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Experimental study of the effect of microstructure on the permeability of saturated soft clays

Bo Chen*[1], De'an Sun[2] and Pan Jin[1]

[1]*College of Civil Engineering and Architecture, Quzhou University,78, Jiuhuabei Road, Quzhou, Zhejiang, 324000, P. R. China*
[2]*Department of Civil Engineering, Shanghai University, 99, Shangda Road, Shanghai, 200444, P. R. China*

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Abstract. The effect of microstructure on the permeability of two saturated marine clays was studied through a series of falling head permeability tests and mercury intrusion porosimetry (MIP) tests. The key findings from this experimental study include the following results: (1) The permeability of undisturbed specimens is larger than that of reconstituted specimens at the same void ratio due to different soil fabrics, i.e., the pore size distributions (PSDs), even though they have the similar variation law in the permeability versus void ratio. (2) Different permeabilities of undisturbed and reconstituted specimens at the same void ratio are mainly caused by the difference in void ratio of macro-pores based on the MIP test results. (3) A high relevant relation between C_k (C_k is the permeability change index) and e^*_{10}, can be found by normalizing the measured data both on undisturbed or reconstituted specimens. Hence, the reference void ratio e^*_{10}, can be used as a reasonable parameter to identify the effect of soil fabric on the permeability of saturated soft clays.

Keywords: undisturbed specimen; reconstituted specimen; permeability; pore size distribution; soil fabric; reference void ratio

1. Introduction

The permeability of saturated soft clay is an important soil parameter to reflect the capacity of water to pass through the soil mass, which is a key element in the design and construction of geotechnical engineering in soft clay region. For example, the permeability of soft clays is related to the design of water retaining structures, the time prediction of building settlement and the analysis of groundwater regimes in the slopes (Hall and Fox 2018, Zhu *et al*. 2018). Therefore, extensive attentions have been paid on the study on the permeability of saturated soft clay in literatures, including the experimental methods to determine the permeability, and the influence factors on the permeability, etc.

It is well recognized that the permeability of saturated soft clay is closely related to void ratio (Mesri and Rokhsar 1974, Tavenas *et al*. 1983, Yuan *et al*. 2019), plasticity index (Horpibulsuk *et al*. 2007, Dolinar 2009, Oren *et al*. 2018) and soil structure (Zeng *et al*. 2011, Lei *et al*. 2018, Yuan *et al*. 2019), based on numerous test results on the permeability of soft clay under different consolidation stresses. Moreover, the empirical e-log k_v model (Mesri and Rokhsar 1974), e/e_L-log k_v model (Nagaraj *et al*. 1991) and modified log (1+e)-log k_v model (Zeng *et al*. 2011), established based on the variation in the permeability k_v with void ratio e, had been widely used to predict the permeability of soft clays with different void ratios.

Many useful contributions on the permeability of saturated soft clays have been obtained from experimental and theoretical results. However, the study on the effect of soil structure, a significant factor regarded as important as porosity and stress history, on the permeability of soft clay is not as intensively as their compression and strength characteristics (Lapierre *et al*. 1990, Horpibulsuk *et al*. 2007, Zeng *et al*. 2011, Yuan *et al*. 2019). Moreover, the effect of soil structure on the permeability property of soft clay is mainly explored by comparing the differences of the permeabilities of undisturbed and reconstituted specimens under the same consolidation stress or the same void ratio conditions (Horpibulsuk *et al*. 2007, Zeng *et al*. 2011, Lei *et al*. 2018). The effect of soil structure on the permeability of clays was rarely discussed based on the microscopic mechanism.

The pore size distribution (PSD) of clays, obtained from the mercury intrusion porosimetry (MIP) tests, have been widely used to investigate the effect of microstructure on the mechanical behaviours of clays (Delage 2006, Zhao *et al*. 2016). And it is also used to predict the permeability of soils (Lapierre *et al*. 1990, Gao and Hu 2013, Deng *et al*. 2015). However, the comparison of the PSDs of undisturbed and reconstituted specimens at the same void ratio to study the influence of soil structure on the permeability of clays is few, by using the MIP experimental data (Yuan *et al*. 2019). Therefore, it is necessary to further investigate the microscopic mechanism for the effect of soil structure on the permeability of soft clays, using the MIP tests on undisturbed and reconstituted specimens.

The paper first presents the permeability test results, obtained from the falling head permeability tests on undisturbed and reconstituted specimens of two saturated

*Corresponding author, Ph.D., Associate Professor
E-mail: chenbo20020178@163.com

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marine clays, and the investigated clays were obtained from Shanghai and Wenzhou cities in China, respectively. The modified oedometer cell is used in the tests to investigate the influence of soil structure on the permeability of saturated clays. Then, the microscopic mechanism about the effect of soil structure on the permeability of soft clays is explored by comparing the PSDs, obtained from the MIP tests on undisturbed and reconstituted specimens with the same void ratio. Finally, the reference void ratio e^*_{10}, used to illustrate the fabric of soil structure simply, was introduced to deal with the permeability change indices of undisturbed and reconstituted specimens of two different soft clays. The measured data was used to verify this new parameter can be used as a reasonable parameter to illustrate the effect of soil fabric on the permeability of soft clays.

2. Testing materials and experimental program

2.1 Testing materials

Two different soft clays (designated as Shanghai clay, Wenzhou clay) used in this study were taken from Pudong district of Shanghai and Wenzhou city of Zhejiang province in China, respectively. Wenzhou city is located away about 450 km southeast from Shanghai, and the investigated clays are typical marine deposit soft clays in the Yangtze River Delta, China. The undisturbed specimens of two different clays were obtained by different sampling methods, including block sampling method on Shanghai clay and thin wall sampling method on Wenzhou clay, respectively. The basic physical properties of the investigated clays are shown in Table 1. The average volumetric strains at effective overburden stress are 3.5% for Shanghai clay and 4.5% for Wenzhou clay respectivly. i.e., the qualities of undisturbed specimens of Shanghai and Wenzhou clays are fair and slight below fair, respecitvely (Lacasse *et al.* 1985).

The corresponding reconstituted specimen was prepared as the method suggested by Burland (1990). The slurry was poured into a rigid cylinder with a diameter of 15 cm and a height of 16 cm, then it was consolidated one dimensionally with different pressures, and the last pressure applied for consolidation was 70 kPa or 30 kPa, respectively. Finally the pre-consolidation stress was released and the specimen was shaped for oedometer tests. In order to avoid the influence of the initial water content of slurry on the mechanical behavior of reconstituted specimens (Burland 1990, Hong *et al.* 2012), the initial water content of slurry was controlled at $2.0w_L$, where w_L is liquid limit.

2.2 Experimental program

With the objective to study the effect of soil structure on the permeability of saturated clays, the undisturbed and reconstituted specimens, with 61.8 mm inside diameter and 40.0 mm height, were placed in a modified oedometer cell to carry out falling head permeability tests under different consolidation stresses. The modified oedometer cell used in tests, as shown in Fig. 1, is the same to the cell suggested by Tavenas *et al.* (1983) and Zeng *et al.* (2011). The

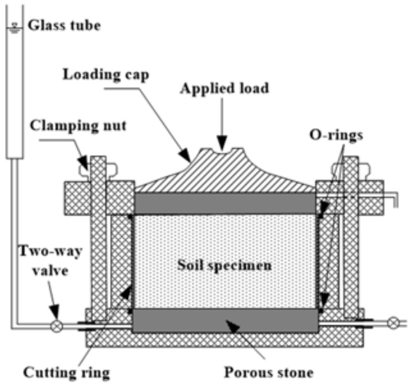


Fig. 1 Modified oedometer cell for falling head permeability tests

Table 1 Basic indexes of natural soft clays

Clays	Sampling method	Depth (m)	σ_y (kPa)	w_n (%)	G_s	ρ (g/cm^3)	w_L(%)	w_p(%)	I_p
Shanghai	Block	9.8	112	47.0-54.4	2.74	1.73	41.5	21.6	19.9
Wenzhou	Thin wall	11.5-12.0	96	73.7-76.7	2.68	1.54	57.5	20.5	37.0

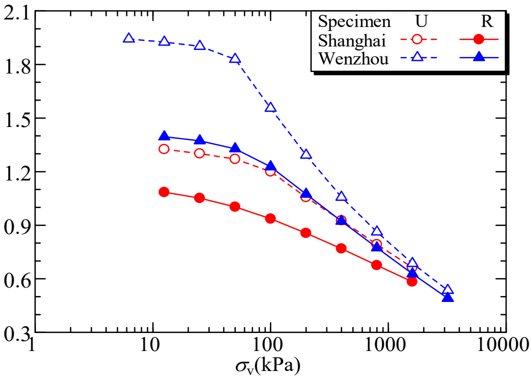
Note: σ_y: structural yield stress; w_n: natural water content; G_s: specific gravity; ρ: density of soil; w_L: liquid limit; w_p: plastic limit; I_p: plastic limit

incremental load was applied with the load incremental ratio of 1.0, and each loading lasted 72 hours to ensure the consolidation was completed at the specified stress (Zeng *et al.* 2011). Then, the falling head permeability test was carried out by connecting the glass tube to the base of the specimen with an initial water head in the order of 100 cm, as suggested by Tavenas *et al.* (1983). The permeability measurements were done and continued for up to two days to obtain sufficient readings.

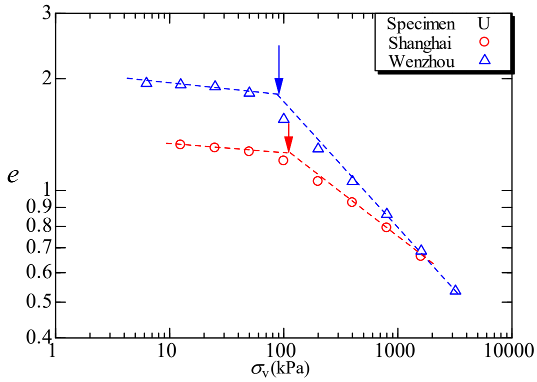
In order to obtain the PSDs of undisturbed and reconstituted specimens of two clays, the specimens with 61.8 mm inside diameter and 20.0 mm height were placed in conventional oedometer cell to carry out standard consolidation tests, and the load incremental ratio was approximately one and each loading took 24 hours. When the consolidation was completed at the specified stress, the water was firstly drained completely from oedometer cell to ensure the void ratio is constant during the rapid unloading (Le *et al.* 2011). Then, the specimens were removed out from oedometer cell quickly and the representative portions of specimens were cut into small cubes to be dehydrated by the vacuum freeze-drying method immediately, which was verified that the method has the least negative impact on soil structure and pore shrinkage of clays (Delage 2006). Therefore, it can be assumed that the pore size distributions are not changed during the specimen preparation for the MIP tests. The MIP tests on the representative small cubes were carried out and the entrance pore diameter ranges from 0.005 to 350 μm approximately.

2.3 Soil structure of undisturbed clays

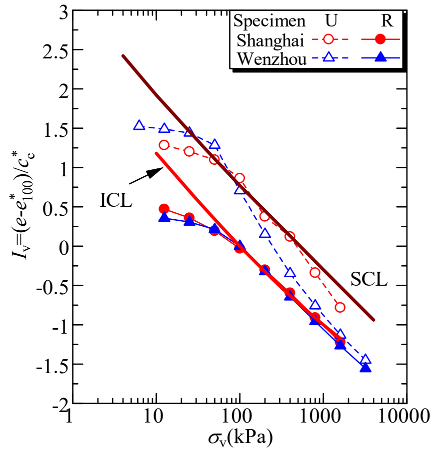
Fig. 2(a) shows e-logσ_v compression curves of undisturbed and reconstituted specimens of two different



(a) e-log σ_v curves



(b) log e-log σ_v curves



(c) I_v-log σ_v curves

Fig. 2 e-log σ_v, log$e$-log σ_v and I_v-log σ_v curves of undisturbed and reconstituted specimens

clays. The letters U and R in the figure denote the results of undisturbed specimen and the reconstituted specimen with pre-consolidation of 70 kPa, respectively, and are with the same meaning in the following figures in this paper. It shows that compression curves of undisturbed specimens lie beyond on that of corresponding reconstituted specimens due to larger void ratio at the same consolidation stress. Moreover, the structural yield stress is obvious in the undisturbed specimens and the compressibility is different when the consolidation stress is beyond the structural yieldstress. It needs to be noted that the structural yield stresses of undisturbed specimens can be determined more precise, from their compression curves in a plot of bi-logarithmic chart (Butterfield, 1979). Hence, the structural yield stresses of undisturbed specimens in this paper are determined from the bi-logarithmic chart of compression curves with the method suggested by the Casagrade (1936). And the detailed structural yield stresses, obtained from the Fig. 2(b), are shown in the Table 1.

Burland (1990) introduced a void index I_v, defined as eq. (1), to normalize the compression curves of undisturbed and reconstituted specimens of various clays, and different normalized curves of undisturbed and reconstituted specimens can be used to quantify the soil structure of undisturbed specimens.

$$I_v=(e-e^*_{100})/(e^*_{100}-e^*_{1000})=(e-e^*_{100})/C_c^* \qquad (1)$$

where e^*_{100} and e^*_{1000} are the void ratios of reconstituted clays at the effective vertical stresses of 100 kPa and 1000 kPa, respectively; C^*_C is termed the intrinsic compression index.

Fig. 2(c) shows the normalized compression curves by using the values of e^*_{100} and C^*_C, obtained directly from oedometer tests on the reconstituted specimens. It can be seen from Fig. 2(c) that when the consolidated stress is larger than the pre-consolidated stress, the compression curves of reconstituted specimens can be expressed by a unique line in terms of the void index against effective vertical stress, which is named the ICL (Intrinsic Compression Line). However, the normalized compression curves of undisturbed specimens are mainly located between the ICL and the SCL (Sedimentary Compression Line), except for undisturbed specimens of Wenzhou clay at low stress. Burland (1990) proposed that if the yield states are lying between the ICL and the SCL, the main difference of sedimentary clay from the reconstituted material is due to micro-fabric with some inter-particle bonding. Therefore, it can be deduced that the microstructure of clays used in the tests is mainly constituted of soil fabric.

3. Permeabiltiy results and discussion

Fig. 3 shows the obtained log k_v-log σ_v curves from the compression tests on undisturbed and corresponding reconstituted specimens of two clays. The R_{30} in the figure denotes the results of reconstituted specimen with pre-

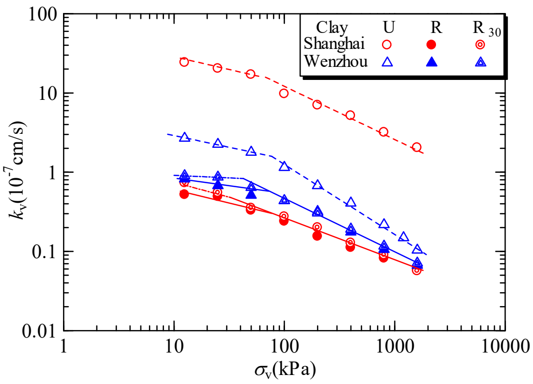


Fig. 3 log k_v-log σ_v curves of undisturbed and reconstituted specimens for different clays

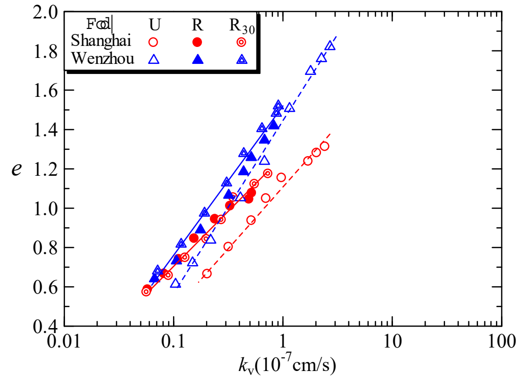


Fig. 4 e-log k_v curves of undisturbed and reconstituted specimens for different clays

Table 2 Permeability of different specimens at close void ratio

Clays	Specimen	σ_v(kPa)	e	k_v(cm/s)	Δk_v(cm/s)
Shanghai	U1	200	1.049	7.03×10^{-8}	4.63×10^{-8}
	R1	100	0.944	2.40×10^{-8}	
	U2	800	0.803	3.19×10^{-8}	2.07×10^{-8}
	R2	400	0.741	1.12×10^{-8}	
	U3	1600	0.665	2.04×10^{-8}	1.46×10^{-8}
	R3	1600	0.586	5.81×10^{-9}	
Wen zhou	U1	400	1.053	4.08×10^{-8}	8.90×10^{-9}
	R1	200	1.066	3.19×10^{-8}	
	U2	800	0.838	2.18×10^{-8}	4.20×10^{-9}
	R2	400	0.890	1.76×10^{-8}	
	U3	1600	0.613	1.04×10^{-8}	3.70×10^{-9}
	R3	1600	0.641	6.70×10^{-9}	

consolidation of 30 kPa, and is with the same meaning in the following figures in this paper. It shows that the variation of permeability is almost the same to the compressibility of clays (Burland 1990, Lei *et al.* 2018). i.e., the permeability decreases little with increasing consolidation stress before the yield stress, however, it decreases rapidly when the consolidation stress exceeds the yield stress, which is more obvious for undisturbed specimens (Zeng *et al.* 2011). Moreover, the log k_v-log σ_v curves of undisturbed specimens are all beyond that of corresponding reconstituted specimens due to larger permeability at the same consolidation stress, but they will converge to the log k_v-log σ_v curves of corresponding reconstituted specimens gradually with the increasing consolidation stress. It can be deduced from test results that the difference in permeabilities between the undisturbed and reconstituted specimens decreases gradually with the increasing consolidation stress, which is consist with the test results reported by Zeng *et al.* (2011).

The difference in permeability between undisturbed and reconstituted specimen at the same consolidation stress was explained by the effect of soil structure (Zeng *et al.* 2011). However, the soil structure, which defined as particles, particle groups, their associations, together with inter-particle forces and applied stresses (Mitchell 1993), can cause the difference in the void ratio and microstructure. Therefore, the difference in permeability between the undisturbed and corresponding reconstituted specimens at the same consolidation stress, shown in the Fig. 3, is caused by the difference in void ratio and the microstructure. It isbecause the undisturbed specimens have larger void ratio at the same stress, as shown in Fig. 2(a), will result in larger permeability of clay (Tevanas *et al.* 1983, Yuan *et al.* 2019). Zhao *et al.* (2016) also reported that the permeability of clays is not uniquely controlled by the void ratio, and the microstructure is also needed to be considered. Moreover, the paper mainly focuses on the effect of soil microstructure on the permeability of saturated clays. Therefore, it needs to compare the permeabilities of undisturbed and reconstituted specimens at the same void ratio, distinguishing the soil microstructure from void ratio, to investigate the effect of soil microstructure on the permeability of clays. Because the bonding of microstructure is weak in the investigated clays, and it has almost no impact on the permeability of clays for the relationship of e against log k_v (Horpibulsuk *et al.* 2007). Therefore, the difference in the permeability between undisturbed and reconstituted specimens at the same void ratio, caused by the microstructure of clays, is the soil fabric, i.e., pore size, shape and arrangement of pores, etc. Moreover, the soil fabric can be reflected by the PSDs of saturated soft clays.

Fig. 4 shows the e against log k_v relationships obtained from undisturbed and reconstituted specimens of two clays. It can be seen from the figure that the e-log k_v curves can be regarded as linear although it is somewhat nonlinear at large volumetric strain (Tevanas *et al.* 1983, Zeng *et al.* 2011). Furthermore, the change law of undisturbed specimens is similar to that of corresponding reconstituted specimens, which is consistent with numerous test results on the permeability (Zeng *et al.* 2011, Yuan *et al.* 2019). It needs to be noted that the e-log k_v curves of undisturbed specimens lie to the right of the curves of corresponding reconstituted specimens with slight steeper slopes, which means that the undisturbed specimen will have larger permeability than corresponding reconstituted specimen at the same void ratio due to soil fabric. However, the difference in permeability between undisturbed and reconstituted specimens with the same void ratio, reduces with the decreasing void ratio, as shown in Table 2.

The effect of the pre-consolidation pressure on the permeability of reconstituted specimens is also studied

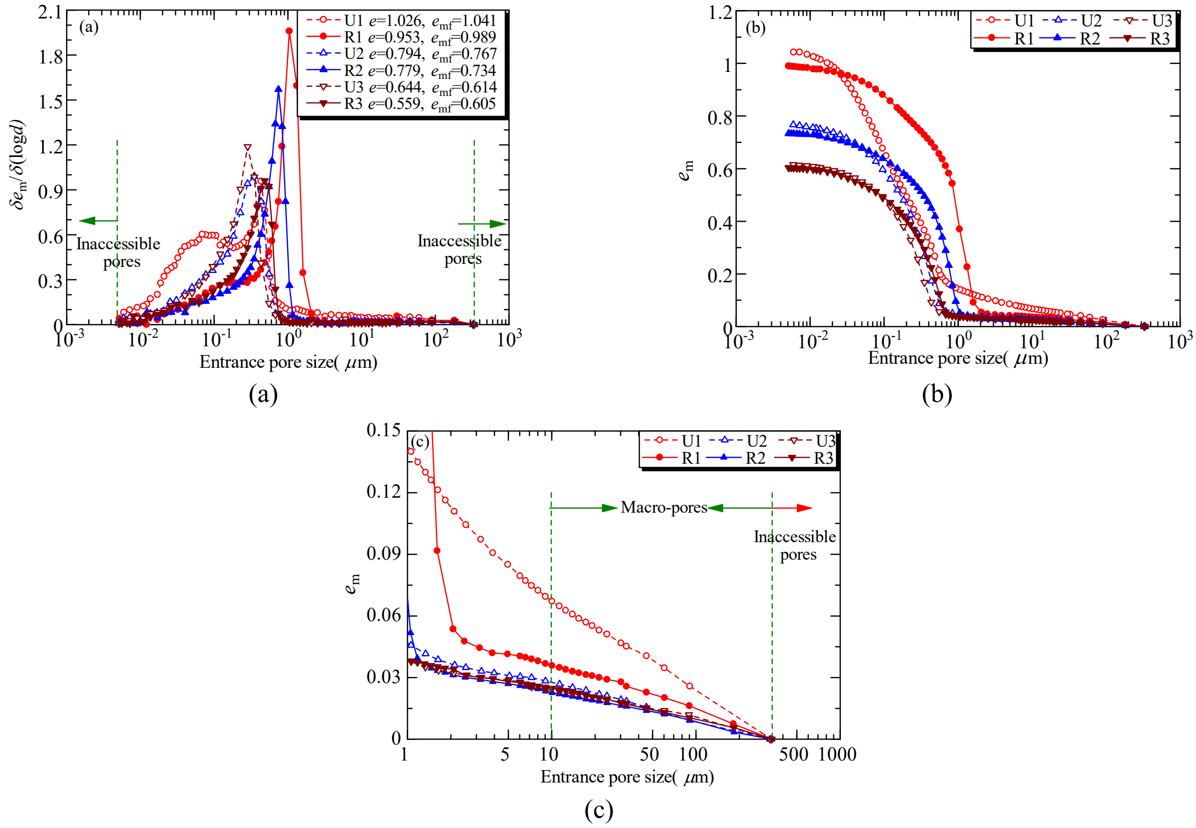


Fig. 5 Pore-size distribution curves of undisturbed and reconstituted specimens of Shanghai clay at close void ratio. (a) density function curves (b) cumulative curves and (c) cumulative curves range from 1 to 350 μm

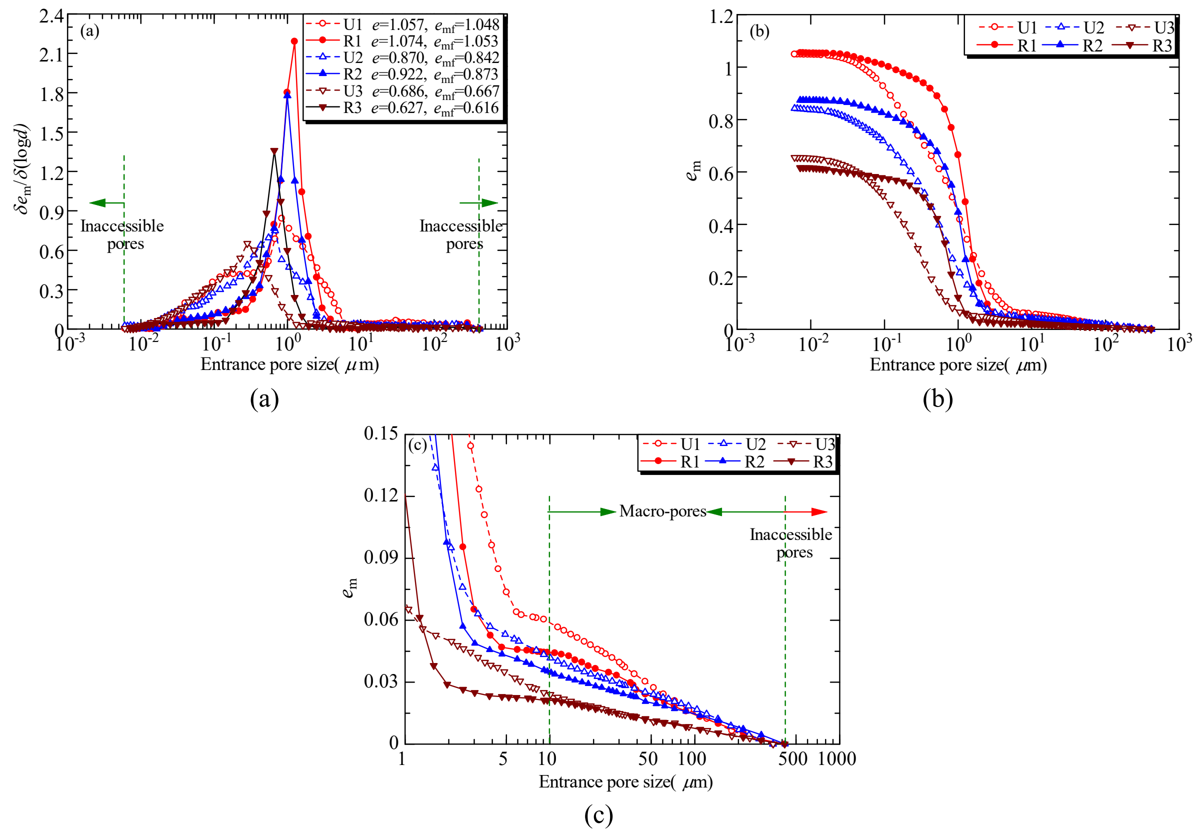


Fig. 6 Pore-size distribution curves of undisturbed and reconstituted specimens of Wenzhou clay at close void ratio. (a) density function curves (b) cumulative curves and (c) cumulative curves range from 1 to 350 μm

in this paper. It can be seen from Fig. 3 that although there is some difference in the log k_v-log σ_v curves when consolidation stress is lower than 100 kPa, the e-log k_v curves of reconstituted specimens with different pre-consolidation pressures are coincided, as shown in Fig. 4, which is the same to the results reported by Horpibulsuk *et al*. (2007). The larger permeability for reconstituted specimens with pre-consolidation stress of 30 kPa, at low consolidation stresses, is just caused by the larger void ratio with the same consolidation stress. Based on above test results, it can be concluded that pre-consolidation stress only has effect on the permeability of soft clays due to the different void ratios, but it has no effect on the relationship of e against log k_v.

4. MIP test results and discussion

Comparing the PSDs of undisturbed and reconstituted specimens, obtained from the MIP tests, is an effective way to investigate the effect of soil fabric on mechanical behaviours of clays (Zhao *et al*. 2016). Therefore, the MIP tests, on undisturbed and reconstituted specimens at close void ratio, were carried out to obtain the differential and cumulative PSDs of Shanghai and Wenzhou clays, respectively, and the test results are shown in Figs. 5 and 6. The letters e and e_{mf} in the figures are the void ratio measured from the conventional macroscopic method and the final intruded void ratio in the MIP tests, respectively. And the intruded void ratio e_{mf} can be calculated by the cumulative intrusion volume multiplies specific gravity of clay. The detailed information, including the maximum consolidation stress, the void ratio after consolidation and final intruded void ratio of specimen, is shown in Table 3.

The void ratio, measured from different tests, shown in the figures indicates that the final intruded void ratio e_{mf} is slight smaller than the void ratio e after consolidation in general, which is caused by inaccessible pores (d<0.005 μm and d >350 μm) exist in the specimens (Delage 2006). Figs. 5(a) and 6(a) also show that the differential PSDs of saturated soft clays are typical unimodal, no matter undisturbed or reconstituted specimens. However, the differential PSDs are different for undisturbed and reconstituted specimens at close void ratio, which means that the PSDs of saturated clay will be affected by the specimen preparation method. The narrower dominant distribution range and the higher peak height in differential PSDs of reconstituted specimen indicate that the pore diameter in reconstituted specimen is more uniform than that of undisturbed specimens. The peak height declines and its corresponding position moves left gradually in process of compression tests mean that the dominant pore diameters become less and smaller with increasing consolidation stress. The differential PSDs of reconstituted specimens get close to that of the undisturbed specimens with decreasing void ratio means that the difference in PSDs between undisturbed and reconstituted specimens reduces with decreasing void ratio. However, there is still some difference in the differential PSDs between undisturbed and reconstituted specimens, even the consolidation stress is up to 1.6 MPa. Based on the test results shown in Figs. 5-6, it can be concluded that the effect of specimen preparation method on the PSDs of soft clay cannot be eliminated only by increasing consolidation stress (Zhang *et al.* 2014).

Figs. 5(a) and 6(a) also show that the peak height in the differential PSDs of undisturbed specimens is situated on the left side, compared with that of corresponding reconstituted specimens at close void ratio. It means that the dominant pore diameter is smaller in undisturbed specimens than that of the corresponding reconstituted specimens. Correspondingly, the pore diameter corresponding to rapid increase in the cumulative intruded void ratio is smaller for undisturbed specimens, and the cumulative curves of undisturbed specimens will lie below that of reconstituted specimens due to the less cumulative intruded void ratio at the same entrance pore size when the pore diameter is smaller than 1 μm, except for the cumulative curve at very small pore size (d<0.1 μm) due to the different final intruded void ratio, as shown in Figs. 5(b) and 6(b).

It is well acknowledged that the permeability of clays is related to the cumulative intruded void ratio (Lapierre *et al*. 1990; Gao and Hu 2013; Deng *et al*. 2015; Yuan *et al*. 2019). However, there are different test results about the dominant pore size on the permeability. Some test results had shown that the permeability was related to median pore-throat diameter (pore-throat diameter corresponding to 50% mercury intrusion) and specimens with larger median pore-throat diameter will have higher permeability (Gao and Hu 2013, Deng *et al*. 2015). Some test results showed that the permeability of clays is dominated by the macro void ratio (Lapierre *et al*. 1990, Yuan *et al*. 2019). The different test results may be caused by the different specimens used in the tests. The former is obtained from the test results on all undisturbed specimens or reconstituted specimens, and the latter is obtained from the results of undisturbed and corresponding reconstituted specimens to study soil structure on the permeability. Moreover, the test results in this paper showed that the median pore-throat diameter of undisturbed specimen is smaller than that of the reconstituted specimen, which will be contradict to the test results that the permeability of undisturbed specimens is larger than that of reconstituted specimens at the same void ratio (Zeng *et al*. 2011, Yuan *et al*. 2019). Therefore, the permeability of clays may be controlled by the macro void ratio.

Although the permeability of clays is mainly controlled by the macro void ratio, the delimited diameter to distinguish macro-pores from micro-pores is still needed to be further discussed. Yuan *et al*. (2019) selected 1μm as delimited diameter to distinguish macro-pores from micro-pores based on the MIP test results, which is close to the diameter at peak height in the differential PSDs. However, it is not suitable to be selected as delimited diameter of macro-pores for the investigated soft clays, because the macro-pores (>10 μm) exists in clays (Zhang *et al*. 2014), and the effect of macro-pores on the permeability of soft clays cannot be ignored (Lapierre *et al*. 1990). Moreover, the detailed cumulative intruded void ratio of d>1μm in undisturbed and reconstituted specimens, listed in Table 3, is contradict to the test results of heading fall permeability. Therefore, the delimited diameter of macro-pore is selected as 10 μm in this paper.

With the objective to show the detailed intruded void

Table 3 PSDs of different specimens at close void ratio

Clays	Specimen	σ_v (kPa)	e	e_{mf}	e_m (>1μm)	e_M (>10μm)
Shanghai	U1	200	1.026	1.041	0.140	0.067
	R1	100	0.953	0.989	0.370	0.036
	U2	800	0.794	0.767	0.046	0.027
	R2	400	0.779	0.734	0.052	0.023
	U3	1600	0.644	0.614	0.038	0.024
	R3	1600	0.559	0.605	0.038	0.022
Wenzhou	U1	400	1.057	1.048	0.414	0.058
	R1	200	1.074	1.053	0.658	0.044
	U2	800	0.870	0.842	0.213	0.041
	R2	400	0.922	0.873	0.441	0.034
	U3	1600	0.686	0.667	0.095	0.024
	R3	1600	0.627	0.616	0.120	0.021

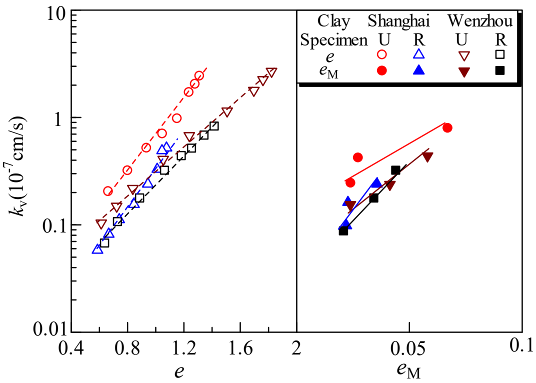


Fig. 7 Variations of permeability with the void ratio e and macro void ratio e_M

ratio of macro-pores more clearly, the cumulative PSD curves of undisturbed and reconstituted specimens ranging from 1 to 350 μm are replotted, as shown in Figs. 5(c) and 6(c). It can be seen from the figures that although the cumulative intruded void ratios of reconstituted specimens are beyond those of undisturbed specimen at pore diameter of 1.0 μm, the test results are reversed in entrance pore diameter range of 10~350 μm, which is in accordance with the test results of heading fall permeability. Moreover, the detailed cumulative intruded void ratio of d>10 μm in undisturbed and reconstituted specimens are also listed in Table 3. It shows that the difference in cumulative intruded void ratio for d>10 μm between the undisturbed and reconstituted specimens decreases with decreasing void ratio, and it can reasonably explain the gap of permeability between undisturbed and reconstituted specimens narrowed gradually at the same void ratio with decreasing void ratio, as shown in Table 3.

Fig. 7 shows the changes in the cumulative intruded macro void ratio (e_M) with the permeability. Despite the relationship of the intruded macro void ratio versus logarithm of permeability (e_M-log k_v) is somewhat scatter, it still can be seen from the figure that the specimen will have higher permeability with larger e_M. Moreover, the relative position of e_M-log k_v curves is the same to e-log k_v curves for undisturbed and reconstituted specimens of two clays, which verified that the permeability of saturated soft clay is dominated by the cumulative intruded macro void ratio (e_M). It needs to be emphasized that e_M-log k_v curves are not parallel to e-log k_v curves, as shown in the Fig. 7, which means that the permeability of saturated clay is not just controlled by the void ratio of macro-pores, and it is also be affected by the void ratio of other pore sizes. The similar conclusion was reported based on the test results on the saturated Maryland clay by Yuan *et al.* (2019). Based on the analysis of above test results, it can be deduced that the permeability is predominately depend on cumulative intruded void ratio of macro-pores (d>10 μm), but it is also affected by the intruded void ratio of other pore size. It needs to be emphasized that the MIP test results in this paper is few and somewhat scatter, therefore, the change law is needed to be investigated by more MIP test results, and the conclusion obtained in this paper is needed to be further explored.

5. Effect of fabric on permeability change index of clays

It is well known that it is laborious and time-consuming to measure permeability of saturated clays under different consolidation stresses. Therefore, many empirical equations between permeability and physical parameters had been established based on numerous measured test results (Mesri and Rokhsar 1974, Tavenas *et al.* 1983, Nagaraj *et al.* 1991). However, the most widely used model is the void ratio e against log k_v relationship, as Eq. (2), proposed by Mitchell (1993).

$$e\text{-}e_0=C_k(\lg k_v\text{-}\lg k_{v0}) \quad (1)$$

where e_0 is the initial void ratio; k_{v0} is the vertical permeability at initial void ratio e_0; C_k is the permeability change index.

Tevanas *et al.* (1983) suggested that the permeability change index can be simply expressed as C_k=0.5e_0. However, the statistic result on measured data, as listed in Table 4 and shown in Fig. 8**,** indicates that C_k=0.407e_0 in average, much lower than the value suggested by Tevanas *et al.* (1983). Moreover, the ratio of permeability change index to the initial void ratio (C_k/e_0) is somewhat scatted and it ranges from 0.314 to 0.489. The data shown in Fig. 8 also indicates that undisturbed specimens have larger permeability change index than that of the corresponding reconstituted specimens at the same void ratio due to soil fabric overall. However, almost the same relationship of C_k-e_0 for undisturbed and reconstituted specimens of clays used in this paper, is caused by the lower initial void ratio in the reconstituted specimens with the pre-consolidation of 70 kPa.

The same e~log k_v curves of reconstituted specimens with different pre-consolidation stresses, as shown in Fig. 4, indicate that the relationship of void ratio versus logarithm of permeability is not influenced by stress history, which had also been verified by Horpibulsuk *et al.* (2007). However, the initial void ratio is different for specimens with different pre-consolidation stresses. Moreover, the

Table 4 Experimental results on different clays by falling head permeability tests

No.	Clay	Specimen	Depth (m)	C_k	e_0	e^*_{10}	Source of data
1	Shanghai	Undisturbed	9.8	0.602	1.35	1.62	This study
		Reconstituted	9.8	0.515	1.24	1.28	
	Wenzhou	Undisturbed	11.5	0.855	1.92	2.11	
		Reconstituted	11.5	0.714	1.47	1.76	
2	Lianyungang	Undisturbed	4	1.002	2.19	2.61	Zeng *et al.* (2011)
		Remolded	4	0.933	2.32	2.29	
		Undisturbed	12	0.763	1.85	1.99	
		Remolded	12	0.702	1.82	1.77	
	Nanjing	Undisturbed	7	0.456	1.13	1.34	
		Remolded	7	0.450	1.13	1.14	
		Undisturbed	9	0.625	1.27	1.67	
		Remolded	9	0.503	1.34	1.31	
3	Wenzhou	Undisturbed	18	0.691	1.56	2.01	Zeng and Cai (2012)
		Remolded	18	0.542	1.58	1.56	
		Undisturbed	20	0.639	1.52	1.91	
		Remolded	20	0.569	1.51	1.68	
		Undisturbed	28	0.572	1.41	1.72	
		Remolded	28	0.530	1.43	1.50	
4	Batiscan	Undisturbed	5.50	0.907	2.13	2.34	Tavenas *et al.* (1983b)
	Bäckeble	Undisturbed	5.40	0.914	2.28	2.45	
	Matagami	Undisturbed	--	1.055	2.59	2.70	
	Louiseville	Undisturbed	9.2	0.899	1.98	2.37	
5	Berthierville	Undisturbed	3.0	0.759	1.77	1.96	Leroueil *et al.* (1988)
		Undisturbed	4.0	0.771	1.74	2.02	
		Undisturbed	5.0	0.639	1.50	1.78	
6	Red earth-1	Reconstituted	-	0.361	1.00	0.99	Sridharan and Nagaraj (2005)
	Silty soil-1	Reconstituted	-	0.453	1.03	1.14	
	Kaolinite-1	Reconstituted	-	0.569	1.27	1.44	
	Red earth-2	Reconstituted	-	0.437	1.30	1.11	
	Kaolinite-2	Reconstituted	-	0.648	1.45	1.62	
	Cochin clay	Reconstituted	-	0.482	1.47	1.45	
	Brown soil-1	Reconstituted	-	0.489	1.56	1.44	
	Kaolinite-3	Reconstituted	-	0.584	1.56	1.59	
	Illitic soil	Reconstituted	-	0.698	1.89	1.91	
7	KGa-1	Reconstituted	-	0.471	1.17	1.28	Dolinar (2009)
	KGa-2	Reconstituted	-	0.661	1.67	1.81	
	K-1	Reconstituted	-	0.624	1.50	1.64	
	K-2	Reconstituted	-	0.729	1.90	2.03	

initial void ratio is affected by many factors, including the stress history, liquid limit; soil structure, etc. Therefore, it may be not reasonable to relate the permeability change index C_k only to the initial void ratio e_0. Nagaraj *et al.* (1991) introduced the void ratio at liquid limit e_L, as another physical parameter to improve the relationship of e against log k_v, and the calculated results are more agreeable with the experimental data. However, the effect of soil structure on the permeability change index C_k is not taken into consideration in the physical parameter. Due to the difference in permeability between undisturbed and reconstituted specimens is only caused by the fabric of soil structure (Horpibulsuk *et al.* 2007), and it is different to determine the detailed pore size to control the permeability

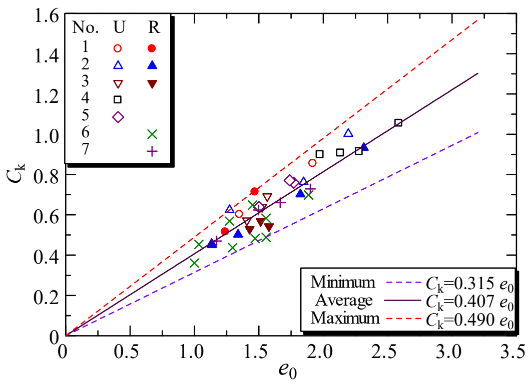


Fig. 8 C_k-e_0 curves of undisturbed and reconstituted specimens from different clays

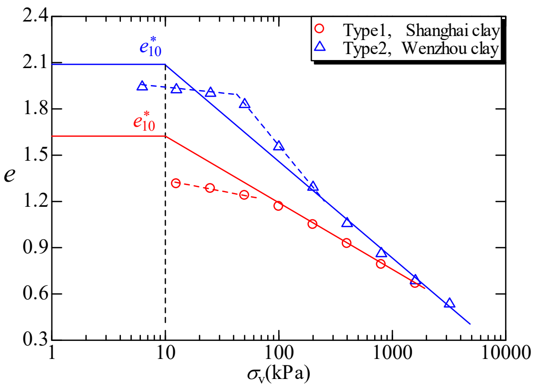


Fig. 9 The methods to determine the reference void ratio $e*$ 10

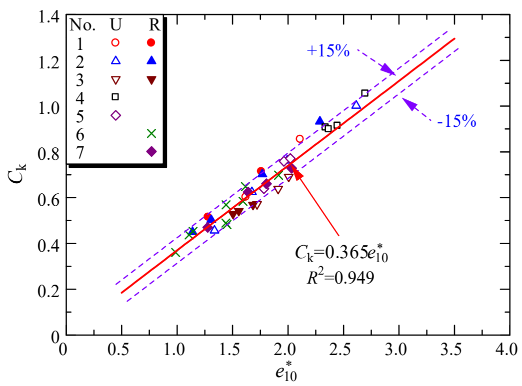


Fig. 10 C_k-$e*$ 10 curves of undisturbed and reconstitute specimens from different clays

of clays. Therefore, the comprehensive parameter, reflecting the soil fabric of clays, is needed to be introduced to improve the calculation of permeability change index C_k.

Sun *et al.* (2014) suggested that a reference void ratio $e*$ 10 can be used as a soil fabric index simply, based on compression and shear test results of undisturbed and reconstituted specimens can be normalized by the reference void ratio $e*$ 10. Therefore, the reference void ratio $e*$ 10, is introduced to improve the prediction of permeability change index C_k. However, the way to determine the reference void ratio $e*$ 10, proposed by Sun *et al.* (2014), by extending line of the compression curves during the post-yield, is not suitable for the compression curves of undisturbed specimen with inverse "S" shape. Hong *et al.* (2012) found that undisturbed and reconstituted specimens have the same change law in compression behavior when the stress is higher than transitional stress if the compression curve of undisturbed specimen has the post-transitional regime, i.e., compression curves with inverse "S" shape. Therefore, the reference void ratio $e*$ 10, can be determined by extending the straight line during the post-transitional stress up to the effective stress of 10 kPa. The methods to determine the reference void ratio $e*$ 10 with two different types of compression curves are shown in Fig. 9.

When the reference void ratio $e*$ 10 is introduced to further deal with the test data shown in Table 4, it is surprised to find that all the data can be normalized to unique C_k-$e*$ 10 curve with high correlation, no matter undisturbed or reconstituted specimens, as shown in Fig. 10. Moreover, all the test data is located around the obtained fitting curve within the accuracy of ±15%. Therefore, it can be deduced that the reference void ratio $e*$ 10 can be used as the fabric index to indicate the effect of soil structure on the permeability of clays. The permeability change index C_k, an important index to predict the permeability of clay at different void ratios or consolidation stresses, can be calculated accurately by the reference void ratio $e*$ 10.

6. Conclusions

The pre-consolidation stress of reconstituted specimens only affects its permeability at low consolidation stress due to different void ratios, but it does not affect the relationship of e against log k_v. Although the relationship of void ratio versus logarithm of permeability (e-log k_v) are similar for undisturbed and reconstituted specimens, the undisturbed specimens will have higher permeability than those of corresponding reconstituted specimens at the same void ratio due to different soil fabrics.

The specimens with larger cumulative intruded void ratio of macro-pores (d>10 μm) have higher permeability indicates that the permeability of clays depends predominately on cumulative intruded void ratio of macro-pores, and it does not depend on the median pore-throat diameter. However, the permeability is not controlled by the void ratio of macro-pores, and is affected by the intruded void ratio of other pore sizes.

A unique relationship between permeability change index C_k and the reference void ratio $e*$ 10, for undisturbed and reconstituted specimens of many different clays, demonstrates that the reference void ratio $e*$ 10 can be reasonably regarded as a fabric index to identify the effect of soil structure on the permeability of clays.

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