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## Analysis of factors affecting permeability of calcareous sand in salt solution environment

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## Analysis of factors affecting permeability of calcareous sand in salt solution environment

### Abstract

Permeability is the capacity of a soil for transmitting a fluid, e.g., a salt solution, through soil pores. The permeability coefficient  $K$  is an important measurement of the soil permeability, which is affected by various factors. The existing research on the permeability of sandy soil is basically carried out in the freshwater environment. However, the calcareous sand is a typical marine sedimentary sand, which is deposited in the seawater environment with certain salt concentrations. In order to investigate the influence of void ratio, particle size and concentration of the salt solution on the permeability of calcareous sand in a salt solution environment, constant head and falling head permeability tests were carried out using the meter KAST-soil saturated hydraulic conductivity. The microscopic characteristics were investigated through Zeta potential and contact angle tests. The results showed that the mean particle size has the greatest influence on the permeability coefficient of a calcareous sand, and the change of the mean particle size will even lead to the difference in the order of magnitude of the permeability coefficient. The permeability coefficient ( $K$ ) is negatively correlated with the salinity of the transmitting solution ( $P$ ), and positively correlated with the porosity ( $n$ ) and the mean particle size ( $d_a$ ). A model for predicting the permeability coefficient of calcareous sand taking into account the salt content of transmitting solution has been proposed based on the current experimental studies on the influencing factors. The proposed model can provide a tool for assessing the permeability of artificially reclaimed islands and reefs in the South China Sea and analyzing the evolution of ground freshwater.

### Keywords

permeability coefficient, salt content, void ratio, particle size, prediction model

## Analysis of factors affecting permeability of calcareous sand in salt solution environment

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**Abstract:** Permeability is the capacity of a soil for transmitting a fluid, e.g., a salt solution, through soil pores. The permeability coefficient  $K$  is an important measurement of the soil permeability, which is affected by various factors. The existing research on the permeability of sandy soil is basically carried out in the freshwater environment. However, the calcareous sand is a typical marine sedimentary sand, which is deposited in the seawater environment with certain salt concentrations. In order to investigate the influence of void ratio, particle size and concentration of the salt solution on the permeability of calcareous sand in a salt solution environment, constant head and falling head permeability tests were carried out using the meter KAST-soil saturated hydraulic conductivity. The microscopic characteristics were investigated through Zeta potential and contact angle tests. The results showed that the mean particle size has the greatest influence on the permeability coefficient of a calcareous sand, and the change of the mean particle size will even lead to the difference in the order of magnitude of the permeability coefficient. The permeability coefficient ( $K$ ) is negatively correlated with the salinity of the transmitting solution ( $P$ ), and positively correlated with the porosity ( $n$ ) and the mean particle size ( $d_a$ ). A model for predicting the permeability coefficient of calcareous sand taking into account the salt content of transmitting solution has been proposed based on the current experimental studies on the influencing factors. The proposed model can provide a tool for assessing the permeability of artificially reclaimed islands and reefs in the South China Sea and analyzing the evolution of ground freshwater.

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## 1 Introduction

Permeability reflects the ability of fluid to transport within the internal pores of a porous medium, which is a crucial indicator for evaluating the properties of sandy soils. Calcareous sand is a porous geological material which is primarily composed of substances that are rich in calcium carbonate or other carbonate salts, such as coral and shells<sup>[1]</sup> formed by the combined effects of wave loading, biological erosion, seawater dissolution, and particle deposition. The highly irregular morphology of calcareous sand particles, along with abundant surface and internal pores result in high porosity and distinctive characteristics in terms of water conductivity, water retention, and permeability. Calcareous sand is typically used as a foundational material in coastal engineering projects like island construction, and the permeability is one of the significant hydrogeological parameters for engineering design, construction, and the study of groundwater evolution. Therefore, it is crucial to conduct research on the permeability and the corresponding influencing factors of calcareous sand, which will benefit the island and reef infrastructure development, provide

better understanding of the evolution of groundwater, and help assess the ecological and environmental benefits.

In recent years, many scholars have conducted extensive research on the permeability of calcareous sand under the mission of building a maritime power. Ju et al.<sup>[2]</sup> conducted permeability tests on medium sand, coarse sand, and gravel sand under different particle size distributions, densities, and hydraulic gradients; they also analyzed the precipitated solids through laser particle size analysis and reveal that calcareous sand particles exhibit low cohesion and loose structure which makes fine particles prone to loss under permeation conditions. This loss process occurs in a pattern of accumulation-breakage-accumulation, finally forming a new soil structure. Fan et al.<sup>[3]</sup> explored the three-dimensional pore structure and permeability of calcareous sands with different particle sizes using CT scans and a pore network model. They stated that the quantity and distribution of pores are key factors influencing permeability characteristics. Cui et al.<sup>[4]</sup> revealed the differences of the permeability between calcareous sand and terrestrial quartz sand from various microscopic perspectives such as roundness, roughness, particle surface charge, and particle hydrophilicity. They

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established conversion equations for the permeability coefficients of the two soils. They also discussed the impact of stratum permeability on the freshwater lens body and the sensitivity of permeability in the process of forming freshwater lens bodies. Wang et al.<sup>[5]</sup> demonstrated the reliability of formulas by Samarasinghe<sup>[6]</sup> and Mesri<sup>[7]</sup> for calculating the permeability coefficient of calcareous silt based on the pattern of changes in the permeability of calcareous silt with dry density and initial moisture content obtained from the falling head permeability tests. They also conducted static adsorption tests which explained the calcareous silt can be considered as a large-pore material; more micro and mesopores will transform into large pores under the seepage force. Wang et al.<sup>[8]</sup> explored the differences in permeability between calcareous sand and quartz sand under different loading conditions. Calcareous sand exhibited greater compression deformation and a larger decrease in permeability coefficient compared to quartz sand with increasing the loading. They established formulas for the permeability coefficient of calcareous sand, including parameters such as relative breakage rate ( $B_r$ ), porosity ( $n$ ), characteristic particle size ( $d_{10}$ ), coefficient of uniformity ( $C_u$ ), and curvature coefficient ( $C_c$ ).

Typically, soil and rock masses are exposed to a solution environment rich in various salt ions and with a certain degree of acidity or alkalinity<sup>[9]</sup>. When the ions in the water contact with the soil, a series of physical and chemical reactions such as adsorption, dissolution, and ion exchange occur that leading to changes in the surface properties and internal microstructure of the soil particles. Consequently, these changes influence the strength, deformation, and permeability of the soil<sup>[10]</sup>. Most of the aforementioned tests are conducted under freshwater conditions, limited tests had been conducted for saline solution environments. Li et al.<sup>[11]</sup> conducted unconfined compression tests to analyze the mechanical properties of MICP-cured calcareous sand in seawater and freshwater environments based on microbially induced calcium carbonate precipitation (MICP) technology. They found that the performance of MICP technology is better utilized in seawater environments compared to freshwater conditions. Li et al.<sup>[12]</sup> revealed the influence of temperature and salinity on the mechanical properties of coral sand by conducting triaxial drained shear tests. The shear strength of coral sand is more sensitive to salinity compared to the temperature. The cohesion decreases as well as the decreased shear strength with the increasing salt concentration. Chen et al.<sup>[13]</sup> conducted falling head permeability tests to explore the impact of salinity on permeability characteristics using sodium chloride and sodium sulfate salts. The results indicate that with an increase in salt content in the solution, the dominant pore size in the soil decreases, leading to a denser soil, and the permeability coefficient decreases exponentially.

Calcareous sand is often found in high salinity seawater environments, characterized by a rough surface, irregular shape, abundant interconnected pores, internal pores, and surficial micropores. These unique structures make calcareous sand more prone to salt adsorption. The aforementioned studies also indicate that the solution environment can have an impact on the structure and strength of calcareous sand, which is primarily composed of calcium carbonate and has a biogenic origin. However, limited research has been conducted focusing on the permeability of calcareous sand in saline solution environments. Therefore, this study focuses on four types of calcareous sand with different particle sizes—coarse sand, medium sand, fine sand, and silty sand. The influence and patterns of salt concentration, porosity, particle size, and other factors on the permeability of calcareous sand were investigated with various prepared concentrations of salt solutions under constant head and falling head permeability tests. The microscopic impact mechanisms of salt solutions on the permeability of calcareous sand were analyzed by Zeta potential and contact angle tests; then a permeability coefficient calculation model that includes the factor of salt concentration was established.

## 2 Experiment study and principles

### 2.1 Experiment cases

The calcareous sand used in the experiment was obtained from a reef in the Nansha Islands. Prior to the experiment, the calcareous sand was dried following the specifications outlined in the *Standard for geotechnical testing method* (GB/T 50123—2019)<sup>[14]</sup>. After cooling, the dried samples were subjected to sieve testing using a national standard vibrating sieve machine. The calcareous sand was divided into four particle size grades: 0.5–1 mm, 0.25–0.5 mm, 0.075–0.25 mm, and 0–0.075 mm. Indoor tests for properties such as relative density and maximum and minimum dry densities were conducted according to standard procedures, and the results are presented in Table 1.

The sodium chloride is the most abundant salt in seawater. Therefore, this experiment utilized solid sodium chloride particles mixed with deionized water to prepare percolating solutions with salt concentrations (denoted as  $P$ ) of 0% (deionized water), 2.5%, 5%, 7.5%, and 10% to simulate the percolating process of calcareous sand in a seawater environment. Orthogonal permeation tests were conducted with four particle size grades, five porosity levels, and five different salt concentrations to analyze the influence of salt concentration, porosity, and particle size on the permeability of calcareous sand in a saline solution environment. A total of 100 test samples were prepared with each sample group containing three same samples. The specific experimental case is detailed in Table 2, and the particle size distribution curve is shown in Fig. 1. The changes in particle surface properties in a

saline solution environment were analyzed through Zeta potential and contact angle tests to explore the microscopic

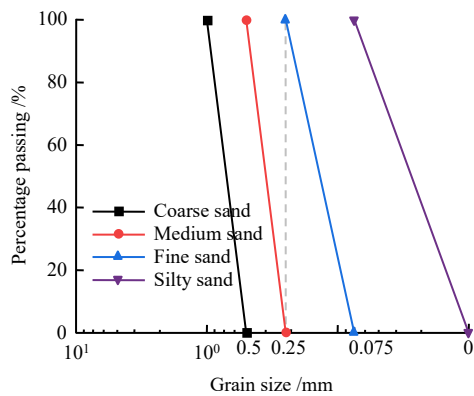
impact mechanisms of salt solutions on the permeability of calcareous sand.

**Table 1 Basic physical properties of the studied soils**

Sand specimen	Grain size $d$ /mm	Medium grain size $d_a$ /mm	Maximum dry density $\rho_{dmax}$ /(g · cm <sup>-3</sup> )	Minimum dry density $\rho_{dmin}$ /(g · cm <sup>-3</sup> )	Specific gravity $G_s$
Coarse sand	0.5–1	0.750 0	1.36	1.09	2.82
Medium sand	0.25–0.5	0.375 0	1.43	1.15	2.81
Fine sand	0.075–0.25	0.162 5	1.49	1.20	2.80
Silty sand	0–0.075	0.037 5	1.61	1.11	2.81

**Table 2 Test program of permeability tests**

Sand specimen	Porosity $n$	Salt content $P$ /%
Coarse sand	0.565、0.555、0.545、0.535、0.525	
Medium sand	0.545、0.535、0.525、0.515、0.505	0、2.5、5
Fine sand	0.525、0.515、0.505、0.495、0.485	7.5、10
Silty sand	0.525、0.505、0.485、0.465、0.445	



**Fig. 1 Grain size distribution curves of studied soils**

## 2.2 Experimental principles

### 2.2.1 Permeability test

The instrument used in this experiment is the KAST Soil Saturated Hydraulic Conductivity Measurement Instrument (refer to Fig. 2). Constant head permeability tests were conducted on well-permeable coarse sand, medium sand, and fine sand, while falling head permeability tests were performed on less permeable silty sand. The inner diameter of the permeation cutting ring of this instrument

is 80 mm, and its height is 50 mm. The effects of sidewall and size on permeability are not considered<sup>[15–16]</sup>.

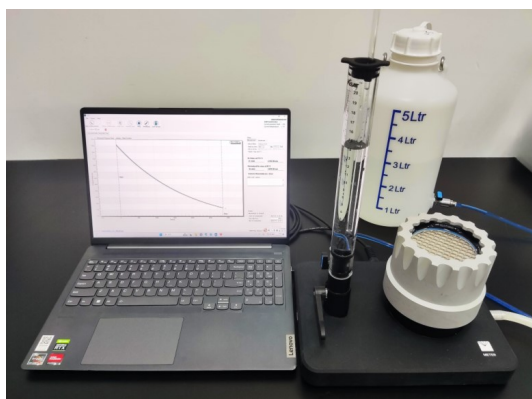
The experimental procedures followed the *Standard for geotechnical testing method*<sup>[14]</sup>. Prior to the experiment, an appropriate amount of Vaseline was applied to the inner wall of the cutting ring to prevent sidewall leakage during the permeation process, which could lead to inflated measurement results. According to the design requirements, calcareous sand of each particle size grade was carefully layered, compacted, and leveled with the top of the sample flush with the edge of the cutting ring. The sand samples were then saturated by gradually filling them with water from the bottom up, using a lower hydraulic head. The permeation flow path during the test was from bottom to top to avoid deformation and failure due to excessive hydraulic head. The hydraulic head was increased incrementally (1 cm, 1.1 cm, 1.2 cm, etc.) to achieve feasible hydraulic heads. The hydraulic head heights used in the constant head and falling head tests in this study were 3 cm and 5 cm, respectively.

In the constant head test, the Mariotte bottle principle is utilized, where the hydraulic head pressure is controlled by the depth of immersion of a capillary tube in water and remains constant over time. The water level in the graduated cylinder exhibits a linear decrease, and the KAST instrument automatically records the cumulative percolation flow. Two or more target water level points are set and marked based on the percolation process. Ultimately, the permeability coefficient measurement values are obtained according to Eq. (1):

$$K = \frac{\eta_T}{\eta_{20}} \cdot \frac{Q}{A_{\text{Sample}} t} \cdot \frac{L}{H} \quad (1)$$

where  $K$  is the permeability coefficient (cm/s);  $t$  is the percolation time (s);  $Q$  is the steady-state percolation flow in the graduated cylinder within time  $t$  (cm<sup>3</sup>),  $A_{\text{Sample}}$  is the cross-sectional area of the sand sample (cm<sup>2</sup>),  $L$  is the length through which the percolation liquid flows, i.e., the height of the sand sample (cm);  $H$  is the head difference between the inlet and outlet of the water (cm);  $\eta_T$  is the dynamic viscosity coefficient of water at temperature  $T$  (10<sup>-6</sup> kPa·s); and  $\eta_{20}$  is the dynamic viscosity coefficient of water at 20 °C (10<sup>-6</sup> kPa·s).

The falling head test was conducted through the KAST



**Fig. 2 METER KAST-soil saturated hydraulic conductivity**

instrument which involves automatic measurement and visual recording of data allowing for the rapid attainment of stable permeability coefficient values. The derivation process of the permeability coefficient is shown as follows:

Based on the change in water level in the graduated cylinder, the specific discharge per unit area is obtained:

$$q = \frac{Q}{A_{\text{Sample}}} = \frac{A_{\text{Bur}}}{A_{\text{Sample}}} \cdot \frac{d_H}{d_t} \quad (2)$$

Combined with Darcy's law:

$$q = -K \frac{H}{L} \quad (3)$$

Equation (4) can be obtained:

$$\frac{1}{H} d_H = -K \cdot \frac{A_{\text{Sample}}}{A_{\text{Bur}}} \cdot \frac{d_t}{L} \quad (4)$$

Integrating from the initial state at  $t=0$  when  $H=H_0$  to time  $t$ :

$$\ln H(t) - \ln H(0) = -K \cdot \frac{A_{\text{Sample}}}{A_{\text{Bur}}} \cdot \frac{t}{L} \quad (5)$$

$$H(t) = H(0) \cdot \exp\left(-K \cdot \frac{A_{\text{Sample}}}{A_{\text{Bur}}} \cdot \frac{t}{L}\right) = a \exp(-bt) \quad (6)$$

Fitting the exponential function to the observed time series  $H(t)$ , the fitting parameter  $b$  can be obtained. Then the saturated permeability coefficient can be obtained by

$$K = \frac{\eta_r}{\eta_{20}} \frac{A_{\text{Bur}}}{A_{\text{Sample}}} \cdot Lb \quad (7)$$

where  $A_{\text{Bur}}$  represents the cross-sectional area of the graduated cylinder( $\text{cm}^2$ );  $t$  denotes the percolation time (s);  $L$  is the length through which the percolation liquid flows, i.e., the height of the sand sample(cm); and  $b$  is a fitting parameter( $1/\text{s}$ ).

### 2.2.2 Zeta potential test

A Zeta potential analyzer (i.e., the Malvern Zetasizer Nano ZS90) is used in the experiment. Zeta potential represents the potential difference between the particle surface in a dispersed system and the solution. It is used to measure the magnitude of attractive and repulsive forces between particles. The positive or negative sign of the potential indicates the type of charge carried by the particles, while the absolute value is used to assess the stability of the dispersed system. A higher absolute Zeta potential value indicates that repulsive forces between particles are greater than attractive forces, making the dispersed system more stable. Conversely, a smaller absolute value suggests that attractive forces are greater than repulsive forces, making the dispersed system less stable and more prone to particle aggregation. The experiment required powdered samples, and in this study, calcareous silty sand

was tested in solutions with different salt concentrations. The results of the experiment are applicable for evaluating the surface properties of calcareous sand particles at various particle sizes<sup>[17]</sup>.

### 2.2.3 Contact angle test

The contact angle measurement instrument, specifically the Dataphysics OCA 20 is used in the experiment. The contact angle refers to the angle  $\theta$  (see Fig. 3) between a solution and the solid surface. The magnitude reflects the interaction forces between liquid molecules and the solid surface, revealing the hydrophilicity or hydrophobicity of the solid surface. If  $\theta < 90^\circ$ , the solid surface is hydrophilic. The smaller the angle, the greater the adhesive force of the liquid to the solid surface, indicating better wetting properties. Conversely, if  $\theta > 90^\circ$ , the solid surface is hydrophobic. A larger angle implies a weaker adhesive force of the liquid to the solid surface, indicating a stronger ability for fluid transport in pores and a larger permeability coefficient. Powdered samples are required in the experiment. In this study, dynamic contact angle tests were conducted to determine the hydrophilicity of calcareous silty sand in solutions with different salt concentrations. Similar to Zeta potential analysis, the results of the experiment are applicable for evaluating the surface properties of calcareous sand particles at various particle sizes.

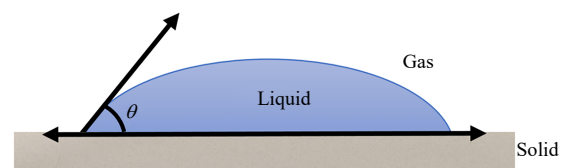


Fig.3 Graphical illustration of contact angle

## 3 Experiment results and analysis

### 3.1 Influence of salt content

Figure 4 shows the variation of the coefficient of permeability with the salt content of the solution. It can be observed that the permeability coefficient decreases exponentially with the increase in salt concentration. The variation range is within one order of magnitude, and the correlation coefficients are both above 0.95, indicating a high correlation. This conclusion is consistent with the findings of Deng et al.<sup>[18]</sup>, Li<sup>[19]</sup> and others. The coarse sand with  $n = 0.565$  is presented as an example. When the salt content of the gradually increases from 0% to 10%, the permeability coefficients decrease by 9.3%, 15.4%, 18.5%, and 20.8%, respectively, compared to the permeating solution only with deionized water.

The influence of salt concentration on the permeability coefficient includes three aspects: the viscosity of the solution affects the intensity of the interaction between fluid molecules; surface tension and contact angle affect the capillary interaction between gas-liquid interface and solid matrix<sup>[20]</sup>; the double electric layer affects the adsorption



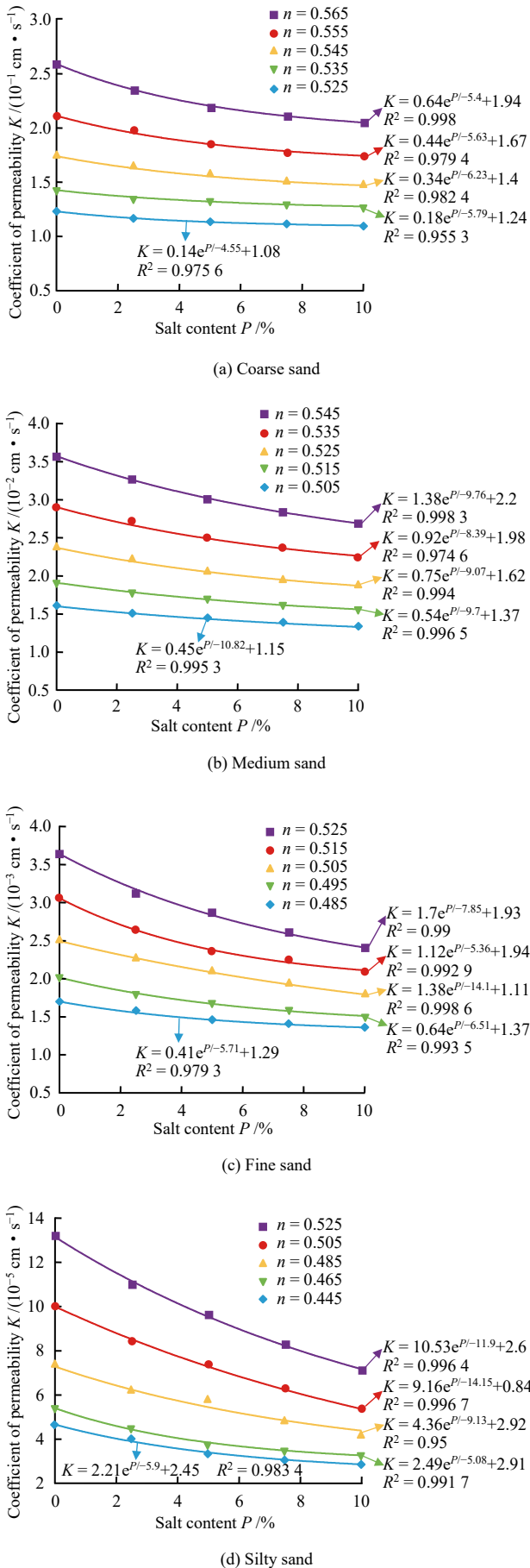


Fig. 4 Variations of permeability coefficient with salt content for different soils

between the solid and liquid phases<sup>[21]</sup>. As the salt content increases, the viscosity of the solution increases, enhancing the interaction forces between fluid molecules. This results in increased resistance when the percolating solution passes through the pores between particles, leading to a reduction in flow velocity and a decrease in the permeability coefficient.

Surface tension exists at the interface between gas and liquid phases and under certain types of solutions and environmental conditions, it is positively correlated with the density difference between the gas and liquid phases<sup>[22]</sup>. If ignoring changes in gas phase density, when the salinity increases, the solution density increases, leading to an increase in surface tension and a change in contact angle. As shown in Fig. 5, with increasing salinity, the contact angle at the solid-liquid interface decreases. This trend indicates enhanced capillary effect between particles, making the solid particles more hydrophilic. As a result, the adhesion of the liquid to the solid surface increases, and the resistance experienced by the liquid as it flows through the pores becomes greater. This leads to a reduction in the permeability of the porous medium and a decrease in the permeability coefficient.

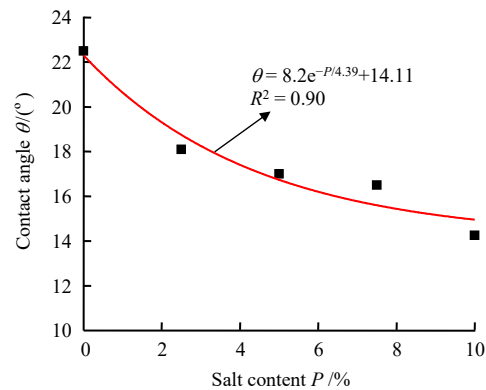


Fig. 5 Variation of contact angle with salt content of solution

Based on the Gouy-Chapman diffused double layer theory, the percolating solution is an electrolyte containing a large number of ions in a saline solution environment. The particles of calcareous sand carry a negative charge on their surfaces. During the percolation process, the particles adsorb cations from the percolating solution, forming a double layer (adsorption layer and diffusion layer). Polar water molecules orient themselves and surround the particle surface under the influence of the microelectric field at the particle surface, forming a viscous film with solid-like properties. This film hinders the flow of free water, leading to a decrease in percolation velocity and a reduction in the permeability coefficient in macroscopic aspect<sup>[23]</sup>. According to the experimental results obtained by Chen et al.<sup>[24]</sup>, the NaCl concentration increases, the loss of Na<sup>+</sup> in the percolating solution increases. This indicates that more cations are adsorbed by the soil during the percolation process, leading to an increase in the particle

surface potential (see Fig. 6). The thickness of the bound water film increases, resulting in greater percolation viscous resistance, increased particle aggregation, reduced pore size, decreased effective porosity, and a lower permeability coefficient.

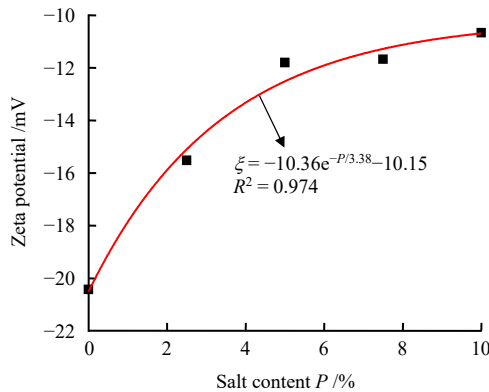


Fig. 6 Variation of Zeta potential with salt content

It can be observed in Fig. 4 that for a constant particle size, when the salt concentration of the solution increases, the experimental group with a larger porosity experiences a greater reduction in the permeability coefficient. Taking medium sand as an example, when the salt content ( $P$ ) of the percolating solution is 10%, and the porosity  $n$  is 0.545, the permeability coefficient decreases by 24.65% compared to the percolating solution being deionized water. However, when the porosity  $n$  is 0.505, the permeability coefficient only decreases by 16.88%. This is because with an increase in porosity, the volume of interparticle pore space increases, leading to a higher pore water content, and the viscous effect of saline water becomes more pronounced.

The coarse sand and silty sand were compared under the same porosity conditions to explain that smaller particle sizes make the permeability coefficient more sensitive to changes in salinity. When the porosity  $n$  is 0.525 and the salt content ( $P$ ) of the percolating solution is 10%, the permeability coefficient of coarse sand decreases by 10.57% compared to deionized water. In contrast, the permeability coefficient of silty sand decreases by 46.14%, roughly 4.5 times that of coarse sand. The reason attributed to this is that smaller particles have a larger specific surface area and accumulate more charges on their surfaces. More free water is bound to the particle surface to form bound water under the interaction between particles and electrolyte solution, resulting in greater percolation viscous resistance and weakening the permeability of the porous medium. For coarse-grained soils, the thickness of the bound water film on the particle surface is much smaller than the pore scale under the influence of the microelectric field, and this has less impact on percolation.

### 3.2 Influence of porosity

Figure 7 depicts the relationship between the permeability

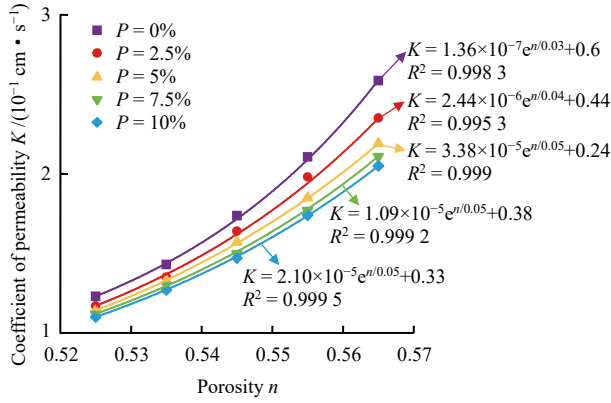
coefficient and porosity. The permeability coefficient is positively correlated with porosity for both deionized water and a saline solution environment. Moreover, the permeability coefficient exhibits an exponential growth with an increase in porosity. The correlation coefficients for both conditions are above 0.97, indicating a highly correlation. This is because a higher porosity corresponds to a larger volume of pores within a unit volume of soil. The soil structure becomes looser with better connectivity between pores. The percolating solution has a stronger ability to flow through the internal pores of the soil under the same hydraulic head. This results in an increased flow rate within a unit time leading to a higher permeability coefficient.

When particle size is constant, lower salt concentrations in the solution lead to a more noticeable variation in the permeability coefficient with porosity. Using fine sand as an example, as the porosity ( $n$ ) increases from 0.485 to 0.525, the permeability coefficient increases by 53.3% for a percolating solution with 0% salt content ( $P$ ), while it only increases by 43.6% for a percolating solution with 10% salt content. This is because higher salt concentrations result in an increase in the viscosity of the percolating solution, leading to an overall reduction in the permeability of calcareous sand. As a result, the extent of variation in the permeability coefficient with porosity diminishes when salt content is higher.

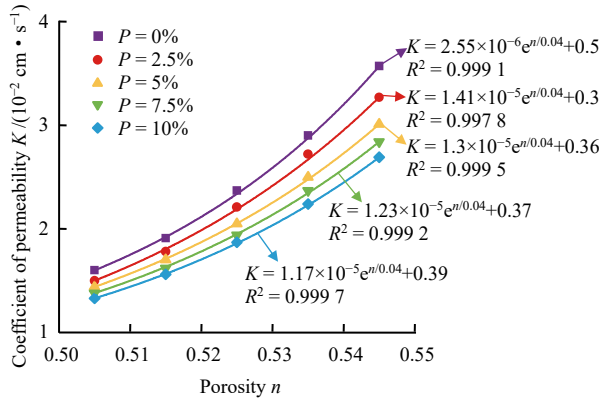
### 3.3 Influence of grain size

The relationship between the permeability coefficient and the medium grain size ( $d_a$ ) in different salt concentration environments is shown in Fig. 8 with the porosity ( $n$ ) of the calcareous sand sample is 0.525. Different particle sizes lead to different permeability coefficients under the same porosity and salt concentration conditions. Additionally, the permeability coefficient exhibits a change in the magnitude as the particle size increases. This is because porosity is the ratio of pore volume to the total material volume; when the porosity and total material volume are the same, the pore volume also keeps same. Smaller medium grain sizes result in smaller intergranular pore sizes, increased number of pores, greater tortuosity of the percolation path during the flow process, increased head loss, decreased flow rate within a unit time, and consequently, a reduction in the coefficient of permeability<sup>[25]</sup>. Furthermore, a significant variation of the permeability coefficient with the medium grain size when salt concentrations in the solution is lower. This is consistent with the discussion in Section 3.2, where it is mentioned that the viscosity of the percolating solution increases with higher salt concentrations. This reduce the permeability of the calcareous sand sample in a saline solution environment, resulting in an overall decrease in permeability of the calcareous sand samples in the saline solution environment, and a decrease in the degree of variation of permeability coefficients with grain size intervals.

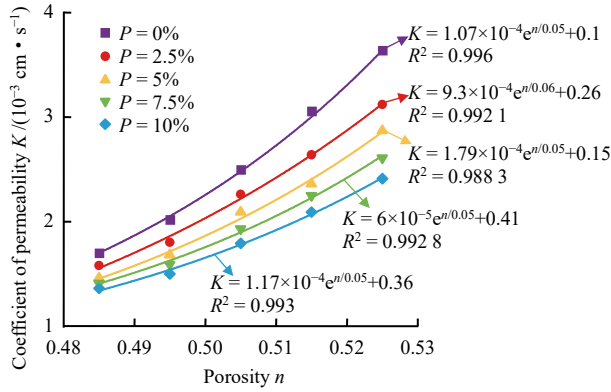




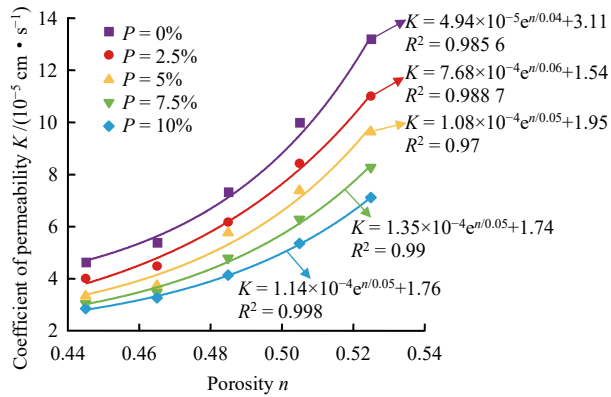
(a) Coarse sand



(b) Medium sand



(c) Fine sand



(d) Silty sand

Fig. 7 Variation of permeability coefficient with porosity for different soils

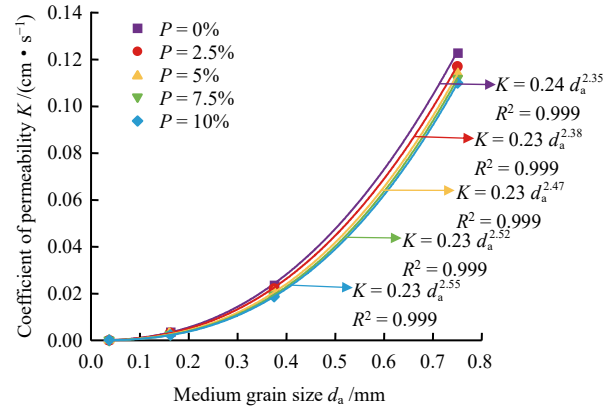


Fig. 8 Variation of permeability coefficient with medium grain size

#### 4 Model for predicting coefficient of permeability

In engineering practice, a fast evaluation of the coefficient of permeability is typically required for a given stratum or soil specimens. Numerous researchers correlated the coefficient of permeability to effective grain size, void ratio, gradation factor, grain shape factor, etc., by experimental and theoretical studies<sup>[26–27]</sup>. However, parameters related to salt content have not been considered in those studies. Typically, calcareous sands deposited in the seawater environment with salts, which are categorized as marine deposited sands. The grain shape of the marine deposited sands with special biogenesis is particularly irregular. Surficial and inner pores are abundant in the marine deposited sands with special pore structures. Based on this study, the coefficient of permeability of calcareous sands in the environment of a salt solution is strongly dependent on the salt content ( $P$ ), the porosity ( $n$ ), and the medium grain size ( $d_a$ ). Thus, the evaluation model for the coefficient of permeability of calcareous sands is proposed considering the effect of salt contents, which can be used to predict the coefficient of permeability of strata in islands and reefs:

$$K = Ad_a^B n^C \quad (8)$$

where  $A$  is a expression related to the salt content; and  $B$  and  $C$  are model parameters.

Figure 9 depicts the variation of the coefficient of permeability of calcareous sands with grain size and porosity in the environment of different salt contents. It can be found that the coefficient of permeability strongly correlated to  $Ad_a^{2.314} n^{10.49}$  with a coefficient of determination higher than 0.99. Thus, the model parameters  $B$  and  $C$  are derived as 2.314 and 10.49.

Figure 10 shows the variation of the expression  $A$  with respect to the salt content ( $P$ ). It can be seen that  $A$  decreases with the salt content ( $P$ ) in a negative exponential fashion. Those two terms are highly correlated with the coefficient of determination of 0.99. Thus, the expression can be written as

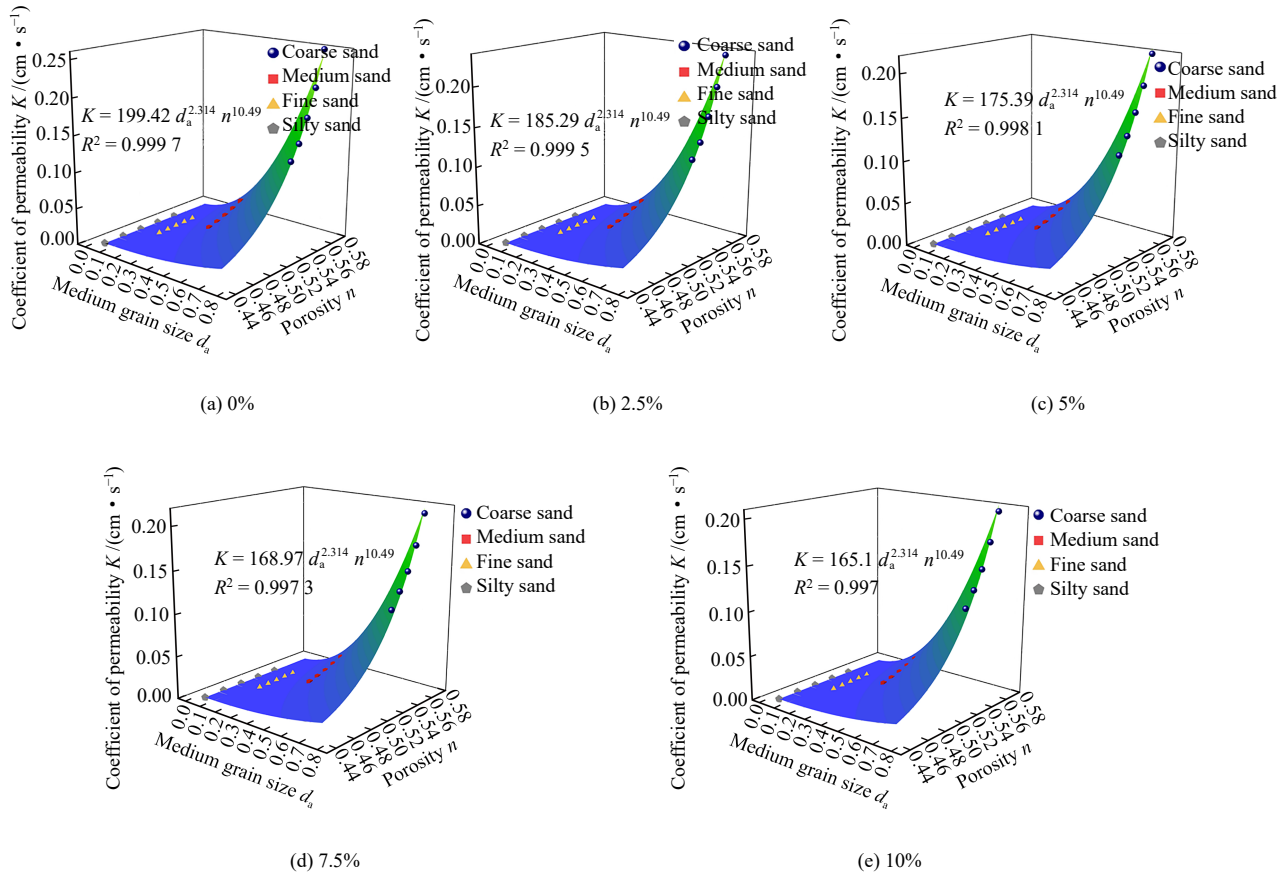


Fig. 9 Variation of permeability coefficient as a function of medium grain size and porosity at different salt contents

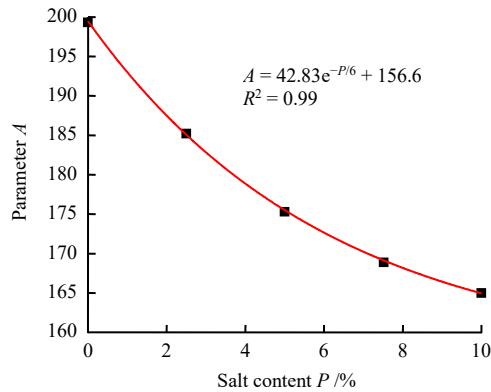


Fig. 10 Variation of coefficient  $A$  with salt content  $P$

$$A = 42.83e^{-P/6} + 156.6 \quad (9)$$

Therefore, the model for evaluating the coefficient of permeability of calcareous sands considering the salt content can be derived as

$$K = (42.83e^{-P/6} + 156.6)d_a^{2.314}n^{10.49} \quad (10)$$

To validate the model for predicting the coefficient of permeability of calcareous sands (Eq. (10)), the predictive values are compared with the measurements, which are shown in Fig. 11. It can be found that the data points in the prediction-measurement plot are close to the 1:1 line, which indicates that the model has a high precision for

predicting the coefficient of permeability of calcareous sands in the environment of different salt solutions.

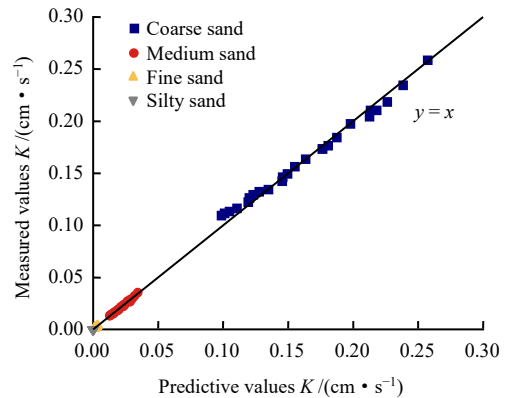


Fig. 11 Comparison between measured and predicted permeability coefficients for different soils

## 5 Conclusions

(1) In the environment of salt solutions, the pore structure of calcareous sands is influenced by the viscosity of the salt solution, surface tension, contact angle, and electrical double layer, etc. The coefficient of permeability of the calcareous sand specimen decreases with the concentration of salt solutions in a negative exponential fashion. The variation of the coefficient of permeability

of calcareous sands is more sensitive to the salt content for the specimens with a higher porosity and a smaller medium grain size.

(2) For calcareous sands in the environment of both deionized water and salt solution, the coefficient of permeability is positively correlated to the porosity and the grain size. In addition, the change in the grain size can change the order of the magnitude of the coefficient of permeability of the calcareous sands.

(3) The model for predicting the coefficient of permeability of the calcareous sands has been proposed, which considers the effect of the porosity, the medium grain size as well as the salt content. The predictive model can be used to predict the coefficient of permeability of strata in islands and reefs.

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