Stability Analysis of Tailings Dam based on the Combination of Seepage and Stress

LU Xiao-hui 1*, CHANG Xiong-shen 2

1 Mining Company limited of Ansteel Group Corporation, liaoyang, Liaoning, 111008, China
2 School of civil engineering, University of Science and Technology Liaoning, Anshan, Liaoning 114051, China
*Corresponding author’s e-mail: changxs1028cxs@163.com

Abstract. According to an example of a tailings dam, a numerical model is established by finite difference software FLAC3D, and a tailings dam is calculated and analyzed by the combination of fluid-solid coupling and strength subtraction method. The distribution of seepage field and flow rate of tailings dam and the approximate position of saturation line are determined. The coupling effect of stress field and seepage field under different dry beach length is analyzed. The result shows that with the decrease of dry beach length, the shear strain region gradually becomes wider and forms a through area, and the area with large shear strain appears at the top of the dam in the initial stage. The seepage flow of the tailings dam increases gradually, the saturation line rises and the safety factor of the tailings dam is reduced, so it is necessary to ensure the length of the tailings dam to be large enough in order to stabilize the tailings dam.

1. Introduction
The tailings dam is the peripheral dam structure of the tailings reservoir which stores the tailings and water. Because of the danger of dam break in the tailings dam, it is still a major hazard source. In the event of an accident, the debris flow with huge destructive power will flood downstream. It will do great harm to the lives and property of the people in the downstream area and cause serious pollution to the environment [1]. For example, on September 8, 2008, a dam burst accident occurred in a tailings pond in Shanxi Province, mainly due to the direct inflow of underground water into the tailings pond, resulting in the continuous rise of the reservoir water level, coupled with the destructive power of soil infiltration of the dam, resulting in the accident, resulting in 277 deaths, 4 missing, 33 injured. Therefore, the research on the stability of tailings dam seepage has always been the focus of the scholars, jian-bo han and others [2] have analyzed the stability of the a tailing by using the finite element strength method. the results show that the position of the critical slip surface obtained by the traditional theoretical method is basically the same as that of the plastic strain of through zone obtained by the strength reduction method. Li qiang [3] et al. also analyzed the seepage field of a tailings dam by combining fluid-solid coupling and strength reduction method, and determined the approximate position of the infiltration line, indicating that the position of the infiltration line is basically consistent with that of the measured infiltration line. Tang zhuo et al. [4] analyzed the seepage field, stress field and fluid-solid coupling effect of tailings ponds based on the seepage flow of unsaturated soil, and summarized the fluid-solid coupling calculation rule of upstream method tailings
ponds. Zhou shuwei et al. [5] studied the coupling effect of seepage flow and stress, and the results showed that different coupling relations had great influence on the prediction of x-direction displacement and permeability. Cao linwei et al. [6] simulated the coupled response characteristics of the seepage field and deformation field of longdu tailings dam, and obtained important indexes such as deformation of dam body and position of infiltration line. Sun conglu et al. [7] use geo-studio software to calculate that the buried depth of the infiltration line of the section is relatively shallow, and the maximum hydraulic gradient is located at the downstream of the initial dam, close to the base of the dam, and the maximum value exceeds the standard, which may cause flow soil or piping. It is suggested to adopt deep drainage measures of the dam body to reduce the free surface of the dam body and improve the stability of the dam body. Jin jiaxu [8] analyzed and calculated the seepage situation of tailing dam under the two conditions of normal seepage and failure, and concluded that the permeability of the initial dam is closely related to the seepage stability of tailing dam. Effective seepage can reduce the infiltration line of the dam body and ensure the safety of the dam body. By establishing the seepage calculation model, kang zhiqiang et al. [9] obtained the location map of infiltration line and color cloud map of each point gradient under different elevations, normal operating conditions and flood operating conditions. The dam stability of tailings pond is calculated and analyzed by comparing with the Swedish arc method. Deng hongwei [10] established a three-dimensional numerical model by using 3Dmine and Midas /GTS software. Based on the principle of seepage stress coupling, he studied the influencing mechanism of dry beach length on the stability of tailings pond dam. As the length of dry beach decreases, the pore water pressure of tailing dam gradually increases, while the overall displacement gradually decreases. The maximum displacement area gradually expands from tail clay layer to tail powder soil layer, and the safety coefficient of tailing pond gradually decreases. It can be seen that fluid-solid coupling is crucial to the stability analysis of tailings dam. In this paper, a numerical model will be established by FLAC3D to analyze the seepage stress coupling.

2. Seepage flow field and stress field are coupled

Porous rock and soil medium exists water head and will cause the flow of water, in the process of seepage, will produce a seepage of water, it will be on the rock and soil medium in a penetration volume force, penetration, as the external load will lead to the change of geotechnical medium of stress field, and the change of stress field can make the rock and soil medium displacement field changed. The change of the deformation field of rock-soil medium will change the porosity and porosity of rock-soil medium. As the permeability coefficient is related to the number of pores and pore size, the change of porosity and porosity will definitely cause the change of the permeability coefficient of media, so the seepage field will change. Therefore, the seepage field and stress field of rock and soil media are a whole interacting and interacting, and there is a coupling relationship between them.

2.1 Effect of seepage flow field on stress field

The effect of seepage field on stress field is reflected by the force exerted by seepage on medium. There are two main forces of water flow on soil. The other is osmotic hydrodynamic pressure. Osmotic hydrostatic pressure is the surface force consistent with normal direction, while osmotic hydrodynamic pressure is the osmotic volume force. According to the seepage theory, the seepage hydrostatic pressure and seepage volume force can be expressed as

\[ P = \gamma (H - z) \]  
\[ \mathbf{f} = \gamma \mathbf{J} \]

in which: \( P \) is the permeable hydrostatic pressure; \( \mathbf{f} \) is the force vector of seepage volume; \( \mathbf{J} \) is hydraulic gradient, \( \mathbf{J} = - \nabla H \).

2.2 Influence of stress field on seepage flow field

The effect of stress on seepage field is to change the porosity of soil medium through stress, thus
causing the change of seepage field. According to darcy's law, permeability coefficient \( K \) is expressed as permeability

\[
K = k \frac{\partial P}{\mu} = k \frac{\rho g}{\mu v} \quad (3)
\]

in which: \( \mu \) is the dynamic viscosity coefficient (ML\(^{-1}\)T\(^{-1}\)); \( v \) is the motion viscosity coefficient (L\(^2\)T\(^{-1}\)).

According to the above equation, the stress field affects the permeability of soil by changing the volume strain and porosity of soil, and then affects the seepage field. This is the effect of the stress field on the seepage field.

2.3 Mathematical model of seepage flow and stress coupling

\[
\Delta e_v = \frac{n}{E_w} \Delta P = \frac{\eta y}{E_w} \Delta H \quad (5)
\]

\[
\Delta P = \frac{E_w}{n} \Delta e_v \quad (6)
\]

Equation (5) indicates that in the seepage field, the change of groundwater head will lead to the change of medium stress state and cause strain; Equation (6) indicates that in the stress field, the change of stress causes the strain, which leads to the change of water head in the seepage field. This is the mathematical expression of the interaction between stress field and seepage field.

2.4 Seepage field model under stress field

Based on the above analysis, the seepage field model under the stress field is

\[
\frac{\partial}{\partial x} \left[ K(\sigma_y) \frac{\partial H}{\partial y} \right] + \frac{\partial}{\partial y} \left[ K(\sigma_y) \frac{\partial H}{\partial x} \right] + K(\sigma_y) \frac{\partial H}{\partial z} = 0; \quad (x, y, z) \in \Omega
\]

\[
H(x, y, z) = H_1(x, y, z); \quad (x, y, z) \in \Gamma_1
\]

\[
K(\sigma_y) \frac{\partial H}{\partial n_2} = q(x, y, z); \quad (x, y, z) \in \Gamma_2
\]

\[
H(x, y, z) = z; \quad K(\sigma_y) \frac{\partial H}{\partial n_3} = 0; \quad (x, y, z) \in \Gamma_3
\]

in which: \( \Omega \) as seepage area; \( \Gamma_1 \) is known water head boundary; \( H_1(x, y, z) \) is its upper head distribution; \( \Gamma_2 \) is known flow boundary; \( n_2 \) is \( \Gamma_2 \) normal; \( q(x, y, z) \) is \( \Gamma_2 \) the flow distribution above; \( \Gamma_3 \) is the free surface boundary of seepage flow; \( n_3 \) is \( \Gamma_3 \) the normal direction; \( K(\sigma_y) \) is the permeability coefficient.

2.5 Stress field model under seepage field

\[
\sigma_{\mu,j} + f_j = 0; \quad (x, y, z) \in \Omega
\]

\[
\varepsilon_{ij} = \frac{1}{2} (u_{ij,j} + u_{ij,i}); \quad (x, y, z) \in \Omega
\]

\[
\sigma_{ij} = \lambda \varepsilon_{ij} \delta_{ij} \quad 2G \varepsilon_{ij}; \quad (x, y, z) \in \Omega
\]

\[
\sigma_{ij} n_j = S_{ij}; \quad (x, y, z) \in S_o
\]

\[
u_i = R_i; \quad (x, y, z) \in S_o
\]

In which, \((i,j=1,2,3)\), \( f_j \) is the infiltration volume force, which is related to the distribution of water head in seepage field; \( \sigma_{ij} \) is the stress tensor field, \( \sigma_{ij} = \sigma_{ij}(x, y, z); \Omega \) is the regional of stress field, which is consistent with the seepage area; \( \varepsilon_{ij} \) is the strain tensor field, \( \varepsilon_{ij} = \varepsilon_{ij}(x, y, z); \); \( \lambda, G \) are elastic constants of soil; \( \varepsilon_v \) is the volume strain, \( \varepsilon_v = \varepsilon_{ii}; \delta_{ij} \)
is the Kronecker symbol; $S_\sigma$ is the known boundary of surface force; $n_i$ is its normal direction cosine; $\mathbf{S_i}$ is the known surface force distribution, which is a function of infiltration water head distribution $H(x, y, z)$; $R_\sigma$ is the known displacement boundary; $\mathbf{R}$ is the known displacement distribution on the known boundary. By combining equations (7) and (8), the mathematical model of the coupled analysis of seepage flow field and stress field can be obtained.

3. Project overview

The wind ditch tailings pond was built in 1991 and began to be used in June 1995. The designed ultimate dam crest elevation is 140m, the total storage capacity is about 228 million m³, the effective storage capacity is about 168 million m³, and the catchment area is 7.828km². The tailings pond adopts the upstream method for tailings dam. The dam body is composed of initial dam and stacking dam. The initial dam is a rockfill dam with good permeability, the length of the dam is about 505m, the top width of the dam is about 6m, the downstream slope is about 1:2, the upstream slope is 1.1:85, the bottom elevation is 30m, the top elevation of the dam is 58m, the dam height is 28m, the upstream slope of the sub-dam is 1:3.5, and the final total height of the heap is about 90m. According to 《GB50863-2013 design specification of tailings facilities》, the tailings dam belongs to the second-class tailings dam.

According to the topographic features of tailings dam, a geometric model of tailings dam was established as (figure 1). Based on FLAC3D’s difficulty in establishing irregular grids, ANSYS-FLAC3D was adopted to realize the subdivision of the model grid of tailings dam (figure 2), which was divided into 7,940 units, and 10140 nodes were generated. As the tailing dam is built on bedrock, the bedrock is not studied. The table 1 for related mechanical parameters of tailings dam.

![Figure 1. Geometric model of tailings dam.](image)

![Figure 2. Meshing diagram of tailings dam.](image)

### Table 1. Physical and mechanical parameters.

| Rock and soil characteristics | Density (kg/m³) | Cohesion (kPa) | Friction angle (°) | Elasticity modulus (MPa) | Poisson ratio | Permeability (cm·s⁻¹) |
|-----------------------------|----------------|----------------|-------------------|--------------------------|--------------|-----------------------|
| Tails medium sand           | 1800           | 4              | 35                | 40                       | 0.3          | 1.25×10⁻²             |
| Tails silty sand            | 1850           | 5.7            | 33                | 40                       | 0.35         | 2.3×10⁻³              |
| Tails powder clay           | 1800           | 8.57           | 29                | 10                       | 0.30         | 1.8×10⁻⁶              |
| Stone                       | 1950           | 0.5            | 38                | 120                      | 0.25         | 0.4                  |
| Moderate weathered bedrock |                |                |                   |                          |              | As rigid and impermeable bedrock |

4. Analysis of calculation results

4.1 Seepage flow calculation results

Because the tailings pond belongs to the secondary tailings pond, the minimum safe length of dry beach is 100 m in the case of flood. In this study, the length of dry beach is taken to be 100 m, 150 m
and 200 m respectively for research. According to the mathematical model of the coupling of seepage field and stress field, the seepage rule and shear strain development trend of tailings dam body are analyzed. Under different length of dry beach, FLAC3D software was used for calculation and analysis. Figure (a1) (a2) (a3) is a cloud map of pore pressure distribution under different length of dry beach. Figure (b1) (b2) (b3) is the velocity vector diagram. It can be seen from the figure that as the length of dry beach decreases, the seepage flow of tailings dam increases accordingly, from $2.574 \times 10^{-3} \text{m/s}$ to $3.146 \times 10^{-3} \text{m/s}$, and then the infiltration line gradually increases, which is very unfavorable to the safe operation of tailings dam. Therefore, ensuring reasonable dry beach length is crucial to the stability of tailings dam.

![Figure 3. The length of dry beach is 200m.](image)

![Figure 4. The length of dry beach is 150m.](image)

![Figure 5. The length of dry beach is 100m.](image)
4.2 Stress calculation results
Due to limited space, this paper only analyzes the stability of the dam under the length of 100 dry beach, and the results of the other two working conditions are shown in table 2. It can be seen from figure (a) (b) that the maximum principal stress of the dam body is all less than zero and uniformly distributed in the dam body, indicating that there is no tensile stress in the dam body, that is, the dam body is always under compression, and it is stable. After water pressure was applied, the stress cloud map changed significantly. The maximum principal stress in the water storage area changed from 0 to 1.25 MPa, and the maximum stress changed from 1.55 MPa to 2.39 MPa. According to figure (c) (d) subsidence displacement cloud map and horizontal displacement cloud map, the maximum subsidence of the dam body occurs at the top of the dam, and the subsidence volume is about 0.049 m. The maximum horizontal displacement occurs in the middle of the dam, and its value is 0.0084 m.

The following table is a summary of calculation results under three operating states:
Table 2. Calculation results analysis.

| operating condition | The initial stress /MPa | Water pressure / MPa | settlement displacement /m | Horizontal displacement /m |
|---------------------|-------------------------|----------------------|---------------------------|---------------------------|
| 100m                | 1.55                    | 2.39                 | 0.049                     | 0.0084                    |
| 150m                | 1.23                    | 2.14                 | 0.038                     | 0.0073                    |
| 200m                | 1.08                    | 1.94                 | 0.031                     | 0.0064                    |

5. Strength reduction

In order to further determine the safety of tailings dam, Griffith\cite{11} proposed strength subtraction to verify it in the 1970s. Then the method was applied to analyzing slope stability in geotechnical engineering, and has been widely used\cite{12-14}, strength subtraction application is the key to reasonable reduction of strength parameters, the point is to use the formula (9) and (10)

\[
c_F = c / F_{\text{trial}} \\
\phi_F = \tan^{-1} \left( (\tan \phi) / F_{\text{trial}} \right)
\]

To adjust the strength of the rock mass index \( c \) and \( \phi \) (in which, \( c_F \) is the adhesive after reduction, \( \phi_F \) is the friction Angle after reduction, and \( F_{\text{trial}} \) is the reduction coefficient), and then according to the numerical simulation analysis was carried out on the slope stability, by constantly increasing reduction factor, through repeated calculation, until it reaches a critical damage, the reduction factor of the \( F_S \) for tailings dam safety coefficient. The calculation results are as follows:

Figure 8 is the incremental cloud map of shear strain in three cases. As can be seen from the calculation results, as the length of dry beach decreased from 200 m to 100 m, the shear strain area of the dam body gradually increased, and a large shear strain area occurred at the initial dam crest. Meanwhile, the shear strain area of the piled dam gradually went through and widened. The main reason is that as the length of dry beach decreases, the infiltration line of tailings dam increases.
accordingly, water enters the pores of the dam body, and the dam body is liquefied, leading to the reduction of shear strength of the dam body. The calculation results are shown in figures (a) (b) and (c). It can be seen from the figure that, as the length of dry beach decreased from 200 m to 100 m, the safety coefficient of tailings dam decreased from 1.74 to 1.43. The results showed that as the length of dry beach decreased, the seepage flow of tailings dam gradually increased, leading to the rise of infiltration line, resulting in the reduction of safety coefficient of tailings dam, which was not conducive to the stability of tailings dam.

6. Conclusion
1) Under the condition of different dry beach lengths, the pore pressure cloud maps of the three conditions show roughly the same law, the top-down pore pressure of the dam gradually increases, and the pore pressure of the tailing dam is uniformly distributed. As the length of dry beach decreases, the seepage flow of tailing dam increases gradually, and the flow velocity vector changes from 2.574e-3m/s to 3.146e-3m/s, and then the infiltration line increases gradually.

2) The maximum principal stress of the dam body is less than zero and uniformly distributed in the dam body, indicating that there is no tensile stress in the dam body, that is, the dam body is always under pressure and stable. Moreover, as the length of dry beach increases, the maximum principal stress of the dam, the maximum principal stress after water pressure is applied, and the settlement displacement and horizontal displacement show a decreasing trend. It can be seen that the length of dry beach and reservoir water level are important factors influencing the stability of the dam.

3) With the decreasing of dry beach length from 200m to 100m, the shear strain region in the middle area of the dam gradually increases, and the safety factor of the tailings dam decreases from 1.74 to 1.43, which indicates that seepage volume of the tailings dam increases gradually with the decrease of dry beach length, and under the condition of flood water level, the safety factor of the secondary dam is 1.15, when the tailings dam dry beach length of 100 m, the safety factor of the tailings dam is 1.43, which meets the code requirements.

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