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ORIGINAL PAPER

Macro-meso effects of gradation and particle morphology on the compressibility characteristics of calcareous sand

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Abstract In order to fully develop the South China Sea, a large number of reclamation projects using calcareous sand have been carried out in this area recently. A deep understanding of the physical and mechanical properties of calcareous sand is of critical importance. Therefore, the calcareous sand near a certain reef of the South China Sea is used in this study to investigate the effect of three-dimensional (3-D) particle morphology and gradation on the compressibility characteristics of calcareous sand. This paper proposes a 3-D mesoscope observation method to obtain the average 3-D angularity parameter S_d and 3-D aspect ratio T_d of calcareous sand with different particle sizes. It is found that the morphology of coarse particles (diameter: 5 ~ 1 mm) is significantly multi-angular, while the morphologies of middle particles (1 ~ 0.25 mm) are mostly dendritic and schistic. Compared to the 3-D S_d of quartz sand, the calcareous sand's particle morphology is much more irregular and multi-angular, which makes it easy for the calcareous sand to form large pores and, thus, be more compressible. In order to systematically study the effect of gradation on the calcareous sand's compressibility characteristics, a number of compression tests on calcareous sand with different gradations are taken. The influential mechanism is then discussed by analyzing the test results from a mesoscopic viewpoint. It is found that changing the coarse fraction content is the most efficient way to reduce the compressibility of the calcareous sand. That is because of the coarse fraction's high angularity, which makes the skeleton-bearing capacity of the calcareous sand sensitive to the change of coarse fraction content. An empirical formula is proposed to evaluate the compressibility of the calcareous sand with different coarse fraction contents.

Keywords Macro-meso effect · Calcareous sand · Particle morphology · Compressibility characteristic · Gradation · Particle fraction

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Introduction

The South China Sea, as a part of China, has very important strategic significance and economic value. In order to better exploit its resources, China has carried out a large number of reclamation projects in this area recently.

Calcareous sand, as the main raw material for reclamation, draws many researchers' attention (Wang et al. 2011; Shaqour 2007). The basic compressibility characteristic of calcareous sand has been studied (Poulos et al. 1982; Coop 1990; Zhang et al. 2005). It was found that the mechanical properties of calcareous sand were affected by its particle size and morphology (McDowell and Bolton 2000). Compared with fine particles, coarse particles' compressibility is higher (Zhang 2004; Zhang 2014).

The mechanical properties of granular material are significantly affected by particle morphology as reported by researchers (Polakowski et al. 2014; Cepuritis et al. 2016). To quantitatively describe the particle morphology of granular materials, many morphological parameters have been proposed (Oda 1978; Mora and Kwan 2000; Hentachel and Page 2003; Hafid et al., 2016), and of all the morphological parameters, parameter *S*, calculated by the particles' contour projection area *A* and perimeter *P*, is considered to be one of the best indicators of a granular materials' particle morphology (Tu and Wang 2004). Calcareous sand, as a granular material, has very irregular particle shape that is related to its particle size (Chen et al. 2005).

The above studies show that gradation and particle morphology have an important influence on the compressibility of calcareous sand, as will be presented in this study. The calcareous sand used for this study was from a certain reef of the South China Sea. This paper proposes a 3-D mesoscope observation method to analyze the 3-D morphology of the calcareous sand aggregates. Then, a number of compression tests are conducted to systematically study the effect of gradation on the calcareous sand's compressibility characteristics. The influential mechanism is finally discussed by analyzing the test results from a mesoscopic viewpoint.

Materials and methods

Test materials

The calcareous sand used in this study was from the Mischief reef of the South China Sea. Before testing, the calcareous sand was dried by air, and then divided into six particle fractions by screening: 5 ~ 2 mm, 2 ~ 1 mm, 1 ~ 0.5 mm, 0.5 ~ 0.25 mm, 0.25 ~ 0.075 mm, ≤ 0.075 mm. The corresponding gradation is shown in Fig. 1.

The quartz sand was also tested in this study as a contrast material. Therefore, the same gradation as the test calcareous sand was used. The basic properties of the test materials were determined by a Chinese Standard (GB/T50123 1999), as shown in Table 1.

Where *G*s is specific gravity; $e_{\min}$ is minimum void ratio; $e_{\max}$ is maximum void ratio; C_u is uniformity coefficient; and C_c is curvature coefficient.

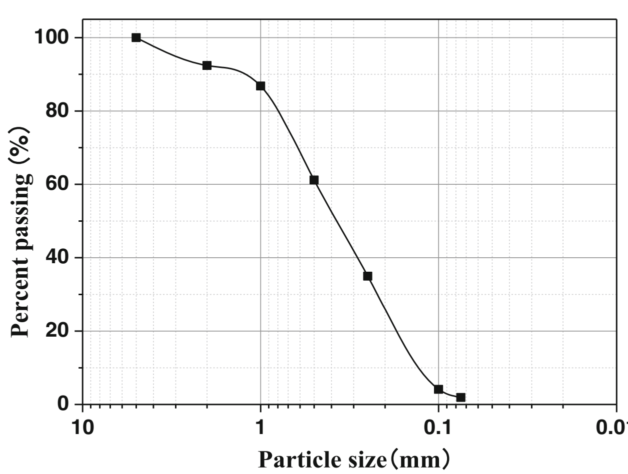

Fig. 1 Gradation of the calcareous sand

Table 1 Basic property of the test sands

Sample	*G*s	$e_{\min}$	$e_{\max}$	C_u	C_c
Calcareous sand	2.70	0.80	1.19	4.8	0.9
Standard sand	2.67	0.39	0.75	4.8	0.9

Mesoscopic observation method of particle's 3-D morphology

The observation method is mainly to use a microscope, from three orthogonal directions, to observe the contour projections of the calcareous sand's particle, which is fixed in a transparent cube specimen, as shown in Fig. 2(a). The specimen is made by customized smooth cubic resin molds as shown in Fig. 2(b) and high-transparency epoxy resin AB glue (3001A/3001B made by Kunshan Xiangfeng-Xin Composite Materials Co., Ltd.).

First, mix the A glue and B glue evenly by the mass ratio of 3:1, and let it stand for 10 min to dissipate bubbles. Then, fill half the cubic holes of the mold with the mixed liquid. After that, put the mold into an incubator (60 ~ 70 °C) and heat for 2 h or more until the mixed liquid is completely solidified. Take the mold out and put one calcareous sand particle onto the surface of the transparent curing body. Then, repeat until the cube specimens are completely solidified. Then, take the cube specimens out of the mold.

Next, use an electron microscope to capture images of the calcareous sand particle from the three orthogonal directions, as shown in Fig. 3.

To study the 3-D morphology of the calcareous sand with different particle sizes, 15 representative particles from four particle fractions (5 ~ 2 mm, 2 ~ 1 mm, 1 ~ 0.5 mm, 0.5 ~ 0.25 mm) were chosen to make the transparent cube specimens and respectively numbered 1 to 15, 16 to 30, 31 to 45, and 46 to 60. We then used a microscope to capture images of the calcareous sand particle from the *x*, *y* and *z* directions. Fig. 4(a) shows the original microscope images of a representative calcareous sand particle (no. 1).

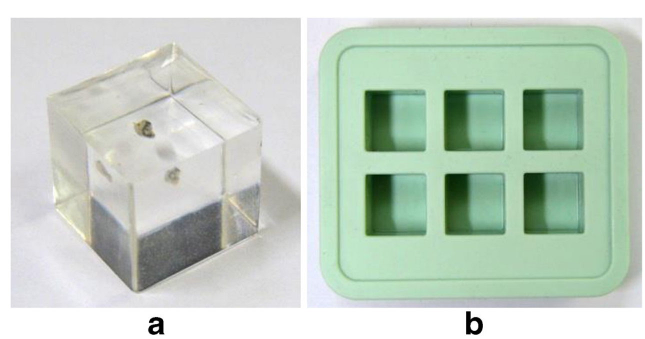

Fig. 2 (**a**) The calcareous sand particle within a transparent cube specimen; (**b**) customized smooth cubic resin mold: its single cubic size is 1.6 × 1.6 × 1.6 mm

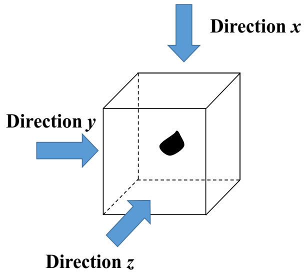

Fig. 3 Three orthogonal directions of the calcareous sand's particle

Then, the original microscope images were binarized by Photoshop software, as shown in Fig. 4(b). After that, Image J software was used to analyze the particle's contour projection area A, perimeter P, maximum Feret's diameter L and minimum Feret's diameter B (Walton 1948) from the three orthogonal directions.

Method of 1-D compression tests

1-D compression tests were conducted using a WG high-pressure consolidation apparatus, and the stress path was 5 kPa – 12.5 kPa – 25 kPa – 50 kPa –100 kPa – 200 kPa – 400 kPa – 800 kPa – 1600 kPa – 3200 kPa.

In order to facilitate the study on the compressibility characteristics of the calcareous sand with different particle fractions, the sand aggregates were divided into three fractions: coarse fraction (5 ~ 1 mm), middle fraction (1 ~ 0.25 mm) and fine fraction (≤ 0.25 mm). The original gradation of the calcareous sand contains 13% coarse fraction, 52% middle fraction and 35% fine fraction. When changing a certain particle fraction, the relative content of the other two particle fractions remains the same.

In addition, to effectively show the compressibility of the calcareous sand, a group of compression tests for quartz sand were set as comparisons. Every compression test was taken under 40% relative compaction, and three parallel tests were set, resulting in a total of 48 compression tests. Table 2 shows the test programs.

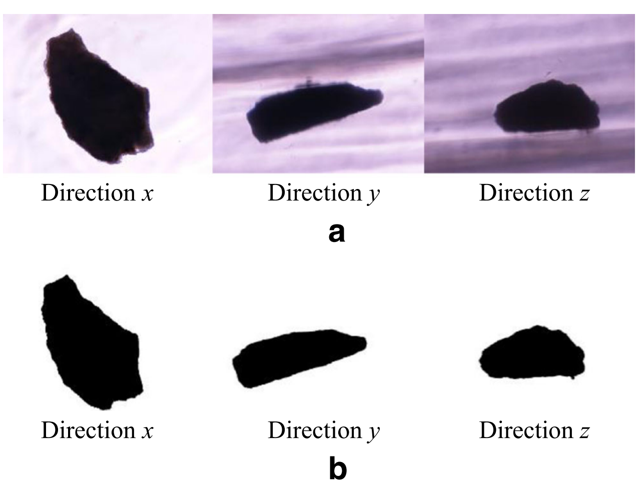

Fig. 4 (**a**) Original microscope images of the calcareous sand particle (no. 1). (**b**) Binarized microscope images of the calcareous sand particle (no. 1)

Results of the calcareous sand particle morphology

According to the study (Tu and Wang 2004), the morphology parameter S calculated by the particle's contour projection area A and perimeter P can better describe the particle morphology of granular materials. Thus, this paper mainly analyzes the morphology parameter S and added aspect ratio T from the three orthogonal directions to study its 3-D morphology characteristics.

Morphology parameter S and aspect ratio T can be calculated by Eqs. (1) and (2):

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

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

where L and B are the maximum and minimum Feret's diameters (Herdan and Smith 1953), respectively.

Morphology parameter S ranges from 0 to 1, describing the particle angularity. When S is equal to 1, it means that the particle shape is like a circle, and the smaller S is, the more angularity the particle has. Aspect ratio T, which is always greater than or equal to 1, describes the ratio of the longest axis to the shortest axis of the particle, and the larger the value is, the more the particle shape resembles dendrites.

As 2-D morphology parameters are difficult to describe the particle's overall shape characteristics, this paper uses the 3-D morphology parameter S_d and 3-D aspect ratio T_d to describe the particles' 3-D morphology characteristics. The 3-D S_d and T_d indicate the geometrical mean of the three orthogonal directions' morphology parameters. The calculation formulas are shown in Eqs. (3) and (4):

$$S_d = \sqrt[3]{S_x \times S_y \times S_z} \tag{3}$$

$$T_d = \sqrt[3]{T_x \times T_y \times T_z} \tag{4}$$

where S_x, S_y and S_z are the particle's morphology parameters of direction x, y and z, respectively. S_d is the particle's 3-D morphology parameter. T_x, T_y and T_z are the particle's aspect ratios of direction x, y and z, respectively. T_d is the particle's 3-D aspect ratio.

According to the particles' 3-D morphology parameter S_d of the calcareous sand with different particle sizes (Fig. 5), the particle morphology of the calcareous sand was studied.

Table 2 Test programs

Coarse fraction content (5 ~ 1 mm)	Particle fraction content (%)					
	5 ~ 2 mm	2 ~ 1 mm	1 ~ 0.5 mm	0.5 ~ 0.25 mm	0.25 ~ 0.075 mm	<0.075 mm
5%	2.9%	2.1%	28.0%	28.7%	36.2%	2.1%
10%	5.8%	4.2%	26.5%	27.2%	34.3%	2.0%
13%	7.6%	5.6%	25.6%	26.2%	33.1%	1.9%
15%	8.6%	6.4%	25.1%	25.7%	32.4%	1.8%
20%	11.5%	8.5%	23.6%	24.1%	30.5%	1.8%
25%	14.4%	10.6%	22.1%	22.6%	28.6%	1.7%
30%	17.3%	12.7%	20.6%	21.1%	26.7%	1.6%
Middle fraction content (1 ~ 0.25 mm)	Particle fraction content (%)					
	5 ~ 2 mm	2 ~ 1 mm	1 ~ 0.5 mm	0.5 ~ 0.25 mm	0.25 ~ 0.075 mm	<0.075 mm
30%	11.0%	8.1%	14.8%	15.2%	48.0%	2.9%
40%	9.5%	7.0%	19.8%	20.2%	41.2%	2.3%
52%	7.6%	5.6%	25.6%	26.2%	33.1%	1.9%
60%	6.3%	4.6%	29.6%	30.4%	27.4%	1.7%
70%	4.7%	3.5%	34.6%	35.4%	20.6%	1.2%
Fine fraction content (≤0.25 mm)	Particle fraction content (%)					
	5 ~ 2 mm	2 ~ 1 mm	1 ~ 0.5 mm	0.5 ~ 0.25 mm	0.25 ~ 0.075 mm	<0.075 mm
15%	10.0%	7.3%	33.5%	34.3%	14.2%	0.7%
25%	8.8%	6.5%	29.6%	30.3%	23.6%	1.2%
35%	7.6%	5.6%	25.6%	26.2%	33.1%	1.9%
45%	6.4%	4.7%	21.7%	22.2%	42.5%	2.5%
55%	5.3%	3.9%	17.7%	18.2%	52.0%	2.9%
Standard sand	7.6%	5.6%	25.6%	26.2%	33.1%	1.9%

As shown in Fig. 5, for all of the four particle fractions of the calcareous sand, the 3-D morphology parameter S_d values are mostly maintained between 0.65 ~ 0.9. In order to study the average distribution of each particle fraction's 3-D morphology parameter S_d, the average value and variance of S_d were calculated, as shown in Fig. 6.

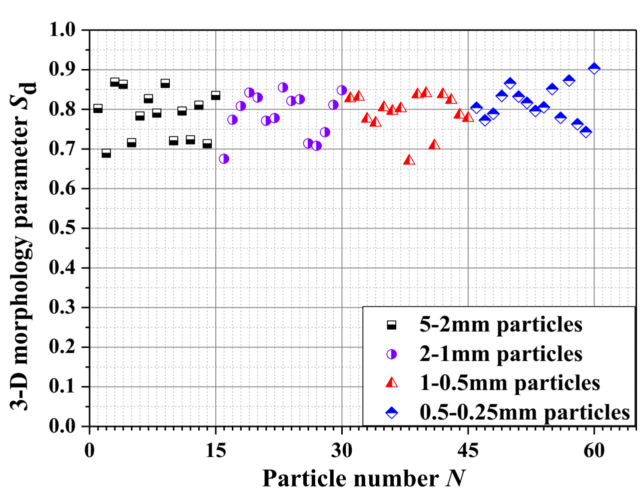

Fig. 5 Distribution of the 3-D morphology parameter S_d of the calcareous sand with different particle sizes

As for the calcareous sand with particle size of 5 ~ 0.5 mm, the mean value of S_d is about 0.787 ~ 0.792. However, as for the calcareous sand with particle size of 0.5 ~ 0.25 mm, the mean value of S_d is 0.815, which is higher than that of 5 ~ 0.5-mm particles. This indicates that in calcareous sand, particles with size of 5 ~ 0.5 mm have higher angularity than that of 0.5 ~ 0.25-mm particles. According to the variance, it can be found that with the increase of particle size, S_d becomes more discrete, which indicates that with the increase of particle size,

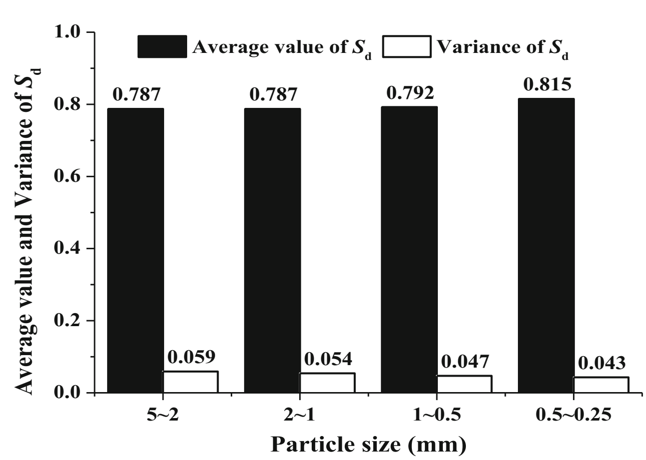

Fig. 6 Average value and variance of S_d of each particle fraction

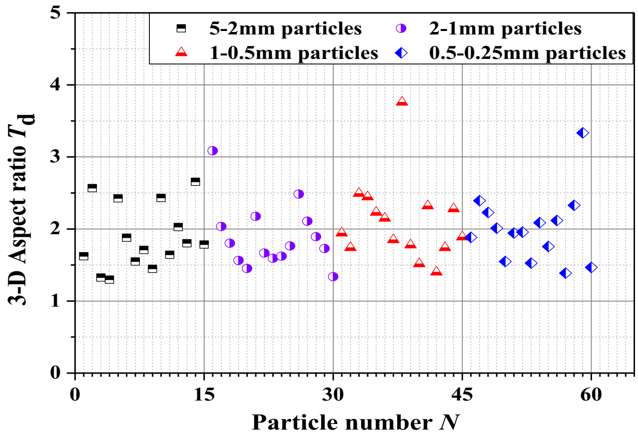

Fig. 7 Distribution of 3-D aspect ratio T_d of the calcareous sand with different particle sizes

the morphology difference of the calcareous sand aggregates is increasingly more obvious.

Fig. 7 shows the distribution of the 3-D aspect ratio T_d of the calcareous sand with different particle sizes. Figure 8 shows the average value and variance of T_d of each particle fraction.

The aspect ratio of the calcareous sand is mostly distributed between 1 to 3 (Fig. 7), and the average value T_d of the calcareous sand with different particle sizes of 5 ~ 2 mm, 2 ~ 1 mm, 1 ~ 0.5 mm, 0.5 ~ 0.25 mm are 1.88, 1.89, 2.1 and 2.0, respectively. However, as the study (Chen et al. 2005) on 2-D morphology of calcareous sand shows, the average value T (2-D) of the calcareous sand with different grain sizes of 2 ~ 1 mm, 1 ~ 0.5 mm and 0.5 ~ 0.25 mm are 2.11, 1.97 and 1.99, respectively. The difference between the 3-D T_d and 2-D T indicates that 3-D morphology parameters can better describe the particle morphology of calcareous sand.

Through comprehensive analysis of different average values of S_d (Fig. 6) and T_d (Fig. 8), it can be found that the calcareous sand particles with size of 5 ~ 1 mm have lower S_d (average value: 0.787) and lower T_d (average value: 1.878 ~ 1.887), which indicates that most of those particles (5 ~ 1 mm) have higher angularity. However, the calcareous sand particles with size of 1 ~ 0.5 mm have lower S_d (average value: 0.792) but higher T_d (average value: 2.102), which indicates that most of those particles (1 ~ 0.5 mm) tend to be dendritic or schistic. For the calcareous sand particles with size of 0.5 ~ 0.25 mm, both of the S_d (average value: 0.815) and T_d (average value: 1.998) are higher, which indicates the most of those particles (0.5 ~ 0.25 mm) trend to be schistic, as shown in Table 3.

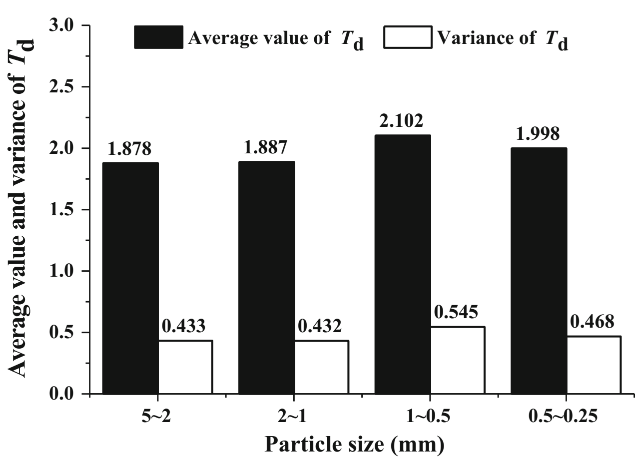

Fig. 8 Average value and variance of T_d of each particle fraction

As a granular material, the irregular and multi-angular particle morphology of calcareous sand is bound to have a great effect on its compressibility characteristics. Compared with quartz sand, the effect of particle morphology on the compressibility of the calcareous sand will be analyzed in the following from a mesoscopic viewpoint.

Results of compression tests

Mesoscopic mechanism analysis of the compressibility of the calcareous sand

As Fig. 9 shows, the compressibility of the calcareous sand is different from that of quartz sand. When vertical load is 100 ~ 200 kPa, the compressibility coefficient of the calcareous sand is 0.152 MPa^{-1}, while the one of quartz sand is only 0.055 MPa^{-1}. Compared with quartz sand, the calcareous sand has higher compressibility and higher initial porosity ratio.

To study whether particle breakage impacts the compressibility of the calcareous sand, the particle breakage rate was calculated. According to Hardin's study (Hardin 1985), the relative breakage ratio B_r is defined by the gradation measured before and after loading and can be calculated by Eq. (5) as:

$$B_r = \frac{B_t}{B_p} \tag{5}$$

where B_r is the relative breakage, ranging from 0 ~ 1. The greater B_r is, the more particles break. B_p is equal to the area between the line that defines the upper limit of the particle size (D = 0.074 mm) and the part of the gradation for which D > 0.074 mm. B_t is equal to the area between the line D = 0.074 mm, and the part of the gradation for which D > 0.074 mm before and after loading.

The relative breakage of the calcareous sand under the vertical load of 3200 kPa is only 0.019, which indicates that under the vertical load of 3200 kPa, the particle breakage extent of the calcareous sand is very limited and even can be ignored. Thus, the high porosity ratio and high compressibility of the calcareous sand are mainly caused by its particle morphology.

Table 3 Morphology of calcareous sand with different particle sizes

Particle size (mm)	5 ~ 1	1 ~ 0.5	0.5 ~ 0.25
Morphology characteristics	Significant angularity	Dendritic, schistic	Schistic

As shown in Table 4, the average value of S_d of calcareous sand is much lower than that of quartz sand, and the particle morphology parameter S_d of calcareous sand is mostly distributed between 0.67 to 0.9, while the one of quartz sand is mostly distributed between 0.75 to 1. It can be found that the particle morphology of the calcareous sand is much more irregular and multi-angular than that of quartz sand, which makes the calcareous sand more likely to form large irregular pores. However, those irregular pores are more difficult to be sufficiently filled with fine particles. As a result, the calcareous sand, under the effect of vertical load, is more likely to be compressed than quartz sand, and shows high compressibility. So the calcareous sand foundation generally has a high settlement, which is adverse to practical engineering.

As the calcareous sand's particle morphology is related to its particle sizes, changing different particle fraction contents of the calcareous sand is bound to influence the compressibility of calcareous sand. The following is mainly to study the effect of changing different particle fraction contents on the compressibility of the calcareous sand.

Effects of coarse fraction content on the compressibility of the calcareous sand

Figure 10 shows the relationship between the vertical deformation and coarse fraction content of the calcareous sand under different vertical loads.

Whenever decreasing or increasing the coarse fraction from the original gradation, the vertical deformation of the calcareous sand decreases. However, when the coarse fraction content exceeds 25%, vertical deformation nearly remains unchanged with a vertical load up to 200 kPa. As vertical load increases, the vertical deformation of the calcareous sand increases at a gradually increasing rate (Fig. 10).

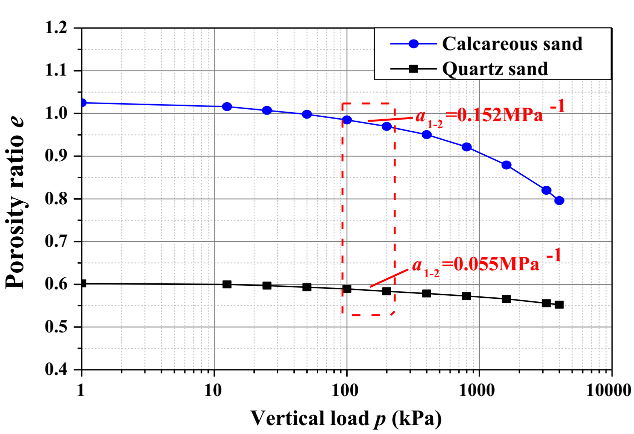

Fig. 9 The e ~ lgp curve of the calcareous sand and quartz sand

The reasons for the above-mentioned trends can be analyzed in terms of particle morphology. The bearing capacity of sand is mainly provided by a sand skeleton, which is composed of interlocking between particles. According to Fig. 10, it can be found that the coarse fraction content equal to 13% is a critical value, which means the coarse fraction content is just not enough for the sand to interlock. As a result, the coarse fraction cannot participate in the formation of the sand skeleton, but as suspended particles they break the sand skeleton formed by the middle fraction. Thus, as coarse fraction content of the calcareous sand decreases from the original gradation, that break effect will be weakened, and the bearing capacity of sand skeleton will be improved, so the vertical deformation will decrease.

However, when the coarse fraction content is over the critical value (13%), coarse particles are no longer independent of each other, but are able to interlock with each other and participate in the formation of the sand skeleton with middle particles. As coarse fraction content increases, the interlocking effect of the coarse fraction becomes stronger, and the large pores are filled by small particles, so the bearing capacity of sand skeleton is improved, and the vertical deformation decreases.

When coarse fraction content is over 25%, the number of large pores formed by the coarse fraction and middle fraction will increase, while the fine fraction content will decrease. That means there are not enough small particles to fill the large pores such that the sand skeleton cannot fully exert its bearing capacity. As vertical load exceeds 200 kPa, the interlocking effect between particles is gradually diminished, and the pores, which are not sufficiently filled by small particles, are gradually compressed. Thus, as coarse fraction content increases, the vertical deformation increases as well.

Table 4 Morphology parameter S_d of the calcareous sand

Test materials	Calcareous sand		Quartz sand
Particle size(mm)	5 ~ 0.5	0.5 ~ 0.25	
Average value of S_d	0.787 ~ 0.792	0.815	0.811 ~ 0.856
Minimum value of S_d	0.67		0.75
Maximum value of S_d	0.90		1

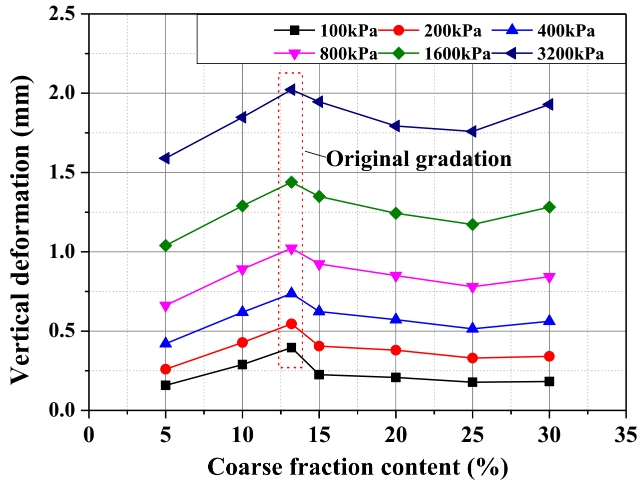

Fig. 10 Relationship between the calcareous sand's vertical deformation and coarse fraction content

Effects of middle fraction content on the compressibility of the calcareous sand

Figure 11 shows the relationship between the vertical deformation and middle fraction content of the calcareous sand under different vertical loads.

As the middle fraction content of the calcareous sand decreases from 52 to 40%, the coarse fraction content is increased to 16.5% (Table 2), which is similar to that of increasing the coarse fraction content from the original gradation. As the coarse particles are able to interlock with each other and participate in the formation of the sand skeleton with middle particles, the vertical deformation decreases (Fig. 11). If the middle fraction content continues to decrease, the contents of coarse fraction and fine fraction are further increased, which will enlarge the proportion of coarse fraction in the formation of the sand skeleton. Considering the significant angularity of coarse particles, the increased coarse particles will increase the number of large pores of the sand skeleton which are insufficient to be filled by the fine fraction. As a result, the sand skeleton cannot effectively exert its bearing capacity. Thus, under the effect of vertical load, the large pores will be compressed, and the vertical deformation will increase.

As the middle fraction content of the calcareous sand increases from the original gradation, the contents of coarse fraction and fine fraction decrease. It will cause two negative influences. One is making the coarse fraction content less than the critical value, which will make coarse particles suspend freely in the sand skeleton. The other one is that there are not enough fine particles to fulfill the pores. Both negative influences will weaken the bearing capacity of the sand skeleton. As a result, the vertical deformation increases.

Effects of fine fraction content on the compressibility of the calcareous sand

Figure 12 shows the relationship between the vertical deformation and fine fraction content of the calcareous sand under the different vertical loads.

As the fine fraction content of the calcareous sand decreases from the original gradation, the vertical deformation increases. However, as the content of fine fraction increases from the original gradation, the vertical deformation decreases (Fig. 12).

That is because when the fine fraction content of the calcareous sand decreases from the original gradation, the content of coarse particles and middle particles will increase, which will inevitably lead to more large pores formed by coarse fraction and middle fraction. However, there are not enough fine particles to fill all the large pores. Thus, as the vertical load increases, the bearing capacity of the sand skeleton will be weakened, which increases the vertical deformation.

On the contrary, when fine fraction content increases, the content of coarse particles and middle particles decrease.

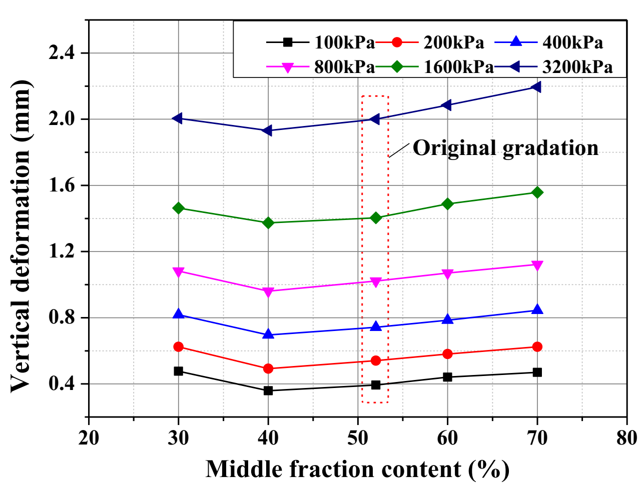

Fig. 11 Relationship between the vertical deformation and middle fraction content of the calcareous sand

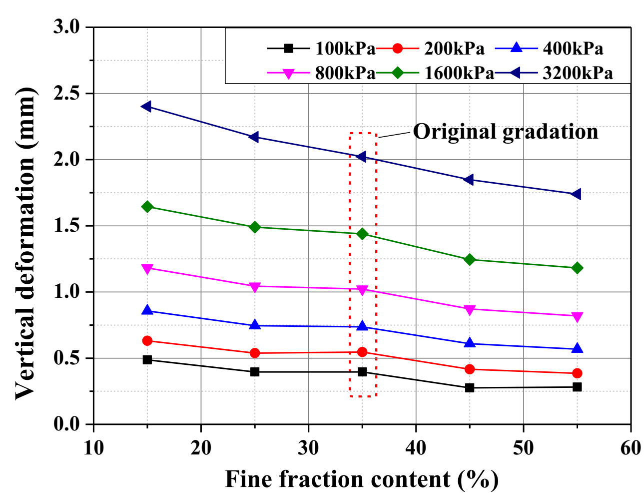

Fig. 12 Relationship between the calcareous sand's vertical deformation and fine fraction content

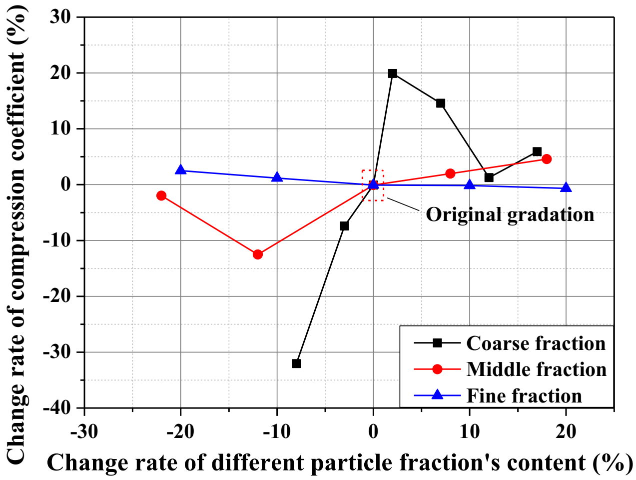

Fig. 13 The relationship between the change rate of the compressibility coefficient of the calcareous sand and change rate of different particle fraction contents

Because fine particles have a small size but large surface area, contact points between particles increase, and the arrangement between particles become more compact. As fine fraction increases, the vertical deformation is reduced.

Effects of different particle fraction contents on the compressibility coefficient of the calcareous sand

Fig. 13 shows the relationship between the change rate of the compressibility coefficient of the calcareous sand and change rate of different particle fraction contents.

According to Fig. 13, compared to changing the middle fraction and fine fraction content, changing the coarse fraction content is the most efficient way to reduce the compressibility coefficient of the calcareous sand. When the content of the coarse fraction is decreased by 8%, the compressibility coefficient of the calcareous sand is reduced by 32%.

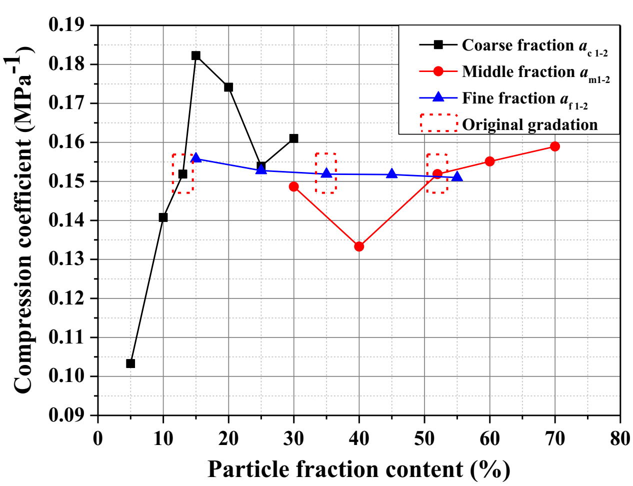

Fig. 14 The relationship between the compressibility coefficient and different particle fraction contents of the calcareous sand

The reasons why changing coarse fraction content has such great influence on the compressibility of the calcareous sand can be analyzed in terms of particle morphology. According to Table 3, compared with the middle particles (1 ~ 0.25 mm), the coarse particles (5 ~ 1 mm) have higher angularity. This makes coarse particles more readily interlock with other particles to form the bearing skeleton, which is bound to increase the coarse particles' effect on the formation of the load-bearing skeleton. As a result, the bearing capacity of the skeleton will be sensitive to the changing of coarse fraction content. As the compressibility of the calcareous sand is well-influenced by the bearing capacity of the skeleton, changing the coarse fraction content is the most efficient way to change the compressibility of the calcareous sand.

Fig. 14 shows the relationship between the compressibility coefficient (when vertical load is 100 ~ 200 kPa) and different particle fraction contents of the calcareous sand.

As shown in Fig. 14, decreasing the coarse fraction content to 5% or even lower can rapidly reduce the compressibility of the calcareous sand, which can effectively reduce the settlement of the foundation. Thus, in reclamation projects of the South China Sea, means of decreasing the coarse fraction content are suggested to rapidly reduce the settlement of the foundation.

Considering that the content of coarse fraction in the South China Sea is generally less than 25%, the relationship between the compressibility coefficient and coarse fraction content of the calcareous sand can be obtained by curve fitting. The fitted curve is shown in Fig. 15. The fitting formula is shown in Eq. (6):

$$a_v = -16.93P^3 + 3.4P^2 + 0.54P + 0.07 \quad (6)$$

where a_v is the compressibility coefficient at a vertical load between 100 ~ 200 kPa, and P is the coarse fraction content. The correlation coefficient of the formula is: $R^2 = 0.94$, which means that the formula is able to depict the relationship in a very appropriate way.

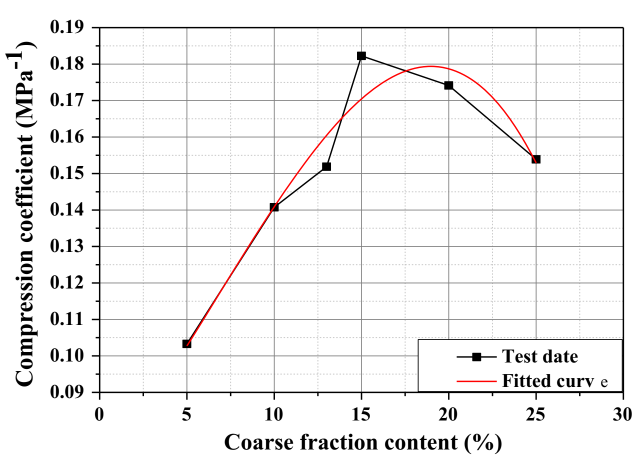

Fig. 15 Fitting curve of the relationship between the compressibility coefficient and coarse fraction content of the calcareous sand

According to the fitted formula, the compressibility coefficient (when vertical load is 100 ~ 200 kPa) is calculated, which can be used for initial evaluation of the compressibility of calcareous sand. In addition, when a replacement method to conduct ground treatment is used, the fitted formula has a guiding significance for the improvement of the gradation of calcareous sand.

However, it should be noted that all the analyses and discussions in this study are based on the mass ratio of middle to fine fractions of the calcareous sand M equal to 1.5. This is because this study is mainly aimed to provide design guidance for a potential engineering project in the Mischief reef of the South China Sea, where M in the field is equal to 1.5. However, for other conditions with $M \neq 1.5$ further study is needed, which is not within the scope of this study. This paper also provides an exemplary method for reference to improve the gradation of the calcareous sand for the reduction of compressibility.

Conclusions

(1) A mesoscope observation method was proposed to analyze the 3-D morphology characteristics of granular materials. The results show that in calcareous sand, the average 3-D morphology parameter S_d of particles with size ranging from 5 mm to 0.5 mm was about 0.787 ~ 0.792, which is lower than that of particles with size ranging from 0.5 mm to 0.25 mm; the average 3-D aspect ratio T_d of particles with size ranging from 5 mm to 1 mm is about 1.878 ~ 1.887, which is lower than that of the one with size of 1 mm to 0.25 mm. Through comparative analysis of S_d and T_d, it was found that the morphology of coarse particles (5 ~ 1 mm) was significantly multi-angular, while the morphologies of middle particles (1 ~ 0.25 mm) were mostly dendritic and schistic.

(2) The 3-D S_d (average value: 0.67 ~ 0.9) of the calcareous sand was much lower than that of quartz sand (average value: 0.75 ~ 1). It indicates that the particle morphology of the calcareous sand is much more irregular and multi-angular than the one of quartz sand, which facilitates the calcareous sand forming large pores and being compressed.

(3) Changing the coarse fraction content is the most efficient way to reduce the compressibility of the calcareous sand. That is mainly benefited from the high angularity of the coarse fraction, which made the bearing capacity of the calcareous sand skeleton sensitive to the change of coarse fraction content. Then, an empirical formula is proposed to evaluate the compressibility of the calcareous sand with different coarse fraction contents.

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