stability than static loadings, then, the adhesion stress and internal friction angle in earthquake were calculated using the reduction method from the "code for seismic design of buildings" of China. The strength parameters of the filtered tailings, which were filter-pressed to a mass concentration of 80%, were also measured. After being filter-pressed and closely compacted, the filtered tailings are close-grained with low porosity; then, the adhesion stress will increase and the osmotic coefficient will decrease.

Table 2. Properties of main materials.

Materials	Volume-Weight ($kN \cdot m^{-3}$)		Adhesion Stress (kPa)		Internal Friction Angle (°)		Osmotic Coefficient ($cm \cdot s^{-1}$)	
	Nature γ	Saturation γ_{sat}	Normal c	Earthquake c'	Normal φ	Earthquake φ'	Horizontal K_1	Vertical K_2
Granite	25.5	25.8	257	188	50.2	44	6.35×10^{-7}	5.22×10^{-7}
Starter dike	24.1	24.5	128	25	36.7	26.2	8.65×10^{-2}	7.53×10^{-2}
Sub dikes	20.2	20.8	1	0	26.5	16.8	5.06×10^{-4}	4.16×10^{-4}
Fine sand	20.5	21.0	0	0	27.5	17.1	5.68×10^{-4}	4.72×10^{-4}
Sility sand	19.8	20.5	3	0	25.2	16.7	3.44×10^{-4}	2.81×10^{-4}
Sility soil	19.2	20.1	5	0	23.6	15.6	9.58×10^{-5}	8.38×10^{-5}
Clay-sized tailings	18.7	19.8	10	0	21.9	15.4	6.80×10^{-5}	5.52×10^{-5}
Filtered tailings	20.5	21.2	13	0	20.8	18.3	3.66×10^{-5}	2.90×10^{-5}

3.2. Saturation Line Calculation

The local groundwater is primarily derived from the rainfall and discharge of the tailings. According to statistical data, approximately 25% of tailings dam accidents are caused by a failure to control the seepage and the high position of the saturation line; thus, the saturation line is also referred to as the lifeline [24]. The saturation line of the WTD of Yinshan is calculated by the Slide software using finite-element analysis. By building the dam model and meshing and setting the boundary conditions, the saturation lines in normal operation (with a normal water level of 105.9 m) and flood situations (with a warning water level of 109.3 m) are shown in Figure 5. To verify the accuracy of the saturation lines calculated by Slide, observation wells were set in the boreholes, and five piezometers were installed along the main channel to locate the phreatic surface. After two years of groundwater level observation, it was demonstrated that the calculated saturation lines were accurate in normal operation and flood situations.

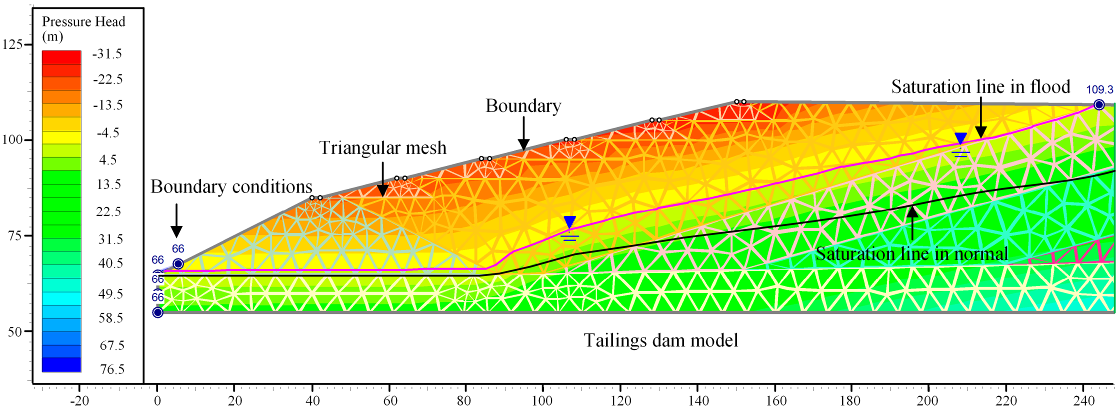
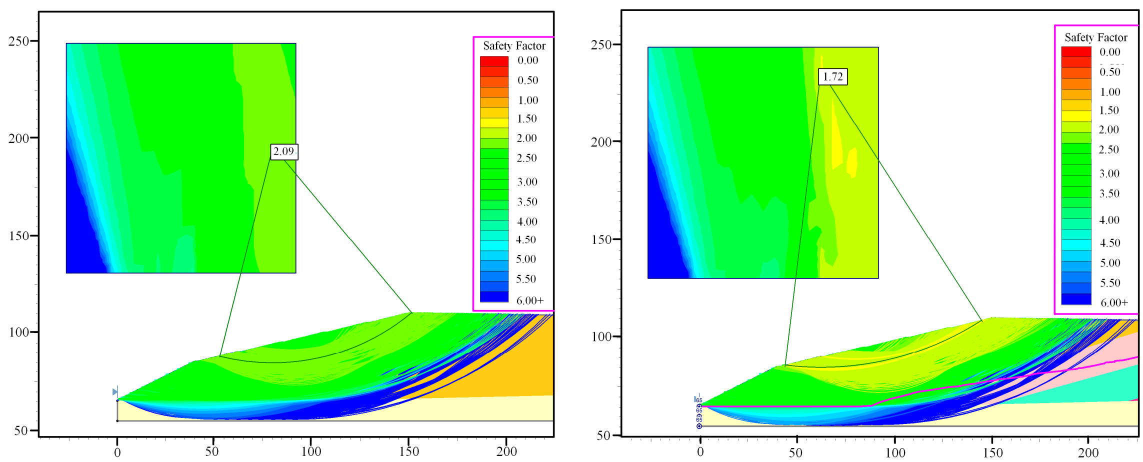


Figure 5. The calculated saturation lines of the WTD of Yinshan.

3.3. Slope Stability Analysis for Normal Operation

After being filter-pressed, the composition of filtered tailings is relatively single and uniform; then, the tailings can be seen as one material for analysis. Considering the differences in the failure surfaces of different materials, the slope safety factors are analyzed by Slide using the Bishop, Janbu, and Fellenuius methods. The safety factors of the FTD and WTD using the Janbu method for normal operation are 2.09 and 1.72 (Figure 6), respectively, both of which exceed the Chinese standard level of 1.30 from the "tailings facilities design standards of beneficiation plant". Owing to the low water content in the filtered tailings, there are no obvious free water surface and saturation line in the FTSF; then, the FTD is more stable than WTD.



(**a**) (**b**)

Figure 6. Slope safety factors for normal operation: (**a**) FTD; (**b**) WTD.

3.4. Slope Stability Analysis under Flood Conditions

The calculated slope safety factors of the FTD and WTD using the Janbu method in a flood situation are shown in Figure 7. With a high water influx in a flood situation, the free water surface and saturation line will appear in a FTSF. As the osmotic coefficient of filtered tailings is very low, the permeation of free water is very slow, and the saturation line still lies at a very low level. Therefore, the calculated safety factor of the FTD using the Janbu method is still as high as 1.90, exceeding the standard level of 1.20 in a flood situation. In contrast, the WTD of Yinshan has a large water surface area during normal operation, and the free water surface will increase rapidly to a very high and dangerous level with a high water influx in a flood situation. The slope safety factor of the WTD in a flood situation is just 1.06 and therefore prone to failure.

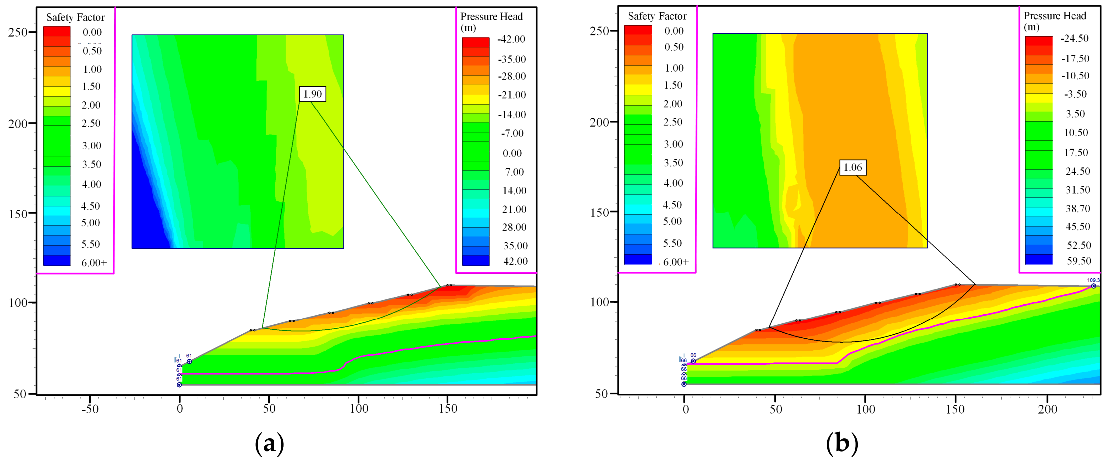


Figure 7. Slope safety factors under flood conditions: (**a**) FTD; (**b**) WTD.

3.5. Slope Stability Analysis for Continuous Rainfall

In a continuous rainfall situation, the discharge of tailings will be halted, and rainwater will be discharged immediately; therefore, the water influx is far less than that in a flood situation. Owing to the small water influx and low osmotic coefficient of the filtered tailings, there is still no free water surface in the FTSF. Similarly, the free water surface in the WTD increases slowly during continuous rainfall. However, the surface tailings will be saturated during continuous rainfall, forming a new saturation line just coincident with the outside slope. The average slope safety factor of the FTD for continuous rainfall is about 1.20 (Table 3), showing that the dam is in the limit equilibrium state. The slope safety factor of the WTD using the Janbu method during continuous rainfall is just 0.86 (Figure 8), which is far lower than the standard level of 1.20. Compared with the WTD, the FTD has less chance of seepage, a lower failure probability, and limited potential destructiveness.

Table 3. Slope safety factors in different situations.

Situtations	**WTD**				**FTD**				**Standard**
	Bishop	**Fellenuius**	**Janbu**	**Average**	**Bishop**	**Fellenuius**	**Janbu**	**Average**	
Normal operation	1.76	1.72	1.72	1.73	2.17	2.10	2.09	2.12	1.30
Flood conditions	1.09	1.06	1.06	1.07	1.95	1.90	1.90	1.92	1.20
Continuous rainfall	0.88	0.90	0.86	0.88	1.24	1.22	1.16	1.20	1.20
Earthquake	1.43	1.40	1.40	1.41	1.77	1.71	1.70	1.72	1.10

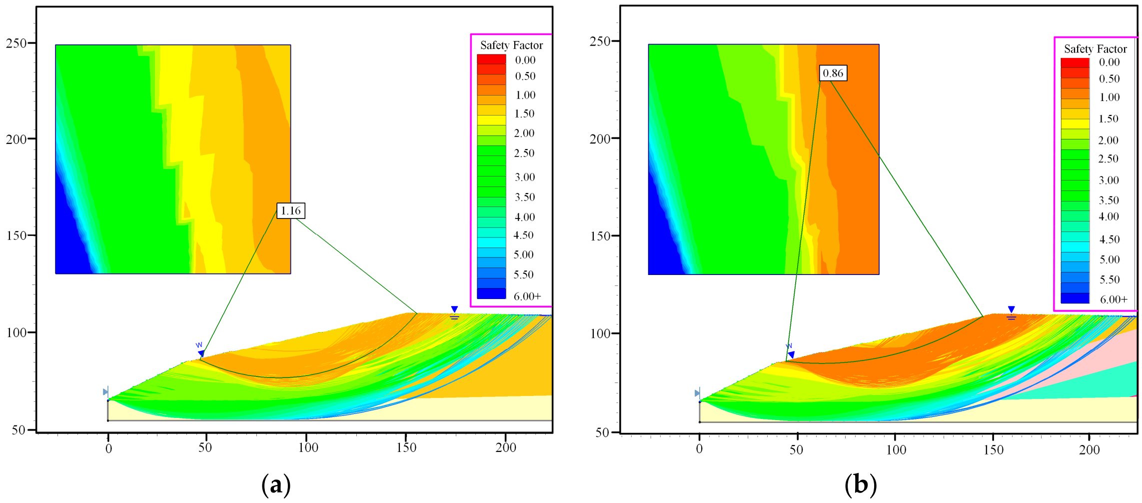


Figure 8. Slope safety factors for continuous rainfall: (**a**) FTD; (**b**) WTD.

3.6. Seismic Slope Stability Analysis

The destructive effect caused by earthquakes is especially serious. Yinshan is located in the Dexing–Huangshan fault zone and suffers earthquakes occasionally [25]. As required, the seismic fortification is set at a magnitude of 6.0, the horizontal seismic acceleration is set to 0.05 g, and the vertical seismic acceleration is set to 0.025 g. The tailings properties are listed in Table 2, and the strength parameters are changed to those for an earthquake. The slope safety factors of the FTD and WTD calculated using the Janbu method for a 6.0 earthquake are 1.70 and 1.40, respectively (Figure 9), which are both above the standard level of 1.10. The FTD shows substantially better seismic stability in a magnitude 6.0 earthquake than the WTD.

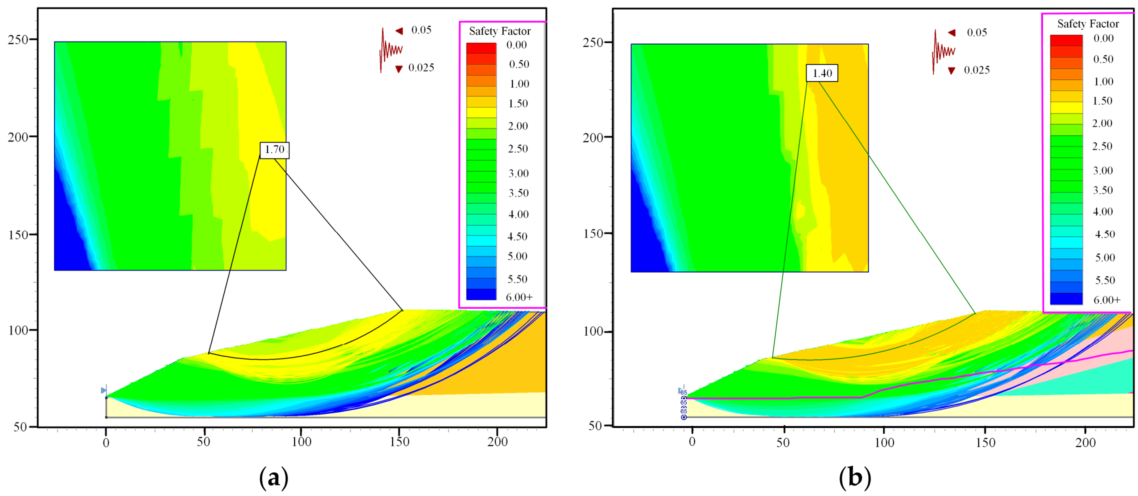


Figure 9. Slope safety factors for earthquake: (**a**) FTD; (**b**) WTD.

The calculated slope safety factors of the FTD and WTD using the Bishop, Janbu, and Fellenuius methods in the above-mentioned situations are listed in Table 3. Compared with the Bishop and Fellenuius methods, the results of the Janbu method are relatively conservative. Therefore, it is safe and reliable to use the Janbu method for a Slide analysis and the supporting design.

4. Disaster Chains and Chain-Cutting Disaster Mitigation Technology

4.1. Disaster Chains

Disaster chains show the formation mechanisms, evolution processes, and destructiveness of different disasters. By analyzing the commonalities and specific properties of different disasters deeply, disaster chains play important roles in disaster prevention and loss reduction [26]. According to an analysis of the tailings leakage and pollution accident in 2009, the disaster chain of the WTD of Yinshan is summarized and shown in Figure 10.

Rainfall, flooding, earthquake, and lightning strike are the main disaster-inducing factors that lead to the disaster preparation stage. With continuous exposure to disaster-inducing factors, dangerous omens such as a saturated dam, a high saturation line, dam piping, dam cracking, and detection system breakdown start to appear continuously. Disasters will reach the latency stage when potential disasters such as tailings liquefaction and dam failure begin to occur in a local area of the dam. Once the destructiveness exceeds the dam carrying ability, destructive disasters such as landslides and mud–rock flow will break out. In disaster explosion stage, a series of secondary disasters will be induced, which will cause death, property loss, and serious environment pollution. The failures type of the WTD of Yinshan is consistent with the bursting and slippage disaster chain [17,26].

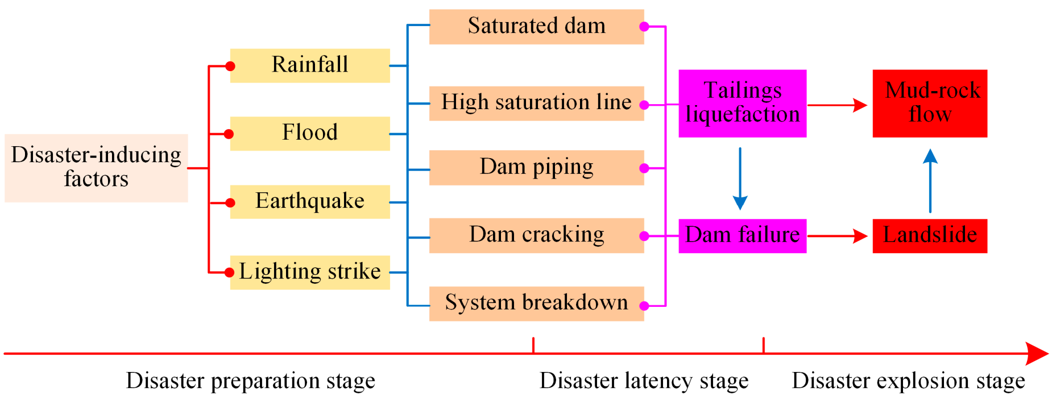


Figure 10. Disaster chain model of the WTD of Yinshan.

4.2. Chain-Cutting Disaster Mitigation Technology

By cutting off the disaster chain that caused the dam failure and preventing the development of the disaster latency stage, chain-cutting disaster mitigation technology plays an important role in disaster control and loss reduction [19]. According to the disaster chain model of the WTD of Yinshan, chain-cutting disaster mitigation measures can be divided into active prevention measures and passive defense measures (Figure 11).

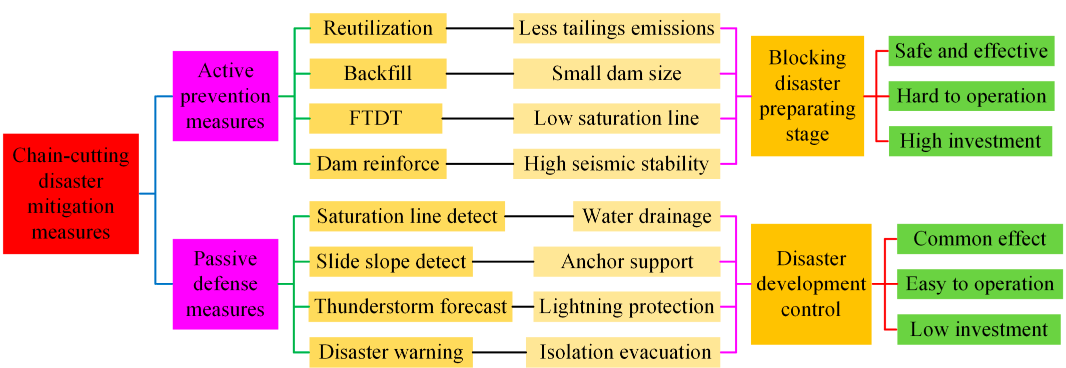


Figure 11. Chain-cutting disaster mitigation measures.

There is general agreement that active prevention measures are the safest and most effective methods, especially in rainy regions. By analyzing the root causes of disaster-inducing factors, effective active prevention measures are taken to cut off the disaster preparation and latency stages, preventing the development of the disaster latency stage, thus reducing losses [27]. As the most important active prevention measure, the FTDT is superior for improving the dam stability and reducing the failure probability. First, after the tailings are filter-pressed, the tailings emission and dam size will be reduced greatly, while the storage capacity and service life will be effectively increased. Moreover, the FTSF has a higher slope stability than the conventional tailings impoundment in both rainfall and flood situations. Furthermore, there are no obvious free water and saturation line in the FTSF, which means that there is less chance of seepage, a lower failure probability, and limited potential destructiveness.

The core passive defense measures are detection, prevention, and evacuation [19]. On the basis of strengthening the detection of the saturation line height, slide slope deformation, and thunderstorm weather forecast, a series of passive defense measures such as water drainage, anchor support, lightning protection, and isolation evacuation will be carried out. Compared with active prevention measures, passive defense measures are easy to implement and require a low investment, but the result is not enough sufficiently safe or effective.

As the most safe and effective active prevention measure in SRRC, the FTDT has the advantages of improving the dam stability in rainfall and flood situations and reducing the dam failure probability and potential losses. Nevertheless, passive defense measures are also effective supplements in extreme conditions.

5. Application

Figure 12 presents a proposed flow chart of FTDT in Yinshan. A tailings slurry with a concentration of less than 25% is pumped into a deep-cone thickener and mixed uniformly with flocculants and coagulants, which are pumped from a dissolving apparatus. The settling velocity of the fine tailings will be accelerated because of the action of the flocculants and coagulants, and the underflow concentration will be improved to 50% or 60%. The overflow water can be recycled for process water and reused, e.g., in the flotation step [13]. Typically, the filtered tailings contain less than 20% water, and pressure filters are then used to compress and dewater further. Filtered tailings are transported to the FTSF by a conveyor belt or truck and then dumped and compacted [14].

Figure 12. A proposed flow chart of FTDT in Yinshan.

The proposed FTDT in Yinshan exhibits superior performance, especially on rainy days. First, the FTD is more stable, essentially immune to geotechnical "failure," and can be designed to withstand thunderstorm days and large floods. Moreover, the FTDT has obvious benefits for improving the storage capacity and service life, reducing land expropriation and dam maintenance costs, saving water, and protecting the environment. In addition, the successful use of the FTDT in Yinshan is greatly applicable to the SRRC.

6. Conclusions

(1) Field research and laboratory tests have indicated that the WTD of Yinshan is not safe, and the tailings are susceptible to liquefaction, especially in rainy days.
(2) The FTSF has less chance of seepage, lower failure probability, and limited potential destructiveness than the WTD with average slope safety factors of 2.120 for normal operation, 1.919 for flooding, 1.204 for continuous rainfall, and 1.724 for a magnitude-6.0 earthquake.
(3) The failures type of the WTD of Yinshan is consistent with the bursting and slippage disaster chain. As the most safe and effective active prevention measure in rainy regions, the FTDT has the advantages of improving the dam stability in rainfall and flood situations and reducing the dam failure probability and potential losses.
(4) The FTDT in Yinshan has obvious benefits for improving the storage capacity and service life, reducing land expropriation and dam maintenance costs, saving water, and protecting the environment, while showing a high application promotion value in SRRC.

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