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Research Article

Reinforcement Mechanism and Engineering Application of Weak Tailing Pond Beach by Soilbag Method

Cui Xuan,[1,2] Li Shuang,[3] Zhou Han-min,[2] and Cao Hui [1]

[1]*School of Civil and Resources Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[2]*BGRIMM Technology Group, Beijing 100160, China*
[3]*Tourism College of Beijing Union University, Beijing 100101, China*

Correspondence should be addressed to Cao Hui; cao_h@ustb.edu.cn

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In light of the engineering characteristics of fine-grained tailings, such as their high moisture content, high compressibility, difficult deposition, and difficult consolidation, and based on the summary and analysis of the experience of tailing dam construction in China and abroad, a new comprehensive treatment technology suitable for dam construction on a weak beach, which is composed of strengthening foundation with the soilbag, subdam stabilization, and collaborative drainage, is proposed. Taking a dam construction project on the weak beach of a tailing pond in China as the research object and through the study of the reinforcement mechanism of the soft beach treated using the soilbag method, it can be seen that the soilbag body has the mechanism of strength growth by sand fixation and water permeability and constraint formation and can achieve an overall stable effect of extrusion and silt replacement, stacking and surcharge, and flexible embedding in a weak beach. Using this method, combined with relevant monitoring technology, a good demonstration of dam construction speed of up to 30 m/a and a safe dam construction height of up to 60 m on a weak beach surface is achieved in a tailing dam construction project, which provides a good reference for the design and construction of fine tailing dam engineering and the cooperative disposal of adverse geological conditions.

1. Introduction

A tailing pond is used to store the tailings of metal and nonmetal mines after mineral processing. Fine tailing storage is a difficult problem that must be managed in tailing treatment technology, and this exits in the fields of gold, copper, lead–zinc, and other materials. Martin and McRoberts [1] pointed out that the stability of tailing dams constructed using the upstream method is a challenging problem due to the great uncertainty of the shear strength of fine tailings or cement. Fine tailings have the following engineering characteristics: high moisture content, high compressibility, difficult deposition, and difficult consolidation. Sedimentary beaches formed by tailings after storage have the characteristics of low bearing and poor drainage capacities. It is difficult for these to directly serve as a dam body in the later stage of dam foundation bearing, which restricts the large-scale production of mining enterprises.

With the continuous and rapid development of mineral resources, tailing dam construction is developing in the direction of using fine-grained and building high dam. Rapid dam constructions on weak beaches caused by a high clay content, high rise rate, and large service scale have become new challenges for the safe operation of tailing reservoirs. Regarding the study of the storage and disposal of fine tailings, foreign countries have mainly focused on improving the performance of fine tailings and improving dam construction technology. To improve the performance of fine-grained tailings, natural drying, cyclone, thickener, filter press, and other types of technical equipment are used to remove the moisture of multiple particles, or flocculant and coagulant is added to promote the polymerization of fine-grained tailings, improve the overall particle size and dehydration effect, and improve the dam performance of tailings [2–4]. In terms of improving dam construction technology, the midline and downstream methods are often used. In recent years, relevant studies have been

Figure 1: Tailing beach surface in the initial dam.

carried out in the context of bag dewatering dam construction and waste rock dam construction [5, 6]. Ferdosi et al. [7, 8] studied the beneficial effects of the combined storage of waste rock mixed with tailings on tailing seepage, consolidation, and seismic liquefaction resistance. Domestic research on fine tailing dam construction has mainly focused on paste/dry tailing storage, seepage reinforcement, and waste rock dam construction. Yang and Ai and Zhang [9, 10] studied the paste characteristics of fine tailings and the stability of dam construction; Zhou [11] proposed a comprehensive dam construction strategy based on the soilbag method; Wei [12] carried out a study on tailing dam technology based on the improved upstream method, seepage control, and reinforcement; Cui and Zhou and Zhao [13, 14] studied and applied waste rock dam construction techniques such as the waste rock midline and waste rock downstream methods, while the strategy of dam constructions with fine tailings has achieved some promising results, but the height of the dam is mostly 20–30 m, and there is little available experience to use as reference for the continuous increase in the dam body. In addition, the existence of a weak beach, thick layer, and insufficient bearing capacity in the process of fine tailing discharge further aggravates the difficulty of dam construction, and similar dam construction projects have not been reported at home or abroad. Therefore, based on summaries of previous experiments, this paper proposes a rapid dam construction technique for a fine-grained tailing dam based on the soft beach bag method, having conducted field dam construction for nearly three years in a domestic tailing dam. The height of the tailing dam is over 60 m, and the operating parameters of the dam body are stable. Relevant engineering experience can provide a reference for dam construction design and the construction of fine tailing reservoirs in the future.

2. Engineering Background

The tailing pond studied is located in southwestern China. It is a valley-type tailing pond with an average slope of about 11% at the bottom of the ditch and a depth of about 2.2 km. On two sides, it is surrounded by high steep mountains, with a slope angle between 20° and 40°. The width of the valley bottom is 260 m~700 m, and the valley has a "U" shape. The strata at the dam site are mainly composed of pebbles, silty clay with gravel, strongly weathered quartz sandstone, and moderately weathered quartz sandstone. To save water resources significantly and reduce transportation costs, the tailing pond was designed as a paste upstream tailing pond, as shown in Figure 1.

Affected by the production process of the concentrator, the actual operation of the tailing pond has three characteristics:

(1) The clay content of the tailings is high, and the amount of particles with a size of $d < 20\,\mu$m is within the range of 49.3–53.09%, whereas the amount of particles with a size of $d < 5\,\mu$m is within the range of 17.87–20.06%. The beach surface is in a state of plastic flow

(2) The actual tailing concentration is 55~60%, the beach tailings are not graded, the permeability coefficient is low, and the tailings are difficult to consolidate

(3) The tailing dam rises fast, and the maximum rise speed can reach 30 m/a. The tailing deposition consolidation time is limited, which makes it difficult to meet the requirements of the dam

In addition, to meet the production requirements of the concentrator, the tailing dam height was designed to be 175 m. How to build dams safely and reliably has become the key concern of tailing dam operations.

3. Analysis of the Mechanism of Reinforcement of a Weak Beach Using the Soilbag Method

A large number of application cases show that [15] the soilbag method has the advantages of having a strong adaptability to a soft soil foundation, good overall continuity, and fast construction speed, and it is widely used in the construction of soft foundation dams, such as beaches and reclamation areas. The application of the soilbag method in tailing dam construction refers to the formation of a soilbag subdam by filling the soilbag with tailings, forming a consolidated filling body through the drainage of pressure, and using the filling body for continuous staggered stacking. The following principles are mainly applied to the reinforcement of weak beach surfaces using the soilbag method:

3.1. The Treatment of Fine Tailings Using the Soilbag Method Has the Mechanism of Strength Growth by Sand Fixation and Permeability, Extrusion and Drainage Consolidation, and Constraint Molding

(1) A soilbag is a bag-like structural material that is constructed by stitching woven geotextiles to encapsulate and filter grouted tailings. According to the distribution of the particle size of the grouted tailings, the appropriate mold bag material can be selected according to relevant criteria, such as soil conservation and permeability, to achieve the purpose of water and sand permeability

(2) After filling the soilbag with the tailings, the soilbag produces tension along the bag by the action of self-weight and external force. The tension produces additional stress extrusion drainage along the long axis and short axis of the soilbag to accelerate the consolidation of the tailings in the bag, as shown in Figure 2

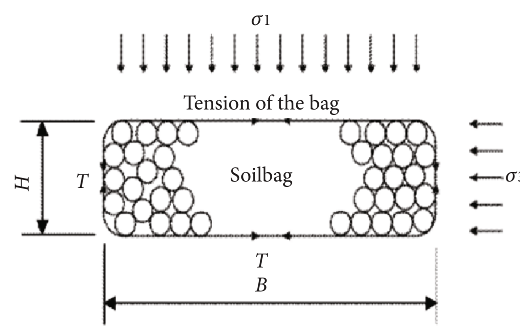

Figure 2: Schematic of the bag tension.

Figure 3: Effect of squeezing silt and replacement by soilbag.

(3) Sihong and Yisen [16] analyzed the constraint-forming effect of the soilbag on the fine tailings and proposed the equivalent additional cohesion theory for soilbag constraint. This theory states that the reinforcement effect of the soilbag originates from the comprehensive mechanism of action of three factors—the bag tension T, the bag shape (B, H), and the internal friction angle of the bag material—and points out that the additional cohesion caused by the tension of the soilbag increases the shear strength of the dam body. Based on the above theory, Cui and Zhou [17] carried out an unconfined compression test on a tailing mold bag. According to the test results, the compressive strength of the soilbag can reach 2.92 MPa, which can meet the needs of the dam materials

3.2. Mechanism of Action of the Replacement of Silt and the Stacking Static Pressure Caused by Bag Dams on the Soft Beach. The settlement of silt occurs when a soilbag is located on a weak beach. The settlement of the foundation is mainly caused by the lateral deformation of the soil and the compression deformation of the soil itself. The mold bag limits the lateral deformation of the soil well, thus effectively inhibiting the settlement of the dam foundation. When the extrusion is stable, the self-weight of the bag body is balanced with the bearing capacity of the soft clay, and the settlement of the bag is basically stable. The height of the single-stage model bag dam in the field test was 5 m. After the test, the top surface of the model bag was about 5 m higher than that of the weak beach. The height of the model bag below the weak beach was 2.4 m, and the bottom width of the model bag was 42 m, as shown in Figure 3.

When the soilbag compresses and replaces the soft fine tailings and fills the extruded space, it can be equivalent to a foundation with buried depth D (as shown in Figure 4). The shear strength of the soft foundation is $C = 2.3$ kPa, the weight is 17.5 kN/m^3, and the weight of the soilbag is

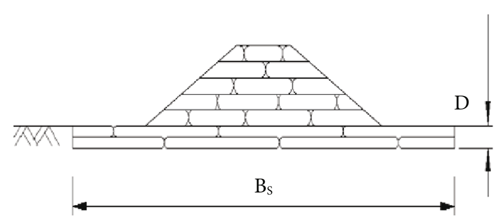

Figure 4: Schematic diagram of the reinforcement of the soft foundation using soilbags.

20 kN/m^3. We adopt the Meyerhof formula to analyze the bearing capacity of the soft foundation.

$$q_f = \frac{cN_c + \gamma DN_q + \gamma B_S N_\gamma}{2}, \quad (1)$$

where q_f is soil-bearing capacity; N_c, N_q, and N_γ are bearing capacity factors; D is soil-bearing capacity; B_S is soil-bearing capacity.

After the calculations, the bearing capacity of the foundation is increased from 11.82 KPa to 59.82 KPa when the thickness of the soilbag reaches 2.4 m, and these values meet the loading requirement of the 5 m bag dam. With the layer-by-layer construction and superimposed compressive load of the soilbag, the underlying soft beach is gradually compacted and consolidated with the multiple generations, development, and dissipation of excess pore water pressure, and the strength of soft foundation materials improves, which can further increase the bearing capacity of the foundation.

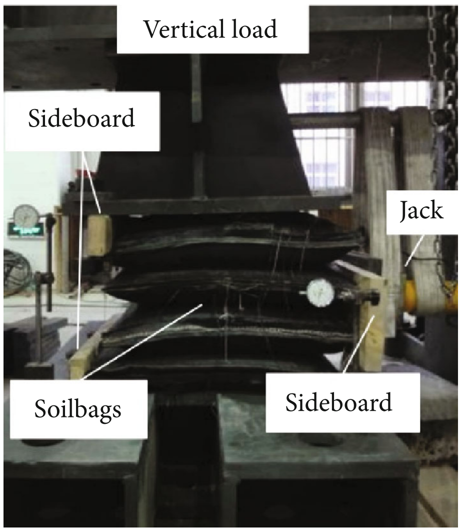

Figure 5: Shearing experiment of the soilbags.

3.3. Mechanical Properties of Formwork Dams with Lateral Force Reduction and Flexible Embedded Reinforcement of the Interlayer. Due to the tensile properties of the molded bag fabric, the horizontal force generated by the tailings in the bag is mostly offset by the tensile effect of the geotextile during the transfer process from the multilayer molded bag to the foundation. Only a small part of the horizontal force is transferred to the foundation soil, thus improving the stability of the molded bag dam. Pan [18] studied the law of distribution of the horizontal earth pressure between mold bags filled with Tongji sand; the coefficient of the horizontal earth pressure between mold bags was 0.035, which was much smaller than the coefficient of static earth pressure of Tongji sand. Fu [19] considered that, as long as the bag cannot be broken, the stability of the bag body will not pass through the bag. If instability occurs, the foundation between or below the bag layer will be destroyed. Liu et al. [20] applied the Fellenius method to check the overall stability of an expansive soil slope reinforced by soilbags. This method treats the soilbag part as the overall compressive load and considers the antislide effect caused by the friction between the soilbag layers at the arcing exit; it has achieved good results in engineering applications.

The interlaminar friction characteristics of the soilbag are affected by the friction performance between the mold bag materials, the particle size of the material in the bag, and the arrangement of the soilbag [21]. In this paper, a direct shear stress apparatus for large soilbags was designed and it was composed of a rigid pad, jack, and baffle, as shown in Figure 5. Vertical normal stress and shear stress were created by a hydraulic jack. Four groups of bag samples ($25 \times 25 \times 10$ cm) were placed horizontally in each test, in which the upper and lower bags prevented the limit deformation and the middle two bags bore the horizontal shear stress.

The raw material of the test bag was a polypropylene woven fabric of 150 g/m^2. The particle size of the filling tailings in the bag was $-74\,\mu$m, whose overall content was 42.8%, and the moisture content was 14–16%. The maximum vertical normal stress applied in the test was 1.2 MPa, and the soilbag was not damaged during the process. The coefficient of the measured interlaminar friction was 0.53. Fan et al. [22] considered that the occlusal and imbedding effect formed on the contact surface of the soilbag during the stacking process had a great influence on the shear strength and failure mode of the soilbag. The shear force of the staggered soilbag was increased by an average of 1.09 times compared with that of the nonstaggered mold bag.

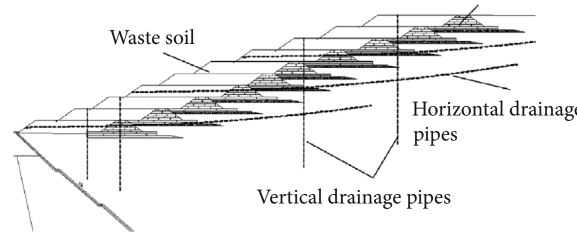

Figure 6: Design profile of the dam body.

4. Application of the Formwork Bag Method in Dam Construction on a Weak Beach

Given the problems regarding the dam construction arising from the weak beach surface, low strength, and slow consolidation of fine tailings in this project, based on the comprehensive analysis of the abovementioned mechanism of dam construction using the soilbag and combined with the rich slag and soil material sources in the reservoir area, this paper proposes a dam construction scheme based on using the formwork bag method for strengthening the foundation of the dam, increasing the stability of the wide-top subdam of the slag and soil, and coordinating the seepage discharge of the dam foundation, as shown in Figure 6.

(1) *Dam Design*. The height of the single-stage subdam was 5 m, the top width was 54 m, and the bottom width was 82 m. It was composed of a soilbag dam and a slag dam, and the slope ratio was 1 : 5.0. The dam section was trapezoidal, the top width was 6 m, the internal to external slope ratio was 1 : 2, and the bottom was 2.4 m high and 42 m wide. The requirements for the geobag materials are shown in Table 1. The requirements for the particle size of the tailings to fill the soilbag were as follows: $d \geq 0.045$ mm; the content of tailing particles should be not less than 50% when $d \leq 0.005$ mm; the content of tailing particles should be less than 10% when the filling concentration is 50-55%; the filling pressure should be controlled at 0.1-0.2 MPa. The dam body of the slag was a parallelogram section with a top width of 48 m and a height of 5 m. The wide slope formed by the soilbag dam and the slag dam could resist an unconsolidated tailing load in advance

(2) *Reinforcement Measures*. A layer of 82 m long TGDG80 unidirectional geogrid was laid at the bottom of each subdam perpendicular to the dam axis

Table 1: Main parameters of the soilbag materials.

Material	Mass per unit area/g/m^2	Tensile strength/kN/m		Elongation/%		Permeability coefficient/cm/s	Equivalent aperture O_{90}/mm
		Warp direction	Latitudinal direction	Warp direction	Latitudinal direction		
Polypropylene	150	28.2	21.6	21.5	20.9	3.45×10^{-3}	0.08-0.15

(a) Present situation of the dam construction (b) Drainage facility of the dam

Figure 7: Field dam construction.

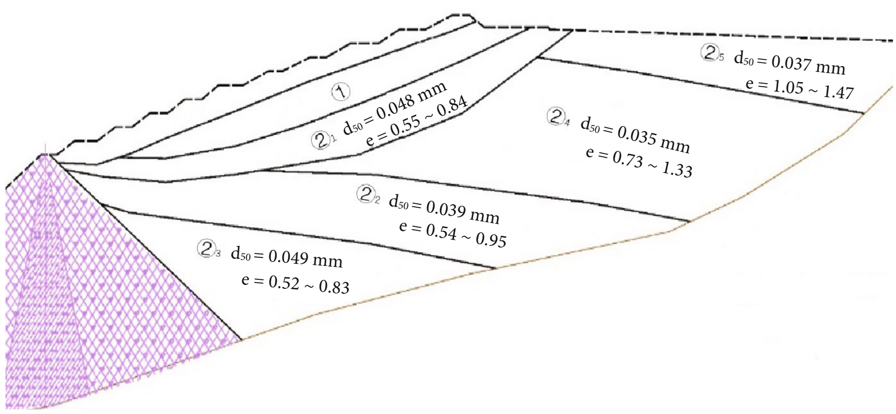

Figure 8: Geological profile of the tailing pond.

(3) *Drainage Measures*. After the formation of the dam slope, vertical and horizontal drainage pipes were arranged on the dam slope to accelerate the consolidation of the tailings. The vertical drainage pipes were arranged in rows every 20 m of the height of the dam, with a hole depth of 50-55 m and spacing of 10 m; the horizontal drainage pipes were arranged in rows every 15 m of the height of the dam. The length of a single pipe was 230 m, and the pipe spacing was 10 m

In this paper, the author used the above scheme to carry out dam construction in the field for nearly three years, as shown in Figure 7.

Since the dam construction project started, the height of the dam in the upstream method of the tailing pond has exceeded 60 m, with a production scale of the mine dressing plant of 40 000 t/d and a maximum rise speed of the dam body of 30 m/a. Through multiple borehole sampling verifications, it can be seen that the consolidation performance and mechanical properties of the tailings in the entire tailing pond are developing in a good direction, the monitoring indexes are stable, and the dam safety meets the operational requirements.

5. Analysis of the Borehole Sampling and Monitoring Data

5.1. Analysis of the Borehole Sampling in the Dam Body. Three typical sections were selected along the dam slope and the soft beach area of the tailing pond, and nine boreholes were arranged on each section for the sampling analysis. Along with the coring situation of each borehole and the results of the static penetration test, the geological section of the tailing pond is shown in Figure 8. The material of tailing silt is represented by layer ②. According to the consolidation of the tailings, layer ② is divided into zone ②$_1$, zone ②$_2$, zone ②$_3$, zone ②$_4$, and zone ②$_5$. The average particle size and pore ratio of each tailing zone is also shown in the figure.

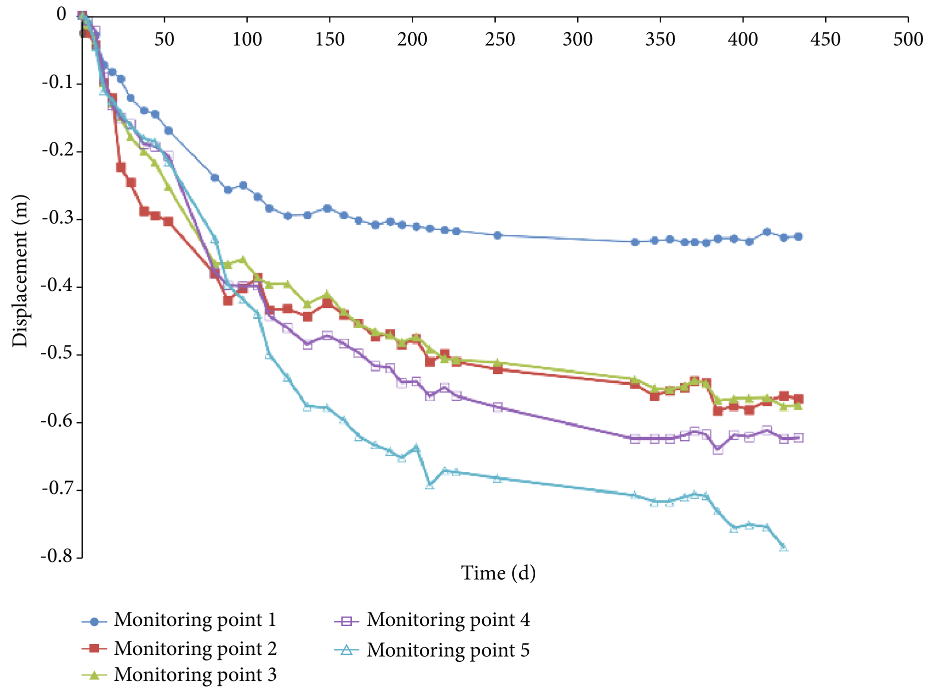

Figure 9: Curves of the time and displacement of the dam surface.

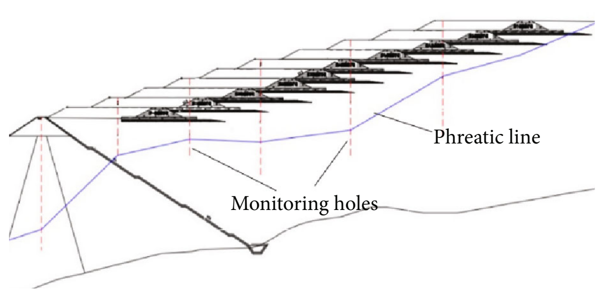

Figure 10: Monitoring hole and buried depth of the dam infiltration line.

From Figure 8, the following can be observed:

(1) High-concentration fine tailings have sorting features on a horizontal beach surface, but the effect is not obvious, and the average particle size is 0.035-0.049 mm

(2) The tailing depth in the weak area of the reservoir, which has the shape of scissor's mouth, is 40 m. The comprehensive shear strength of the cross plate shear test is 3.4–28.6 kPa

(3) Under the action of self-weight and drainage consolidations, with the increase in the accumulation dam, the weak zones are gradually transformed from zone $②_4$ to zone $②_1$ and zone $②_2$. The performance of the weak zones is gradually transformed in a good direction

5.2. Analysis of Displacement Monitoring of the Dam. The relation curves of the time and displacement of the dam surface are shown in Figure 9. The monitoring points are arranged at the subdam platform per 10 m of the height of the dam, and the monitoring begins after the synchronous construction of the dam body is completed. A comparative analysis of the same time interval was performed according to the increase in the monitoring points from low to high, numbered 1-5.

It can be seen from Figure 9 that, after the completion of each subdam construction, the surface displacement of the dam body shows a large settlement at the early stage, gradually decreasing and tending towards stability at the later stage. With the continuous increase in the dam, the settlement of the dam gradually increases. According to the long-term monitoring of the data, the maximum cumulative settlement of the first ten subdams is 78.6 cm. In the construction process, the settlement deformation can be rolled and repaired in a timely manner.

5.3. Monitoring and Analysis of the Dam Phreatic Line. The monitoring hole and buried depth of typical dam phreatic lines are shown in Figure 10. The dotted line in the figure represents the monitoring hole of the phreatic line, and the blue line indicates the location of the dam phreatic line. With the long-term operation of drainage facilities, the water discharge of the single pipe of the vertical drainage pipes changed from 5.81 m^3/d to 0.31 m^3/d, and the water discharge of the single pipe of the horizontal drainage pipes changed from 15.55 m^3/d to 1.88 m^3/d.

It can be seen from Figure 10 that, under the combined action of the vertical and horizontal drainage pipes, the buried depth of the dam phreatic line is controlled between 25 m and 39 m. However, the drainage pipe of the fine tailing reservoir is clogged, and the horizontal drainage pipe performs better than the vertical drainage pipe in anticlogging. The reason for this is that the hydraulic gradient around the vertical drainage pipe is much larger than that of the horizontal drainage pipe, and the tailings around the vertical drainage pipe hinder the entry of the seepage due to the rapid consolidation of the tailings. Additionally, frequent air exchange in the process of vertical drainage pipe drainage can easily lead to chemical congestion. Therefore, attention should be paid to this in the subsequent research and application of fine tailing drainage technology.

According to the above drilling conditions and the distribution of the phreatic line, the Bishop method was used to analyze the stability of the operation status of the tailing dam. The safety coefficient of the dam under normal conditions is 1.951–1.980, and the safety coefficient of the dam under seismic conditions is 1.287–1.295, values which meet the normal operation requirements of a tailing dam.

6. Conclusion

In light of the practical problems of fine tailing particles, the difficult consolidation of tailing discharge, and the low efficiency of dam construction in a mining concentrator, this study proposed an efficient dam construction process based on the fine tailing soilbag method for the cooperative reinforcement and disposal of a weak beach, having carried out field dam construction for nearly three years and the monitoring and analysis of dam safety for more than one year. The research and analysis show that the application effect of this technology is good, which is beneficial to ensure the safe and efficient construction and operation management of mine tailing dam. Based on the above research and practice, the results can be summarized as follows:

(1) The fine tailing soilbag has the mechanism of strength growth by solid sand permeability, extrusion and drainage consolidation, and constraint molding. This method was applied to the construction of a dam on a weak beach with the principles of silt replacement, stacking static pressure, and the flexible embedded reinforcement of the interlayer, which can help to achieve rapid dam construction on a weak beach

(2) With the new dam construction technique proposed in this paper, which includes the strong foundation of the dam using the soilbag method, the enhancement of the stability of the wide-top subdam with slag soil, and the synergistic drainage of the dam foundation, the rise speed of the fine tailing reservoirs reached 30 m/a in the project, and the height of the dam construction has exceeded 60 m

(3) From the field drilling and monitoring data, under the action of self-weight and drainage consolidation, the weak area gradually moved to the reservoir, taking the form of scissors. The maximum surface displacement was 78.6 cm, and the depth of the infiltration line was 25-39 m. In practice, the analysis of drilling information and monitoring data should be performed thoroughly, and relevant measures should be implemented in time to find abnormalities

(4) Although this technique has a good applicability in the construction of dams with a complex foundation environment and the effective utilization of fine tailings, there are also shortcomings, such as high cost compared with the traditional dam construction techniques and the materials of the soilbag being predisposed to aging when exposed for a long time. Therefore, further research should be carried out on the development of rapid filling equipment and mold bag materials to improve the efficiency and universality of the technology

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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