The characteristics of internal and accumulated pores of calcareous sand

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Abstract. Calcareous sand is characterized by irregular shapes and high porosity, which makes its engineering properties more special. Based on the calcareous sand from a reef island in the South China Sea, the characteristics of the internal pores and the accumulated pores between the calcareous sand particles were explored by a microscopic system and image analysis techniques. The results show that for calcareous sand particles with different particle sizes, the distributions of internal pores and accumulated pores follow the exponential distribution. The probability distribution of internal pores is the same as that of accumulated pores, and the area of accumulated pores between particles is about 100 times that of internal pores of particle itself. The characteristics of accumulated pores are affected by the size and shape of the particles.

1. Introduction
Calcareous sand, as the main material of island and reef reclamation, is the debris of coral reefs, dead corals and shells formed by long-term biological, physical and chemical actions, and mostly distributed between 30° north latitude and 30° south latitude [1,2]. With the characteristics of irregular shape, more internal pore, high content of calcium carbonate (more than 50% or even more than 97%) and easy crushing [3-11], its engineering properties are also relatively special and different for the traditional silica sand. The particle shape and pore characteristics of calcareous sand have always been the focus of scholars at home and abroad.

Due to the limitation of equipment and means, many researchers previously focused on the study of particle shape mainly by scanning electron microscope, microscope, CT three-dimensional scanning and other means. Jiang et al. conducted a quantitative study on the pore size, abundance and orientation of calcareous sand [12]. Jiang et al. used the connected pore images on the surface of particles by scanning electron microscope to obtain the surface porosity of calcareous sand [13]. Zhu and Chen used femtosecond laser technology to cut calcareous sand and performed image processing on its section, and quantitatively analysed the internal pores of calcareous sand with parameters such as surface porosity [9]. Zhou et al., based on the high-precision X-ray scanning technology, reconstructed the three-dimensional structure of calcareous sand through the multi-angle and high-precision cross-section images, and found that the pores in calcareous sand not only meet the three-dimensional fractal characteristics, but also increase the fractal dimension with the increase of internal porosity [14]. Zhang et al., based on the experiments of sand microstructure extraction and image post-
processing technology, analysed the changes in the microstructure of calcareous sand caused by particle crushing under compression [15]. Lv et al. carried out the scanning electron microscope and X-CT tests, and found that the internal pores of calcareous sand could be up to 41%, and most of them were connected pores [16]. Fan et al. established the pore network model of calcareous sand with different particle sizes by X-ray and CT scanning technology, and found that the number and volume of pores in calcareous sand particles were positively correlated with particle size, and the internal pores had a great influence on their permeability [17].

Both the internal pores of calcareous sand and the accumulated pores between particles have a great influence on the macroscopic mechanical properties of calcareous sand. Based on the microscope and image analysis technology, the pore characteristics of calcareous sand particles with different particle sizes are studied in this paper, which can provide a theoretical basis for exploring the special engineering and mechanical properties of calcareous sand.

2. Experimental details

2.1 Experimental sample

The sample in this study was a calcareous sand sample from a reef island in the South China Sea. The surface impurity of the sample was removed by filtration. In order to study the distributions of internal pores and accumulated pores in calcareous sand with different particle sizes, the samples were divided into five groups: <0.5mm, 0.5mm ~1mm, 1mm ~2mm, 2mm ~5mm, >5mm. A total of 100 effective particles for each particle size were selected and photographed by super-high magnification lens zoom 3D microscope (VHX-5000). Each particle size group can also be classified into four categories according to particle shape: round block particles, strip particles, angular particles and flaky particles (Fig. 1) [18]. The proportion of round block calcareous sand particles ranges from 50% to 70%, and the proportion increases with the decrease of particle size. The strip particles with the proportion between 10% and 20% are mostly cylindrical, and the aspect ratio is generally greater than 2; with the decrease of particle size, the proportion becomes smaller. The shape of angular particles is the most irregular, which increases the interlocking between particles and thus inhibits the movement and rearrangement of particles [19]: the larger the particle size is, the larger the proportion of angular particles is and the larger the accumulated pores are. The flaky particles with relatively smooth surface are thin, and the apparent internal pores are less than those of other types, and the proportion of flaky particles is less than 5%.

![Fig 1. Different shapes of calcareous sand particles: (a) round block; (b) strip; (c) angular; and (d) flaky.](image)

The image of accumulated pore of larger particle size (2~5mm, >5mm) was obtained by camera (Canon EOS 6D Mark II), while the images of smaller particle sizes (<0.5mm, 0.5-1mm, 1-2mm) were still taken by the microscopic test instrument with clearer imaging, as shown in Fig. 2.
2.2 Image analysis and calculation

In this paper, MATLAB image processing software is used for image analysis, as shown in Fig. 3. First, the original image is binarized, and after this, for the convenience of pore differentiation and calibration, the binarized image is inverted (Fig. 3c). Then, the area (number of pixels) of each pore boundary contour was calculated. According to the scale of the image, the area of each pore was converted into the real area value (μm²) [20], and the related pore characteristics were analysed further.

3. Pore characteristics with different particle sizes

For calcareous sand particles with different particle sizes, 100 groups in total for each particle size were included, and the relative proportion of the number of pores in each interval was counted, as shown in Fig. 4a ~ 4e. The probability and statistical distribution curves of pore area size in calcareous sand particles with different particle sizes are shown in Fig 4f.
The results show that the distribution curves of internal pore areas for different particle sizes obey a compound function distribution,

\[ y = A (1 - e^{Bx})^C \]

Where, A, B and C are the parameters of the fitting curve. The specific parameters of the probability distribution curve are shown in Table 1. The larger A is, the smaller the proportion of the number of pores in the minimum interval of pore area is, that is, the smaller the relative frequency of pores in the minimum interval is. The smaller B is, the smaller the curvature of the fitting curve is. C affects the convergence rate of the curve, the larger C is, the faster the convergence rate is.

| Particle size | Parameters | A(×10^{-6}) | B(×10^{-5}) | C   |
|---------------|------------|-------------|-------------|-----|
| >5mm          |            | 54.14       | 0.19        | -0.95 |
| 2~5mm         |            | 17.75       | 0.31        | -1.13 |
| 1~2mm         |            | 12.87       | 2.70        | -1.09 |
| 0.5~1mm       |            | 0.58        | 3.41        | -1.24 |
| <0.5mm        |            | 1.03        | 20.98       | -1.35 |

4. Accumulated pore characteristics of different particle sizes

The distributions of accumulated pore areas of calcareous sand particles with different particle sizes are shown in Fig 5. As can be seen from Fig 5, the probability distribution curves of accumulated
pores with different particle sizes also follow the compound function distribution above, and the fitting curve equation is the same as the internal pore probability distribution curve. The parameters for the probability distribution curves of the accumulated pore areas between calcareous sands are illustrated in Table 2.

![Graphs showing probability distribution curves](image)

**Fig5.** Area distribution of accumulation pores of different particle sizes: (a) >5mm; (b) 2~5mm; (c) 1~2mm; (d) 0.5~1mm; (e) <0.5mm; (f) probability statistical distribution curve.

**Table 2.** Parameters of fitting curve of accumulation pore in calcareous sand with different particle sizes.

| Parameters       | A(×10^-5) | B(×10^-5) | C    |
|------------------|-----------|-----------|------|
| >5mm             | 9.71      | 3.12×10^-4| -0.79|
By comparing Fig 4f and Fig 5f, it can be found that for different sizes of calcareous sand particles, when the size of internal pore area in particle differs by two orders of magnitude from that of accumulated pore, the trend of the curve is roughly the same. That is, the probability distribution of the area of the accumulated pore is the same as that of the internal pore within the particle, as shown in Fig 6 which are the normalized probability distribution curves, and the absolute area of accumulated pore is about 100 times that of internal pore. In other words, the pore characteristics of a single particle can be used to predict the characteristics of the accumulated pores, and then the possible soil deformation can also be predicted. The probability distribution curves of accumulated pores of 2~5mm and >5mm groups are obviously lack of small-pore areas. The possible reason is that the size of these two particle groups is relatively large. The larger the particle size is, the larger the proportion of angular particle is, and the larger the accumulated pore area are. Therefore, the accumulated pores of 2~5mm and >5mm particle size groups are lack the part of small-pore area. In other words, the characteristics of accumulated pores are affected by particle size and shape.

Fig6. Probability distribution curves of internal pores and accumulated pores of calcareous sand with different particle sizes.

5. Conclusion and analysis
In this paper, through the analysis of the pore characteristics of calcareous sand particles with different particle sizes, the main conclusions are as follows: (1) for calcareous sand particles with different particle sizes, the distribution curves of internal pores and accumulated pores both follow the compound function distribution; (2) for calcareous sand particles with the same particle size, the area of particle accumulated pores is about 100 times that of internal pores; the probability distribution of particle accumulated pores is the same as that of internal pores, and their normalized probability distribution curves are consistent; in other words, the pore characteristics of a single particle can be used to predict the characteristics of the accumulated pores, and then the possible soil deformation can also be predicted; (3) for calcareous sand particles with different particle sizes, the characteristics of accumulated pores are affected by particle size and shape. Due to the large proportion of angular particles, the accumulated pores of calcareous sand with particle size larger than 2mm lack the small pore areas.

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