Seismic finite element analysis of tailings dam in high seismic intensity area

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Abstract. As an important facility for mine exploitation, the safety of tailings dam is very important in high seismic intensity area. In this paper, the seismic stability analysis of tailings dam located in high intensity area was carried out by taking the example of one tailings dam. Three-dimensional finite element model was established, and the calculation results were analyzed and compared under fixed boundary condition and viscous spring boundary condition. The results showed that, (1) Under the static condition, the deformation value is distributed in layers from top to bottom. (2) Under the seismic condition, it can be seen that the Z direction deformation is the largest, followed by the X direction, and the Y direction deformation is the smallest. (3) It is too conservative to evaluate the seismic stability of dam slope with the minimum safety coefficient, while it is more practical to use the minimum average safety factor as the evaluation index.

1. Introduction
China is a big mining country, and tailings produced by mineral processing are about $3 \times 10^8$ t each year. Tailings dam is an important mine production facility and also an important dangerous source. According to the statistical analysis of the International Commission On Large Dams(ICOLD), since the beginning of the 20th century, there have been no less than 200 tailings pond accidents, most of which are related to earthquakes¹. The operation safety condition of tailings dam is not only related to the economic benefits of mining enterprises, but also closely related to the life and property of the downstream residents and the surrounding environment²,³. Once this kind of high dam in high intensity area crashed, consequence is
very serious, so it is necessary to analyze and evaluate the safety state of the tailings dam in case of earthquake.

2. Computing method
At present, there are mainly two methods to solve the dynamic stability safety coefficient of tailings dam: the pseudo-static method and the time history analysis\[4-5\]. In the 1970s, the pseudo-static analysis method was mostly adopted, but this method did not consider the dynamic characteristics of soil materials well. When the time history analysis is used to solve the problem, because the dynamic shear stress varies with time, the dynamic anti-sliding stability safety coefficient of dam slope is also a function of time, and a safety coefficient will be obtained at every moment. After the time history curve of safety coefficient is obtained, the stability is further evaluated on this basis. According to different evaluation methods, there are mainly minimum mean safety coefficient, minimum dynamic safety coefficient and mean safety coefficient\[6\].

3. Project overview
The tailings dam consists of two parts: the initial dam and the fill dam. The elevation of the initial dam crest is 1100m, the height of the dam is 70m, the storage capacity is about $526 \times 10^4$ m$^3$, the upstream slope ratio is 1:2.0, and the downstream slope ratio is 1:2.2. The initial dam consists of rolled earth and rock dams, rolled rockfill dams, and drainage body. The fill dam elevation is 1180m, the stacking height is 80m, the total storage capacity is $3239.2 \times 10^4$ m$^3$, and the slope ratio of the outside of the tailings dam is 1:5.0. Fill dam is composed of tailings, which are mainly divided into tail-fine sand, tail-silt and tail-silty clay.

The seismic intensity of the dam slope area of this mine is VIII degrees, the site type is class II, and the designed basic seismic acceleration value is 0.30g.

![Figure 1. Overall longitudinal profile](image1)

![Figure 2. FEM model](image2)

4. Calculation process
The seismic stability calculation process of a tailings dam can be summarized into the following four aspects: finite element model, material properties, boundary conditions and dam slope stability evaluation.

4.1 Finite element model
The coordinate system takes the middle point of the initial dam crest as the coordinate origin, the river-long direction is x, the transverse river direction is y, and the vertical direction is z. The overall computing model is shown in Figure 2.

4.2 Material properties
The stress-strain curve of tailings dam material has obvious nonlinear characteristics. The parameters of Duncan-Chang E-B model for the initial dam and tailing dam are listed in Table 1. The $c$, $\varnothing$ and $R_f$ in the table are the intensity parameters, $K$ and $n$ are young's modulus parameters, $K_d$ and $m$ are volume modulus parameters, and $\gamma$ is the natural bulk density of the material.
### Table 1 Static characteristic parameters of various materials

| Groups           | Designation               | $c$/kPa | $\phi^\circ$ | $R_f$  | $K$   | $n$  | $K_h$  | $m$  | $\gamma$(t/m³) | $G_{max}$ |
|------------------|---------------------------|---------|--------------|--------|-------|------|--------|------|----------------|------------|
| Initial dam      | Drainage body             | 23      | 54.3         | 0.64   | 935   | 0.2  | 355.5  | 0.50 | 2.29           |            |
|                  | Rolled earth and rock     | 23.4    | 20.3         | 0.90   | 69    | 0.75 | 140    | 0.50 | 1.95           |            |
|                  | rockfill dams             | 12      | 35           | 0.64   | 1100  | 0.2  | 355.5  | 0.51 | 2.35           |            |
| Fill dam         | Tail-fine sand            | 5       | 34           | 0.84   | 539   | 0.3  | 68     | 0.41 | 2.01           |            |
|                  | Tail-silt                 | 9.8     | 28           | 0.74   | 556   | 0.4  | 107    | 0.18 | 2.05           |            |
|                  | Tail-silty clay           | 15.82   | 20           | 0.75   | 526   | 0.6  | 85     | 0.28 | 2.00           |            |

The foundation is simplified as homogeneous elastic material, the material parameters are: bulk density $\gamma$ is 2.3 t/m³, the elastic modulus $E_s$ is $15 \times 10^6$ kPa, and the Poisson ratio $\mu$ is 0.18.

The maximum dynamic shear modulus $G_{max}$ and the mean effective principal stress $\sigma_m'$ can be fitted with the following formula by using the equivalent linear model.

$$G_{max} = k_d P_a \left( \frac{\sigma_m'}{P_a} \right)$$

(1)

The equivalent shear modulus can be expressed as

$$G_{eq} = \frac{G_{max}}{(1 + \gamma_d)^n_d}$$

(2)

where $P_a$ is the atmospheric pressure, for the triaxial test, $\sigma_m' = (\sigma_1 + 2\sigma_3)/3$, $k_d$ and $n_d$ are the parameters for calculating dynamic shear modulus (as listed in Table 2), $\gamma_d$ is the dynamic shear strain.

The equivalent damping ratio $\lambda$ uses the empirical formula:

$$\lambda = \lambda_{max} \frac{k_1 \gamma_d}{1 + k_1 \gamma_d}$$

(3)

where $k_1$ is the calculated parameter of the dynamic shear modulus, $\gamma_d$ is the normalized dynamic shear strain.

In the case of earthquake, the dam body produces irreversible deformation, that is, permanent deformation. And the permanent deformation adopt Shen Zhuijiang model for calculation. The parameters $C_1 \sim C_5$ of deformation are listed in Table 2 (in the table, $K_d$ and $n_d$ are the parameters for the calculation of dynamic shear modulus, and $C_1 \sim C_5$ are the parameters for the calculation of permanent deformation).

### Table 2 Dynamic characteristic parameters of various materials

| Groups           | Designation               | $K_d$ | $n_d$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|------------------|---------------------------|-------|-------|-------|-------|-------|-------|-------|
| Initial dam      | Drainage body             | 862   | 0.34  | 0.93  | 0.97  | 0     | 7.38  | 1.00  |
|                  | Rolled earth and rock     | 667   | 0.50  | 0.79  | 1.03  | 0     | 7.29  | 1.11  |
|                  | rockfill dams             | 890   | 0.42  | 0.5   | 0.82  | 0     | 7.76  | 0.85  |
| Fill dam         | Tail-fine sand            | 160   | 0.45  | 0.85  | 0.94  | 0     | 7.17  | 0.97  |
|                  | Tail-silt                 | 152   | 0.43  | 0.80  | 0.90  | 0     | 6.20  | 1.00  |
|                  | Tail-silty clay           | 98.6  | 0.49  | 0.82  | 0.90  | 0     | 6.56  | 1.00  |

### 4.3 Boundary conditions

The river-along acceleration’s time history curve is shown in Figure 3. In the figure, the peak of acceleration is the unit acceleration. In the actual calculation, it is amplified according to the designed peak acceleration, and the vertical peak acceleration is two thirds of the horizontal peak acceleration.
4.4 Analysis of calculation results

Under static condition, the overall vertical settlement of tailings dam reaches the maximum of 3.012m, which appears in the reservoir area upstream of the fill dam crest at 1180m, as shown in Figure 4. The most dangerous sliding circle is searched by static calculation and the corresponding sliding circle radius is given, as shown in Figure 5. The minimum safety factor is 1.63.

Under earthquake condition, the permanent deformation of the dam body is calculated as shown in Table 3. It can be seen that the Z direction deformation is the largest, followed by the X direction, and the Y direction deformation is the smallest, which is caused by the Y direction is restricted by the mountain on both sides.

| Table 3 Displacement value of permanent deformation of dam body |
|---------------------------------------------------------------|
| item                      | X direction | Y direction | Z direction |
| Maximum /m                 | 0.154       | 0.148       | 0.284       |

Based on the dynamic stability analysis of tailings dam slope, the time history curve of dynamic safety coefficient of dam slope is obtained, as shown in Figure 6. It can be seen that the minimum safety coefficient of the middle section (CutM section) in the tailing dam reservoir area is 1.16, which occurs at 14.84s of the earthquake. If the minimum safety factor is used to evaluate the stability of dam slope, it is too conservative and be inconsistent with the reality. Taking the minimum average safety coefficient as the evaluation index, the average safety coefficient is calculated to be 1.57, which meets the stability requirement. As shown in Figure 7, the position of the sliding circle corresponding to the minimum average safety coefficient is found, which is basically the same as the position of the static sliding circle (shown in Figure 5.), but the radius of the sliding circle is larger than that of the static sliding circle.
5. Conclusion

Through the static and dynamic calculation and analysis of a tailings dam located in the high intensity zone, the following conclusions are obtained:

(1) Under the static condition, the deformation value is distributed in layers from top to bottom. The settlement of the middle area at the top of the reservoir area is the largest, with a maximum of 3.012m.

(2) Under the seismic condition, it can be seen that the Z direction deformation is the largest, followed by the X direction, and the Y direction deformation is the smallest.

(3) It is too conservative to evaluate the seismic stability of dam slope with the minimum safety coefficient, while the minimum average safety coefficient as the evaluation index is relatively practical. Due to the randomness of seismic load, the evaluation criterion of dynamic safety of dam slope under seismic action is worth further discussion.

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