Experimental study on shear characteristics of reef coral sand

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Abstract. Coral sand is an important raw material for the construction of ocean infrastructure. Due to its special chemical composition, loose granular structure and great difference in physical and mechanical properties between coral sand and land-based silica sand, it is of great significance to conduct in-depth research on it. The shear characteristics of coral sand from the south China sea were studied by setting different relative compactness and vertical loads. The results show that both the relative compactness and the vertical load affect the shear stress-shear displacement curve of coral sand. With the increase of vertical load, the curve gradually changes from strain hardening to strain softening. With the increase of relative compactness, coral sand showed strain softening characteristics gradually. The increase of relative compactness can enhance the shear strength of coral sand, and the internal friction angle and cohesion increase linearly with the increase of relative compactness level. Therefore, the bearing capacity of coral sand foundation can be effectively enhanced by continuously increasing the relative compactness of soil in engineering.

1. Introduction
Coral sand, also known as calcareous sand, was developed in tropical Marine environments. It is widely distributed in the south China sea islands, Southern Arabian gulf, Waters off the west of India, Western continental shelf of Australia, Bass strait, Central American waters, Florida waters of North America and other places. With abundant reserves and convenient materials, it is an ideal material for the construction of ocean engineering facilities. Its physical and mechanical characteristics are quite different from those of continental quartz sand [1-4]. Due to the loose structure of coral sand particles, they are easy to break under stress and become the focus of people's attention [5].

The unique physical and chemical composition, external shape and internal structure of coral sand are closely related to its formation environment. Coral sand comes from coral reef, which is formed by the skeleton remains of algae, shells and other Marine calcareous organisms after long-term physical, chemical and biological effects in the warm Marine environment. Therefore, its chemical composition contains high content of calcium carbonate and magnesium carbonate, and the mineral composition is mainly calcite and aragonite [6]. Coral sand undergoes little disturbance in the formation process and is not transported over long distances like river sand and sea sand. Therefore, its shape is irregular and its internal voids are developed [7-11].

With the continuous development of infrastructure construction and the continuous exploitation of oil in offshore areas, people have encountered an increasing number of engineering geological problems related to calcine-sand, such as the north Rankin A and B oil platform on the northwest continental shelf.
of Australia [12-13]. In the 1980s, the international coral sand research boom began, among which the Sydney University, Western Australia University, Cambridge University, Sheffield University, McClelland engineering company of the United States, Yamaguchi University of Japan and other famous research institutions with fruitful results [14]. In 1988, the first national conference on calcareous sediments was held in Perth, Australia, and a comprehensive summary was made of the physical and chemical origin of calcareous sand, the testing and evaluation of its bearing capacity, in situ testing methods and indoor geotechnical testing methods.

At present, there are many studies on the mechanical properties of calcareous sand. Fahey carried out static triaxial and cyclic triaxial tests on calcareous sand to study its shear properties. It is believed that the shear properties of calcareous sand are greatly affected by confining pressure. When confining pressure is low, calcareous sand presents rigidity at the early stage of loading and strain hardening characteristic with the appearance of yield point, while when confining pressure is high, there is no obvious yield point [15]. The shear test of calcareous sand by Coop indicates that calcareous sand has a tendency of constant volume and constant stress difference in drainage shear, similar to clay [16]. By means of resonance column and cyclic triaxial test, Hamed Javadian and Yaser Jafarian compare the shear stiffness and damping ratio of Marine calcined sand and siliceous sand, and the results show that, compared with siliceous sand, calcined sand has higher shear stiffness and lower damping ratio [17]. Brandes compared and analyzed the monotonic and cyclic shear behaviors of loose skeleton calcareous sand and ordinary Nevada and Ottawa quartz sand. It was believed that the mobile friction resistance and cyclic strength of calcareous sand were relatively large, and the difference was related to the geometric shape, hardness, gradation, internal pores and other properties of particles [18].

However, due to the differences in the development environment of coral sand, the mechanical properties of coral sand in different geographical locations vary greatly, and the shear characteristics of coral sand have not been fully understood and mastered at present. In order to fully understand the mechanical properties of coral sand, a direct shear test was conducted on coral sand from a reef in the south China sea to study its mechanical properties. The research results of this paper will play an important role in fully understanding the mechanical properties of coral sand, and can better guide the island reclamation and infrastructure construction in the south China sea.

2. Test scheme

2.1. Test materials

The coral sand used in the test was taken from a reef in the south China sea. Its appearance is shown in Fig.1, which is light gray with a certain smell of sea. Most of the particles are in the shape of bars and sheets, with sharp edges and corners.
The particles below 2mm are the main part, so the direct shear test is mainly carried out on this part. The physical character parameters are shown in Tab 1. The effective particle size \(d_{10}\) is 0.17mm, the median particle size \(d_{30}\) is 0.3mm, and the limited particle size \(d_{60}\) is 0.47mm.

| Physical indicators | Maximum pore ratio | Minimum pore ratio | Relative ratio | Nonuniform coefficient \(C_u\) | Curvature coefficient \(C_c\) |
|---------------------|--------------------|--------------------|----------------|-------------------------------|--------------------------|
| Value               | 1.41               | 0.77               | 2.739          | 0.17                          | 0.3                      |

2.2. Scheme design

Relative compactness \(D_r\) can comprehensively reflect factors such as soil grain gradation, soil grain shape and structure. In the experiment, \(D_r\) was set as 0.3, 0.4, 0.5, 0.6 and 0.7, respectively. The vertical load was set as 50 kPa, 100 kPa, 200 kPa, 300 kPa, and 400 kPa, and the water content was controlled as 25%. The calculation formula of \(D_r\) was as follows:

\[
D_r = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}}
\]

Where, \(e_{\text{max}}\) and \(e_{\text{min}}\) are the maximum and minimum pore ratios.

The specific test scheme and number are shown in Tab 2. The mechanical properties are tested by the traditional strain direct shear instrument.

| Relative compactness \(D_r\) | Vertical load /kPa | 50 | 100 | 200 | 300 | 400 |
|-----------------------------|---------------------|----|-----|-----|-----|-----|
| 0.3                         | S0.3-1              | S0.3-2 | S0.3-3 | S0.3-4 | S0.3-5 |
| 0.4                         | S0.4-1              | S0.4-2 | S0.4-3 | S0.4-4 | S0.4-5 |
| 0.5                         | S0.5-1              | S0.5-2 | S0.5-3 | S0.5-4 | S0.5-5 |
| 0.6                         | S0.6-1              | S0.6-2 | S0.6-3 | S0.6-4 | S0.6-5 |
| 0.7                         | S0.7-1              | S0.7-2 | S0.7-3 | S0.7-4 | S0.7-5 |

3. Test results and discussion

3.1. Stress-strain curve

(a) \(D_r=0.3\)

(b) \(D_r=0.4\)
Fig. 3 shows the shear stress-shear displacement curves under different vertical loads and relative compactness. The figure shows that with the increase of shear displacement $\Delta l$, the shear stress $\tau$ increases. The overall trend of the curves under different vertical loads and relative compactness is consistent, which shows the rapid growth of shear strength at the early stage of shear and the tendency to stabilize at the later stage of shear. Therefore, the residual strength of coral sand remains relatively high after shear failure.

By comparing and analyzing the shear stress-shear displacement curves under different test conditions, it can be seen that the strain hardening or strain softening characteristics are closely related to the vertical load and relative compactness. When the vertical load is low, coral sand shows strain hardening characteristics, such as under 50kPa load. With the increase of vertical load, the curve gradually transfers to strain softening, which is especially evident when $D_r=0.7$. The relative compactness also affects the shear stress-shear displacement curve. Under the same vertical load, the strain softening characteristics of coral sand tend to be obvious with the increase of the relative compactness. It can be known from the comparison and analysis of the curves under the conditions of 200kPa, 300kPa and 400kPa.
3.2. Shear strength analysis

The expression of shear strength proposed by coulomb is as follows:

$$\tau = \sigma \tan \phi + c$$  \hspace{1cm} (2)

Where, $\tau$ - shear strength of soil (kPa); $\sigma$ - normal stress on the shear plane; $\phi$ - angle of internal friction of sandy soil (°); $c$ - cohesion of soil (kPa).

According to the coulomb strength theory, the test results were analyzed, and the shear stress peaks and their corresponding vertical loads at different relative compactness levels were fitted linearly. The results were shown in Fig 4, and the results of the fitting equation were shown in Tab 3.

![Fig 4. Relationship curve between shear strength and vertical load](image)

**Tab 3. Vertical load - shear strength fitting results**

| Dr  | Fitted equation | $\tau$-intercept | $\tau$-slopes |
|-----|-----------------|-------------------|---------------|
| 0.3 | $\tau=0.590\sigma+17.211$ | 17.21085 ± 11.07445 | 0.58999 ± 0.04502 |
| 0.4 | $\tau=0.731\sigma+16.883$ | 16.38299 ± 3.79297 | 0.67884 ± 0.01542 |
| 0.5 | $\tau=0.760\sigma+17.740$ | 17.73992 ± 9.5189 | 0.75997 ± 0.0387 |
| 0.6 | $\tau=0.838\sigma+17.956$ | 17.95607 ± 12.11531 | 0.80954 ± 0.04926 |
| 0.7 | $\tau=0.852\sigma+18.921$ | 23.96064 ± 11.02534 | 0.88067 ± 0.04482 |

![Fig 5. Sample status after direct shear](image)

According to Fig. 4 and the fitting results, the intercept of the straight line and the vertical axis is not 0, and the intercept value is the cohesion of the soil. Coral sand shows properties similar to clay, but its C value can be understood as false cohesion, which is completely different from the nature of clay. For coral sand, the C value mainly comes from the mutual occlusion of particles. Due to the irregular shape of coral sand particles, the C value is relatively high. In this experiment, the C value was between 16.883...
and 18.921kPa. At the end of sample preparation and test, it can be observed that coral sand maintains a certain cementing property under unconstrained conditions. Fig. 5 are coral sand samples after the direct shear test.

![Fig 6. Three dimensional representation of shear strength](image)

Fig. 6 shows that the shear strength of the sample is also high due to its high relative compactness. The influence of relative compactness and vertical normal stress on the shear strength of coral sand can be clearly observed by drawing all the influencing parameters and peak shear strength in Fig. 6 through three-dimensional diagram. In the sand, the shear strength mainly comes from the mutual occlusion and friction between the particles. When the relative compactness is higher, the contact between the particles in the coral sand is closer, and there are more contact points between the particles on the shear plane. The mutual fixation is more complete, so the shear strength is higher.

![Fig 7. Fitting result of internal friction angle](image)

![Fig 8. Fitting result of cohesive force](image)

The relative relations between internal friction angle and cohesion and relative compactness were fitted linearly, as shown in Fig. 7 and Fig. 8, respectively. The correlation coefficients $R^2$ were 0.8449 and 0.8221. As can be seen from the figure, with the increase of relative density, the angle of internal friction and the cohesion increased linearly. When $D_r=0.7$, the Angle of internal friction was 40.439° and the cohesion was 18.921kPa.

4. Conclusion
Due to the differences in development environment, the physical and chemical composition of coral sand in different areas are different, and the mechanical properties are also different. The direct shear test of coral sand taken from a reef in the south sea of China is conducted to study the mechanical properties differences under different relative compactness conditions, and to reveal the changing rules of the strength indexes in the shearing process.
The research results show that, when the vertical load is low, the coral sand shows strain hardening characteristic. With the increase of the vertical load, the curve gradually transfers to strain softening property. Under the condition of the same vertical load, the strain softening property of coral sand tends to be obvious with the increase of the relative compactness. The angle of internal friction and cohesion of coral sand increase linearly with the relative compactness. Therefore, in the coral sand engineering foundation, the bearing capacity of the foundation can be strengthened by continuous compaction. The research results of this paper can provide some references for engineering construction.

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