

Experimental Study on Permeability Characteristics of Geotubes for Seepage Analysis on Safety Assessment of Dams

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Abstract: Geotubes are heterogeneous structures composed of filling sand and bag material, and its permeability characteristics are different from that of filling sand. The uncertainty of geotubes permeability characteristics results in the failure of seepage analysis of geotube dams, which restricts the safety assessment of the dams. As the basis of the study on the seepage mechanism of the geotubes, the influence of particle grading on permeability coefficient of filling sand and sand covered with geotextiles were explored by the permeability tests of filling sand with different particle grading under the condition of sand covered with or without geotextiles. And the influence of geotextiles on the permeability coefficient was analyzed by comparing permeability coefficient of sand covered with and without geotextiles. The test results show that the influence of single particle size content on permeability coefficient is consistent under the condition of sand covered with and without geotextiles. The content of powder, fine, medium and coarse particles is linearly related to their respective permeability coefficients. And the content of powder, fine, medium particles is negatively correlated with their permeability coefficients, while the content of coarse particles is positively correlated with the permeability coefficient. But the permeability coefficient of sand covered with geotextiles is smaller than that of filling sand under the same conditions. Finally, the parameter $d_{50}^2 \frac{C_c}{C_u}$ was selected as a variable representing the particle grading to fit the empirical formula of permeability coefficient of filling sand and sand covered with geotextiles.

Keywords: Geotextile; filling sand; permeability coefficient; geotube dam; seepage analysis; safety assessment

1 Introduction

Geotubes were first used in 1950's [1], and were widely used in many coastal protection projects [2–4]. Especially in China, geotubes have been widely used in the construction of many kinds of infrastructures, such as the reservoirs in estuarine area, the channels in deep water, and the other offshore traffic facilities [5–7]. However, the seepage mechanism of the geotubes is not yet clear, and the penetration model has not been established. Therefore, the seepage analysis for the structures composed of geotubes, especially



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for geotube dams, cannot be carried out so far, which greatly limits the safety assessment of existing structures in the operation period.

At present, the seepage analysis of homogeneous dams is enough for their safety assessment [8]. However, since geotubes, as the important part of geotube dams, are heterogeneous structures composed of filling sand and geotextiles, the permeability of geotubes is affected by the filling sand and the geotextiles. Hence, it is necessary to study the permeability characteristics of sand covered with geotextiles for the seepage analysis and the safety assessment of geotube dams. However, there are few researches on the permeability characteristics of geotubes in operation period, but more researches on their dewatering characteristics in construction period.

Koerner et al. [9] proposed that the test results of the hanging bag dewatering test method could be used as the prediction performance index of the field test. The effect of the water content of the filling sand, the particle gradation of the filling sand, and the equivalent pore diameter of geotextiles as the bag material on the geotubes dewatering performance was studied through hanging bag tests by Muthukumaran et al. [10]. Furthermore, Malik et al. [11] studied the influence of the filling sand density on the dewatering performance of the geotubes. With the results of the hanging bag tests, Weggel et al. [12–14] analyzed the dewatering process of the geotubes, and established the analytical model of geotubes dewatering. In addition, Moo et al. [15] improved the hanging bag test and proposed the pressure filtration test to consider the influence of filling pressure during construction. In order to avoid the influence of the shape of the bag used in the hanging bag test on the dewatering performance, Suits et al. [16] carried out dewatering tests on pillow bags with different filling soil materials. And the test results show that the filling sand has a significant impact on the permeability characteristics of the hanging bags and geotubes. In addition to the laboratory model test, many large-scale field filling tests have been carried out. Shin et al. [17] conducted the on-site filling tests of geotubes with two kinds of filling materials, sand and clay, respectively. Through the observation of filling process, the height and shape changes of the bags during the filling process were obtained. Through monitoring the process of bag height reduction in the process of drainage and consolidation after filling, the calculation method of bag shape change after drainage was proposed.

The permeability characteristics of geotubes in operation period are determined by the geotextiles and the filling sand. However, as basics, the researches on the permeability characteristics of geotextiles and filling sand have been relatively sufficient.

Considering the difference of the stress state of the geotextiles in the construction and operation period of geotubes, the permeability coefficient of geotextiles under different stress conditions have been studied. Fourie et al. [18] carried out single and two-way tensile tests on the geotextiles of different thickness. The results showed that the equivalent pore diameter of the geotextiles would change with the change of tensile force no matter in one-way or two-way tensile. Wang et al. [19] studied the relationship between the permeability coefficient of the geotextiles and normal pressure by placing porous pressure plates on the top and bottom of the geotextiles, and then applying pressure to measure the permeability coefficient of geotextiles under the current pressure. The results showed that with the increase of normal pressure, the permeability coefficient of the geotextiles decreased significantly. Bai et al. [20] summarized the microstructure and permeability principle of the geotextiles through qualitative analysis. Hong et al. [21] studied the change of permeability coefficient of the geotextiles under different types of load. The results showed that the overall permeability coefficient of the geotextiles system all increased with the increase of different types of load. Wu et al. [22] tested the permeability of the geotextiles after applying unidirectional tensile force along the weft direction. The results showed that the equivalent pore diameter and permeability coefficient of the geotextiles would increase when subjected to unidirectional tensile force.

For the permeability characteristics of soil, the effect of particle grading to the permeability coefficient is summarized and analyzed quantitatively by constant head test. It is generally considered that the permeability

coefficient of soil is related to d_{10} or d_{20} with a fixed void ratio. Terzaghi et al. [23] and Hansen [24] both proposed that the permeability coefficient of the soil is proportional to d_{10}^2 , while Liu et al. [25] found that the permeability coefficient is only related to d_{20} . Furthermore, many other formulas for calculating the permeability coefficient of sandy soil have been proposed. Zhu et al. [26] pointed out that the permeability coefficient of coarse-grained soil has a large correlation with the non-uniform coefficient and the curvature coefficient, and the relationship between the permeability coefficient and the gradation characteristics was established by the modified Terzaghi Formula. Su et al. [27] studied the variation law of permeability coefficient of sand with different particle size grades with the average particle diameter under the same porosity, and finally fitted the experience formula of the permeability coefficient with the average particle diameter. Yang et al. [28] studied the influence of nonuniformity coefficient, curvature coefficient, and average particle size of sand on the permeability coefficient by the constant water head tests. The results showed that the permeability coefficient increased linearly with the decrease of the nonuniformity coefficient, and with the increase of the curvature coefficient and the average particle size.

Recently, the preliminary investigations on the permeability characteristics of the system consisting of geotextiles and sand have been conducted. The permeability tests under the condition of sand covered with or without geotextiles were carried out with a set of self-developed multi-functional penetration test device by Wu et al. [29]. The results showed that the permeability coefficient of the sand covered with geotextiles is smaller than that of the filling sand due to the inhibition effect of the geotextiles on the seepage of the sand. In order to further quantitatively analyze the effect of geotextiles on the permeability coefficients of filling sand with different gradations, the constant head permeability tests of filling sand with different particle grading under the condition of filling sand covered with or without geotextiles were carried out in this study.

2 Test Materials and Test Process

2.1 Test Materials

2.1.1 Filling Sand

The sand used in the test is natural quartz sand, which can be divided into five levels including powder grain ($d < 0.075$ mm), fine grain ($0.075 < d < 0.125$ mm), medium grain ($0.125 < d < 0.18$ mm), coarse grain ($0.18 < d < 0.3$ mm) and large particles ($0.3 < d < 0.6$ mm) according to the particle size. Compared with other particle sizes, the influence of super large particles on the permeability coefficient can be ignored. Therefore, when adjusting the content of a certain target particle size and the content of large particles at the same time, the change of permeability coefficient can be considered to be completely caused by the change of the target particle size content. The grading curve of filling sand used in each test is shown in Fig. 1.

And the other specific information of filling sand in the tests including d_{10} , d_{30} , d_{50} , and d_{60} is shown in Tab. 1.

2.1.2 Geotextiles

As shown in Fig. 2, the geotextiles used in the tests are woven by polypropylene materials. This geotextiles commonly used for geotubes, especially in various engineering in China. The geotextiles has good application characteristics, with a surface density of 150 g/m^2 , a thickness of 1.2 mm, and an equivalent pore diameter of 0.07 mm. The other detailed parameters of the geotextile materials are shown in Tab. 2.

2.2 Test Process

A set of self-developed multi-functional penetration test equipment is used to test the permeability of sand covered with or without geotextiles, and the test equipment is shown in Fig. 3.

The test equipment consists of water supply device, infiltration device and water collecting device. The water supply device, including the inlet tank and outlet tank, can provide a stable constant head difference for the infiltration device. The sand filling chamber of infiltration device is filled with filling sand covered with or without geotextiles. In the water collecting device, the weight of water tank with water can be weighed by the electronic scale.

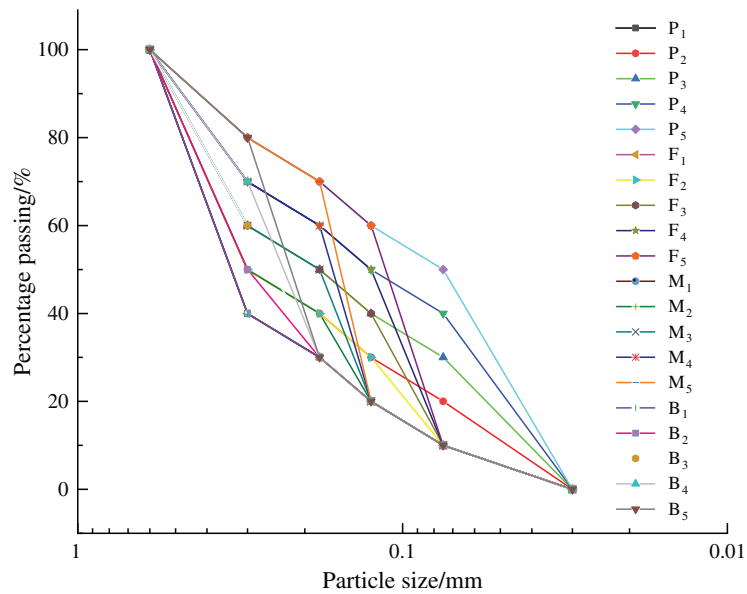


Figure 1: Particle gradation curve

Table 1: Information of filling sand

Test numbering	Particle size	Content (%)	d_{10}	d_{30}	d_{50}	d_{60}	
P	P ₁	Powder partical	10	0.075	0.180	0.330	0.387
	P ₂		20	0.058	0.125	0.300	0.320
	P ₃		30	0.042	0.075	0.180	0.300
	P ₄		40	0.037	0.068	0.125	0.180
	P ₅		50	0.035	0.054	0.075	0.125
F	F ₁	Fine partical	10	0.075	0.180	0.330	0.387
	F ₂		20	0.075	0.125	0.300	0.318
	F ₃		30	0.075	0.107	0.180	0.300
	F ₄		40	0.075	0.106	0.125	0.180
	F ₅		50	0.075	0.094	0.123	0.125
M	M ₁	Medium partical	10	0.075	0.180	0.330	0.387
	M ₂		20	0.075	0.167	0.300	0.330
	M ₃		30	0.075	0.143	0.180	0.300
	M ₄		40	0.075	0.132	0.168	0.180
	M ₅		50	0.075	0.126	0.156	0.171
B	B ₁	Coarse partical	10	0.075	0.180	0.330	0.387
	B ₂		20	0.075	0.180	0.300	0.354
	B ₃		30	0.075	0.180	0.265	0.300
	B ₄		40	0.075	0.180	0.238	0.285
	B ₅		50	0.075	0.180	0.225	0.249

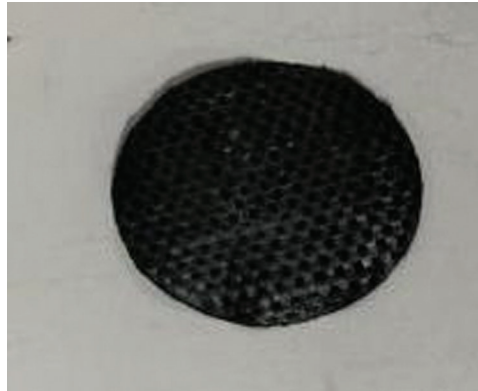


Figure 2: Geotextile

Table 2: Geotextile material parameters

Specification (g/m ²)	Mass deviation per unit area	Thickness (mm) ≥	Transverse and longitudinal breaking strength (N/m) ≥
150	-5%	1.2	375
Corresponding elongation of horizontal and vertical standard strength (%)	CBR bursting strength (N) ≥	Horizontal and vertical tearing strength (N) ≥	Equivalent aperture (mm)
50	1600	210	0.07

In the pre-test, it was found that the permeability coefficient changed with time, as shown in Fig. 3. But, after a period of time, the permeability coefficient would gradually stabilize. Hence, the final stability values were selected as the test results. Accordingly, the test process could be divided into three steps.

1. When the test starts, the water flows from the inlet tank to the outlet tank through the infiltration device.
2. After the seepage stabilized, the weight of the water in the water tank coming from the outlet tank will be weighed by the electronic scale according to a fixed time interval.
3. After the test, the data will be used for the calculation of the permeability coefficients.

3 Test Results and Analysis

3.1 Test Results

The permeability coefficients of filling sand and sand covered with geotextiles under different gradations are shown in Tab. 3. The permeability coefficient of filling sand is expressed in k , and that of sand covered with geotextiles is expressed in k' .

As shown in Fig. 5, the permeability coefficients of filling sand k vary with the single particle size content C . And the permeability coefficients of sand covered with geotextiles k' vary with the single particle size content C , as shown in Fig. 6.

3.2 Analysis of Test Results

3.2.1 Influence of Geotextiles on the Permeability Coefficient

In order to analyze the influence of geotextiles on the permeability coefficient at different particle size levels, the permeability coefficients at the same particle size level are selected from Figs. 5 and 6, and

compared in Fig. 7. Among them, Fig. 7a shows the permeability coefficients variation of filling sand covered with or without geotextiles with powder particles content. And Fig. 7b shows the permeability coefficients variation of filling sand covered with or without geotextiles with fine particles content. While Fig. 7c shows the permeability coefficients variation of filling sand covered with or without geotextiles with medium particles content. And Fig. 7d shows the permeability coefficients variation of filling sand covered with or without geotextiles with coarse particles content. Moreover, the relationships between the permeability coefficients of filling sand covered with or without geotextiles and the particle contents of different particle sizes are fitted in Fig. 7, respectively.

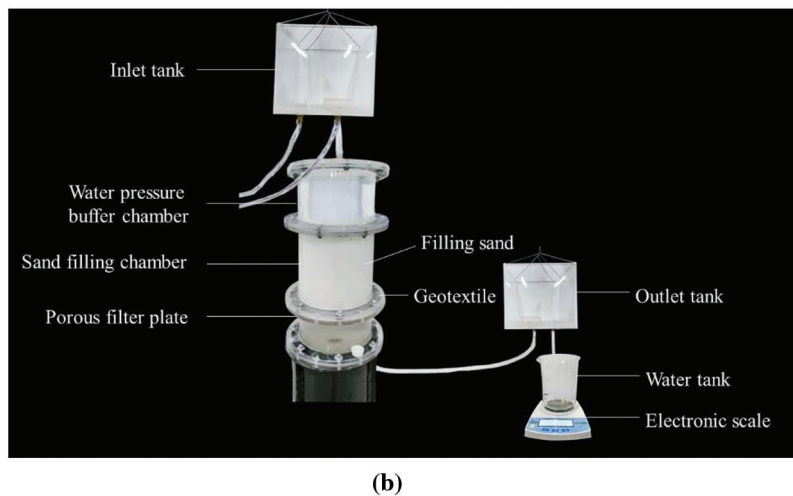
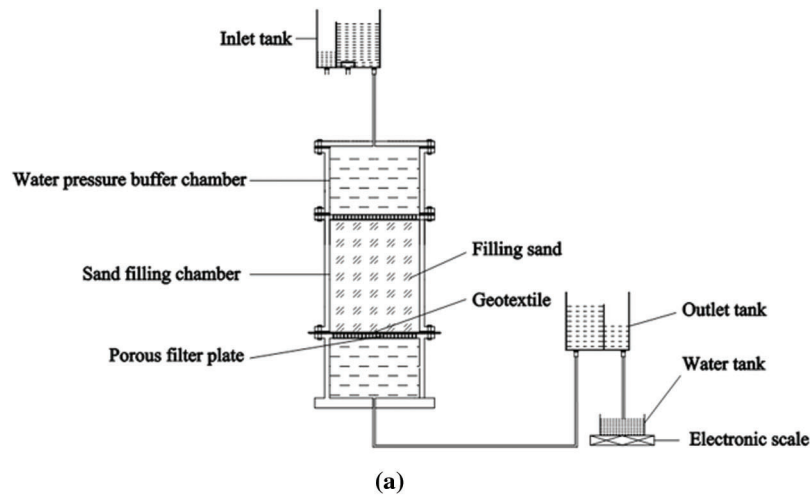


Figure 3: Test equipment (a) Sketch map (b) Physical map

As shown in Fig. 7, the influence of single particle size content on the permeability coefficient is consistent under the condition of sand covered with and without geotextiles. The content of powder, fine, medium and coarse particles is linearly related to their respective permeability coefficients. And these relationships can be fitted to Eqs. (1)–(8). Among them, the content of powder, fine, medium particles is negatively correlated with their permeability coefficients, while the content of coarse particles is positively correlated with the permeability coefficient.

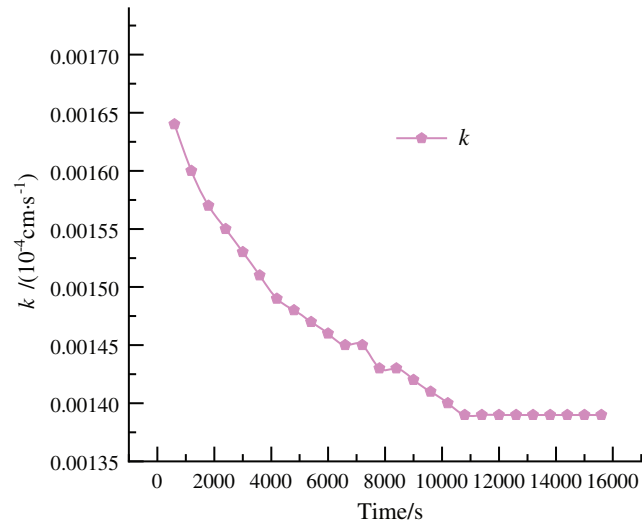


Figure 4: Variation of k with time

Table 3: Test results

Test numbering		$k (10^{-4} \text{cm}\cdot\text{s}^{-1})$	$k' (10^{-4} \text{cm}\cdot\text{s}^{-1})$
P	P ₁	11.8	10.60
	P ₂	8.71	7.26
	P ₃	3.17	2.23
	P ₄	0.52	0.48
	P ₅	0.40	0.39
F	F ₁	11.80	10.60
	F ₂	8.87	3.78
	F ₃	3.27	2.28
	F ₄	2.59	1.56
	F ₅	1.39	1.37
M	M ₁	11.80	10.60
	M ₂	11.10	10.40
	M ₃	8.76	8.30
	M ₄	8.15	7.66
	M ₅	4.00	3.76
B	B ₁	11.80	10.60
	B ₂	13.50	10.80
	B ₃	14.50	10.50
	B ₄	15.50	13.60
	B ₅	20.30	16.20

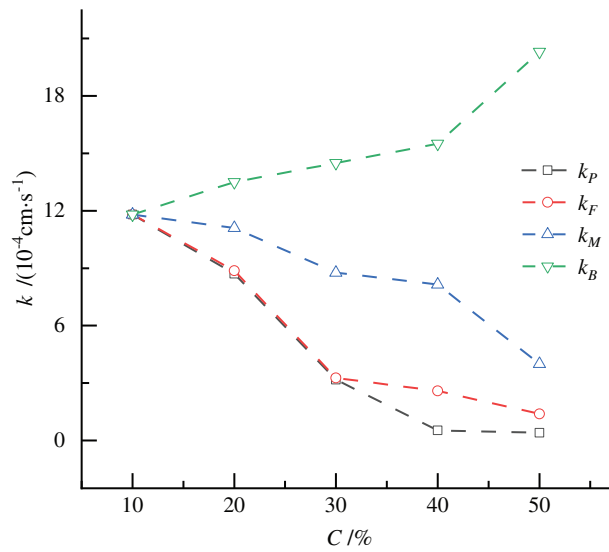


Figure 5: Variation of k with C

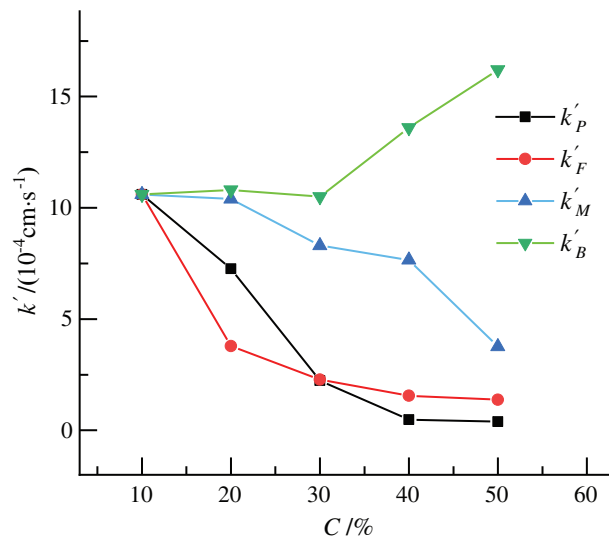


Figure 6: Variation of k' with C

$$k_P = -0.310C_P + 14.217 \quad (1)$$

$$k'_P = -0.272C_P + 12.352 \quad (2)$$

$$k_F = -0.271C_F + 13.714 \quad (3)$$

$$k'_F = -0.207C_F + 10.122 \quad (4)$$

$$k_M = -0.186C_M + 14.327 \quad (5)$$

$$k'_M = -0.164C_M + 13.070 \quad (6)$$

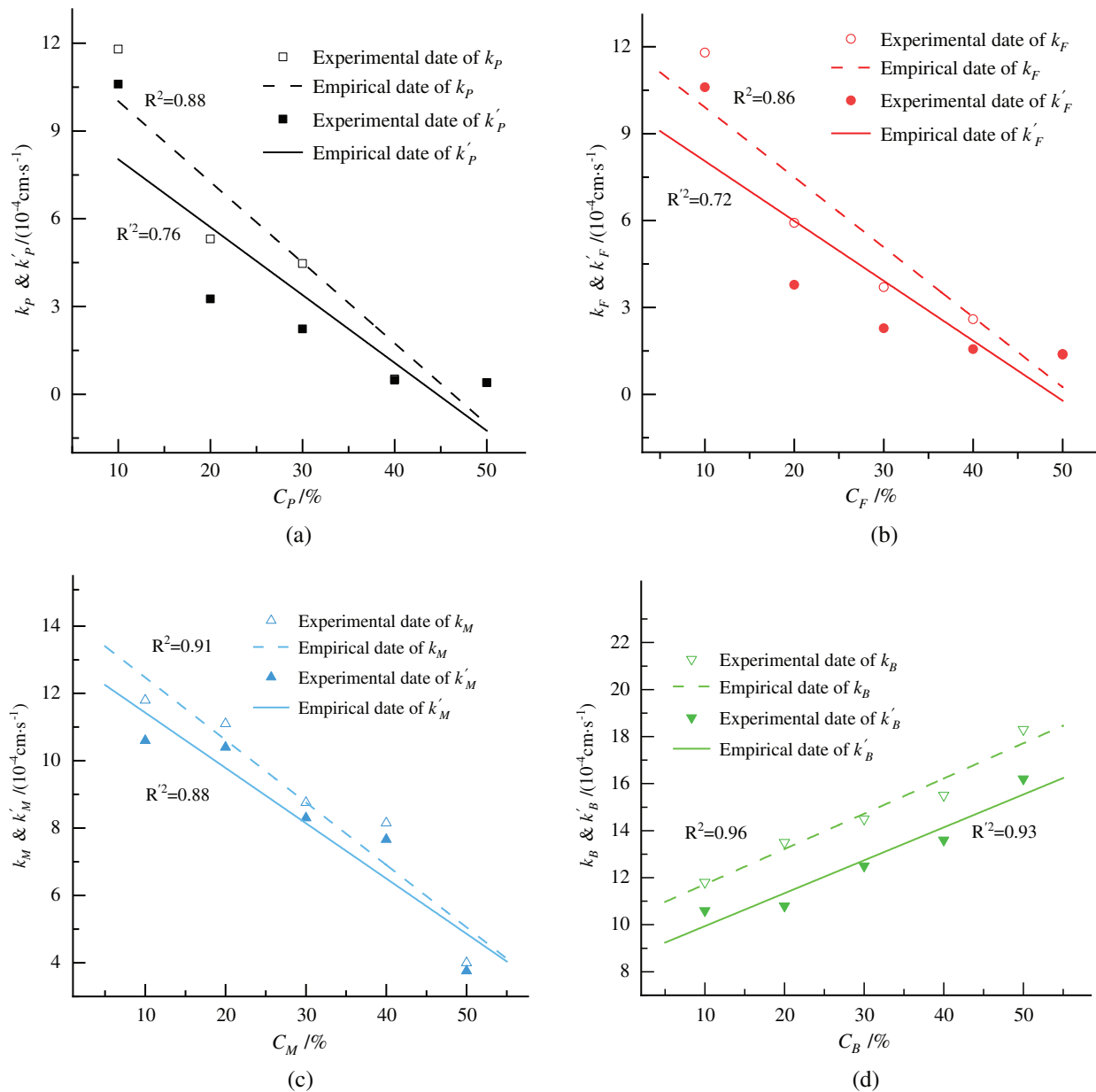


Figure 7: Comparison of k and k' with C (a) Tests P (b) Tests F (c) Tests M (d) Tests B

$$k_B = 0.190C_B + 9.420 \quad (7)$$

$$k'_B = 0.140C_B + 8.140 \quad (8)$$

According to the comparison of coefficients of Eqs. (1)–(8), the permeability coefficient of sand covered with geotextiles is smaller than that of filling sand with the same content. The influence of geotextiles on permeability coefficient decreases with the increase of powder, fine and medium grain contents, but increases with the increase of coarse grain content. Therefore, the permeability of coarse sand is more affected by geotextiles.

3.2.2 Influence of Particle Grading on the Permeability Coefficient

According to literature [28], the permeability coefficient increased linearly with the decrease of the nonuniformity coefficient, and with the increase of the curvature coefficient and the average particle size. Meanwhile, combined with the preliminary analysis of the test results, the parameter $d_{50}^2 \frac{C_c}{C_u}$ is selected as a variable representing the particle grading to fit the empirical formula of permeability coefficient of filling sand. And the correlation between k and $d_{50}^2 \frac{C_c}{C_u}$ and its fitting curve are both shown in Fig. 8.

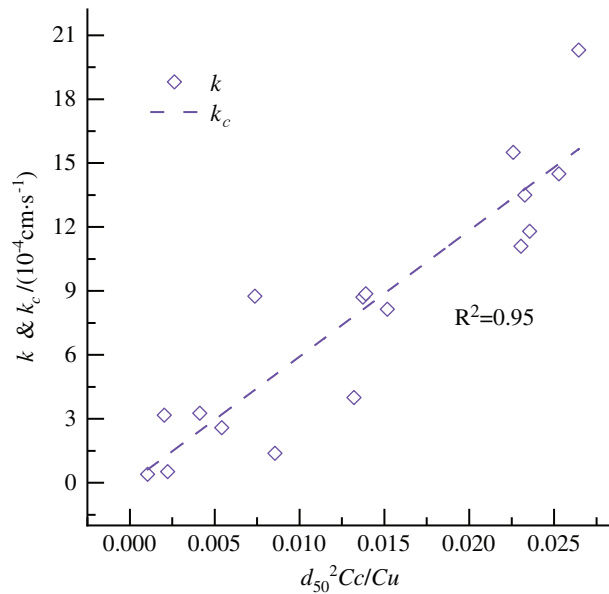


Figure 8: Variation of k and k_c with $d_{50}^2 \frac{C_c}{C_u}$

As shown in Fig. 8, the permeability coefficient k increases linearly with the increase of $d_{50}^2 \frac{C_c}{C_u}$, and the relationship between them can be fitted into Eq. (9).

$$k_c = 592 d_{50}^2 \frac{C_c}{C_u} \quad (9)$$

In order to verify the accuracy of this formula, the calculation results of k_H , k_L , k_Z and k_S of different empirical formulas including Eqs. (10)–(13) from literature [24–27] are compared with the calculation results k_c of Eq. (9).

$$k_H = 2400 d_{10}^2 \quad (10)$$

$$k_L = 864 d_{10}^2 \quad (11)$$

$$k_Z = 1220 d_{10}^2 \frac{d_{60}}{d_{30}} \quad (12)$$

$$k_S = 417 d_{10}^2 C_c C_u \quad (13)$$

Firstly, the calculated value of different empirical formulas in each are obtained with Eqs. (10)–(13). And then the ratios of the calculated value of different empirical formulas and the test results in each are

calculated. Finally, the average ratios of the calculated value of different empirical formulas and the test results in each are calculated. All the calculation results are shown in Tab. 4 for comparing the calculation accuracy of each empirical formulas.

Table 4: Ratio of the calculated value of different empirical formulas and the test results

Test numbering	k ($10^{-4}\text{cm}\cdot\text{s}^{-1}$)	$\frac{k_H}{k}$	$\frac{k_L}{k}$	$\frac{k_Z}{k}$	$\frac{k_S}{k}$	$\frac{k_c}{k}$
P ₁	11.80	1.14	1.14	1.25	1.14	1.18
P ₂	8.71	0.93	0.56	1.21	0.75	0.93
P ₃	3.17	1.34	1.22	2.72	0.74	0.38
P ₄	0.52	6.32	3.83	8.50	3.71	2.54
P ₅	0.40	7.35	3.12	8.65	3.04	1.55
F ₁	11.80	1.14	1.14	1.25	1.14	1.18
F ₂	11.80	1.52	1.18	1.97	0.73	0.93
F ₃	8.87	4.13	2.09	5.89	1.46	0.75
F ₄	3.27	5.21	1.98	4.50	1.81	1.24
F ₅	2.59	9.71	3.78	6.57	2.65	3.64
M ₁	11.80	1.14	1.14	1.25	1.14	1.18
M ₂	1.39	1.22	1.22	1.22	1.05	1.23
M ₃	11.80	1.54	1.54	1.64	0.97	0.50
M ₄	11.10	1.66	1.66	1.15	0.89	1.10
M ₅	8.76	3.38	3.38	2.33	1.65	1.96
B ₁	11.80	1.14	1.14	1.25	1.14	1.18
B ₂	8.15	1.00	1.00	1.00	1.00	1.02
B ₃	4.00	0.93	0.93	0.79	0.93	1.03
B ₄	11.80	0.87	0.87	0.70	0.87	0.86
B ₅	13.50	0.67	0.67	0.47	0.67	0.77
Average	7.85	2.62	1.68	2.72	1.37	1.26

And the average ratios between the calculated values of different empirical formulas and the test results are shown in Fig. 9. In this figure, \bar{k}_c represent the calculated values of different empirical formulas. From Tab. 4 and Fig. 9, it is found that the calculation results of Eq. (9) are the closest to the test results, which indicates that this formula is more suitable for the calculation of permeability coefficient of filling sand.

Similarly, the parameter $d_{50}^2 \frac{C_c}{C_u}$ is selected as a variable representing the particle grading to fit the empirical formula of permeability coefficient of sand covered with geotextiles. The fitting formula for the relationship between the permeability coefficients of sand covered with geotextiles k' and $d_{50}^2 \frac{C_c}{C_u}$ is shown in Eq. (14). And the correlation between k' and $d_{50}^2 \frac{C_c}{C_u}$ and its fit curve are shown in Fig. 10.

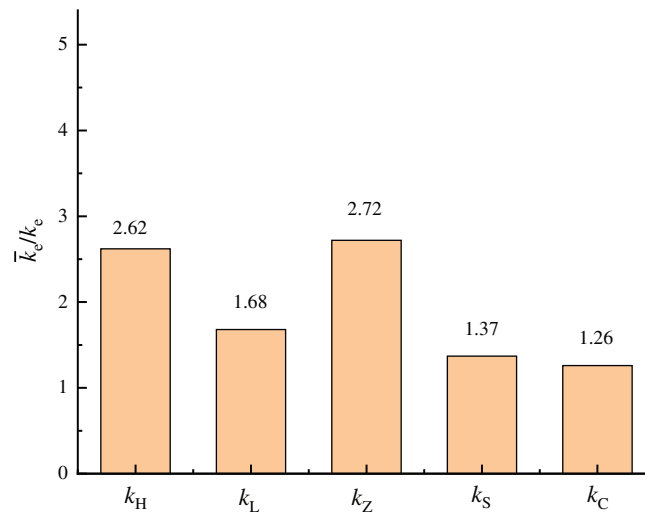


Figure 9: \bar{k}_e/k_c of different empirical formulas

$$k'_c = 485 d_{50}^2 \frac{C_c}{C_u} \quad (14)$$

As shown in Fig. 10, it is found that the correlation coefficient of fitting curve from Eq. (14) is 0.94, which indicates that the parameter $d_{50}^2 \frac{C_c}{C_u}$ could be selected as a variable to represent the particle grading for calculating the permeability coefficient of sand covered with geotextiles. Meanwhile, Eq. (14) is suitable for the calculation of permeability coefficient of filling sand covered with geotextiles.

According to Figs. 9 and 10, permeability coefficient of filling sand covered with geotextiles is consistent with that of filling sand. The permeability coefficients of filling sand and sand covered with geotextiles both have a positive proportional function relationship with the parameter $d_{50}^2 \frac{C_c}{C_u}$. In order to explore the different influence of parameter $d_{50}^2 \frac{C_c}{C_u}$ on the permeability coefficients of filling sand k_c and the permeability coefficients of sand covered with geotextiles k'_c , the relationship between k_c and $d_{50}^2 \frac{C_c}{C_u}$ is compared with that between k'_c and $d_{50}^2 \frac{C_c}{C_u}$ as shown in Fig. 11.

As shown in Fig. 11, the permeability coefficient of sand covered with geotextiles k' also increases linearly with the increase of $d_{50}^2 \frac{C_c}{C_u}$. But, according to the coefficient comparison between Eq. (9) and Eq. (14), the permeability coefficient of sand covered with geotextiles is smaller than that of filling sand under the same conditions, which indicates that geotextiles can inhibit the seepage of filling sand.

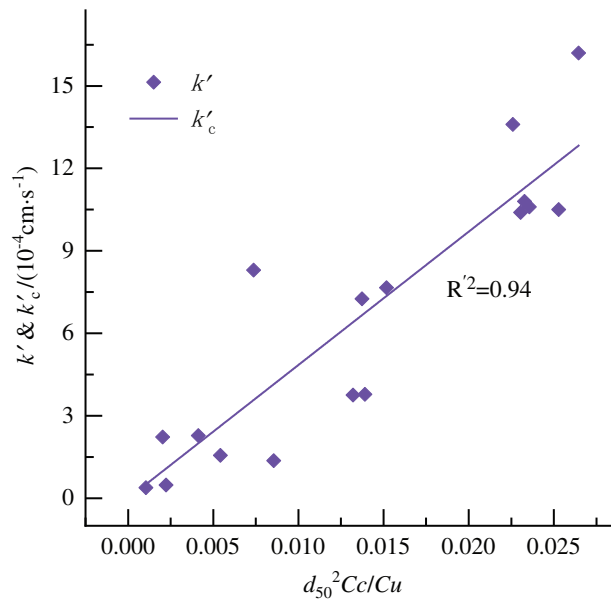


Figure 10: Variation of k' and k'_c with $d_{50}^2 \frac{C_c}{C_u}$

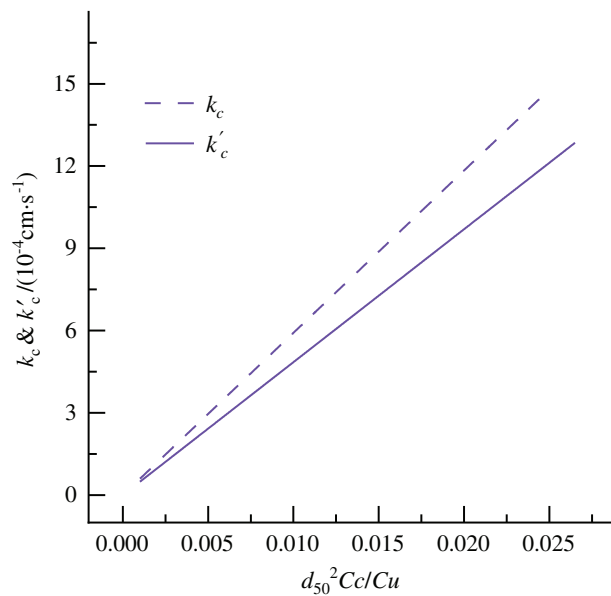


Figure 11: Comparison of k_c and k'_c with $d_{50}^2 \frac{C_c}{C_u}$

4 Conclusions

1. The influence of the content of single particle size on the permeability coefficient of filling sand and sand covered with geotextiles is consistent. The content of powder, fine and medium grains is negatively correlated with the permeability coefficient, while the content of coarse grains is positively correlated with the permeability coefficient. And these relationships can be fitted to Eqs. (1)–(8).

2. Under the same grading condition, the permeability coefficient of sand covered with geotextiles is smaller than that of filling sand because of the inhibition of geotextile on the loss of fine particles in the process of seepage.
3. The permeability coefficients of filling sand and sand covered with geotextiles both have good linear relationships with $d_{50}^2 \frac{C_c}{C_u}$. With this parameter as an independent variable, the formula of permeability coefficient of filling sand Eq. (9) and that of sand covered with geotextiles Eq. (14) could be fitted to calculate the permeability coefficient of filling sand covered with or without geotextiles under different gradations.

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