Study on size effect of sandstone deformation characteristics under cone penetration test

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Abstract. Cone penetration test is a critical method to examine the mechanics parameters of rock in laboratory. This method has also been applied in field to indirectly assess the mechanical properties of in-situ rock mass in recent years. However, the difference of the size of the test rock between in-situ test and laboratory test will lead to the difference of test results. In order to reasonably evaluate the influence of rock mass size on cone penetration test characteristics, this paper studies cone penetration test of diverse sizes of rock mass by laboratory test and the numerical simulations utilizing PFC3D particle flow, and the deformation law of loaded rock mass is analyzed. The results showed that: (1) The influence of point load on rock deformation is mainly manifested as the increase of core area and volumetric strain in core area. When the specimen size reaches a certain level, the rock mass only generates large volumetric strain within a certain range before failure. For sandstone, this range is within 100 mm from the loading point. (2) Under the same load, the volume strain at the same position from the loading point decreases exponentially with the increase of the specimen size, and the relationship between the sample size and the volume strain is established.

1. Introduction

Cone penetration test is a critical method to examine the mechanics parameters of rock in laboratory. This method has also been applied in field to indirectly assess the mechanical properties of in-situ rock mass in recent years\(^{[1-3]}\). However, the difference of the size of the test rock between in-situ test and laboratory test will lead to the difference of test results\(^{[4-7]}\). Therefore, it is necessary to explore the influence of rock size on cone penetration test. At present, several scholars have conducted a lot of research on the evaluation of material strength, hardness, fracture toughness and other mechanical parameters through cone penetration test, and considered the influence of crack, shape, indenter shape and other factors on the test\(^{[8-11]}\). However, there are few researches on the deformation characteristics of cone penetration under different sizes. In this paper, the deformation characteristics of rock samples with dissimilar sizes are studied by means of laboratory test and numerical simulation. The size effect of cone penetration test is analyzed quantitatively, and the relationship between rock volumetric strain and specimen size is given.
2. Rock test and numerical simulation

2.1 Rock cone penetration test of different sizes

2.1.1 Preparation of experimental samples.
In order to study the influence of size effect in cone penetration test, indoor cone penetration tests were carried out on rock samples of different sizes. The sandstone produced in Linyi, China was selected as the test material. In order to study the influence of rock specimen size on rock deformation characteristics in cone penetration test, the sandstone was processed into cube specimens. The rock specimens were divided into four control groups with side lengths of 50 mm, 100 mm, 150 mm and 200 mm, respectively. The processed rock specimen is shown in Figure 1. In order to reduce the test error caused by the discreteness, 5 pieces of each size were produced.

![Figure 1. Different size sandstone specimen.](image)

![Figure 2. Experimental device.](image)

2.1.2 Experimental scheme.
Rlzw-2000 computer-controlled rheological testing machine was adopted to carry out point loading on the center of upper surface of rock. A conical indenter with a tip radius of 4mm and a cone angle of 60° was used to applied the load. The loading mode of displacement control was adopted in the test, and the axial load and displacement were recorded by computer system.

| Rock Specimen | $\sigma_c$ (MPa) | $\sigma_t$ (MPa) | $E$ (GPa) | $\nu$ |
|---------------|------------------|------------------|-----------|------|
| Sandstone     | 91.73            | 4.84             | 7.20      | 0.25 |

In order to observe the deformation rule of specimens with different sizes, strain gauges were pasted 20mm away from the loading point to record the strains in two mutually perpendicular directions. The whole bridge connection method is used to arrange the strain gauge. There are two points of symmetry in a set, and two sets of data are recorded for the strain in each direction. The pasting method of strain gauge and the layout scheme of bridge and road are shown in Figure 3.

![Figure 3. Schematic diagram of strain gauge pasting](image)
2.1.3 analysis of experimental results.

The contact load displacement curves of rock samples with different sizes are shown in Figure 4. The specific penetration test peak load and axial displacement data are listed in Table 2.

![Figure 4. Penetration load displacement curves of rock samples with different sizes.](image)

**Table 2.** Penetration test data of samples with different sizes.

| Number | d (mm) | P (kN) | S (mm) | Number | d (mm) | P (kN) | S (mm) |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 1      | 50     | 19.03  | 0.64   | 7      | 150    | 74.90  | 2.22   |
| 2      | 50     | 18.19  | 0.64   | 8      | 150    | 84.72  | 2.29   |
| 3      | 50     | 16.17  | 0.67   | 9      | 150    | 88.36  | 2.55   |
| 4      | 100    | 47.96  | 1.45   | 10     | 200    | 52.17  | 1.44   |
| 5      | 100    | 45.26  | 1.43   | 11     | 200    | 82.24  | 2.58   |
| 6      | 100    | 48.65  | 1.50   | 12     | 200    | 45.39  | 1.57   |

As can be seen from Figure 4, with the increase of rock size, the peak load and peak displacement of rock in the cone penetration test present an increasing trend. When the size of specimen increases from 50 mm to 200 mm, and the peak load increases by 161.1%, 316.1% and 355.5%, respectively. When the size of the specimen reaches 150 mm, the influence of the increase of rock size on the peak load and displacement of rock decreases obviously. The axial displacement increases by 126.6%, 246.9% and 303.1% respectively, when the specimen size increases from 50mm to 200mm.

A fixed monitoring point, which is 20 mm away from the loading point, was choosed as reference points to record the strain data of different sizes of specimens. The strain records of two mutually perpendicular directions at the monitoring point are shown in Figure 5.

![Figure 5. Strain load diagram of different size samples.](image)
As can be seen from Figure 5, during the point load loading process, the X direction of monitoring point on the upper surface will experience a process of tension followed by compressing, and the Y direction will experience a process of compression followed by tension. With the increase of specimen size, it is more and more difficult to increase the strain in both directions of the monitoring point in the process of axial loading. In order to find out the limit size of specimen which influences the strength and deformation characteristics of rock, the numerical simulation is conducted according to the test results.

2.2 numerical simulation of PFC with different sizes

2.2.1 model establishment.

In this paper, PFC is utilized to simulate the rock cone penetration test of different sizes. In order to analyze the influence of rock sample size on the strength and deformation characteristics of rock, a rock model with the same geometric shape as the laboratory test was established. The diameter range of the elementary balls of different size specimens is consistent. In the simulation, the loading indenter adopts a conical wall surface similar to the experimental indenter. The modeling process is shown in figure 6 (a). In order to monitor the strain data at the same position in the test, on the cross section of the specimen passing through the loading point, a measuring circle is set every 10 mm to obtain the volumetric strain at the fixed point of the specimen. The sphere shown in the measuring circle circled in figure 6 (b) is the position where the strain is monitored during the test. The mesoscopic parameters of PFC model are listed in table 3.

![Modeling diagram and distribution diagram of measuring circle.](image)

**Figure 6.** Modeling diagram and distribution diagram of measuring circle.

| Rock Specimen | Ec/MPa | k_v/k_h | σc/MPa | τc/MPa | θ |
|---------------|--------|---------|--------|--------|---|
| Sandstone     | 6.88   | 1.6     | 12.1   | 14.9   | 30 |

2.2.2 deformation characteristics of rock.

The simulation results were compared with the experimental results. Figure 7 shows the volumetric strain values in X and Y directions at a distance of 20 mm from the loading point for both test and simulation results. When the specimen size is large, the axial displacement is large, and the strain measured by the strain gauge contains part of the axial strain. Therefore, it can be seen from figure 7 that when the specimen size is large, there is a certain difference between the simulation data and the test data.
Figure 7. Comparison of numerical simulation data and experimental data

Figure 8. Absolute value of volumetric strain of specimens with different sizes under ultimate load.

By observing the volume strain of specimens with diverse sizes under peak load in figure 8, it can be seen that when the size of specimen is small, the overall volumetric strain under peak load is large. When the specimen size reaches 150 mm, there is no longer a large volumetric strain in the whole specimen. The large range of volumetric strain is mainly concentrated in a core area near the loading point, and the volumetric strain of rock mass outside the core area is small, which can be ignored. With the increase of specimen size, the core area of volumetric strain will increase to a certain extent. When the sample size increases from 50 mm to 250 mm, the core areas of volumetric strain are 50 mm, 100 mm, 105 mm, 120 mm and 117 mm away from the loading point. When the specimen size reaches 200 mm, the core area does not increase. Therefore, it can be considered that when the specimen size is greater than 200 mm, the increase of specimen size basically does not affect the deformation characteristics of rock.

3. Theoretical analysis

In order to quantitatively describe the relationship between volumetric strain and specimen size, based on Boussinesq solution [12], the theoretical volumetric strain under axial point load is shown in equation (1).
\[ \theta = \frac{(1-2\nu)}{E} \left[ \frac{3Pz^2}{2\pi (r^2 + z^2)^{3/2}} \right] \]  

Considering the difference between theory and practice, a correction parameter is introduced to fit the results of different size samples, and the specific coefficients under different sample conditions are obtained. The specific equation and conditions are listed in Table 4. In order to reasonably analyze the parameter values under different sample sizes, the inversion coefficients are fitted, and the fitting curve is shown in Figure 10. The relationship between rock size and volume strain is shown in equation (2).

**Table 4.** Fitting results of volumetric strain for different size specimens.

| d (mm) | P (kN) | Fitting formula | \( R^2 \) |
|-------|--------|-----------------|----------|
| 100   | 20     | \( \theta = 0.483 \times \frac{(1-2\nu)}{E} \left[ \frac{3Pz^2}{2\pi (r^2 + z^2)^{3/2}} \right] \) | 0.789    |
| 150   | 20     | \( \theta = 0.395 \times \frac{(1-2\nu)}{E} \left[ \frac{3Pz^2}{2\pi (r^2 + z^2)^{3/2}} \right] \) | 0.722    |
| 200   | 20     | \( \theta = 0.32 \times \frac{(1-2\nu)}{E} \left[ \frac{3Pz^2}{2\pi (r^2 + z^2)^{3/2}} \right] \) | 0.89     |
| 250   | 20     | \( \theta = 0.324 \times \frac{(1-2\nu)}{E} \left[ \frac{3Pz^2}{2\pi (r^2 + z^2)^{3/2}} \right] \) | 0.87     |

\[ \theta = \left[ 0.311 \times 1.48 \times 4.78 \times 10^{-10} \right] \left[ (1-2\nu) \left[ \frac{3Pz^2}{2\pi (r^2 + z^2)^{3/2}} \right] \right] \]  

Where: \( \theta \) — volumetric strain; \( \nu \) — Poisson's ratio; \( E \) — modulus of elasticity, Pa; \( P \) — peak load, N; \( d \) — side length of square specimen, m.

**Figure 9.** Influence of rock size on correction coefficient of volumetric strain.
4. Conclusion
The main research results are as follows:
1. The influence of point load on rock deformation is mainly manifested as the increase of core area and volumetric strain in core area. When the specimen size is small, the whole specimen will produce large volume strain. When the specimen size reaches a certain level, the rock mass only generates large volumetric strain within a certain range before failure. For sandstone, this range is within 100mm from the loading point.
2. Under the same load, the volume strain at the same position from the loading point decreases exponentially with the increase of the specimen size, and tends to be stable when the specimen size reaches 200 mm.

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