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EFFECTS OF LOADING RATIO ON THE COMPRESSION CHARACTERISTICS OF SOUTH CHINA SEA CALCAREOUS SAND

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ABSTRACT

China has been carrying out hydraulic fill projects of coral reefs in the South China Sea. Calcareous sand is the main material of hydraulic fill ground. Based on 1-D compression tests on calcareous sand under different loading ratios, this paper analyses the effects of loading ratio on the compression characteristics and particle breakage of calcareous sand, and explains the effect mechanism combined with particle shape analysis of calcareous sand. The results show that calcareous sand particles have richer angles and more irregular shapes than quartz sand particles, and their shape characteristics are markedly different at three perpendicular directions; the increase of loading ratio leads to the increase of compressibility and particle breakage; calcareous sand particles break evidently when the axial stress reaches 400 kPa. The above conclusions have reference value for the treatment of hydraulic fill ground and settlement calculation in practical engineering.

Key words: Calcareous sand, loading ratio, compression characteristics, particle shape analysis, particle breakage.

1. INTRODUCTION

Calcareous sand is a kind of marine biogenic sand in which calcium carbonate content exceeds 50%, mostly distributes between south latitude 30 degree and north latitude 30 degree. It has high internal friction angle, high void ratio, high compressibility and high breakability (Coop 1990). Calcareous sand in the South China sea is mainly coral debris and its calcium carbonate content mostly exceeds 90% (Liu *et al*. 1998). In order to safeguard territorial integrity and ensure the safety of shipping, China has been carrying out hydraulic fill projects of coral reefs in the South China Sea. As the main material of hydraulic fill ground, calcareous sand has a crucial influence on the ground stability of hydraulic fill island. Therefore, based on 1-D compression tests and particle shape analysis, this paper analyses effects of loading ratio on the compression characteristics and particle breakage of calcareous sand, as well as explains the mechanism of the effects.

2. EXPERIMENTAL MATERIAL AND PROCEDURES

2.1 Experimental Material

The calcareous sand tested was taken from hydraulic fill foundation in a reef of Nansha Islands. It was uncemented loose particles, mainly consisted of coral debris and marine organism skeletal bodies. Its particle shape was extremely irregular. Most of the calcareous sand particles are white, yet a few particles are dark red.

Before the tests were carried out, the salt on the surface of calcareous sand should be washed out first. Then the calcareous sand should be sieved. The sieving result showed that the proportion of particles with size greater than 5 mm was very small, only 0.1%. Considering the size of 1-D compression test sample, the calcareous sand with particle size greater than 5 mm was eliminated, in order to reduce the error caused by large particles. After eliminating the large particles, the grading curve for calcareous sand is shown in Fig. 1. Table 1 gives main physical properties of calcareous sand.

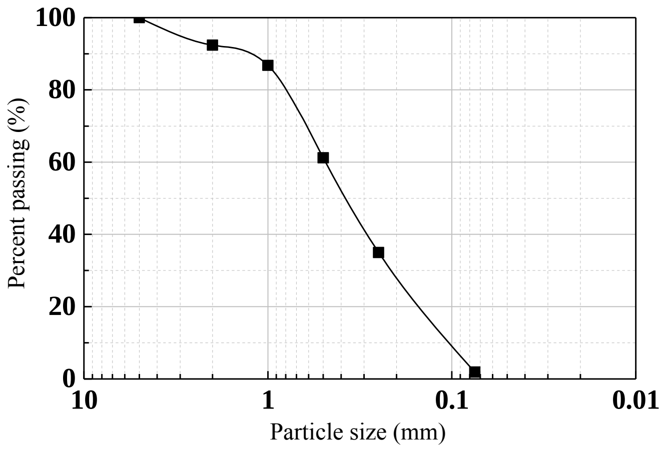

Fig. 1 Grading curve for calcareous sand

Table 1 Main physical properties of calcareous sand

C_u	C_c	G_s	e_{min}	e_{max}
4.8	0.9	2.69	0.799	1.186

C_u: coefficient of uniformity; C_c: coefficient of curvature;
G_s: specific gravity; e_{min}: minimum void ratio;
e_{max}: maximum void ratio

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2.2 Particle Shape Analysis Procedures

Calcareous sand particles have extremely irregular shapes, rich angles, rich void (including inner void) and low strength (Chen *et al*. 2005). The angles of calcareous sand particles are easily broken when loaded. Therefore, the particle shape of calcareous sand is closely related to its compression characteristics.

In the previous research on the particle shape, the microscope could only photograph the particle shape in one direction, but it could not fully reflect the shape characteristics of irregular particles. Therefore, a method for photographing the particle shape from three perpendicular directions was invented in this paper. Calcareous sand particles were made into transparent cubic specimen by using epoxy resin and cubic molds, as shown in Fig. 2. Through rotating the specimen under the microscope, particle shape could be photographed from three perpendicular directions.

In order to study particle shape characteristics of calcareous sand, 30 representative particles from particle groups of 5 ~ 2 mm, 2 ~ 1 mm, 1 ~ 0.5 mm, 0.5 ~ 0.25 mm were selected. These particles were made into transparent cubic specimens and photographed. Moreover, quartz sand particles from the same particle groups were selected to conduct the comparison experiments. For the convenience of study, the three perpendicular directions were denoted as x, y, and z in this paper.

After photographing the particle profiles of x, y, and z directions by microscope, two valued processing for the profile photographs was couducted, as shown in Fig. 3. The geometric parameters of sand particles of x, y, and z directions could be obtained by using Image J software to analyze the particle shape.

2.3 1-D Compression Test Procedures

In order to study the effect of loading ratio on the compression characteristics of calcareous sand, a series of 1-D compression tests as well as 1-D rebound and re-compression tests were conducted. Compression test procedures are given in Table 2.

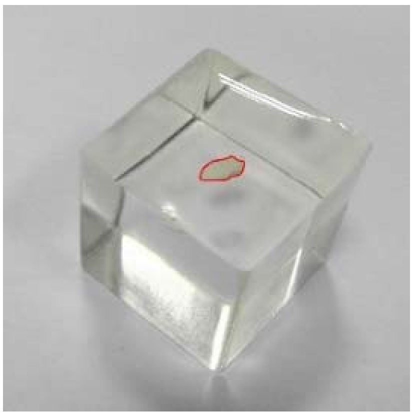

Fig. 2 Calcareous sand particle cubic specimen

Fig. 3 Particle profiles of x, y, and z directions after two valued processing

Table 2 1-D compression test procedures

No.	Loading and unloading ratio	Constant stress increment (kPa)	Loading and unloading (kPa)
1	1	/	1—12.5—25—50—100—200—400—800—1600—3200
2	3	/	1—12.5—50—200—800—3200
3	15	/	1—12.5—200—3200
4	255	/	1—12.5—3200
5	/	25	1—25—50—…—200
6	1	/	1—12.5—25—50—100—200—100—50—100—200—…—3200
7	1	/	1—12.5—…—400—200—100—50—100—…—3200
8	1	/	1—12.5—…—800—400—200—100—50—100—…—3200

1-D compression tests were conducted on the single lever type high pressure consolidometer. It was pressurized with weights. The sample was 61.8 mm in diameter and 20 mm in high. Its axial strain was measured by the dialgauge which had 10 mm of range and 0.01 mm of division value. The standard of compressive stability was that the axial strain of the sample did not exceed 0.005 mm per hour.

3. RESULTS OF PARTICLE SHAPE ANALYSIS

According to the previous research (Tu *et al*. 2004), the shape parameter S calculated from projection area A and projection perimeter P of the particle profile can well reflect the shape characteristics of particle materials. This paper analyzes the shape characteristics of calcareous sand particles according to the shape parameter S and their axial ratio T of x, y, and z directions, and compare them with quartz sand.

The expressions for shape parameter S and axial ratio T are shown as follows:

$$S = \frac{2\sqrt{\pi A}}{P} \tag{1}$$

$$T = \frac{L}{B} \tag{2}$$

where L is particle length, namely the maximum outer tangent parallel distance of the particle profile, and B is particle width, namely the minimum outer tangent parallel distance of the particle profile.

The shape parameter S (value range from 0 to 1) reflects the angles of sand particles. The smaller the value, the richer the angles of sand particles, and $S = 1$ represents a circular particle. The axial ratio T (value greater than or equal to 1) is the ratio of the longest axis to the shortest axis. The greater the value, the closer the sand particles to branch shape.

After obtaining the particle geometric parameters of calcareous sand and quartz sand by Image J software, S and T of x, y, and z directions and their averages can be calculated respectively. Figure 4 gives average of S of x, y, and z directions of calcareous sand and quartz sand, and Fig. 5 gives average of T of x, y, and z directions of calcareous sand and quartz sand (each particle group is represented by its median size on the abscissa).

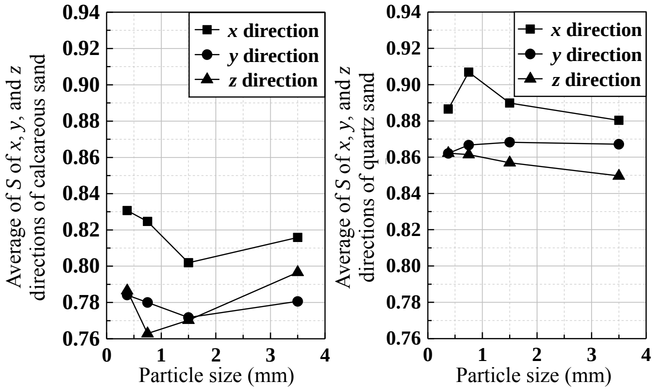

Fig. 4 Average of *S* of *x*, *y*, and *z* directions of each calcareous sand and quartz sand particle group

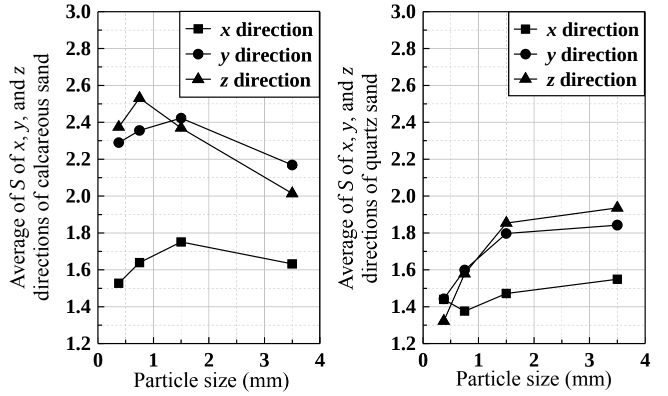

Fig. 5 Average of *T* of *x*, *y*, and *z* directions of each calcareous sand and quartz sand particle group

Left figures of Figs. 4 and 5 show that *S* of *x* direction of calcareous sand is evidently greater than that of *y* and *z* directions and that *T* of *x* direction is far smaller than that of *y* and *z* directions. It illustrates that calcareous sand particles have richer angles and more irregular shapes in *x* direction than that in *y* and *z* directions. The principal reason is that *x* direction shows the profile projections of calcareous sand particles at rest under the action of gravity, therefore, the shape of *x* direction is more regular. This is also reflected in quartz sand particles, as shown in right figures of Figs. 4 and 5. When researchers studied the shape characteristics of sand particles in the past, they usually placed sand particles on the microscope stage naturally to photograph, the particle profile was basically the same as that in *x* direction. As a result, the irregularity of particle shape was conservative, and it could not fully reflect the shape characteristics of sand particles. Calcareous sand is one of the typical examples.

As shown in Figs. 4 and 5, with the increase of particle size, *S* decreases at first and then increases, and *T* increases at first and then decreases. It illustrates that the particle shape of medium grained calcareous sand (0.5 ~ 2 mm) is the most irregular. It may be due to the fact that medium grained particles are embedded in the large and small particles, they have less wear and fragmentation during erosion and movement, thus maintaining good original shape (Wang *et al*. 2018). Compared with quartz sand, the particle shape of calcareous sand tends to branch shape, and the angles are richer. The special particle shape characteristics have effect on the compression characteristics of calcareous sand.

4. RESULTS OF 1-D COMPRESSION TESTS

4.1 1-D Compression Tests and Particle Breakage

Tests 1, 2, 3, 4 represented 1-D compression tests with loading ratios of 1, 3, 15, and 255 respectively, and all of their final stress is 3200 kPa. Figure 6 shows their *e*-log *p* curves. After compression, the samples were dried and sieved. The compacted sample gradings were obtained to analyze particle breakage under different loading ratios. The contents of each particle group before and after compression are shown in Table 3.

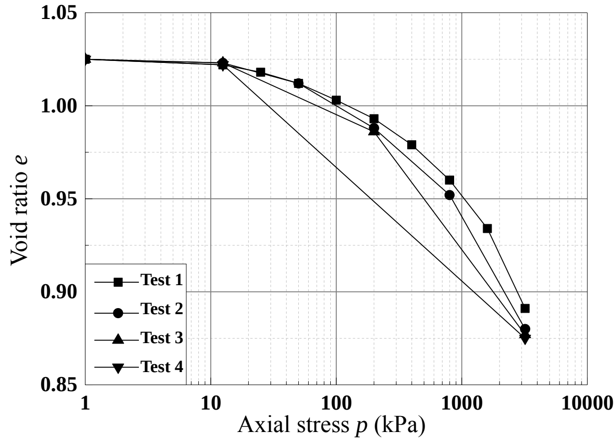

Fig. 6 *e*-log *p* curves of 1-D compression tests with different loading ratios

Table 3 Content of each particle group before and after compression

Particle group (mm) \ No.	Origin	Test 1	Test 2	Test 3	Test 4
5 ~ 2	7.6%	6.5%	6.2%	6.1%	5.6%
2 ~ 1	5.6%	4.8%	4.6%	4.7%	4.2%
1 ~ 0.5	25.6%	25.9%	26.0%	25.3%	25.8%
0.5 ~ 0.25	26.2%	26.5%	26.0%	26.6%	26.5%
0.25 ~ 0.075	33.1%	33.5%	33.9%	33.9%	34.0%
≤ 0.075	1.9%	2.8%	3.3%	3.4%	3.9%

As shown in Fig. 6, the loading ratio has effect on the compression characteristics of calcareous sand, and the effect is related to particle breakage. The increase of loading ratio leads to the increase of compressibility under the same axial stress.With the increase of axial stress, the effect becomes more evident. As given in Table 3, the content of particle size within 5 ~ 1 mm decreases and the content of particle size less than 0.075 mm increases significantly, as well as the content of particle size within 1 ~ 0.075 mm remains unchanged basically after compression. It indicates that the large particles are easier to break up. The particle breakage gives priority to abrasion and breaking of large particle angles. Therefore, the content of particle size less than 0.075 mm increases significantly. It reflects the irregular shape and rich angles of calcareous sand particles.

The relative breakage factor B_r was defined by Hardin (1985). He defined the breakage potential B_p as the area below the original grading curve till 0.075 mm, representing the total possible change in the soil grading. He also defined the total breakage B_t as the area between the original and final grading curves till 0.075 mm. Hardin then defined the relative breakage factor B_r as the B_t/B_p. The calculated values of B_r of Tests 1, 2, 3, and 4 is 1.0%, 1.4%, 1.5%, and 2.0%, respectively. With the increase of load ratio, particle breakage becomes increasingly significant and more small particles filled into the pores. Therefore, the compressibility of calcareous becomes greater.

At the same time, 1-D compression tests with constant stress increment (the number is Test 5) are conducted. The stress increment of each stage is 25 kPa, and the final stress is 200 kPa. In order to show the effects of loading ratio on the compression characteristics intuitively, volume strain of calcareous sand samples is shown in Fig. 7. The left column of Fig. 7 is the volume strain of each sample under axial stress of 200 kPa, including Tests 5, 1, 2, and 3. The right column of Fig. 7 is the volume strain of each sample under axial stress of 3,200 kPa, including Tests 1, 2, 3, and 4.

As shown in the left column of Fig. 7, under axial stress of 200 kPa, volume strain of Test 5 is smaller than that of Tests 2 and 3, but greater than that of Test 1. The reason may be that in Test 5, the small stress increment result in the small frictional resistance increment between calcareous sand particles. Therefore, compared with Test 1, the particles are more easily to slip, adjust positions and rearrange in Tset 5, and the volume strain of Test 5 is greater.

As shown in the right column of Fig. 7, the increase of loading ratio leads to the increase of volume strain under axial stress of 3200 kPa. Volume strain of Test 2 is 8.6% greater than that of Test 1. This value is much greater than 2.6%, which of common sand (Wang *et al*. 2009). It illustrates that effect of loading ratio on the compression characteristics of calcareous sand is more evident than that of common sand, which may be due to the special particle shape characteristics of calcareous sand.

4.2 1-D Rebound and Re-compression Tests with Different Unloading Stresses

Tests 1, 6, 7, and 8 represent 1-D rebound and re-compression tests with loading ratio and unloading ratio of 1 and final stress of 3200 kPa. Thereinto, Test 1 is not unloading, Tests 6, 7, and 8 are unloaded from 200, 400, and 800 kPa, respectively, to 50 kPa and then reloaded. Figure 8 shows their *e*-log *p* curves.

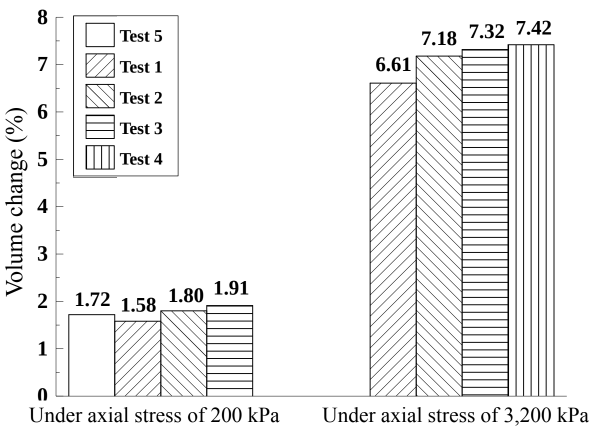

Fig. 7 Volume strain of each sample under axial stress of 200 kPa and 3200 kPa

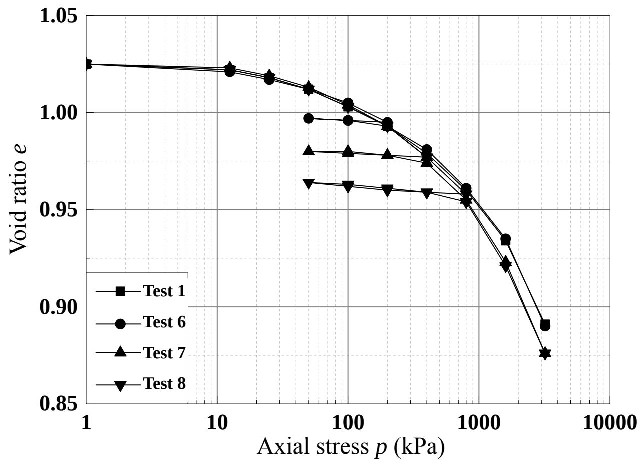

Fig. 8 *e*-log *p* curves of 1-D rebound and re-compression tests with different unloading stresses

As shown in Fig. 8, the unloading rebound of calcareous sand is very small. It illustrates that the deformation of calcareous sand during the compression process is mainly no-recoverable plastic deformation. Volume strains of Tests 1 and 6 are approximately equal, but evidently smaller than that of Tests 7 and 8. The reason may be that calcareous sand particles break evidently when the axial stress reaches 400 kPa. Unloading makes the broken particles no longer contact closely, and reloading makes the broken particles easier to slip and dislocation. As a result, the volume strains increase evidently. Figure 8 shows when Tests 7 and 8 reloading to 400 and 800 kPa, respectively, their void ratios are evidently smaller than the void ratios when unloading. This phenomenon can reflect the above conjecture. It is known that B_r of the sample under 400 kPa is 5 times more than that of the sample under 200 kPa through screening. It proves the above conjecture.

5. CONCLUSIONS

1. Compared with quartz sand, calcareous sand particles have richer angles and more irregular shapes, and tend to branch shape. The special particle shape characteristics have effect on the compression characteristics and particle breakage of calcareous sand.
2. The particle shape characteristics of calcareous sand in three perpendicular directions are evidently different. Therefore, the particle shape in one direction can not fully reflect the particle shape characteristics of calcareous sand.
3. Under the same axial stress, the increase of loading ratio leads to the increase of the compressibility of calcareous sand, which is related to particle breakage.
4. Calcareous sand particles break evidently when the axial stress reaches 400 kPa. The particle breakage gives priority to abrasion and breaking of large particle angles.

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