Experimental study on the Influence of Load on Permeability Coefficient of Calcareous Sand

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Abstract: The permeability coefficient of calcareous sand is an important hydraulic parameter in reef engineering. The loading and permeation tests of calcareous sand and quartz sand under the same conditions were carried out by self-developed loadable sand permeability device, and the influencing factors were studied to obtain the calculation formula of the permeability coefficient of calcareous sand under load, containing void ratio $e$, particle gradation, permeability coefficient $K_s$, and the relative crushing rate $B_r$, proposed by Hardin. The results show that under the same load, the permeability coefficient and compressive deformation of calcareous sand decrease more than that of quartz sand, and the relative breakage rate of calcareous sand increases with the increase of load, while there is exponential correlation between its $K_s$ and $B_r$. It can be concluded that the pores of calcareous sand are compacted under load, and the granule breakage leads to gradation change, which affects the permeability coefficient of calcareous sand.

1. Introduction
Calcareous sand is widely distributed between 30° south and north latitude. It is a kind of debris after whitening of coral death with 50%+ CaCO$_3$ content, featuring loose porous and broken particles[1-2]. Used as the backfill material for island reef and offshore structures, its permeability characteristics are critical to the safety and stability of the structure. Researching the permeability of calcareous sand is helpful in analyzing the migration and desalination process of groundwater, and the liquefaction performance in the lime-sand island[3].

To analyze the factors affecting the permeability of calcareous sand, Hu Mingjian[1] conducted a field double-loop test and Qian Kun et al. [2] conducted constant head permeability test, respectively. Ren Yubin[4] studied the influence of calcareous sand particle gradation and void ratio on its permeability coefficient under the non-Darcy penetration through self-developed high-speed water flow permeation device. Mo Hongyun[3] studied the permeability characteristics of calcareous sand with different compactness and particle size. They all provided different computational models of permeability coefficient. However, the above studies lack the consideration of the effect of loading on the permeability coefficient of calcareous sand.

Fu Hongyuan[5] studied the influence of load change on the permeability coefficient of quartz sand through self-developed loadable osmosis device, and obtained the relationship among load, void ratio and permeability coefficient. However, unlike quartz sand, calcareous sand breaks under low stress.
conditions, leading to particle gradation changes, resulting in the complexity of calcareous sand permeability change, so its applicability needs to be explored in depth.

This test designs a device for testing the permeability of calcareous sand so as to observe the variation law of the permeability coefficient of calcareous sand under different loads. The prediction based on the calcareous sand survey, the engineering construction load level, and the change of the calcareous sand permeability coefficient can provide reference for engineering construction.

2. Test overview

2.1. Specimens and Test device
The calcareous sand specimens (HCS) was taken from the South China Sea, which is unconsolidated and clastic. Its curvature coefficient $C_c=1.54$, non-uniformity coefficient $C_U=5.08$, and it was a fine sand with good gradation(Figure 1). The quartz sand (HQS) with the same gradation was designed as the specimen in the control group. Take 1~2 mm calcareous sand (DCS) as the single-particle specimen and obtain their maximum and minimum void ratio $e_{\text{max}}$ and $e_{\text{min}}$. The basic physical properties of the specimens are shown in Table 1. The size of the specimens is $\phi 61.8*50$ mm.

The test was carried out on a self-developed test device. The reaction frame provides the reaction force and the hydraulic station provides the power source and applies constant load. During the test, the displacement of the specimen is obtained using an electric displacement meter in real time, and the permeability coefficient of the specimen is measured at the time. The device is shown in Figure 2.

![Figure 1. Calcareous sand particle gradation curve](image1)

![Figure 2. Test device](image2)

2.2. Test Plan
This test applies load on the specimens shown in Table 2. The load per stage is maintained for 30 minutes. Specimens with different gradations, different load amplitudes and loading paths were used to ensure the applicability of the test results.

| Specimens | $e_{\text{max}}$ | $e_{\text{min}}$ | Proportion $\gamma$ | Water content (%) | Control pore ratio $e_0$ |
|-----------|----------------|----------------|-------------------|----------------|------------------|
| HCS       | 1.10           | 0.59           | 2.67              | 0.35           | 0.76             |
| HQS       | 0.82           | 0.52           | 2.65              | 0.1            |                  |
| DCS       | 1.37           | 1.09           | 2.69              | 0.5            | 1.17             |

| specimen | Loading path | Termination of pressure |
|----------|--------------|-------------------------|
| HCS      | 0, 50kPa, 100kPa, 200kPa, 300kPa, 400kPa | 200kPa, 400kPa |
$K_s$ is measured using the constant head method. The permeability coefficient $K_s$ is calculated by the following formula:

$$K_s = \frac{QL}{Aht} \tag{1}$$

($K_s$: permeability coefficient of the specimen (cm/s); $Q$: extracted water volume during time $t$ (cm$^3$); $L$: distance between the centers of two gauge tube (cm); $A$: cross-sectional area (cm$^2$); $H$: waterhead (cm); $t$: time (s))

After the test, take out the specimen carefully and place it in a drying oven to be dried to constant weight. Then, sieve the particles using a vibrating sieve for 15 min. The parallel test was carried out 3 times, and the average value was taken as the test result.

3. Results

3.1. Relationship between $K_s$ and $P$

Figure 3 shows the change of the permeability coefficient $K_s$ under load $P$. As $P$ increases, $K_s$ decreases. $K_s$ of the mixed grading specimens is an order of magnitude smaller than that of quartz sand specimen, because of the surface of the types of sand. Calcareous sand is rougher and its particles break under load, leading to change of its structure, then changing $K_s$. The function fitting equation is:

$$K_s = aP^b \tag{2}$$

(a, b are the constants related to the nature of the soil.)

Define the permeability coefficient reduction rate $\lambda$ as $\frac{K_i-K_j}{P_i-P_j}=\frac{\Delta K}{\Delta P}$, representing the percentage change of the permeability coefficient under per unit load. It can be seen from Figure 3(d)
that under the same load $P$, the $K_s$ of calcareous sand changed more significantly. With the increase of load $P$, $\lambda$ of the two specimens rapidly increased in pre-loading period, and the growth weakened later. $\lambda$ has a correlation with the logarithmic function of $P$, as shown in Formula (3):

$$\lambda = \frac{\Delta K}{\Delta P} = a \ln P + b$$  \hspace{1cm} (3)

### 3.2. Particle gradation changes and particle breakage

![Figure 4. specimen porosity ratio $e$ changes](image)

(a)HCS and HQS ($C_C=1.54$, $C_U=5.08$)  \hspace{1cm} (b)DCS (1~2mm calcareous sand)

![Figure 5. Particle gradation at different termination pressures](image)

(a)HCS  \hspace{1cm} (b)DCS

The void ratio $e$ (Figure 4) and the particle gradation (Figure 5) change under load $P$, respectively. In pre-loading when the load is small, the calcareous sand particles were broken, while the quartz sand particles are not broken due to the high strength. And the particle gradation change was not obvious firstly. At this moment, the compressive deformation of the specimen is mainly caused by the compaction of inter-particle pores and the grinding and breaking of the edges and corners of the particles. When $P$ increased, the calcareous sand particles broke, forming more fine particles. The broken fine particles are filled into the soil skeleton, which sharing the upper stress and resulting in the increasing breakage stress, coordination number between the particles and effective stress area, and a weakening pores change.

The relative fragmentation rate $B_r$ model proposed by Hardin is widely recognized by domestic scholar, and it is commonly used to measure the particle breakage of soil. The total breakage potential $B_t$ and the initial breakage potential $B_0$ are taken to evaluate the overall particle breakage. Formula of the relative breaking rate $B_r$ followed:

$$B_r = \frac{B_t}{B_0}$$  \hspace{1cm} (3)
Figure 6. Curve of calcareous sand relative breaking rate \( B_r \) and load \( P \). As shown in Figure 6, \( B_r \) of calcareous sand increases with the increase of \( P \). They are in logarithmically functional correlation.

\[ B_r = a \ln P + b \]  

(4)

4. Discussion

4.1. Effect of void ratio \( n \) and relative particle breakage rate \( B_r \) on permeability coefficient \( K_s \)

Figure 7 shows the relationship between \( K_s \) and the porosity \( n \) of the calcareous sand under different \( P \). Under the same water flow force, the resistance encountered by the fluid increased, and the seepage rate decreased with the decrease of \( n \), showing the decreasing \( K_s \), because under load, the fine particles are filled in the soil skeleton.

Figure 8 shows the relationship between \( B_r \) and \( K_s \) under different loads. As the load \( P \) increased, \( K_s \) and \( B_r \) are in good exponential relation. The fitting formula is:

\[ y = 0.0046 \ln(x) - 0.0108 \quad R^2 = 0.9887 \]

\[ y = 0.0952 \ln(x) - 0.4779 \quad R^2 = 0.9804 \]
4.2. Multi-factor formula fitting

Table 3 shows the $K_s$ formula of non-cohesive soil permeability coefficient frequently used. It can be found that the permeability coefficient of calcareous sand has a function-fitting relationship with the void ratio $n$ and the relative breakage rate of the particles. This paper considers the influence of multiple factors like pore compaction and particle breakage, and lists multi-factor fitting equation parameters (Table 4):

$$K_s = a \times e^{\beta(n/b)} + c$$

(5)

Table 3. $K_s$ formula of permeability coefficient of commonly used non-viscous soil

| No. | Formula Name | Expression          | Features                                                                 |
|-----|--------------|---------------------|--------------------------------------------------------------------------|
| 1   | Cosin        | $K_{18} = 780d_9^2n^2/(1-n)^2$ | Research sand permeability coefficient only with particle size parameters involved |
| 2   | Zhu          | $K = 4eC_cC_ud_{10}^2$ | Analyze permeability coefficient according to sand compaction degree and gradation characteristics |
| 3   | Chonghui     | $K = 157C_cC_ud_{10}^2n^2/(1-n)$ | The influence of specimen compactness and particle size matching on calcium sand permeability |
| 4   | Zhang Yijian | $K = 10e^{0.017d_9}$ | Consider the effect of dry density and compaction on The permeability coefficient of calcareous sand |
| 5   | Qian Kun     | $K = 10e^{0.017d_9}$ | Kozeny-Carman Hydraulic Radius Theory |
| 6   | Hu Mingjian  | $K = 4.74e^{0.7d_9}$ | Consider the influence of multiple factors so as to reflect the influence of load on the permeability coefficient of calcareous sand and indirectly reflect the influence of load |
| 7   | Kozeny-Carmen| $K = 10e^{0.017d_9}$ | Kozeny-Carman Hydraulic Radius Theory |
| 8   | This paper   | $K_s = TC_cC_uB_r d_{10}^2n^2/(1-n)^2$ | Consider the influence of multiple factors so as to reflect the influence of load on the permeability coefficient of calcareous sand and indirectly reflect the influence of load |

(Note: $K_m$ is the permeability coefficient of soil at $m ^\circ C$ (cm/s); $d_9$, $d_{10}$, $d_{20}$ are the effective particle size in corresponding formulas, or the particle diameter (mm) when the cumulative content is $x$%; $R$ is the dimensionless coefficient; $S_0$ is the specific surface area. $Br$ is the relative breakage rate of particles; $T$, $H$ are the coefficients related to sand properties.)

Table 4. Multi-factor fitting equation parameters

| No. | $K_s = TC_cC_uB_r d_{10}^2n^2/(1-n)^2$ |
|-----|--------------------------------------|
| T   | H                                    | $R^2$     |
| HCS | 1.0966                               | 0.0116   | 0.9818     |
| DCS | 0.0178                               | -0.0108  | 0.9928     |

5. Conclusion

This study conducted the loading and penetration test of calcareous sand by using a self-developed test device. Based on the tests, the following conclusions can be drawn:

(1) As the load $P$ increases, the void ratio $e$ of the calcareous specimen gradually decreases with larger compressive deformation than quartz sand. The permeability coefficient $K_s$ of calcareous sand decreases with the increase of $P$, and the two have a functional correlation. Under the same load $P$, the permeability coefficient of calcareous sand is reduced more than that of quartz sand.

(2) The relative breakage rate of calcareous sand $Br$ increases with the increase of load $P$, while $K_s$ decreases with the increase of $Br$, and the two are in exponential function correlation.

(3) Obtain the fitting formula of calcareous sand permeability coefficient and find that $K_s$ and $C_cC_uB_r d_{10}^2n^2/(1-n)^2$ are related by comprehensively considering the relative breakage rate of calcareous sand particles $Br$, porosity $n$, characteristic particle size $d_{10}$, gradation and other factors.
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