Experimental study on particle breakage and fractal characteristics of coarse-grained soil

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Abstract. Particle breakage is an important factor affecting the strength and deformation of coarse-grained soil. In order to study the compaction characteristics and particle breakage effect of coarse-grained soil, the compaction tests of coarse-grained soil with different stone content and water content were designed. The results show that the dry density of coarse-grained soil first increases and then decreases with the increase of water content. With the increase of stone content, the maximum dry density and optimal moisture content of coarse-grained soil increase. After compaction test, the coarse-grained soil has obvious particle breakage phenomenon, and the particle breakage index increases with the increase of stone content and water content. The fractal dimension $D$ can characterize the coarse-grained content of coarse-grained soil. With the increase of coarse-grained content, the fractal dimension $D$ decreases gradually.

1. Introduction

Coarse-grained soil is a kind of granular accumulation, which is widely used in fill engineering such as railway, earth rock dam, expressway and so on [1]. Under the action of load, coarse-grained soil usually produces particle breakage, which changes the grading composition of soil, affects the mechanical properties of soil, and has a significant impact on the safety and stability of high fill slope. Through the large-scale compaction test of earth rock mixture, Wang [2] shows that compaction work and stone content are two important factors affecting the maximum dry density of soil. Du [3] studied the factors influencing the shear properties of rockfill materials, and the results showed that there was an exponential relationship between the internal friction angle and the coarse grain content. Liang [4] has carried out compaction test and shear test of coarse-grained soil with different stone content. The research shows that the compaction characteristics of coarse-grained soil is significantly affected by stone content, and the shear strength of soil sample is the largest under the condition of maximum dry density. Zhang [5] studied the deformation of rockfill materials under the action of cyclic stress history, which shows that the rockfill materials will slip and rotate relative to each other, resulting in particle breakage. Liu [6] carried out large-scale shear tests on four kinds of soil with different water content, which showed that the water content affected its macro mechanical properties by affecting its micro particle breakage. In order to describe and reflect the pore structure characteristics of granular materials, fractal theory is applied to the study of mechanical properties of coarse-grained soil [7-8]. Although scholars at home and abroad have carried out a variety of tests to study the mechanical properties of coarse-grained soil, it still needs to be further studied to consider the water content and stone content of coarse-grained soil, and to analyse the particle breakage characteristics of soil using fractal theory. In order to provide theoretical support for coarse-grained soil filling engineering, the
compaction tests of different coarse-grained content of coarse-grained soil were carried out, and the fractal theory was used to analyse the breakage effect of soil particles after compaction.

2. Test process and method

2.1. Test materials and instruments
The materials used in the test are selected from the filling materials of an earth rock dam. In order to meet the loading requirements of the test, the on-site gradation of soil is scaled according to the equivalent substitution method. The results are shown in table 1. DDJ30-6 electric compaction instrument is used for compaction test. The sample size of the instrument is Φ 300x288mm, hammer drop height is 600mm ±1, hammer speed is 8 blows/min, hammer mass is 15.5kg, and compaction work is 591.9kJ/m³.

| gradation     | percentage content of each particle size /% |
|---------------|---------------------------------------------|
| <2mm          | 42.23                                       |
| 2~5mm         | 20.75                                       |
| 5~10mm        | 3.89                                        |
| 10~20mm       | 6.52                                        |
| 20~40mm       | 10.23                                       |
| 40~60mm       | 8.02                                        |
| >60mm         | 8.36                                        |

2.2. Test plan
Stone content refers to the percentage of block stone in the total mass of earth rock mixture. Generally, the particle size of 5mm is used as the dividing line between block stone and soil, which is expressed by P₅. The compaction test is carried out according to different stone content and water content. The stone content is designed as 15%, 30%, 45% and 60%, and the water content is designed as 4.7%, 6.5%, 8.2%, 9.8% and 11.4%. The cumulative curve of soil gradation under different stone content is shown in figure 1.

![Figure 1. Cumulative curve of particle size distribution](image)

2.3. Test process
The soil samples were prepared according to the stone content and water content of the designed soil samples. The prepared soil samples were loaded into the compaction machine in three layers, and each layer was compacted 44 times. After the test, 2kg representative soil sample was taken from the middle of the soil sample to determine the moisture content. The soil samples after compaction test were dried and screened, and the change of particle size was counted.

3. Test results and analysis

3.1. Compaction characteristics of coarse-grained soil
The compaction curve of coarse-grained soil with different stone content is shown in figure 2. It can be seen from figure 2 that the dry density of coarse-grained soil first increases and then decreases with the increase of water content. The reason is that when the moisture content is small, the whole soil
particle, including the gap between soil particles, is surrounded by film water. At this time, due to the lubrication of water, the shear resistance is large, the soil is not easy to be compacted, and the dry density is small. The water content of soil will be increased continuously, and the above thin film layer will thicken, which will reduce the shear resistance, and the dry density will gradually reach the peak, namely the maximum dry density. As water is incompressible and its density is generally smaller than that of soil particles, the dry density decreases with the increase of water content. When the water content is the same, with the increase of coarse content, the maximum dry density shows an upward trend. This is because when the stone content is different, the coarse and fine content are also different, resulting in different dry density.

3.2. Particle breakage characteristics of coarse grained soil

The degree of particle breakage is measured by multi particle size index $B_g$. Marsal [9] reflects the particle breakage by summing the absolute value of the percentage difference of particle composition before and after the test. It can be expressed as:

$$B_g = \sum |w_{ki} - w_{kf}|$$  (1)

Where $w_{ki}$ is the content of a certain fraction on the grading curve before compaction, $w_{kf}$ is the content of a certain fraction on the grading curve after compaction.
The gradation changes of coarse-grained soil before and after test under different stone content and water content are shown in table 2. According to table 2, the mass percentage of 60-40mm and 40-20mm coarse-grained soil decreased, the mass percentage of 10-5mm and less than 2mm increased. The test results show that the coarse-grained soil has obvious particle breakage during compaction.

Table 2. statistical results of soil gradation after compaction test

| P5/% | w/%  | mass percentage content of different particle sizes /% |
|------|------|-------------------------------------------------------|
|      |      | <2mm  | 2~5mm | 5~10mm | 10~20mm | 20~40mm | 40~60mm |
| 4.7  | 58.31| 27.48 | 2.09  | 3.78   | 4.87    | 3.47    |
| 6.5  | 58.49| 27.37 | 2.00  | 3.98   | 4.76    | 3.4    |
| 15%  | 8.2  | 58.74 | 27.14 | 2.13   | 4.10    | 4.64    | 3.25    |
| 9.8  | 58.89| 27.04 | 2.26  | 4.05   | 4.59    | 3.17    |
| 11.4 | 59.08| 26.88 | 2.39  | 4.08   | 4.51    | 3.06    |

According to formula (1), the particle breakage index $B_g$ of coarse-grained soil after compaction test is calculated, as shown in table 3. It can be seen from table 3 that under the same water content condition, with the increase of stone content, the particle breakage index $B_g$ increases. Under the same stone content, the particle breakage index $B_g$ increases with the increase of water content.

Table 3. Calculation results of particle breakage index $B_g$

| P5/% | different moisture content w/% |
|------|--------------------------------|
|      | 4.7  | 6.5  | 8.2  | 9.8  | 11.4 |
| 15   | 3.64 | 4.10 | 5.22 | 5.70 | 6.38 |
| 30   | 4.20 | 5.10 | 6.18 | 6.86 | 8.00 |
| 45   | 8.16 | 9.74 | 11.70| 13.02| 15.08|
| 60   | 9.28 | 12.02| 14.08| 15.50| 17.40|

3.3. Fractal characteristics of coarse grained soil
The fractal dimension can be used to characterize the grading characteristics of soil [10]. The calculation method of fractal dimension of coarse-grained soil is as follows:

$\log \left[ M_t(d_i)/M_t \right] = (3 - D)\log (d_i/d_{max})$ (2)

Where $M_t$ is total mass, $M_t(d_i)$ is total mass of particles larger than a certain particle size, $M_t(d_i)/M_t$ can be obtained by particle screening statistics, $d_{max}$ is maximum particle size, $D$ is fractal dimension.
According to formula (2), the fractal dimension $D$ of coarse-grained soil before and after the test is calculated as shown in Table 4.

| $P_5 \%$ | Initial | different moisture content $w / \%$ |
|----------|---------|-----------------------------------|
|          |         | 4.7 | 6.5 | 8.2 | 9.8 | 11.4 |
| 15       | 2.8791  | 2.8855 | 2.8861 | 2.8871 | 2.8878 | 2.8886 |
| 30       | 2.8088  | 2.8184 | 2.8204 | 2.8224 | 2.8243 | 2.8261 |
| 45       | 2.7225  | 2.7479 | 2.7526 | 2.7571 | 2.7617 | 2.7661 |
| 60       | 2.6020  | 2.6514 | 2.6625 | 2.6670 | 2.6710 | 2.6751 |

It can be seen from the analysis in Table 4 that the fractal dimension $D$ of coarse-grained soil can characterize the grading characteristics of coarse-grained soil. The decrease of fractal dimension $D$ results in the increase of coarse-grained content in coarse-grained soil, that is, the fractal dimension of coarse-grained soil is inversely proportional to the coarse-grained content. After compaction test, the fractal dimension of coarse-grained soil decreases with the increase of stone content under the same water content. Under the same stone content, the fractal dimension of coarse-grained soil increases with the increase of water content.

4. Conclusions
(1) With the increase of coarse-grained content, the optimal moisture content and maximum dry density of coarse-grained soil increase.

(2) The larger the content of coarse particles, the more significant the particle breakage. Particle breakage is directly proportional to water content and coarse particle content of coarse-grained soil.

(3) The fractal dimension $D$ value can be used to characterize the grading characteristics of coarse-grained soil, and the fractal dimension decreases when the coarse-grained soil particles are broken.

(4) The research of coarse-grained soil particle breakage has a good theoretical support to guide the practice of high fill engineering. The micromechanical mechanism of coarse-grained soil particle breakage needs to be further studied by combining with the discrete element numerical simulation method.

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