Mechanical characteristics of mine tailings and seismic responds of tailing reservoir

Pengwei Zhang 1), Liming Hu 2), Hui Wu 3) and Lin Zhang 1)

1) Ph.D Student, State Key Laboratory of Hydro-Science and Engineering, Tsinghua University, Beijing 100084, P. R. China
2) Associate Professor, State Key Laboratory of Hydro-Science and Engineering, Tsinghua University, Beijing 100084, P. R. China

ABSTRACT

Tailings are one of the primary solid wastes of mining industry. They are made of fine-grained particles of the parent rock from which the ore is extracted by crushing, grinding, and other milling processes. Furthermore, volumetrically, tailings impoundments are among the largest structures created by human kind. The safety of the tailing reservoir is one of the major concerns. The characteristics of tailings are a result of the composition of the parent rock and the method of ore processing. In this paper, the two types of tailings from an iron mine in South China were systematically investigated in terms of their mechanical characteristics including the physical features and dynamic response. The deformation of tailing reservoir in design was evaluated considering the earthquake load. This study provides a scientific basis for optimal design and safe operation of the future tailings storage facility.

Keywords: tailings, cyclic stress ratio, cyclic triaxial tests, dynamic response

1 INTRODUCTION

Mine tailings are solid waste products of ore milling operations. It is commonly in slurry form with high water content and high compressibility, and disposed in a tailings reservoir retained by tailings dams. The main problem for impounded tailings is liquefaction under cyclic loading conditions (James et al. 2011; Geremew and Yanful 2013). Therefore, in seismic region, the dynamic properties of tailings are quite important for analysing safe operation of tailings dams. Cyclic shear tests are commonly conducted for mine tailings (Wijewickreme et al. 2010; Geremew and Yanful 2011; Sanin and Wijewickreme 2006). Geremew et al. (2013) studied the effect of clay mineral content on cyclic strength of tailings, and obtained the relation of void ratio and cyclic resistance ratio. Wijewickreme et al. (2010) analysed the mechanical responses of mixtures of waste rock and tailings, and found that the mixtures show a higher tendency for strain development under cyclic loading.

Dynamic properties for natural soil have been widely studied, however for tailings it is highly dependent on the milling process and ore type. In this paper, the tailings from an iron-milling site in South China were studied in terms of the mechanical characteristics, including the behavior under dynamic loading. Two types of tailings were tested in geotechnical testing laboratory, which were the coarse tailings from the bottom and fine tailings from the overflow of the hydro-cyclone separation facility. Dynamic properties tests, including cyclic stress tests, cyclic elasticity modulus tests were conducted. Based on the experiments data, a numerical simulation on seismic response of tailings reservoir under earthquake load was conducted.

2 PHYSICAL PROPERTIES

2.1 Specific gravity of tailings

Pycnometer method was chosen for testing the coarse and fine tailings specific gravity. Each material was conducted with three parallel tests, and the arithmetic mean value obtained are 3.23 and 3.08 for coarse and fine tailings, respectively. Tailings contain several types of metal elements, hence the specific gravity is larger than natural soil.

2.2 Grain size distribution

As the specific gravity of tailings is relative large, the hydrometer method is not available for tailings as the settling velocity of grain is fast. The sieving method and the laser particle size analysis were combined for tailings size gradation. The size distribution curve is shown in Fig. 1, and the characteristic grain size of tailings is listed in Table 1.

The results show that the mass percentage of grain size less than 0.075 mm takes up 12% and 78% for coarse tailings and fine tailings respectively, and the mass percentage of finer grain in fine tailings is significantly higher than that of coarse tailings. According to the coefficient of uniformity (Cu) and coefficient of curvature (Cc) results of mine tailings, coarse tailings and fine tailings are all belong to poorly graded soils.

http://doi.org/10.3208/jgssp.CHN-06
3 DYNAMIC PROPERTIES

Dynamic tests were conducted on DDS-70 type cyclic triaxial test apparatus, manufactured by Beijing New Technology Research Institute. A total of 24 groups of tailings samples (12 for coarse tailings and 12 for fine tailings) were tested for the cyclic strength and cyclic elasticity modulus experiments. The stress-controlled and undrained conditions were adopted, and the frequency of cyclic loading is 1 HZ.

In order to reflect the in-situ state of tailings, coarse tailings samples were prepared initially as slurry form to simulate hydraulic deposition. In contrast, fine tailings samples cannot be upright due to the sludge state during the sampling process. Therefore, the samples of fine tailings were prepared with a constant dry density ($\rho_d$), and vacuum saturated method was adopted for fine tailings. The dry density of fine tailings is 1.65 g/cm$^3$ in this test, which corresponds to the value at the confining pressure of 100 kPa during confining consolidation process. The sample size 3.91 cm in diameter and 8.00 cm in height.

3.1 Cyclic strength of tailings

The cyclic strength tests are under a constant consolidation ratio ($K_c=1.0$) condition. The failure criteria adopted in this experiment is 5% for double amplitude axial strain.

Fig. 2 shows the cyclic strength curve of coarse tailings and fine tailings respectively. The results indicate that the changing tendency at different cyclic stress ratio (CSR) and confining pressure conditions are quite similar for coarse and fine tailings. Besides, the cyclic stress ratio is not sensitive to confining pressure, and with the increases of cyclic stress ratio the number of failure cycles decreases obviously. The cyclic strength of coarse tailings is slightly higher than that of fine tailings. According to the experiments results, the CSR can be estimated for coarse and fine tailings as follows:

$$CSR_{coarse} = 0.507 \times N_f^{-0.186}$$  \hspace{1cm} (1)

$$CSR_{fine} = 0.507 \times N_f^{-0.184}$$  \hspace{1cm} (2)

where $N_f$ is the number of failure cycles.

Pore water pressure during cyclic loading was also recorded during the tests. Fig. 3 shows the cyclic pore pressure ratio changes with cycle ratio (number of cycles divides number of failure cycles) of coarse tailings and fine tailings.

The pore water pressure responding curve of coarse tailings is similar to that of other tailings (James et al. 2011) and sand soils (Seed et al. 1975). Besides, under different confining pressures and different CSR conditions, the pore pressure responding curves show a relative constant tendency. Pore water pressure increases at a relative constant slope at the initial stage (around 0.7 of the cycle ratio), then the pore water pressure increase quickly.

Unlike the coarse tailings, the pore water pressure responding curve for fine tailings experiences a fast increase stage at the early time. Pore water pressure of fine tailings cumulates more quickly than that of coarse tailings, therefore, the liquefaction occurs much easier for fine tailings. Therefore, the drainage system in storage facility is necessary for fine tailings during tailings reservoir operation.
Seed et al. (1975) developed a cyclic pore water pressure predicting model for saturated sand at isotropic consolidation condition \((K_c=1.0)\). The expression is as follows:

\[
\frac{u}{\sigma_0} = \frac{2}{\pi} \arcsin\left(\frac{N}{N_L}\right)^{1/2} \quad (3)
\]

where \(u\) is the pore water pressure, \(\theta\) is the experiment constant, and \(\sigma_0\) is the effective consolidation pressure.

Zhang et al. (2006) developed a similar model to predict cyclic pore pressure for mine tailings based on Seed’s model. The expression is,

\[
\frac{u}{\sigma_0} = \frac{4}{\pi} \arcsin\left(\frac{N}{N_L}\right)^{1/2} \quad (4)
\]

In order to verify that the two cyclic pore water pressure predicting models, the comparison was conducted for coarse and fine tailings. As shown in Fig. 3 (c), Seed model matches well with the coarse tailings result when \(\theta\) equals to 0.9. In contrast, the predicting model by Zhang et al. (2006) can better predict the pore water pressure developing process for fine tailings. From the results, coarse tailings are quite similar to sand, while fine tailings have unique properties, which needs further investigation.

3.2 Cyclic elasticity modulus of tailings

Fig. 4(a) shows the reciprocal of cyclic elasticity modulus changes with cyclic strain of coarse tailings. It can be matched by a linear relation. The cyclic elasticity modulus decreases with the increases of cyclic strain. Fine tailings show the similar characteristics under different confining pressure conditions, as shown in Fig. 4(b). The maximum cyclic elasticity modulus and maximum shear modulus can be obtained based on the experiment results (Table. 2). The cyclic analysis parameters \((k, n)\) can be obtained by fitting the maximum elasticity modulus value,

\[
(E_d)_{max} = kP_a (\frac{\sigma_{sw}}{P_a})^n \quad (5)
\]

where \(P_a\) is barometric pressure, \(\sigma_{sw} = (\sigma' + 2\sigma_r)/3\), \(k\) and \(n\) are the cyclic analysis parameters as listed in Table. 3.
The upstream method is employed to construct the tailings reservoir, and the typical section is shown in Fig. 5. The geological condition of the reservoir site is weathered rock layer, which has a high hydraulic conductivity to facilitate the drainage of the pore water. Based on the dynamic parameters of mine tailings, the seismic response of tailings reservoir was analyzed using GEO-SLOPE software, a finite element method (FEM) software for geotechnical engineering. The United States EI Center seismic wave was adopted as the input seismic acceleration time-history curve. During the seismic analysis period, horizontal and vertical acceleration time-history curves were input separately. The peak acceleration of horizontal wave is 0.20 g, while the peak acceleration of vertical wave is 0.13 g. The duration time is 15 s (Fig. 6).

Fig. 7 shows the results of cyclic displacement responds under flood condition. The results indicate that the maximum horizontal displacement appeared in the downstream of the tailing reservoir, and the maximum is about 0.02 m. The maximum vertical displacement is about 0.01 m. The displacement of tailings reservoir is within the normal range. Furthermore, the liquefaction tendency was also analyzed. According to the numerical results, the liquefaction does not occur during the seismic period. Therefore, this tailings reservoir is safe under such an earthquake condition in design.

![Graph](image-url)
5 CONCLUSIONS

The mechanical properties of the iron mine tailings were investigated, including the cyclic strength and cyclic elasticity modulus. Coarse tailings samples were prepared in a slurry state to simulate hydraulic deposition. In contrast, fine tailings samples were prepared in a specific dry density. Different cyclic pore water pressure models were verified with the experiment data. The mechanical properties of coarse tailings are quite similar to sand. While the dynamic properties of fine tailings cannot be predicted by model proposed by Seed, and the further research of fine tailings properties is still required.

The seismic response of the tailings reservoir was simulated using finite element method. The liquefaction does not occur in this tailings storage facility. The tailings reservoir is safe under such an earthquake condition according to the numerical results.

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