Effect of Particle Size on Mechanical Properties of Coarse-grained Soil

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Abstract. In order to explore the effect of particle size on the mechanical properties of coarse-grained soil, 40 groups of direct shear tests were conducted on 3 kinds of coarse-grained soil with the same dry density by DHJ50-2 shear test machine. The results show that the cohesive forces decreases with the increase of particle size, and the internal friction angle increases with the increase of particle size. Under low density and low vertical load, the peak shear stress of coarse-grained soil decreases with the increase of particle size. The threshold porosity of 3 kinds of coarse-grained soil was calculated. When the porosity of soil sample is lower than the corresponding threshold porosity, the peak shear stress increases with the increase of particle size. The research results have certain significance for the follow-up study of mechanical properties of complex graded soil.

Keywords: Coarse-grained soil, mechanical property, direct shear test, particle size.

1. Introduction

Coarse grained soil refers to the soil rock mixture with particles larger than 0.075mm accounting for more than 50% of the total mass of the sample. It is widely used in engineering construction because of its’ good compaction performance, high shear strength, and not easy to liquefy. In order to ensure the safety and economy of engineering design and construction, it is necessary to master the mechanical properties of coarse-grained soil with various particle sizes.

Many scholars have done a lot of research on complex graded coarse-grained soil [1-3], but the conclusions are different. The research results of Varadarajan [4], Hennes [5] show that the internal friction angle increases with the increase of particle size. However, Marachi [6], Lewis J G [7] believe that the internal friction angle decreases with the increase of particle size. Some scholars [8, 9] draw the conclusion that the larger the particle size, the greater the strength through numerical simulation and experimental methods. However, many scholars [10, 11] have shown that the peak shear stress decreases with the increase of particle size. Some scholars [12, 13] have proposed that with the increase of particle size, the peak shear stress increases under high confining pressure and decreases under low confining pressure.
Previous studies on the mechanical properties of single grain size coarse-grained soil are few. Mastering the mechanical properties of single size coarse-grained soil is the basis of analyzing the properties of complex graded coarse-grained soil theoretically, so it is necessary to carry out the research in this field.

2. Tested materials and testing methods

2.1. Tested materials
The sand gravel coarse-grained soil used in the experiment was taken from the valley of the lower reaches of the Niyang River in Tibet. After air drying, coarse-grained soil with particle size of 2~5, 5~10, 10~20mm was screened out. It is found that the shape of coarse-grained soil particles changes from full of edges to spherical with the increase of particle size. The natural dry bulk density of 3 kinds of coarse-grained soil was measured (Table 1).

| Particle size (mm) | 2~5 | 5~10 | 10~20 |
|-------------------|-----|------|-------|
| Dry bulk density (KN/m$^3$) | 13.08 | 15.04 | 15.72 |

2.2. Testing methods
Control the dry density to 1.55, 1.60, 1.65 and 1.70g/cm$^3$. The DHJ50-2 shear test machine was used to conduct direct shear tests on the samples with different particle size and dry density under the vertical load of 100, 200, 400 and 600kPa, and the shear rate was 0.8mm/min. The experimental data were obtained (Table 2).

| Vertical load (kPa) | 1.55g/cm$^3$ | 1.60g/cm$^3$ | 1.65g/cm$^3$ | 1.70g/cm$^3$ |
|-------------------|-------------|-------------|-------------|-------------|
| mm                | 2~5         | 5~10        | 2~5         | 5~10        | 10~20       | 2~5         | 5~10        | 10~20       |
| 100               | 98.35       | 27.01       | 109.41      | 116.87      | 120.09      | 130.43      | 115.27      | 130.48      |
| 200               | 195.60      | 178.58      | 197.90      | 200.70      | 220.07      | 248.95      | 218.92      | 222.77      |
| 400               | 272.59      | 321.92      | 335.28      | 347.90      | 361.35      | 383.18      | 398.85      | 375.83      |
| 600               | 384.21      | 462.16      | 420.82      | 515.77      | 466.55      | 554.05      | 572.22      | 628.85      |

3. Test results and analysis

3.1. Effect of particle size on cohesive force and internal friction angle
It can be seen from Table 2 that the peak shear stress of coarse-grained soil increases with the increase of vertical load, showing a good linear relationship. According to Mohr-Coulomb failure criterion, the test data were analyzed, and the cohesive force and internal friction angle were counted (Table 3).

| Shear strength parameters | 1.55g/cm$^3$ | 1.60g/cm$^3$ | 1.65g/cm$^3$ | 1.70g/cm$^3$ |
|--------------------------|-------------|-------------|-------------|-------------|
| mm | 2~5 | 5~10 | 2~5 | 5~10 | 10~20 | 2~5 | 5~10 | 10~20 |
| $c$ (kPa) | 62.47 | 27.01 | 64.21 | 38.51 | 69.75 | 38.31 | 63.34 | 31.11 |
| $\phi$ (°) | 28.33 | 36.13 | 31.82 | 38.31 | 34.37 | 39.28 | 42.25 | 35.64 |

It can be seen from Table 3 that the cohesive force of coarse-grained soil decreases with the increase of particle size. The larger the particle size is, the more loose the sample accumulation is
(Table 1). At the same time, the particle shape changes from full edge to spherical shape, and the embedded structure weakens and the cohesive force decreases.

The internal friction angle increases with the increase of particle size. The internal friction angle comes from the friction force between particles. The larger the particle size, the larger the contact area between particles, the greater the work done by external load to overcome particle friction, and the greater the internal friction angle [9].

3.2. Effect of particle size on peak shear stress

It can be seen from Table 2 that for the same dry density, the vertical load exceeds a certain value, or the same vertical load, the dry density exceeds a certain value, and the peak shear stress increases with the increase of particle size.

For the combination where the peak shear stress does not increase with the increase of particle size, the relationship curve between peak shear stress and vertical load was drawn (Figure 1), and the vertical load corresponding to the intersection point of the curve was calculated (Table 4), which is defined as "threshold vertical load". When the vertical load of coarse-grained soil is greater than the "threshold vertical load", the peak shear stress increases with the increase of particle size.

![Figure 1](image-url)

**Figure 1.** Relationship between peak shear stress and vertical load.

**Table 4.** Threshold vertical load.

| Dry density (g/cm³) | 1.55 | 1.65 | 1.65 |
|---------------------|------|------|------|
| Particle size (mm)  | 2~5mm| 5~10mm| 2~5mm| 5~10mm| 10~20mm| 10~20mm| 331.42kPa |

According to the vertical displacement of soil sample at the peak shear stress, the porosity at the peak point was calculated, and the curve (Figure 2) was drawn. It is found that the good logarithmic function relationship is satisfied. The relationship is listed in Table 5.
Figure 2. Relationship curve between porosity at peak point and vertical load.

Table 5. Fitting formula of porosity at peak point and vertical load.

| Dry density (g/cm$^3$) | 2~5mm | 5~10mm | 10~20mm |
|------------------------|-------|--------|---------|
| 1.55                   | $n = -0.29 \ln \sigma + 42.85$ | $n = -0.08 \ln \sigma + 43.73$ |
| 1.60                   | $n = -0.17 \ln \sigma + 40.30$ | $n = -0.11 \ln \sigma + 42.13$ |
| 1.65                   | $n = -0.24 \ln \sigma + 38.87$ | $n = -0.25 \ln \sigma + 41.22$ | $n = -0.2 \ln \sigma + 39.51$ |
| 1.70                   | $n = -0.23 \ln \sigma + 37$ | $n = -0.1 \ln \sigma + 38.58$ | $n = -0.06 \ln \sigma + 37.02$ |

According to Tables 4 and 5, the threshold porosity corresponding to the threshold vertical load was calculated (Table 6).

Table 6. Threshold porosity.

| Dry density (g/cm$^3$) | 1.55 | 1.65 | 1.65 |
|------------------------|------|------|------|
| Particle size (mm)     | 1.55 | 1.65 | 1.65 |
| 2~5mm                  | 41.24% | 37.60% | 39.79% |
| 5~10mm                 | 43.26% | 38.44% | 38.35% |

When the porosity of 3 kinds of coarse-grained soil is less than the corresponding porosity of Table 6, the shear strength increases with the increase of particle size.

According to the threshold vertical load (331.42kPa) of 5~10, 10~20mm coarse-grained soil at dry density of 1.65g/cm$^3$ (Table 4) and the fitting formula of 2~5mm coarse-grained soil under same dry density (Table 5), the threshold porosity of 2~5mm coarse-grained soil at 1.65g/cm$^3$ is calculated as
37.49%. That is to say, when the porosity of 2~5, 5~10, 10~20mm coarse-grained soil is less than 37.49%, 39.79% and 38.35%, the peak shear stress increases with the increase of particle size.

4. Conclusions
A total of 40 groups of direct shear tests were carried out on 3 kinds of coarse-grained soil with four dry densities under four vertical loads. It is found that the cohesive force of coarse-grained soil with 2~5, 5~10 and 10~20mm decrease with the increase of particle size, and the internal friction angle increase with the increase of particle size. The threshold porosity of 3 kinds of coarse-grained soil is obtained by calculation. When the porosity of soil sample is less than the corresponding threshold porosity, the peak shear stress increases with the increase of particle size.

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References
[1] Lei Han, Xu Peng, Wei Wei, et al. Influence of Content of Gravels on the Mechanical Properties of Chengdu Clays [J]. Sichuan Building Materials, 2013, 39 (01): 109-111.
[2] Jie Shi, Yi Wang, Yinli Fan, et al. Study on Mechanical Characteristics of Soils Mixed with Coarse and Fine Particles [J]. Northwest Hydropower, 2013 (01): 54-56.
[3] Qi Wu, Guoxing Chen, Zhenglong Zhou, et al. Experimental investigation on liquefaction resistance of fine-coarse-grained soil mixtures based on theory of intergrain contact state [J]. Chinese Journal of Geotechnical Engineering, 2018, 40 (03): 475-485.
[4] Varadarajan A, Sharma K G, Venkatachalam K, et al. Testing and Modeling Two Rockfill Materials [J]. Journal of Geotechnical & Geoenvironmental Engineering, 2003, 129 (3): 206-218.
[5] Hermes R G. The strength of gravel in direct shear [M]. University of Washington, 1952.
[6] Marachi N D, Chan C K, Seed H B, Evaluation of properties of rock fill materials [J] Journal of Soil Mechanics & Foundations Div., 1972, 97 (SM1): 95-114.
[7] Lewis J G. Shear Strength of Rockfill [C] // Proceedings ofthe 2nd Australia-New Zealand Conference on Soil Me-chanics and Foundation Engineering, 1956: 181-202.
[8] Cai Tan, Yong Wu, Li Wan, et al. Size effects on the shear strength of the cohesionless coarse-grained soils under the triaxial compression condition [J]. Journal of Jiangnan University (Natural Science Edition), 2015, 14 (06): 810-813.
[9] Lingling Zhang, Yong Yao. Study on direct shear test of sandy pebble soil in Sichuan Northwest area [J]. Subgrade Engineering, 2010 (03): 162-164.
[10] Gupta A K. Effect of particle size and confining pressure on breakage and strength parameters of rock fill materials [J]. Electronic Journal of Geotechnical Engineering, 2009, 14: 1-12.
[11] Barton N, Kjaernsi B. Shear strength of rock fill [J]. Journal of Geotechnical Engineering, 1981, 107 (136): 873-891.
[12] Jungao Zhu, Zhong Liu, Houyang Weng, et al. Study on effect of specimen size upon strength and deformation behaviour of coarse-grained soil in triaxial test [J]. JOURNAL OF SICHUAN UNIVERSITY (ENGINEERING SCIENCE EDITION) 2012, 44 (06): 92-96.
[13] Chen Sun, Wenxi Han, Hao Wang. Influence of particle size on mechanical parameters of coarse grain soil [J]. Yangtze River, 2018, 49 (10): 97-103.