Experimental Study on the Effects of Internal Erosion on the Physical and Mechanical Properties of Tailings Under Unsteady Seepage

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Research Article

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Experimental study on the effects of internal erosion on the physical and mechanical properties of tailings under unsteady seepage

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Abstract:
In this paper, the hydraulic sedimentary model was established to investigate the effects of dry beach slope on the sedimentary characteristics of tailings, and the sand column model was built to investigate the effects of seepage erosion on the physical and mechanical properties of sedimentary tailings under unsteady seepage. The results show that the slope of dry beach have a great effect on the sedimentary characteristics of tailings, the average particle size of tailings decreases along the slope of dry beach, and the larger the slope, the more obvious the stratification of the tailings. The migration of fine-grained tailings caused by seepage erosion increases the permeability of the tailings and reduces the shear strength of the tailings. After seepage erosion, the average particle size of 1#tailings sample, 2#tailings sample and 3#tailings sample increased by 6.4%, 12.0% and 2.4% respectively, the hydraulic conductivity of 1# tailings sample, 2# tailings sample and 3# tailings increased by 27.2%, 17.9%, and 15.3% respectively after internal erosion, and the shear strength of 1#tailings sample, 2#tailings sample and 3#tailings sample tailings sample decreased by 20.9%, 15.1% and 12.4% respectively.

Key words: Upstream tailings dam; Sedimentary characteristics; Unsteady seepage; Seepage erosion; Particle size distribution; Hydraulic conductivity
1. Introduction

As the third-largest mining country, China produces about 300 million tons of tailings every year. And most of the tailings were stored in more than 2,000 tailings reservoirs. However, more than 20% of these hydraulic structures are at risk of dam failure, which has been one of the most dangerous sources for the mining enterprises\textsuperscript{1,2}. Serious tailings dam-failure accidents have happened all over the world. For example, tailings dam-failure accidents of Xinta Mining Company (Shanxi Province, China) in September 2008 claimed the deaths of 270 people and the direct economic loss of 96.19 million RMB Yuan\textsuperscript{3}. On the 25th January 2019, the collapse of Córrego do Feijão tailing dam at Brumadinho city (Minas Gerais, Brazil), causing at least 12 million cubic meters of tailing were spread into Paraopeba River and the surrounding area, leaving over 250 people dead\textsuperscript{4}.

The United States Committee on Large Dams (USCOLD) evaluated the causes of dam-failure accidents, indicated that heavy rainfall was the critical factor that contributes to 30% of the dam-failure accidents\textsuperscript{5-7}. When the heavy rainfall infiltrates into the tailings, the saturation line of dam will rise rapidly, the increased hydrostatic and dynamic water pressure will promote the migration of fine-grained tailings in the pore-channel, and further affect the physical and mechanical properties of tailings. Therefore, it is necessary to investigate the erosion mechanism and the effects of seepage erosion on the stability of tailings dams under heavy rainfall.

For the past few years, many researches have been conducted to analyze the influence of seepage erosion on geotechnical structure from theoretical analysis, physical model and numerical simulation. Chen et al investigated the migration trend of the fine particles in cohesionless soils and the change law of content of the remaining fine particles during the internal erosion process using self-designed equipment\textsuperscript{8}. Zhang established the numerical model of slope to analyze the effects of seepage erosion on the stability of the slope\textsuperscript{9}. Yao et al. investigated the mechanism of unstable embankment caused by seepage erosion, and analyzed the effect of the increasing water level and hydraulic conductivity on the stability of the embankment\textsuperscript{10}. Zhang et al. proposed the prediction formula of the critical vertical upward hydraulic gradient of the gravel soil based on the force balance theory of a particle group under seepage erosion\textsuperscript{11}. Wilson et al. investigated the impact of soil properties on seepage erosion, and built the streambank stability model to demonstrate the increase of bank's instability due to undercutting by
seepage erosion. Chu-Agor et al. develop an empirical sediment transport function to predict seepage erosion and undercutting of cohesive bank with time based on three-dimensional soil block experiments. Ke et al. performed a series of one-dimensional upward seepage tests at a constant water head to cause internal erosion in a soil sample, and pointed out that internal erosion causes a significant increase in void ratio and hydraulic conductivity, resulting in a reduction of soil strength. Midgley et al. performed the seepage research on a streambank of Dry Creek, and pointed out seepage erosion plays an important role in the streambank failure, especially when acting in concert with fluvial erosion processes. Jiang et al. used MICP technology to control the internal erosion of sand-clay mixtures by test apparatus in the laboratory, and pointed out that MICP treatment facilitates the reduction of erosion and volumetric contraction of sand-clay mixtures. Liu et al. (2018) designed a large-scale triaxial testing system to investigate seepage erosion properties of water inrush in completely weathered granite by monitoring the mass transfer and the flow properties over time.

Upstream tailings dam is the most commonly used mode for dam construction of tailings reservoirs in China, its safety has aroused extensive attention due to the disadvantages of poor dam stability, high saturation line and poor seismic performance. Upstream tailings dam is more susceptible to produce seepage erosion under the hydrodynamic and hydrostatic pressure caused by heavy rainfall due to the distinctive deposition characteristics of tailings. Taking an upstream tailings dam in southern China as research object in this paper, the hydraulic sedimentary model was established to analyze the sedimentary characteristics of tailings on the dry beach, the unsteady seepage test was performed to investigate the effect of seepage erosion on the physical and mechanical properties of tailings. The research results play an important role in analyzing and predicting the effect of seepage erosion on the stability of tailings dam under heavy rainfall.

2. **Sedimentary characteristics of tailings under different dry beach slopes**

Seepage erosion of tailings dam is influenced by the gradation, spatial distribution and porosity of tailings on the seepage path. The tailings in upstream tailings dam show a distinctive deposition characteristics along the dry beach slope due to hydraulic sedimentation during the discharge process. The fine-grained tailings and coarse-grained tailings locate in the upstream and downstream of seepage field respectively, resulting in fine-grained tailings are easier to migrate to the downstream under the action of seepage force, as shown in Fig.1. Therefore, it is necessary to analyze sedimentary characteristics of the tailings before investigating seepage erosion of upstream tailings dam.
2.1 Experimental materials and model

2.1.1 Raw tailings

The raw tailings were chosen came from the discharge outlet of a tailings reservoir in southern China. The height of the tailings reservoir is 42.1 m with a slope ratio of 1:4, and the length of dry beach is 50 m with a slope of 1% - 2%. The physical properties of the raw tailings were determined according to the Standard for Geotechnical Testing Method (GB/T 50123-2019), as shown in Table 1.

| Raw material | Density $\rho (g/cm^3)$ | Moisture content % | Pore ratio $e$ | Relative density $G_s$ | Dry density $\rho_d (g/cm^3)$ |
|--------------|------------------------|--------------------|--------------|-----------------------|---------------------------|
| Tailings sample | 1.42 | 14.0 | 1.11 | 2.68 | 1.27 |

The particle characteristics of the raw tailings sample were analyzed by Screening Test, and the particle size smaller than 0.075 mm was determined by Winner2000 Laser Particle Size Analyzer\textsuperscript{18}. The particle size distribution curve was plotted according to test results, as shown in Fig. 2.
The particle characteristics of the raw tailings sample were calculated according to Fig.2, as shown in Table 2.

| Characteristic values | Effective particle size $d_{10}$ (mm) | Median particle size $d_{30}$ (mm) | Average particle size $d_{50}$ (mm) | Restricted particle size $d_{60}$ (mm) | Non-uniformity coefficient $C_u$ | Curvature coefficient $C_c$ |
|-----------------------|--------------------------------------|-----------------------------------|------------------------------------|--------------------------------------|-------------------------------|--------------------------|
| Raw tailings sample   | 0.031                                 | 0.092                             | 0.097                              | 0.102                                | 3.33                          | 2.66                     |

### 2.1.2 Experimental model

A physical model of tailings hydraulic sedimentation was established to simulate the tailings discharge process of the upstream tailings dam and to analyze the sedimentary characteristics of tailings on the dry beach. The main body of the model is a length of 500cm plastic groove with trapezoidal cross-section (30cm wide of the topline, 20cm wide of the baseline, and 10cm high) to simulate the dry beach of tailings dam. A height-adjustable cushion set at the upstream of the model to adjust the slope of the groove (1%-2%), which is consistent with the dry beach slope of the tailings dam. A plastics discharge pipe with an inner diameter of 0.3cm is installed at the bottom of the mixing tank for discharging the tailing slurry, as shown in Fig.3.
According to the Froude criterion, the model and prototype should have the same Froude number to meet the dynamic similarity conditions when the fluid flow is dominated by inertial force and gravitational force. The Froude number is a ratio of inertial and gravitational forces in fluid flow, as shown in Formula (1):

$$F_r = \frac{v}{\sqrt{gL}}$$  \hspace{1cm} (1)

Where, $F_r$ is the Froude number; $g$ is gravity; $v$ is water velocity; $L$ is the length of fluid flow.

The flow of the tailings slurry on the dry beach is dominated by inertial and gravitational forces, so the Froude number of the model should be the same as that of the prototype, that is $F_{rm} = F_{rp}$.

$$\frac{v_m}{\sqrt{gL_m}} = \frac{v_p}{\sqrt{gL_p}}$$  \hspace{1cm} (2)

$$\frac{L_p}{L_m} = \frac{v_p^2}{v_m^2}$$  \hspace{1cm} (3)

Where, $F_{rm}$, $L_m$, $v_m$ is the Froude number, length, water velocity of model; $F_{rp}$, $L_p$, $v_p$ is the Froude number, dry beach length, water velocity of prototype.

The similarity ratio of the hydraulic parameters between the model and the prototype was derived according to the Froude criterion, as shown in Table 3.

| Parameters           | Similar ratio |
|----------------------|---------------|
| length               | 1:100         |
| Fluid flow area      | 1:400         |
| Flow rate            | 1:100$^{1/2}$ |
| Volume flow          | 1:200$^{5/2}$ |

The actual flow rate of tailings slurry at the discharge outlet of the tailings dam is measured by a flow meter, is 1.72 m/s, as shown in Fig.4.
The hydraulic parameters for the model test were calculated according to the actual flow rate, as shown in Table 4.

**Table 4  The hydraulic parameters of the model**

| Similar parameters | Water velocity $\text{cm/s}$ | Volume flow $\text{m}^3/\text{s}$ | Mass ratio of water and tailings |
|--------------------|-----------------------------|---------------------------------|---------------------------------|
| Test values        | 17.2                        | 1.21e-6                          | 3:1                             |

### 2.2 Experimental procedures

(1) The slope of the trapezoidal groove is maintained at 1% by adjusting the height of the cushion.

(2) Put the tailings and water in the mixing tank at a mass ratio of 1:3. When the tailings slurry is uniformly stirred, drain it into the trapezoidal groove according to the design volume flow of the model until the stack height of upstream tailings exceeds 10cm.

(3) The samples are taken from the tailings at the downstream, midstream and upstream of the trapezoidal groove, which are numbered as 1 # tailing sample, 2 # tailing sample and 3 # tailing sample when the water is completely drained out of the groove.

(4) Dry the tailings samples with a thermostatic drying chamber (105~110°C) for no less than 10h. The particle size distribution curves of tailings samples are plotted according to the results of Screening Test and Laser Particle Size Analysis., and the effect of the slope of the Trapezoidal groove on the sedimentary characteristics of tailings are analyzed.

(5) Change the slope of the Trapezoidal groove to 1.5% and 2.0% by adjusting the height of the cushion, and repeat the procedures of step (2) to step (5).
2.3 Results and Discussion

The particle size distribution curves of tailings samples at different slopes of the trapezoidal groove were plotted according to test results, as shown in Fig.5.

(a) 1% slope

(b) 1.5% slope
Fig. 5 Particle size distribution curves of sedimentary tailings samples at different slopes

As can be seen from Fig. 5, the raw tailings were stratified along the slope of the trapezoidal groove under the action of hydraulic alluvium and the self-weight of the tailings, and the downstream tailings were finer than the upstream tailings. The slope of the trapezoidal groove has an important effect on the sedimentary characteristics of tailings; the greater the slope, the more obvious the stratification deposition of tailings. When the slope is 1%, the particle size distribution curves of downstream tailings (1# tailings), midstream tailings (2# tailings) and upstream tailings (3# tailings) in the trapezoidal groove are shown in Fig. 5(a). We can see that the average particle size of upstream tailings (3# tailings) is 0.108 mm, increased by 11.4% compared to 0.097 mm of the raw tailings. And the particle size distribution curves of 2# tailings and 3# tailings have no significant change compared with that of the raw tailings, indicating that 1% slope is not conducive to the sedimentation of downstream tailings due to low horizontal kinetic energy of tailings slurry; when the slope is 1.5%, we can see from Fig. 5(b) that the sedimentary characteristics of tailings are more obvious than that of 1% slope, the average particle size of 3# tailings sample and 2# tailings sample increased by 16.4%, 11.4% respectively, the average particle size of 1# decreased by 16.4% compared with that of the raw tailings. And the non-uniformity coefficient $C_u$ of 3# tailings sample and 2# tailings sample increased due to amounts of fine-grained tailings are carried to the downstream by the water. The amount of mid-grained tailings increased in the midstream, and decreased significantly in the downstream of the model; When the slope is 2%, we can see from Fig. 5(c) that the average particle size of 3# tailings sample and 2# tailings sample have more significant increase than that of 1.5% slope. The coarse-grained tailings and fine-grained tailings are more concentrated in the upstream and
downstream of the model respectively, only 27.6% of the upstream tailings have particles size smaller than 0.1mm, while more than 75.8% of the downstream tailings have particles size smaller than 0.1mm.

According to the literature\textsuperscript{19}, the sedimentary probability of tailings can be expressed by Formula (4):

$$\lambda = \frac{v_i}{W}$$

Where,
- $\lambda$ - judgment factor for tailings sedimentation
- $v$ - water velocity (m/s)
- $i$ - hydraulic gradient
- $W$ - sedimentary velocity of tailings (m/s)

When the $\lambda$ value is greater than 1, the horizontal kinetic energy is greater than sedimentary energy of the tailings slurry, and the tailings are hard to deposit; when the $\lambda$ value is less than 1, the tailings are easy to deposit. According to the particle size distribution curves of the hydraulic sedimentary test, the tailings with a diameter smaller than 0.075 mm are hard to deposit, mainly located in the downstream of the model; the tailings with a particle size of 0.075~0.15mm are mid-grained tailings primarily located in the middle of the model, its particle size distribution along the model slope is most influenced by the hydrodynamic value; the tailings with a particle diameter larger than 0.15mm are quickly deposited on the downstream to form the tailings dam.

The average particle size distribution of sedimentary tailings along the slope of dry beach obeys the statistical law. According to the results of hydraulic sedimentary test, the average particle size $D_{50}$ as a linear function of the dry beach length $L$ at the dry beach slope of 1.5% can be expressed by the Formula (5).

$$D_{50} = 0.4394 - 6.51 \times 10^{-4} \times L$$

The relationship of average particle size $D_{50}$ with the distance of sampling point from upstream $L$ is shown in Fig.6. We can see that the test value of average particle size was consistent with that of on-site measured values, indicating that the results of hydraulic sedimentary test can accurately reflect the sedimentary characteristics of dry beach tailings.
3. The effect of internal erosive on the physical and mechanical properties of tailings under unsteady seepage

3.1. Critical condition of seepage erosion

The hydraulic conductivity $K$ can be derived from Darcy’s law due to sedimentary tailings have low hydraulic conductivity, as shown in Formula (6).

$$ K = \frac{Q}{iSt} $$  \hspace{1cm} (6)

Where,

$K$ - Hydraulic conductivity (m/s)
$Q$ - Total volume flow at $t$ time (m$^3$)
$i$ - Hydraulic gradient
$S$ - Cross-sectional area of specimen (m$^2$)
$t$ - Seepage time (s)

In the porous medium, the fine-grained tailings are easy to be washed away under the action of seepage force, and the derivation process of the critical hydraulic gradient of seepage erosion is derived as follows$^{20}$:

The weight of saturated fine-grained tailings $G'$:

$$ G' = (\gamma_s - \gamma_w) \cdot V $$  \hspace{1cm} (7)

Where,

$G'$ - Weight of fine-grained tailings (N)
\( \gamma_s \) - Bulk unit weight of fine tailings (N/\( m^3 \))

\( \gamma_w \) - Bulk unit weight of water (N/\( m^3 \))

\( V \) - Volume of fine tailings

The seepage force of fine-grained tailings is \( F \):

\[
F = i \gamma_w \cdot V
\]  

(8)

The initiation of fine-grained tailings should overcome the static friction force between the particles due to the cohesion of saturated tailings is 0:

\[
f = G' \cdot \tan \varphi
\]  

(9)

Where,

\( f \) - the static frictional resistance between the fine-grained tailings (N)

\( \varphi \) - internal friction angle of underwater fine-grained tailings (°)

The critical equilibrium condition for fine-grained tailings initiation is \( F = f \), so the critical hydraulic gradient of internal erosion is \( i_{cr} \):

\[
i_{cr} = \frac{G' \cdot \tan \varphi}{\gamma_w \cdot V}
\]  

(10)

3.2. Experimental model

A sand columns model was established to investigate the effect of internal erosion on the physical and mechanical properties of tailings under unsteady seepage, as shown in Fig.7. The main body of the physical model was consists of three sand columns (Column 1, Column 2 and Column 3) which were connected by flanges, each sand column was made of polyvinyl chloride (PVC) with a maximum internal diameter 15 cm and a length of 30cm. The water pressure gauges were installed on the top of the model at a distance of 15 cm to measure the height of the water head. The water head differences between water pressure gauges can be controlled by adjusting the flow rate of the outlet flowmeter. A water tank with a maximum height of 3m connected the end of the model to simulate the raising saturation line of tailings dam under heavy rainfall.
3.3. Experimental procedures

(1) Put the sedimentary tailings into the corresponding sand columns according to the hydraulic sedimentary test. The downstream tailings (1# tailings sample), midstream tailings (2# tailings sample) and upstream tailings (3# tailings sample) in hydraulic sedimentation test are put into the column 1, the column 2 and the column 3 respectively, which is consistent with the actual seepage and tailings deposition characteristics of the tailings dam.

(2) After installing the experimental model, open the inlet valve to let the water saturate the sand columns for 24h.

(3) After the tailings sample is saturated, the outlet flowmeter is adjusted to control the water head gradient of water pressure gauges. When the readings of each water pressure gauges are stable, the flow Q and water head differences of each column are recorded, and the initial hydraulic conductivity of each sand column was calculated.

(4) Unsteady seepage under heavy rainfall was simulated in this test. Keep the water level of the water tank increasing at a rate of 0.1m/h for 24 hours, which is consistent with the rising rate of saturation line of the tailings dam under heavy rainfall in 50-years return period. The flow volume and the water head differences between the water pressure gauges were recorded over time, and the hydraulic conductivity K of each sand column was calculated.

3.4 Results and Discussion

3.4.1 The effect of internal erosion on the hydraulic conductivity of tailings samples

The effect of internal erosion on the hydraulic conductivity of each sand column under unsteady seepage as shown in Fig. 8.
As can be seen from Fig. 8, initial hydraulic conductivity of each sand columns is $3.35 \times 10^{-3}$ cm/s (1# tailings sample), $3.75 \times 10^{-3}$ cm/s (2# tailings sample) and $3.93 \times 10^{-3}$ cm/s (3# tailings sample). After 24 hours, the hydraulic conductivity of three sand columns increase to $4.26 \times 10^{-3}$ cm/s, $4.42 \times 10^{-3}$ cm/s, $4.53 \times 10^{-3}$ cm/s, which increase by 27.2%, 17.9%, and 15.3% respectively.

The variation characteristics of hydraulic conductivity coefficient with time can divide into four stages: rapid compaction stage, stable compaction stage, seepage erosion stage and stable seepage stage. In stage 1 (1h–3h), there was the maximum decrease in hydraulic conductivity, the hydraulic conductivity of 1# tailings sample, 2# tailings sample and 3# tailings sample reduced by 9.5%, 14.9% and 10.7% respectively. The fine-grained tailings have a small range of migration due to the sudden increase of seepage force, which reduces the pore volume of downstream tailings and reduces the permeability coefficient due to the compaction of tailings. In stage 2 (3h–6h), the hydraulic conductivity of each sand column tends to be stable due to the migration of fine-grained tailings and the increase of water head contributes to the balance of the hydraulic conductivity. In stage 3 (6h–14h), there was the maximum increase in hydraulic conductivity, the hydraulic conductivity of 1# tailings sample, 2# tailings sample and 3# tailings sample increased by 37.1%, 39.8% and 29.7% respectively. When the continuously rising water head reaches the critical water head height of tailings, lots of fine-grained tailings are washed away to the
downstream, resulting in seepage erosion and changing the skeleton structure of tailings. The critical hydraulic gradient of 1# tailings sample, 2# tailings sample and 3# tailings sample are calculated according to formula (10), are 0.32, 0.36, 0.41 respectively. In stage 4(14h–24h), the hydraulic conductivity of tailings samples remains constant regardless of the increase of water head, the tailings achieve a new stable state of hydraulic conductivity due to the particles of tailings were reorganized under the seepage force.

3.4.2 The effect of internal erosion on the shear strength of tailings samples

The tailings samples taken from each sand column in situ for Direct Shear Test after the internal erosion. The control shear rate was 0.8 mm/min. The shear strength and internal friction angle of each tailings sample before and after internal erosion were shown in Table 5.

| Time               | Tailings samples | Reduction rate of shear strength (%) | Internal friction angle (°) |
|--------------------|------------------|-------------------------------------|-----------------------------|
| Before seepage     | 1#tailings sample| 35.14                               |                             |
|                    | 2#tailings sample| 36.69                               |                             |
|                    | 3# tailings sample| 38.70                              |                             |
| After seepage      | 1# tailings sample| 20.9                                | 30.21                       |
|                    | 2# tailings sample| 15.1                                | 32.94                       |
|                    | 3# tailings sample| 12.4                                | 35.48                       |

As can be seen from Table 5, the shear strength and internal friction angle of the tailings samples decreased after internal erosion, the shear strength of 1# tailings sample, 2# tailings sample and 3# tailings sample in Column 1, Column 2 and Column 3 decreased by 20.9 %, 15.1% and 12.4% respectively under 100 kPa normal press. The internal friction angle of 1#tailings sample, 2#tailings sample and 3#tailings sample tailings sample decreased 14.0%, 10.2% and 8.3% respectively. It is indicated that seepage erosion changed the structure of tailings samples, and has the greatest influence on the shear strength and internal friction angle of upstream fine-grained tailings.

3.4.3 The effect of internal erosion on the particle size distribution curves of tailings samples

To further analyze the effect of seepage erosion on the physical properties of the tailings samples, the tailings samples after internal erosion were taken for Screening Test. And the comparison of particle-size distribution curves of tailings samples before and after internal erosion is shown in Fig. 9.
(a) 1# tailings sample

(b) 2# tailings sample
As can be seen from Fig. 9, the average particle size of 1# tailings sample, 2# tailings sample and 3# tailings sample in Column 1, Column 2 and Column 3 increased by 6.4%, 12.0% and 2.4% respectively due to the migration of the fine-grained tailings along the seepage direction from upstream to downstream. There are about 20% tailings with particle size smaller than 0.075mm, and about 10% tailings with the size of 0.075~0.1mm migrated to the downstream in the 1# tailings sample. The change of average particle size is not obvious, however the mass of tailings with the particle size below 0.1 mm increase by about 4% in 3# tailings sample.

4. Conclusions

Based on the above analysis and discussion, the following conclusions can be drawn:

(1) The average particle size $D_{50}$ of sedimentary tailings decreases along the slope of dry beach. The slope of beach slope has an important effect on the sedimentary characteristics of tailings, the greater the slope, the more obvious the stratification deposition of tailings.

(2) The average particle size distribution along the groove slope in hydraulic sedimentary test was consistent with that of on-site measured values, indicating that the test results can accurately reflect the sedimentary characteristics of dry beach tailings.

(3) The critical hydraulic gradient of 1# tailings sample, 2# tailings sample and 3# tailings sample are 0.32, 0.36, 0.41 respectively. When the hydraulic gradient of various tailings exceeds the critical value, the migration of the fine-grained tailings will result in seepage erosion.
(4) The migration of fine-grained tailings caused by seepage erosion increases the permeability of the tailings and reduces the shear strength of the tailings. After seepage erosion, the hydraulic conductivity of 1# tailings sample, 2# tailings sample and 3# tailings sample increase by 27.2%, 17.9%, and 15.3% respectively, and the shear strength of 1# tailings sample, 2# tailings sample and 3# tailings sample tailings sample decreased by 20.9%, 15.1% and 12.4% respectively.

(5) The average particle size of 1# tailings sample, 2# tailings sample and 3# tailings sample increased by 6.4%, 12.0% and 2.4% respectively due to the migration of the fine-grained tailings along the seepage direction. More than 20% fine-grained tailings in the 1# tailings sample was migrated to the downstream.

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Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions
Authors GH designed the model and supervised the research, R.G reviewed and edited the manuscript. All authors participated in improving the manuscript.

Competing interests
The authors declare no competing interests.
Additional information

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