Investigation on Shear Wave Velocity and Triaxial Mechanical Performance of Tailings Core from Tailings Dam

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The physical and mechanical parameters of tailings are important to study the stability of tailings dams (TDs). In this study, a series of laboratory experiments (shear wave velocity, triaxial compressive, and peak strain strength testing) were conducted to obtain the mechanical properties of tailings from TD. The results showed the following. (1) The linear function fitting could characterize the quantitative relationship between shear wave velocity and hole depth. (2) The corresponding static pressure coefficient increased as the confining pressure increased. The exponential fitting could characterize the quantitative function relation between the static pressure coefficient and the confining pressure. (3) The cohesion and internal friction angle of the tailings sample were 20 kPa and 41°, respectively, and the logarithmic fitting could better characterize the quantitative relation between shear peak strength and confining pressure. The results of this study can provide important references for further research on the stability of TD.

1. Introduction

Mineral resources have provided important material support for the development of human civilization. The main methods for obtaining mineral resources are open-pit mining and underground mining. Orebody is subjected to a series of processes such as rock drilling, blasting, transportation, grinding, flotation, and smelting to obtain the required metal. The solid wastes obtained after flotation are collectively called tailings. At present, the main ways of tailings disposal are tailings backfilling and tailings discharge [1]. Some scholars and engineers have also tried to use tailings as a building material, but the effect is not very satisfactory. TDs are used to dispose of tailings waste, as shown in Figure 1. Once the TD collapses, an enormously destructive debris flow will flock to the downstream area, causing great harm to downstream lives and property and polluting the environment seriously [2]. 300 people were killed in the disaster of Brumadinho in Brazil [3]. Nowadays, the TD failure has become one of the major dangerous sources of mines all around the world.

To date, there are lots of references on TD, such as TD failure, stability numerical simulation, and stability measurements [4–9]. The research methods mainly include numerical simulation and on-site monitoring method [10–13]. Yang et al. [14] found that the application of geotextile tubes in the construction of TD is a good alternative for fine tailings disposal. The impedance ratio and the depth of foundation have the significant effect on the seismic factor of safety of TD [15]. The Earth observation-based service could be used to forecast any potential risk from TDs several weeks in advance [16]. Generally, TD is constructed from compacted tailings, and its mechanical properties are different from the cemented tailings backfill (CTB) or cemented paste backfill (CPB). Lots of scholars and engineers have investigated the macro-mechanical, micro-behaviors of CTB and CPB [17, 18].

However, there are few references on the compacted and loose tailings from TD. The main purpose of this study is to obtain the basic mechanical parameters of tailings from Makeng TD. A series of laboratory experiments (shear wave velocity, triaxial compressive, and peak strain strength tests) were conducted to obtain the above mechanical properties.
TQ_he obtained mechanical parameters of tailings from TD will provide an important reference for further research on the stability of ultra-high TDs.

2. Materials and Methods

2.1. Tailings Characteristics. The tested tailings samples were obtained in a TD of Makeng Iron Mine, Fujian, China. In this study, the Shandong Nikeite NKT6100-D laser particle size analyzer was used to analyze the particle size distribution (PSD) of tested tailings. A total of 5 tailings samples were selected for testing. It is found that the tested tailings is mainly composed of SiO2, CaO, Fe2O3, MgO, and Al2O3. The PSD curve is shown in Figure 2. The particle size and chemical components are shown in Tables 1 and 2, respectively.

2.2. Experimental Content

2.2.1. Tested Specimens from the TD. There are a total of 11 boreholes from TD, and the tested specimens were numbered ZK1, ZK2, ZK3, ZK4, ZK5, ZK6, ZK7, ZK8, ZK9, ZK10, and ZK11, respectively. The coring at the scene is shown in Figure 3.

2.2.2. Shear Wave Test. According to the Code for Seismic Design of Buildings (GB 50011-2010), shear wave test was conducted in this study. The suspended wave speed testing system named XG-I was used to analyze the relation between shear wave velocity and drilling depth. The basic parameter is shown as follows: dynamic range is 96 dB; preamp gain is 18-60 dB; and the probe used to receive signals from the instrument uses a suspended borehole detector. The main technical indicators are as follows: the horizontal detector has a natural frequency of 60 Hz and a sensitivity of 30 V/(m·s). The equivalent shear wave velocity could be measured as follows:

\[ v_{se} = \frac{d_0}{t} \left( \frac{d_i}{v_{si}} \right), \]

where \( v_{se} \) is the equivalent shear wave velocity of soil layer; \( d_0 \) is the calculated depth, which is smaller than the thickness of the cover and 20 m; \( t \) is the shear wave which is between the ground and the calculated depth; \( d_i \) is the thickness (m) of the \( i \)-th soil layer; \( v_{si} \) is the shear wave velocity of the \( i \)-th soil layer; and \( n \) is the number of layers.
2.2.3. Triaxial Compression Laboratory Test. The SLB-1 stress-strain controlled triaxial shear penetration tester was used in this study, which could perform unequal consolidation, isotropic consolidation, reverse pressure saturation, stress path test, and penetration test. Besides, the device could transfer the data to the computer during the whole testing. The testing standard was obtained according to the results from [19]. The main technical parameters of the equipment include the following: the range of axial force was 0–20 kN and the measurement accuracy was ±1%; the loading rate was set as 0.002–4 mm/min ±10%; the diameter and height of tested specimen were 39.1 mm and 80 mm, respectively; and the confining pressure was set as 100 kPa, 200 kPa, 300 kPa, and 400 kPa, respectively. Figure 4 shows the process steps of the triaxial test.

3. Results and Discussion

3.1. Shear Wave Velocity Test Results. Table 3 shows the tested original data of shear wave and hole depth. In order to visually describe the quantitative relationship between the TD core and wave velocity at different drilling depths and to facilitate the prediction of the wave velocity of subsequent deep drilling tailings cores, the relationship curve was plotted as shown in Figure 5.

It was observed from Figure 5 that the multiple correlation coefficients of exponential, linear, logarithmic, and power function fitting were 0.9554, 0.9601, 0.757, and 0.8181, respectively. It showed that the linear fitting could realize the quantitative characterization of the relation between the shear wave velocity and the hole depth, which could be shown in the following equation:

\[ y = ax + b, \]  

where \( y \) was the shear wave velocity; \( x \) represented the hole depth; and \( a \) and \( b \) were relative coefficients related to the shear wave velocity and the hole depth.

It was also found that tailings of TD less than 20 m belong to medium soft soil, while the tailings of TD between 20 and 30 m belong to medium hard soil according to the Code for Seismic Design of Buildings (GB 50011-2010).
3.2. Confining Pressure Effect on Triaxial Shear Strength. Figure 6 shows the relationship between the static pressure coefficient and the stress path under different confining pressure conditions. \(\sigma_3\) was the minimum principal stress, and \(\sigma_1\) was the maximum principal stress.

It can be seen from the analysis of Figure 6 that as the main pressure difference and the confining pressure gradually increase, the value of \(K_0\) also gradually decreases and eventually approaches a stable value. When the confining pressure was 100 kPa, 200 kPa, 300 kPa, and 400 kPa, the corresponding values of \(K_0\) were 0.18, 0.19, 0.21, and 0.23, respectively.

In order to quantitatively characterize the relationship between confining pressure and static lateral pressure coefficient, the linear, logarithmic, exponential, and power function fitting methods were used to calculate its complex correlation coefficient. The result is shown in Figure 7.

As shown in Figure 7, it was found that the multiple correlation coefficients of linear, exponential, logarithmic, and power function fitting were 0.9797, 0.9861, 0.8887, and 0.906, respectively. It shows that exponential fitting could better characterize the quantitative relationship between static lateral pressure coefficient and confining pressure.

3.3. Confining Pressure Effect on Shear Peak Strength. Figure 8 shows the Mohr envelope circle under different confining pressures.

The cohesion and internal friction angle of the tested tailings specimen could be calculated by calculating the slope and intercept of the envelope circle tangent. Finally, the calculated cohesion and internal friction angle of the tailings sample were 20 kPa and 41°, respectively.

In order to quantitatively characterize the relationship between confining pressure and shear peak strength, the linear, logarithmic, exponential, and power function fitting methods were used to calculate its complex correlation coefficient. The result is shown in Figure 9.

As shown in Figure 9, it was found that the multiple correlation coefficients of linear, exponential, logarithmic, and power function fitting were 0.9595, 0.8961, 0.9965, and 0.9833, respectively. It shows that logarithmic fitting could...
Table 3: The original data of hole depth and shear wave in this study.

| Hole depth (m) | Shear wave (m/s) | Hole depth (m) | Shear wave (m/s) | Hole depth (m) | Shear wave (m/s) |
|----------------|------------------|----------------|------------------|----------------|------------------|
| 1              | 98               | 11             | 15               | 141            | 11              |
| 2              | 110              | 12             | 17               | 158            | 21              |
| 3              | 108              | 13             | 18               | 161            | 22              |
| 4              | 113              | 14             | 16               | 167            | 23              |
| 5              | 116              | 15             | 19               | 185            | 24              |
| 6              | 117              | 16             | 20               | 212            | 25              |
| 7              | 118              | 17             | 21               | 234            | 26              |
| 8              | 121              | 18             | 22               | 238            | 27              |
| 9              | 124              | 19             | 23               | 243            | 28              |
| 10             | 130              | 20             | 24               | 247            | 29              |

Figure 5: Relations between shear wave and hole depth.

Figure 6: Continued.
Figure 6: Relations between static pressure coefficient and the stress path. (a) 100 kPa. (b) 200 kPa. (c) 300 kPa. (d) 400 kPa.

Figure 7: Relations between confining pressure and $K_0$. 

\[ y = 0.017x + 0.16 \quad \text{R}^2 = 0.9797 \]  

\[ y = 0.1636e^{0.0835x} \quad \text{R}^2 = 0.9861 \]  

\[ y = 0.0348\ln(x) + 0.1749 \quad \text{R}^2 = 0.8887 \]  

\[ y = 0.1759x^{0.172} \quad \text{R}^2 = 0.906 \]
better characterize the quantitative relationship between shear peak strength and confining pressure.

4. Conclusion

In this study, a series of laboratory experiments have been conducted to evaluate the mechanical performance of tailings specimens from TD. The following conclusions can be drawn from the current study based on the analysis and discussion of the experimental results.

(1) The quantitative relationship between shear wave and hole depth can be expressed as linear equation. It was found that the tailings of TD less than 20 m belong to medium soft soil, while the tailings of TD between 20 and 30 m belong to medium hard soil.

(2) The corresponding static pressure coefficient increased as the confining pressure increased. The quantitative relation between the static pressure coefficient and confining pressure was exponential equation.

(3) The cohesion and internal friction angle of the tailings sample were 20 kPa and 41°, respectively. Besides, the logarithmic fitting could better characterize the quantitative relation between shear peak strength and confining pressure.

The basic mechanical characteristics of tailings from TD provide an important reference for further research on the stability of ultra-high tailings dams. In the future, the author will use on-site monitoring and numerical simulation to study the stability of TDs.

Data Availability

The data in this study were obtained by laboratory testing. The data analysis is included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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