Experimental Study on Permeability Coefficient in Layered Fine Tailings under Seepage Condition

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Nearly half of the tailings dams in China are in a state of high-security risks and overservice, and the safety of these tailings dams has always been a concern for relevant scholars. The seepage characteristics of tailings are one of the essential factors affecting the safety of tailings dam. Now, due to the improvement of mineral processing technology, there are many fine tailings dam; the study of the seepage characteristics of the tailings dam is no longer applicable. Fine-grained tailings form uneven deposition in these tailings dams, resulting in the permeability of tailings not conforming to the previous law. Therefore, it is of great significance to study the permeability of fine-grained tailings with uneven deposition. In this paper, the physical model of the simulated tailings dam is established to study the influence of the dry beach slope on the distribution and deposition law of fine tailings during discharge. The test results show that the average particle size of tailings decreases along the length of dry beach, showing the phenomenon of coarsening upstream and thinning downstream. Then, based on the data of fine tailings deposition, the variation characteristics of the permeability coefficient of layered tailings under stable and unstable seepage conditions are studied. The test results show that the variation process of tailings permeability coefficient can be divided into four stages: rapid compaction stage, slow compaction stage, failure stage, and stable stage. Under stable and unstable seepage conditions, the permeability coefficients of unstratified tailing sand are about 10% and 15% higher, respectively, than those in the initial state. The permeability coefficient of layered tailings formed by uneven settlement changes more obviously, which is about 12% and 20% higher than the initial state.

1. Introduction

With the development of the mining industry [1–3], tailings as the waste after ore smelting also increased sharply [4–6]. The primary disposal method of tailings is to deposit them on the surface of the earth to form tailings dams [7]. There are more than 12,000 tailings dams of various types in service in China, and nearly 44% of the tailings dams in some industries are in a state of dangerous safety and extended service. About 95% of them used the upstream tailings dam construction method [8–13], which is to discharge tailings from the top of the dam and then flow naturally to form the dry beach surface under the action of the gravity field. As a kind of unique industrial structure, the tailings dam often causes serious disasters due to various reasons [14, 15]. The safety failure of Merriespruit tailings dam (1994) [16], Banglake tailings dam (2005) [10], and Brazil Brumadinho tailings dam (2015) [7] needs much money and human resources to repair for many years. The loss and damage caused by the break of the tailings dam were second only to nuclear pollution, earthquake, and debris flow. Due to the development of mineral processing technology, the slag is ground to a finer and finer size, forming fine tailings. The fine tailings have a small particle size, poor gradation, high water content, poor mechanical properties, and high-risk coefficient [10]. Moreover, the fine tailings contain a large amount of silt, which enhances the plasticity, shrinkage, and compressibility of the tailings but decreases the permeability [17] and internal friction angle [18], resulting in liquefaction under the influence of external factors [19–24]. With the accumulation height of the fine tailings dam getting higher, the safety management requirements of the dam become more stringent.
The stability of the tailings dam depends on the structural strength of the tailings, the safe distance between the tailings pond and the structural zone, and the later maintenance [25]. To study the strength and deformation of the tailings dam, it is necessary to consider the structural strength of tailings from the microlevel. The structural strength of tailings is an essential factor that affects the deformation [26]. It mainly includes the particle size, quantity, mass, volume distribution, and mechanical properties. Qiu and Sego [27] studied the physical and mechanical properties of tailings of different grades under unsaturated conditions. The particle size distribution of tailings can reflect the microstructure and mechanical properties. Zhang et al. [28] found that the stratified distribution of tailings in the tailings dam has an essential influence on the stability of the dam. The mechanical properties of the layered structures were studied systematically to determine the shear strength, particle motion, and local stress of the thick and thin layers. Due to the influence of the seepage field, stress field, and external environment, the particle arrangement, permeability coefficient, and mechanical characteristics at the microlevel of tailings are not invariant. Ryan and Boufadel [29] used a tracer to find the apparent variability of permeability coefficient in the spatial distribution. Genereux et al. [30] found that the permeability coefficient changed obviously in time and space by the method of actual measurement. And it has a vital impact on the design, service, and maintenance of the tailings dam. The change of external factors is the primary inducement that leads to the partial collapse of the dam [31]. The seepage erosion of rainwater is the most typical one. From the macroscopic analysis, the rainfall directly affects the moisture content and matrix suction of the tailings dam and then alters the safety of the tailings dam. The increase of rainwater in the dam body will cause the unsaturated tailings above the original diving line to gradually enter the saturated state or even the supersaturated state [32]. They are resulting in the gradual decrease and disappearance of the capillary force generated by matric suction acting on the particles, finally reducing the strength of tailings [33]. At the same time, unsteady seepage of rainwater will lead to the migration of fine particles in sandy soil and the tiny particles block the space between the coarse particle [34, 35]. The flow rate, water level, and other factors are the main external factors affecting the migration range and deposition process of fine particles [36]. Finally, the tailing structure changes and is likely to form the impervious layer, the permeability coefficient is changed, and the stability of the tailings dam has fallen dramatically [37].

At present, the stability of the dam based on the theory of steady seepage and saturated sand has been mature. However, the model does not apply to the tailings dam formed by unsaturated fine particle tailings in the actual working condition. Moreover, it cannot be used to accurately study the stability of the fine tailings dam under the sudden unstable seepage condition such as heavy rainfall. Due to the limitation of test conditions and the consideration of a simplified research model, most studies on the seepage of fine tailings dams fail to consider the stratification distribution of tailings. The permeability coefficient varies with time and space and the influence of the soil structure change under unsteady seepage erosion on mechanical properties. Therefore, this paper adopts a self-designed seepage measurement device to study this kind of situation in detail.

2. Data and Methods

2.1. Tailing Deposition Test

2.1.1. Experimental Materials. The tailing used in the experiment was the discharged tailing from a fine-grained tailing pond in Hunan Province of China. The indoor geotechnical test was carried out on the tailing. The cumulative curve of the tailing particles is shown in Figure 1. The screening results of the particle size characteristic values of the tailing are shown in Table 1, and the basic physical and mechanical properties of the tailing are shown in Table 2.

2.1.2. Experimental Device and Method. The method of field test has many disadvantages, such as long period, high cost, and much limitation. However, the simulation of the actual working condition with different scales can simplify the experimental process and get similar experimental results [38–40]. Based on the design data of a tailing pond in Hunan Province of China, the physical experiment of dam stacking with a simulated vertical section was used to study the deposition rule of fine tailings in the process of dam building. When the slope of the dry beach surface was moderate or the length of the dry beach surface was long, the distance between the infiltration point of the tailings pond and the initial dam or sub-dam of the tailings pond was far. The free water surface was far away from the downstream of the tailings pond, which was conducive to the overall stability of the tailings pond, so the slope or length of the dry beach surface will affect the tailings pond. To study the deposition distribution of tailings under different slopes, the physical model was designed as follows: U-shaped groove with a length of 6 m, upper width of 60 cm, lower width of 40 cm, and height of 10 cm. The main body of the model simulates the flow path of tailings along the length direction of the dry beach surface. A certain height was padded at one end of the U-shaped groove to simulate the different slopes of the dry beach surface of the tailings pond. Figure 2 shows the schematic diagram of the deposition test. A bucket with mixed tailings sample was placed upstream of the model. The bucket was connected with the pressure pump through a water pipe with a valve. The tailings sample entered the shunt pipe after being pressurized by a pressure pump. Finally, the pressurized tailings sample was sprayed into the U-shaped groove.

Based on the similarity model theory and combined with the actual working conditions, similarity parameters and the model similarity ratio were determined, as shown in Table 3. The experimental device was designed according to the parameters of the experimental model, and a physical model was built to simulate the tailings discharge process. After the physical model was built, the tailing mortar was put into the mortar mixer and the opening of the discharge pipe was controlled so that the tailing mortar flowed out at the design flow rate. When the tailing mortar reached the single discharge
volume flow of the test design, close the discharge pipe opening. After standing for some time, continue to discharge the tailing mortar according to the above steps. After the tailing stacking height reached the design elevation, place it for several days and take samples, remove 0.25 m tailings at both ends, divide the tailings between the model into five sections in 1 m along the direction of the dry beach surface, and number them after sampling in sequence. Dry the sand sample, make the cumulative curve of particle composition after the screening, analyze the tailing sedimentation law, change the slope size of the simulated tailing dam, repeat the above steps. Furthermore, study the change of tailing sedimentation law under the different slope of the dry beach surface.

2.2. Tailing Seepage Test

2.2.1. Basic Theory of Seepage Calculation. Henry Darcy, a French Water Conservancy Engineer, has done experiments on the relationship between hydraulic gradient and seepage velocity. From the tests, it can be concluded that seepage velocity \( v \) is directly proportional to seepage flow \( Q \), head height difference \( h \), hydraulic gradient \( I \), and inversely proportional to cross-sectional area \( A \) and seepage path \( l \) of soil. Thus, the famous Darcy’s law is summarized as follows [41]:

\[
v = \frac{Q}{A} = kI = -k \frac{dh}{dl},
\]

where \( v \) is the seepage velocity, \( Q \) is the seepage flow, \( A \) is the cross-sectional area perpendicular to the seepage direction, \( k \) is the permeability coefficient, \( I \) is the hydraulic gradient, \( dh \) is the differential of the head height difference \( H \), and \( dl \) is the differential of the seepage path \( l \).

In soil mechanics, the comprehensive index of soil permeability is defined as the permeability coefficient \( k \), which can be directly deduced from Darcy’s law:

\[
k = \frac{Q}{\Delta HA},
\]

where \( \Delta H \) is the head height difference.

2.2.2. Seepage Test Device. The main part of the device is a segmented transparent plexiglass tube, which is mainly used...
to store the tailings and measure the water pressure. A hydraulic pressure gauge is installed on the transparent plexiglass tube, and a permeable stone is placed at both ends of the transparent plexiglass tube. A 500-mesh screen covers one side of the permeable stone towards the inside of the tube. Transparent acrylic plates are used as cover plates at both ends, flanges connect all joints, and all joints of the main part are equipped with an O-type rubber sealing ring. The upstream of the main unit is the water supply system, which is mainly used to provide seepage liquid. It is composed of a pump, water intake, flow control valve, storage tank safety relief valve, and pipe. Downstream of the main body of the device is the flow measurement system, which is mainly used to monitor the liquid flow, which is composed of the atmospheric storage tank, pipe, water stop valve, flow monitor, and water outlet; Figure 3 is the design drawing of the seepage experiment device. The blue arrow represents the flow direction, and the blue dotted line represents the flow direction. At present, the device has been applied for an invention patent [42].

Table 3: Similar scale coefficients of the dam test.

| Similarity parameter | Similar ratio |
|----------------------|---------------|
| Length               | 1 : 100       |
| Volume               | 1 : 400       |
| Velocity             | 1 : 200\(^{1/2}\) |
| Volume flow          | 1 : 200\(^{5/2}\) |
| Mud density          | 1 : 1         |

2.2.3. Experimental Steps and Methods. According to the particle grading curve of tailing at different positions of the tailing dam obtained from the tailing sedimentation test, layered tailing is prepared and the original mixed tailing is ready for the control test. In the actual tailing dam, water is easy to accumulate at the end of the dry beach surface. Combined with the tailing stratification test, it is not difficult to infer that water permeates from finer tailing to coarser tailing. In this test, the tailings loaded upstream of the seepage flow are the finest, which are defined as the upstream fine sand, while the tailings loaded downstream of the seepage flow are relatively coarse, which are defined as the downstream fine sand. The tailings loaded in the middle of the seepage flow are between the two, which are defined as the middle stream fine sand.

The porosity of tailing is adjusted by controlling the quality of tailing in a single seepage pipe so that the porosity is consistent with the actual working condition. Fill the tailings according to the assembly steps of the test device, install a complete set of experimental equipment, and use a vacuum pump to make the main body of the seepage pipe in a vacuum state. And make the tailings gradually saturated under the conditions of low water head and low flow rate. After the tailing is saturated, adjust the flow controller to control the head gradient. After the readings of the flow controller and the water pressure gauge are stable, record the flow \(Q\) and the corresponding readings of each water pressure gauge and calculate the permeability coefficient \(k\). The procedure of the seepage test is shown in Figure 4.

In the unsteady seepage test, after 48 hours of stable seepage, adjust the pressure of the upstream hydraulic pump to make the hydraulic gradient gradually rise to a certain fixed value in a fixed time. And then adjust the pressure of the upstream hydraulic pump to the pressure in the steady seepage state to make the hydraulic gradient naturally drop to the level in the steady seepage. It can be used to simulate the situation when the tailings in the tailings dam enter into the unsteady seepage state. Record the data of the flow rate and water pressure gauge during the whole test and calculate the permeability coefficient \(k\).

3. Results

After the experiment was completed according to the experimental steps, the tailing along the dry beach surface was divided into five sections with the unit of 1 m. The mean value data of the most downstream sand sample was 1# data, which was numbered up in sequence and named as 1# lower reaches, 2# middle and lower reaches, 3# middle reaches, 4#
middle and upper reaches, and 5# upper reaches. Finally, the particle size distribution along the length direction of the dry beach surface was obtained and the results of particle grading curve screening are shown in Figure 5.

3.1. Analysis on the Screening Results of the Particle Grading Curve of Comprehensive Tailings.

Compared with the grain grading curve of the original sand, the grain grading curves of the 1# lower reaches and the 2# middle and lower reaches show a significant right shift, that is, the refinement phenomenon, and the silt grade particles of the downstream tailings significantly increase. In the 3# middle reaches, the 4# middle and upper reaches, and the 5# upper reaches, the grain grading curves show a noticeable left shift, that is, the coarsening phenomenon, and tailing with the particle size of 0.2 mm–0.4 mm increases significantly. When the slope of dry beach surface is 1%, the stratification of tailings is not apparent, the gradation of tailings in the middle and lower reaches is almost the same as that of the original sand, and the upstream tailings slightly coarsen. When the slope of the dry beach surface is 1.5%, the tailing is stratified after discharge, the gradation of tailing in the downstream is not apparent, and the tailing in the middle and upstream is obviously coarsened. When the slope of the dry beach is 2%, the tailing stratification is visible, the tailing in the middle and upper reaches is obviously coarsened, and the tailing in the lower reaches is obviously refined.

According to the research [43], the probability of separation and deposition of tailings can be simplified as follows:

$$\lambda = \frac{vI}{W},$$  \hspace{1cm} (3)

where $\lambda$ is the judgment factor of tailings deposition, $v$ is the seepage velocity, $I$ is the hydraulic gradient, and $W$ is the deposition velocity of tailings.

When $\lambda$ is greater than 1, the horizontal flow kinetic energy of tailings sand is higher than its deposition kinetic energy. At this time, the tailings particles will not be deposited on the dry beach surface; on the contrary, the tailings particles will be deposited on the dry beach surface. Combined with the engineering practice and the analysis of tailings deposited in the simulated tailings pond, tailings with a particle size greater than 0.4 mm are sedimentary particles, which are not easy to be impacted in the middle and lower reaches. The tailings in this particle size range are mainly deposited to form the upstream part of the simulated tailings dam, that is, the impacted beach of the actual tailings dam, as shown in Figure 6(a). Fine sands with the particle size of 0.40–0.15 mm are bedload particles, which are greatly affected by the flow of water. The tailings in this particle size range are mainly deposited to form the middle part of the simulated tailings dam. The upstream region is the transition section and the underwater sedimentary slope of the actual tailings dam, as shown in Figure 6(b), the fine sand and silty sand with the particle size of 0.15–0.075 mm are mobile.
Figure 5: Continued.
particles, and the tailings in this particle size range are mainly deposited to form the downstream part of the simulated tailings dam, which is the slime area of the actual tailings dam, as shown in Figure 6(c).

The particle size distribution of tailings is random and can only obey the regular statistics. After data processing, the functional relationship between weighted average particle size $D_{50}$ and beach length $L$ under different slopes is obtained, as shown in Figure 7. It is not difficult to see from the fitting line of average particle size $D_{50}$ that the average particle size $D_{50}$ gradually decreases from near to far and the average particle size $D_{50}$ of middle and lower reaches is similar to that of raw sand. With the increase of the slope, the distribution of average grain size $D_{50}$ along the dry beach is more uneven. Compared with the original sand, the coarsening phenomenon of the upstream tailings is higher than that of the downstream tailings and the coarsening aspect is more evident with the increase of the slope.

The average particle size distribution of tailings under different slopes and the grading of tailings in different regions are obtained through the tailing’s deposition test. The test
can well restore the distribution of tailings in the tailings dam after discharge. Based on the experimental data of tailings deposition, we can restore the stratification of tailings in the tailings dam. This provides effective data for a subsequent seepage test of layered tailings. The layered sample in the tailings seepage test was made according to the tailing’s deposition test. The permeability coefficient of layered tailings obtained from this method will be more in line with the actual conditions.

4. Analysis and Discussion

4.1. Analysis of Test Results of Tailings Seepage. Based on the analysis of the change of the permeability coefficient of the original sand with time, the change process of the permeability coefficient of the tailings sand is divided into the following four stages: rapid compaction stage, slow compaction stage, seepage failure stage, and seepage stability stage. The division interval is shown in Figure 8.
Under the condition of stable seepage, the permeability coefficient of tailings decreased by about 11.6% in 16 hours. Through the polymethyl methacrylate (PMMA) tube, it is found that the fine tailings particles in the tube migrate with the flow of water to the downstream direction of seepage and the tailings are in the stage of rapid compaction. After 56 hours, the permeability coefficient decreased by about 6%. The migration of fine particles in the pipe was not obvious, and the tailing was in the stage of slow compaction. After 72 hours of seepage, the permeability coefficient reaches the minimum value of $3.36 \times 10^{-3}$. The tailing in the transparent glass tube begins to show apparent cracks. After that, the permeability coefficient increases rapidly. In the next 48 hours, the permeability coefficient increases quickly by about 30%, which is 9% larger than the initial permeability coefficient. The tailings are in the stage of seepage failure. Through the transparent plexiglass tube, it is found that the tailing structure of the upstream section has apparent changes. The original intact soil structure has showed cracks due to the migration of fine-grained tailing, and the cracks gradually increase with time, as shown in Figure 9. After 120 hours of seepage, the permeability coefficient is gradually stable. At this time, the soil structure no longer changes significantly and the previous cracks no longer increase. At this time, the tailings are in the stable seepage stage after the soil structure changes. The final permeability coefficient is increased by 9% compared with the initial state.

When other test conditions remain unchanged, the water head gradient will be changed after the tailing seepage is stable for 48 hours, so that the tailings which have not completed the seepage compaction will enter the unstable seepage situation. In the process of water head gradient from a gradual rise to a slow decline, tailings enter the seepage failure stage ahead of time. Compared with the steady seepage, the change rate of the permeability coefficient increases obviously, and when the water head gradient returns to the stable seepage state, the permeability coefficient is still increasing continuously. After about 56 hours, the permeability coefficient is stable. Under the condition of unsteady seepage, the permeability coefficient of the seepage failure stage increases by about 21% compared with the original one. The main reasons are that the flow impact force is large, the migration of fine sand is visible, and the cracks and voids in the sand are more than those in the steady seepage state. Even after the tailings enter the stable seepage state again, the permeability coefficient is still larger than that of the tailings which have been in the steady seepage state. Through the transparent plexiglass tube, it is found that the fracture of fine tailings caused by unstable seepage is more than that by stable seepage and the fracture is larger. After the tailings are subjected to seepage potential erosion, the soil structure has significantly changed, which leads to the change of the permeability coefficient. After the tailings enter the stable seepage state again, the soil is recombined to achieve a new stable state. After the continuous stable seepage, the gap between the original tailings filled still and the permeability coefficient showed a downward trend after the 6th day. The final permeability coefficient was 15% larger than that in the initial state and 5% larger than that in the stable seepage state.

4.2. Analysis of Seepage Test Results of Layered Tailings.

Adopt the same test method as the original sand to carry out the stable and unstable seepage test of layered tailings, and the change of permeability coefficient of the final layered tailings test is shown in Figure 10.

Under the condition of stable seepage, the seepage characteristics of layered tailing are consistent with that of original sand. In the early stage of rapid compaction, the permeability coefficient of fine sand in the middle and upper reaches has a wide range of variation and the permeability coefficient has decreased by about 11%. In comparison, the variation range of fine sand in the downstream is only about 8%. After a period of seepage, the layered tailing enters the stage of slow compaction. The minimum permeability coefficient of the upstream fine sand is $3.06 \times 10^{-3}$, which is about 15% lower than the initial state. The minimum permeability coefficient of the fine sand in the middle stream is $3.10 \times 10^{-3}$, which is about 16% lower than the initial state. The minimum permeability coefficient of the downstream fine sand is $3.40 \times 10^{-3}$, which is about 12% lower than the initial state. Finally, the permeability coefficient of fine sand in the upper reaches is stable at about $3.90 \times 10^{-3}$, which is about 8% higher than the initial permeability coefficient. The permeability coefficient of fine sand in the middle stream is stable at about $4.10 \times 10^{-3}$, which is about 11% higher than the initial permeability coefficient. The permeability coefficient of the downstream fine sand is stable at about $4.45 \times 10^{-3}$, which is about 14% higher than the initial permeability coefficient, this is, slightly different from the permeability coefficient of the original sand only increased by 9% after steady seepage. In the whole process of seepage, the permeability coefficient value is always increasing from upstream to
Figure 10: Continued.
downstream. Still, compared with the initial state, the variation range of permeability coefficient of tailings in middle and lower reaches is larger than that in upstream.

Similarly, the stratified tailings also meet the previously mentioned classification law of seepage characteristics under the condition of unsteady seepage. After the rise of the water head gradient, the slow compaction stage of layered tailing ends ahead of time and enters the seepage failure stage. Moreover, after the water head gradient returned to normal, the permeability coefficient continued to increase. At the same time, visible damage and cracks were found in the soil structure through the transparent plexiglass tube. Until the soil structure of layered tailing is stable again, the permeability coefficient gradually tends to be stable. The permeability coefficient of tailings with different layers after unsteady seepage is significantly increased compared with that after stable seepage. Among them, the permeability coefficient of fine sand in the upstream increases by 4%, that in the middle stream increases by about 10%, and that in the downstream increases by about 8%, which is different from that of the original sand which only increases by 5% after unsteady seepage. Compared with the initial seepage state of tailings, the variation range of the permeability coefficient of middle and lower reaches is larger than that of upstream.

Through the study of permeability coefficient variation of layered tailings under stable or unstable seepage conditions, it is found that the influence of tailings particle migration with seepage on the permeability coefficient is holistic. Among them, the tailings in the middle and lower reaches are most affected by it, corresponding to the actual tailings dam, underwater sedimentary slope, transition section, and shoal which are greatly affected by seepage. And it provides the basis for the stability research and numerical simulation of the actual tailings dam in the next step. Therefore, the influence of tailing stratification and unsteady seepage on the permeability coefficient should be considered in the study of tailings seepage.

### 4.3. Analysis of Screening Test Results after Seepage

Through screening test on the tailings after seepage, the change of grading of layered tailings before and after seepage is obtained, as shown in Figure 11. In the process of seepage, the tailing with a small particle size migrates from upstream to downstream. After the seepage potential erosion, the tailing of each layer shows an obvious coarsening phenomenon. Because the upstream fine sand is in the middle and upper reaches of seepage and the content of small- and medium-sized tailings in this position is high, the coarsening phenomenon of upstream fine sand is the most obvious. However, the downstream fine sand is in the downstream of seepage flow. Therefore, the content of small-size tailings is not high, which leads to the nonobvious coarsening phenomenon of the downstream fine sand in the middle and downstream, and the content of small-size tailings also increases.

It is not difficult to find from Figure 11 that the grading curve of upstream fine sand after seepage erosion coincides with the initial grading curve of fine midstream sand. And the grading curve of midstream fine sand after seepage erosion coincides with the initial grading curve of downstream fine sand. The coarsening phenomenon of the upstream fine sand is the most obvious. In the upstream fine sand, the particles with the particle size of 0.20–0.40 mm migrate by about 10%–30% to the downstream. And the particles with the particle size of 0.18 migrate most to the downstream, by about 30%. The fine sand in the middle stream also has a coarsening phenomenon, and the tailings particles with the particle size of 0.18–0.50 mm all migrate by about 10%–15% to the downstream. In the process of seepage, the coarsening

![Figure 10: Comparison of unsteady seepage and stable seepage permeability coefficient.](image-url)
phenomenon of the fine sand in the middle stream is weaker than that of the fine sand in the upper reaches. It is mainly because the particle size distribution of the tail sand in the middle stream is affected by the migration of the tail sand in the upper reaches and the decrease of the hydraulic gradient of seepage. In the same way, influenced by the movement of fine particles from the middle and upper reaches to the lower reaches, there is almost no coarsening phenomenon in the downstream fine sand. There is a certain refining phenomenon in the range where the particle size of the tailings is less than 0.16 mm. The content of the tailings with the particle size less than 0.16 mm in the downstream fine sand increases by about 5%. And the similar phenomenon also occurs in the content of the tailings with size less than 0.16 mm in the middle stream fine sand.

Seepage will eventually lead to worse tailings with poor grading. The small-sized tailings upstream of seepage will continue to migrate to the downstream with the flow, and the gap between the downstream tailings will continue to be filled by these small-sized tailings. The upstream void increases gradually, the downstream void decreases gradually, and the permeability coefficient changes, even forming an impermeable layer in a part of the downstream. At this time, the saturation line in the tailings dam also changes. When the water in the dry beach area of the tailings dam is at the average level, the influence of seepage on the safety of the tailings dam may not be significant. Still, when encountering sudden downpour and rainstorm, the water level rises suddenly or the seepage erosion is experienced all the year-round and the change of permeability coefficient caused by seepage will undoubtedly affect the safety of the tailings dam.

5. Conclusion

(1) When the tailings are put into the tailings dam, the tailings show the phenomenon of coarsening in the upstream and refining in the downstream under the scouring effect of the water flow. The average grain size of tailings decreases along the length of the dry beach. When the dry beach slope is 1%, the tailing layer is not apparent. When the dry beach slope is 1.5%, the tailings in the middle and upper reaches are coarsened. When the dry beach surface slope is 2%, the tailings in the middle and upper reaches are coarsened and the tailings in the downstream are refined.

(2) Based on the analysis of the change of the permeability coefficient of the original sand with time, the change process of the permeability coefficient of the tailings sand is divided into the following four stages: the rapid compaction stage, slow compaction stage, seepage failure stage, and seepage stability stage. The permeability coefficient of tailings increases by about 10% under a stable seepage condition and increases by about 15% under an unsteady seepage condition.

(3) Variation of the permeability coefficient of layered tailings is the same as that of ordinary tailings. Under the condition of steady seepage, the permeability coefficient of the middle and lower reaches changes significantly. Compared with the initial state, the permeability coefficient increases by about 12%. Similarly, the unsteady seepage has a significant
influence on the middle and lower reaches of layered tailings and the permeability coefficient is generally about 9% larger than that of steady seepage.

(4) The screening test of tailings after seepage is carried out. The results show that the coarsening phenomenon of the upstream fine sand is the most obvious and the particles with the size of 0.20–0.40 mm in the upstream fine sand migrate by about 10%–30% to the downstream. The fine sand in the middle stream also has a coarsening phenomenon. Moreover, the particle with a size of 0.18–0.50 mm migrates by about 10%–15% to the downstream. The grain size of the downstream fine sand is smaller than 0.16 mm, and the content of the tailings increases by about 5%.

**Data Availability**

Data are available upon request.

**Conflicts of Interest**

The authors declared that they have no conflicts of interest.

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