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The Characteristics of Microstructure Change of Sand Grain Mucky Soil under Different Consolidation Pressures

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Abstract

Sand grain mucky soil is a type of lacustrine sedimentary soft soil of Dongting Lake with a modest layer of silty fine sand in between. It has an unique structure of thin sand layer. In order to study the microstructure particularity of sand grain mucky soil, the paper selects the other three types of Dongting Lake soil as comparison, and collects parameters of equivalent diameter, average roundness, average shape factor and directionality of structure unit body by examining the undisturbed samples and samples under different consolidation pressure of the four types of soil with the use of scanning electron microscope, as well as picture processing technology and mathematical model. At the same time, the paper analyzes relations between surface void ratio, consolidation pressure, and probability entropy and permeability coefficient. The result of the study shows: 1) the main microstructure of sand grain mucky soil is laminated structure; 2) compared with other three types of soil, as consolidation pressure increased, the growth of equivalent diameter of sand grain mucky soil is the fastest in the early stage while slowing down significantly in the later stage, the decreasing range of average roundness is the most, and changes of average shape factor and directionality are the smallest; 3) the effect of different

consolidation pressure on surface void ration of sand grain mucky soil is relatively small; 4) the k_H and k_V of sand grain mucky soil decline as probability entropy decreased, and k-H_m curves of horizontal section and vertical section have big differences due to the modest layer of silty fine sand.

Key words

Sand grain mucky, Physical and mechanical properties, Soil microstructure types, Microscopic parameters

1. Introduction

Because of the long-term effect of crustal rise and fall, climate, flowing water, and sedimentation, sedimentary facies of Dongting Lake changes quite frequently, which lead to the formation of sand grain mucky soil with a modest layer of silty fine sand in between. It presents in the shape of layer cake, and the thickness of each layer is about 1-2mm (see Figure 1). First, the existence of the modest layer of silty fine sand makes sand grain mucky soil enjoy better horizontal drainage, which is conducive to consolidation. Second, sand grain mucky soil, compared with marine soft soil and delta soft soil, has characteristics of low void ratio, moisture content, compressibility and clay content. These characteristics may be unfavorable to mechanical strength growth of the soft soil during consolidation process. Extensive studies have shown that the complexity and randomness of microstructure are important factors that affect macroscopic property of soft soil. Therefore, the study on the engineering properties of sand grain mucky soil, in essence, can provide a theoretical basis for building railways and highways in the local region.

Fig. 1 Sand grain mucky soil

Now, many scholars have carried on a large amount of research of soil microstructure. P. Dudoignon (2001) compared the change law of pores during the shear process of kaolin [1]. J.P. Latham (2001), through Monte Carlo Method, studied shape factor among microstruture parameters [2]. Zhang Minjiang (2005) revealed relations between orientation parameter and macromechanics of micro unit body of soft soil in Yingkou City during the rheological process [3]. H. Bock (2006), by using PFC software, stimulated the shape of clay particles, bound water and free water in soil, as well as the structure of soil particles after deformation [4]. Fang Houguo (2007) studied quantitative index system of microstructure of marine soft soil under different consolidation pressure [5]. Zhang Xianwei (2010) suggested analyzing microstructure deformation of soft soil in terms of abundance and circularity, studying regular extent of the shape of pores and particles in terms of complexity, and using radar chart to reflect the distribution intensity of soft soil [6-7]. D. R. Katti (2011) analyzed the change of microstructure of expansive soil during the expansion [8]. Laura Kosoglu (2011) proposed a kind of DEM Model to study the movement of clay particles when compressed in three dimensions [9]. Liu Yongjian (2013), taking RBF neural network as theoretical basis, established a physical mechanical index of soft soil, and an analysis model of microstructure diameter of Guangzhou Nansha District [10]. Manish V. Shah (2013), with the use of MIC software, studied consolidation process of clay particles in vertical drainage radial flow [11]. C. Vipulanandan (2014) studied mineral composition and microstructure of clay in Huston and Galveston through X-ray diffraction and scanning electron microscope [12]. Zhou Jian (2014) discussed distribution characteristics of the scale of pores, the arrangement of pores, and features of morphological changes of saturated soft soil in Hangzhou [13]. Tan Rujiao (2015) studied micro changes of Tianjin coastal soft soil before and after creep[14]. Zhou Hui (2015) established revised consolidation model with consideration of soft soil microstructure [15].

The above literatures, by means of laboratory soil test, scanning electron microscope test, and numerical simulation software, analyze soft soil microstructure, and morphological characteristics of pores and unit body. But so far, there is not analyze the microstructure characteristics of sand grain mucky soil. To study features of microstructure changes of sand grain mucky soil under different consolidation pressure, this paper selects the other three types of soil of Dongting Lake as comparison. By doing scanning electron microscope test of four types of soil under different consolidation pressure, the paper obtains microstucture types of soil. Meanwhile, with the use of PCAS software, the paper carries out quantitative analysis of equivalent diameter, shape factor and directionality of soil structure unit body, and connects these analysis of parameters to engineering property, in order to analyze relations between surface pores and consolidation pressure, and probability entropy and permeability coefficient.

2. Soil microstructure test scheme

2.1 Test material

This test, to study the particularity of microstructure of sand grain mucky soil, selects silty clay, mucky silty clay and clay of Dongting Lake as comparison. The basic physical and mechanical properties of these four types of soil can be seen in Table 1.

Table 1. Physical and mechanical properties of four types of soil

Soil layer	Water content w/%	Density ρ (g/cm^3)	Plasticity index I_P/%	Liquidity index I_L	Cohesion C/kPa	Internal friction angle φ /°	Compressibility a_{v1-2}/MPa^{-1}
Silty clay	39.2	1.87	20.66	0.45	17.9	7.1	0.414
Mucky silty clay	43.6	1.71	17.99	1.40	8.8	2.3	1.046
Clay	32.7	1.93	25.43	0.42	20.2	6.2	0.392
Sand grain mucky soil	39.4	1.75	17.97	1.33	7.4	15.7	0.830

2.2 Test scheme

This test, with the use of Quanta FEG 250 field emission scanning electron microscope of FEI Corporation, scans undisturbed samples and samples under different consolidation pressure of silty clay, mucky silty clay, clay and sand grain mucky soil. First, the consolidation tests of four types of soil under different pressure (25kPa, 50kPa, 100kPa, 200kPa, 300kPa, 400kPa) are carried out. The method of slow consolidation stability is adopted in the test, which means adding each load every 24 hours when the deformation of soil samples becomes totally stable the next level load will be added.

Then cut soil samples after consolidation into 4mm×8mm×4mm observation samples, and freeze-dry them under Scientz-10ND in situ common type freeze dryer. To make the surface of samples conductive, 10nm thin gold conductive films are vapor plated on the surface, and analysis being carried on immediately after plating to avoid surface contamination or exfoliation of conductive films. Before putting observation samples into microscope sample room, use rubber ball to blow floating particles away gently, then observe relatively even areas of the samples. The temperature of sample room should be controlled at 5°C, and the focal length of electron microscope should be controlled within the range of 6.5mm-8.5mm. When shooting microscopic images, set focal length from high power, and find structure unit body by aiming the center, then decrease magnification to promise definition of images. Finally select 2000 magnification and 5000 magnification for analysis.

2.3 Picture processing technology

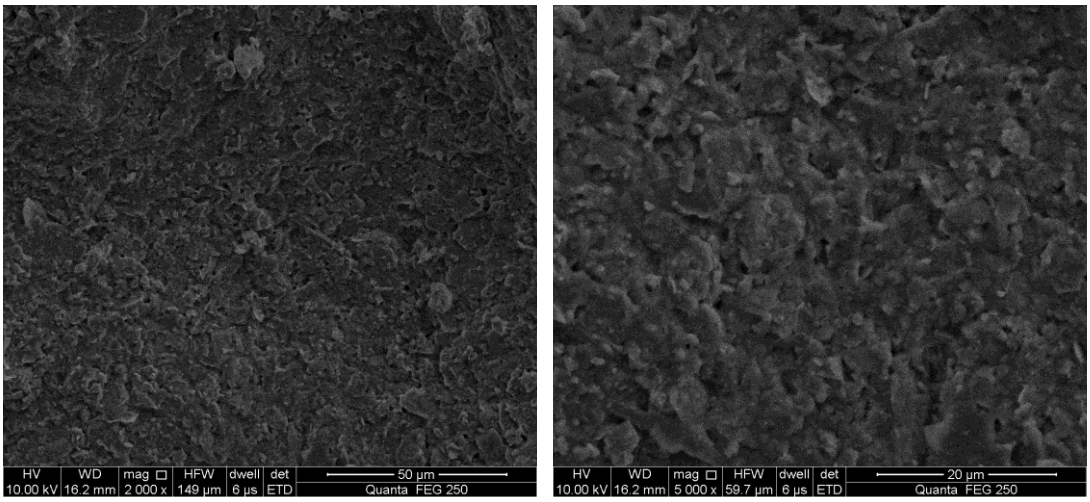
As the photos taken by the scanning electron microscope were gray scale images, the PCAS software is used to preprocess the microstructure in this paper. Firstly, the SEM image was scanned into a digital file with the gray range from 0 to 255, and then the brightness correction and two value processing are carried out to easily get the microstructure parameters of the soil.

3. Soil microstructure types

Figures 2-5 are respectively SEM images of undisturbed samples magnified 2000 times and

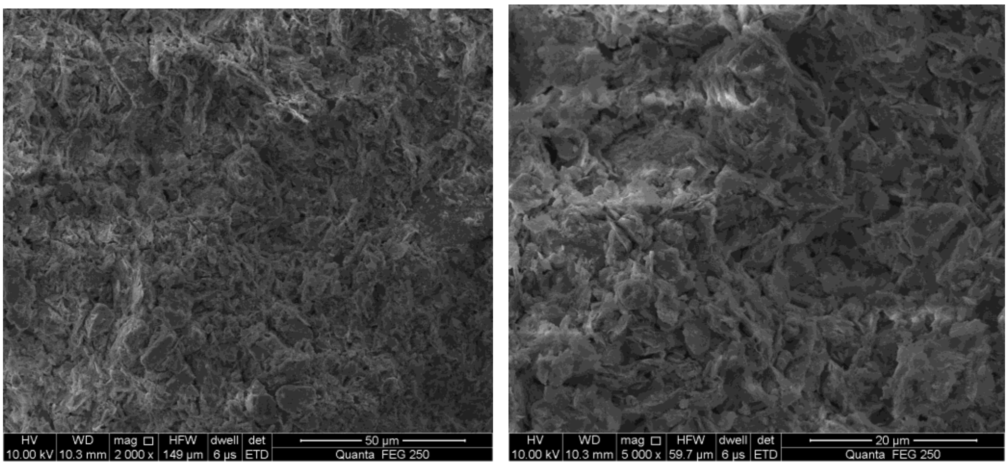
5000 times of four types of soil. From these figures, it can be speculated that the main microstructure of sand grain mucky soil is laminated structure, and the clay of the soil is not affected by salts during the sedimentation. However, the clay of the soil fully play repulsive force between clay and clay aggregate, so that the sedimentary structure develops in a certain direction. The contact style is surface-to-surface contact, and particles overlap with each other in a parallel manner. In addition, the load may change the connection way of part of flocculated structure of the soil, and make it array in horizontal direction, resulting anisotropic of soil structure.

The main microstructure of silty clay is clot-like structure. The clay of the soil forms block masses whose diameter are over 30μm. The main contact style is surface-to-surface contact, and particles distribute on the surface of or between block masses. Non-directional fractures through block masses often develop between structure unit body. Microstructures of mucky silty clay and clay are mainly spongy structure. The content of clay is high. Pores evenly distribute between structure unit bodies. The contact styles are surface-to-surface and edge-to-edge contact, and particles tend to form multiple and fine network structure.



(a)2000 magnification (b)5000 magnification

Fig. 2 SEM image of silty clay microstructure



(a)2000 magnification (b)5000 magnification

Fig. 3 SEM image of mucky silty clay microstructure

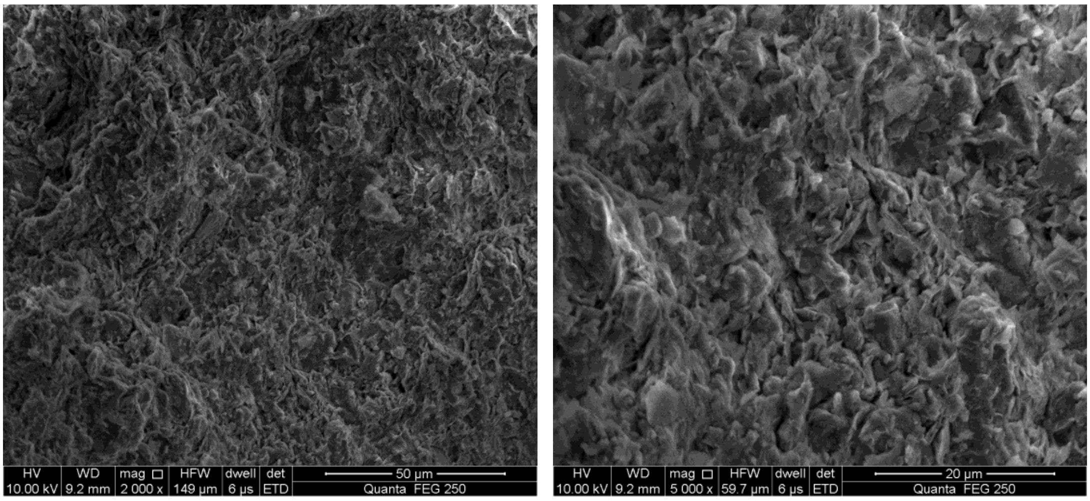


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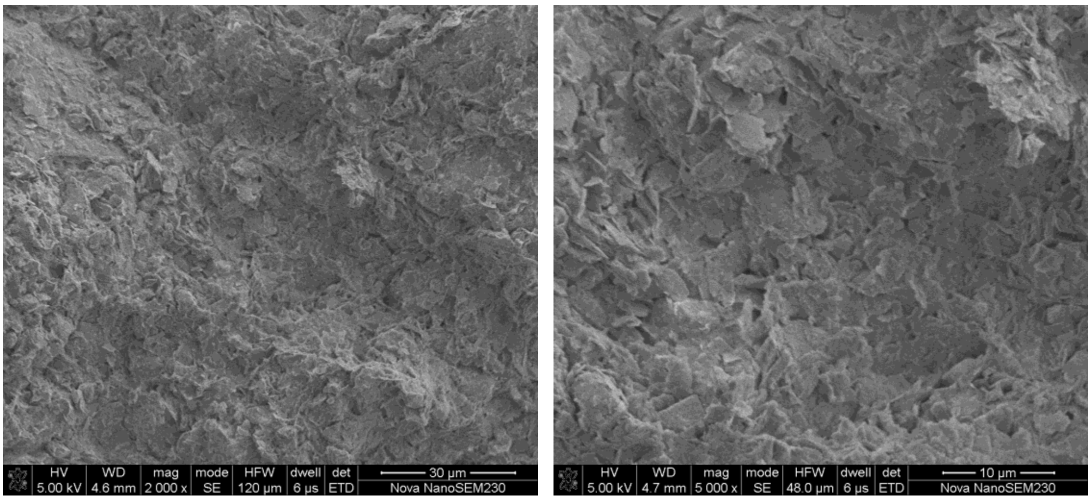
Fig. 4 SEM image of clay microstructure



(a)2000 magnification (b)2000 magnification

Fig. 5 SEM image of sand grain mucky soil microstructure

4. Quantitative analysis of microstructure of soil

4.1 Equivalent diameter

Equivalent diameter is spherical particle diameter that is equal or similar to actual particle diameter. From Figure 6, it can be seen that equivalent diameter of sand grain mucky soil is between 0.617-1.053μm, silty clay 0.965-1.466μm, mucky silty clay 0.912-1.174μm, and clay 0.574-1.235μm. Equivalent diameter of sand grain mucky soil is shorter than that of the other three types of soil. Besides, as consolidation pressure increased, the growth of equivalent diameter of sand grain mucky soil is first rapidly then becomes slow. When the pressure is 0kPa ＜p≤50kPa, equivalent diameter of sand grain mucky soil increases the fastest, at a growth of 42.1%. However, equivalent diameters of silty clay, mucky silty clay and clay increase relatively slow, which respectively grows at 32.4%, 23.4%, 6.1%. When the pressure is 50kPa＜p≤400kPa, the growth of equivalent diameter of sand grain mucky soil becomes obviously slow, which increases only 0.176μm. This phenomenon happened due to the modest layer of silty find sand of sand grain mucky soil which speeds up the dissipation of pore water pressure, so structure unit body of sand grain mucky soil can adjust itself quickly in the early stage of consolidation. However, with the increase of the effective stress, the growth of equivalent diameter slows down gradually.

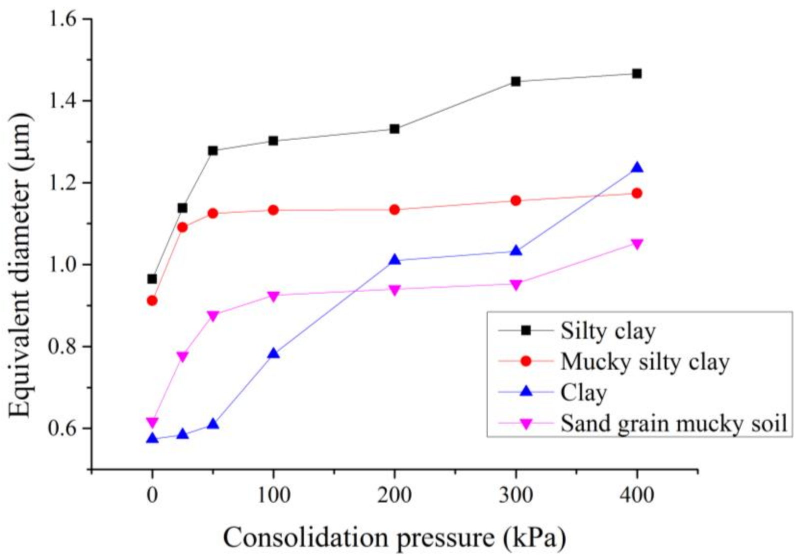


Fig. 6 Equivalent diameter distributions of four types of soil under different consolidation pressures

4.2 Shape factor

Figure 7 (a) and (b) are respectively curves of average roundness, average shape factor, and consolidation pressure of structure unit body on vertical section of four types of soil. Specific numerical values can be seen in Table 2, and the formulas are as follow:

$$R = \frac{1}{n}\sum_{i=1}^{n} R_i \quad (1)$$

$$R_{\mathrm{i}} = 4\pi A_{\mathrm{i}} / L_{\mathrm{i}}^2 \quad (2)$$

In the formulas: R—average roundness, A_i—region area, L_i—perimeter of region. The value range of R is between (0,1). The bigger R is, the region is closer to a circular, and when R=1, the region is a standard circular.

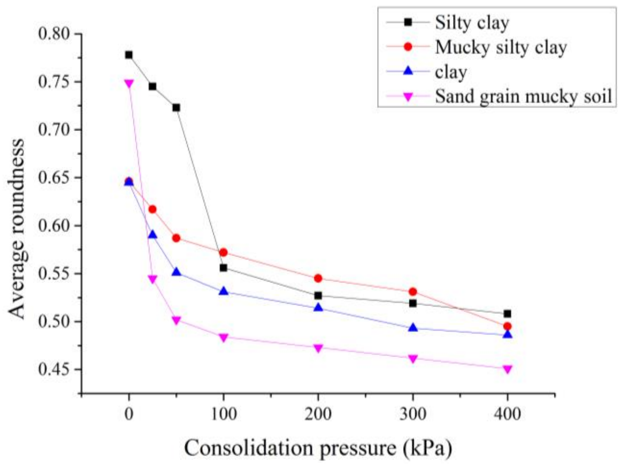
$$F = \frac{1}{n}\sum_{i=1}^{n} F_i \quad (3)$$

In the formula: shape factor of single pore or particle: F_i=C/S, F—average shape factor, C-—circle with an equal area of one particle or pore, S—actual perimeter of one particle or pore.

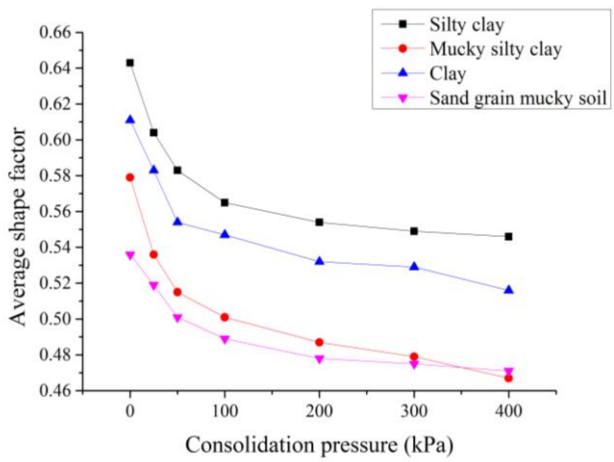
Table 2, Figure 7 (a) and (b) show that average roundness and average shape factor of four types of soil decline with the increase of consolidation pressure, and the shape of structure unit body becomes relatively narrow and long gradually. The average roundness of sand grain mucky soil is between 0.451-0.749, and average shape factor is between 0.471-0.536. The average roundness of sand grain mucky soil changes the most, with a decrease of 39.8%, while that of silty clay, mucky silty clay and clay respectively declines 34.7%, 23.4% and 24.7%. This means consolidation pressure has the greatest effect to structure unit body of sand grain mucky soil in four types of soil. On the whole, the change range of average shape factor is smaller than average roundness, and the average shape factor of sand grain mucky soil has the smallest change, as it only decreases 12.1%, but that of silty clay, mucky silty clay and clay respectively drops 15.1%, 19.3% and 15.1%.

Table 2. Average roundness and average shape factor of soil structure unit body under different consolidation pressures (vertical section)

Shape parameter	Soil samples	Consolidation pressure(kPa)						
		0	25	50	100	200	300	400
Average roundness of structure unit body	Silty clay	0.778	0.745	0.723	0.556	0.527	0.519	0.508
	Mucky silty clay	0.646	0.617	0.587	0.572	0.545	0.531	0.495
	Clay	0.645	0.59	0.551	0.531	0.514	0.493	0.486
	Sand grain mucky soil	0.749	0.545	0.502	0.484	0.473	0.462	0.451
Average shape factor of structure unit body	Silty clay	0.643	0.604	0.583	0.565	0.554	0.549	0.546
	Mucky silty clay	0.579	0.536	0.515	0.501	0.487	0.479	0.467
	Clay	0.611	0.583	0.554	0.547	0.532	0.529	0.516
	Sand grain mucky soil	0.536	0.519	0.501	0.489	0.478	0.475	0.471



(a)Average roundness



(b)Average shape factor

Fig. 7 Shape factors of four types of soil under different consolidation pressures

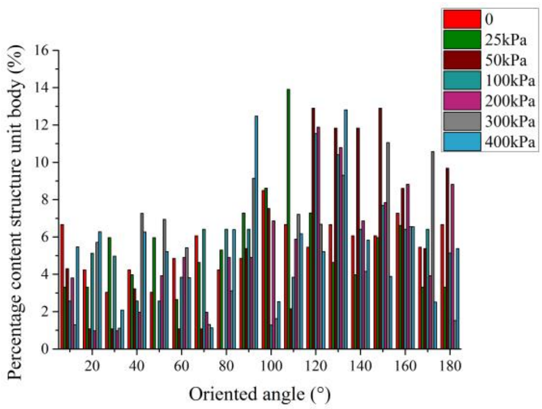
4.3 Directionality

To study the directionality of structure unit body, the mean direction after the weight of plane area of structure unit body is adopted to represent the mean direction of diameter. The formula of orientation angle is as follows:

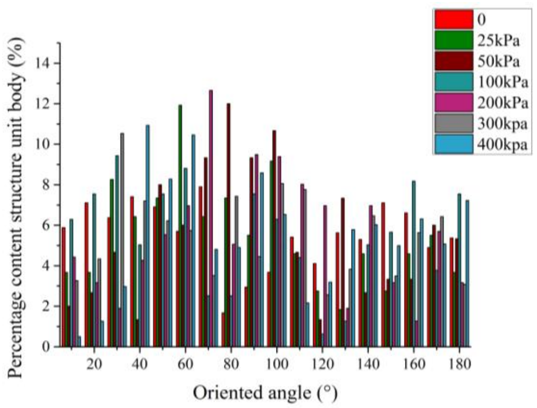
$$\overline{\alpha} = \frac{1}{n}\sum_{i=1}^{n} W_{\mathrm{i}}\alpha_i \tag{4}$$

In the formula: $\overline{\alpha}$ —average direction after the weight; W_i—the weight of the No.i structure unit body; α_i—angle between long axis and X axis of No.i structural unit body. When the angle is ≤90°, the value adopted directly; when the angle is >90°, the value is 180°+α_i, and when the angle between α_i and X axis is an acute angle, the value of α_i is negative. Therefore, the change range of 180°+α_i is between 90°-180°.

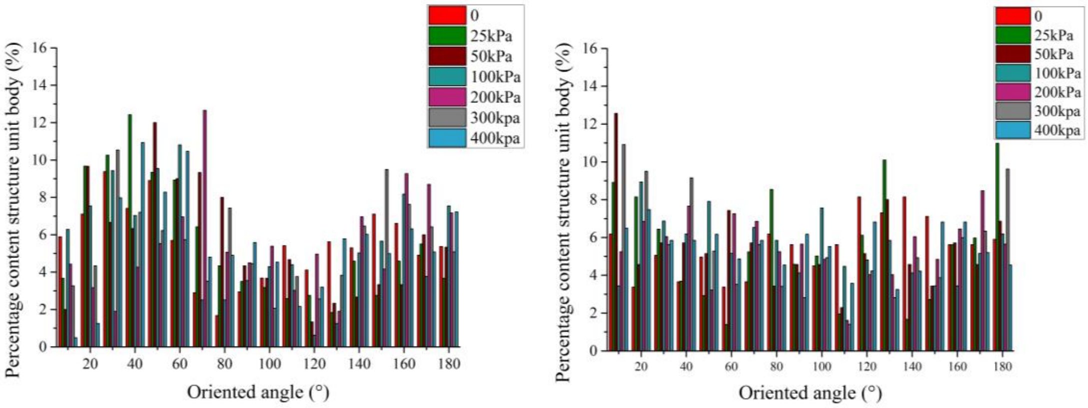
In Figure 8, it can be seen that the distribution of undisturbed particles on vertical section of four types of soil is disordered, and there is no obvious orientation angle. With the increase of consolidation pressure, the directionality of sand grain mucky soil is not apparent, and the angles are within a wide range. However, the directionality of the other three types of soil are increased significantly, for the optimum direction of silty clay is mainly between 70°-150°, mucky silty clay 40°-100°, and clay 20°-80°and 140°-180°. Combined with section 4.1 and 4.2, in the early stage of consolidation, structure unit body of sand grain mucky soil can reconstruct its skeleton rapidly, but when consolidation pressure goes high, there is no need for structure unit body to adjust itself for enough effective stress, so the directionality is not obvious.



(a)Silty clay



(b)Mucky silty clay



(c)Clay (d)Sand grain mucky soil

Fig. 8 Oriented angles of structure unit body on vertical section of four types of soil under different consolidation pressures

4.4 Relations between surfaces void ratio and consolidation pressure

The surface void ratio of four types of soil is calculated in formula (5) as follows.

$$e_{\mathrm{m}} = \frac{A_{\mathrm{V}}}{A - A_{\mathrm{V}}} \tag{5}$$

In the formula: e_m—surface void ratio, A—area of the pore, A_V—the total observed area.

As shown in Table 3 and Figure 9, when 0kPa＜p≤100kPa, the surface void ratio of silty clay, mucky silty clay, clay and sand grain mucky soil respectively drops 29.4%, 28.7%, 62.6% , and 48.2%, and when 100kPa＜p≤400kPa, the void ratio of four types of soil respectively drops 48.8%, 42.9%, 43%, and 25.2%. It can be seen that different consolidation pressure have a little effect on the surface void ratio of sand grain mucky soil, though at the early stage of consolidation, the compactibility of sand grain mucky soil grows fast, but with further increase of consolidation pressure, it becomes difficult for structure unit body to adjust itself, so the surface void ratio undergoes a smaller decline in the later stage. The change law of the surface void ratio is similar to the law of average roundness and average shape factor as shown in section 4.2.

Table 3. The surface void ratio of four types of soil under different consolidation pressure

Shape factor	Soil sample	Consolidation pressure(kPa)						
		0	25	50	100	200	300	400
The surface void ratio	Silty clay	1.80	1.46	1.40	1.27	1.18	0.87	0.65
	Mucky silty clay	1.57	1.35	1.29	1.12	0.86	0.66	0.64
	Clay	2.11	1.29	0.98	0.79	0.57	0.49	0.45
	Sand grain mucky soil	1.68	1.45	1.31	0.87	0.69	0.67	0.65

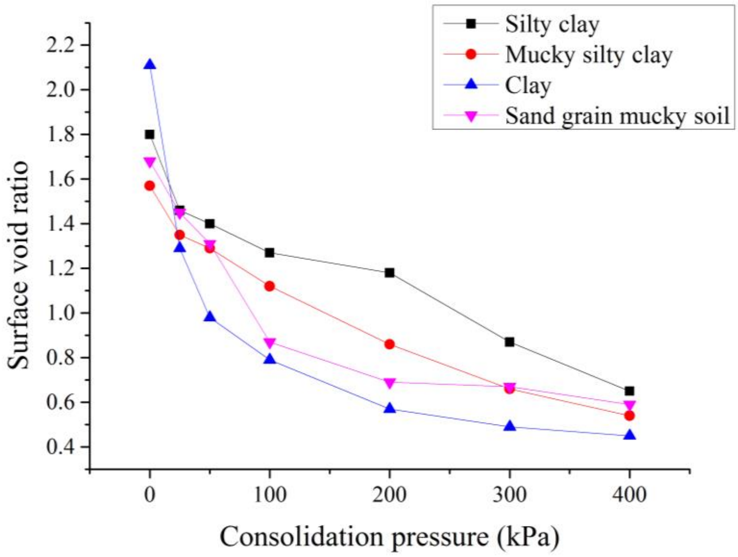


Fig. 9 Curves e_m-p of four types of soil under different consolidation pressure

4.5 Relations between probability entropy and permeability characteristics

Research shows that probability entropy is one of the essential parameters that can decide permeability characteristics of soil, since it reflects arrangement orderliness of structure unit body. Thus, correlation between probability entropy and permeability coefficient need to be discussed. The calculation formula of probability entropy is as follows:

$$H_m = \sum_{i=1}^{n} P_i \log_n P_i \tag{6}$$

In the formula: H_m— probability entropy of the arrangement of soil structure unit body; P_i—probability of structure unit body in certain orientated region, n—the number of equal divided oriented region in arrangement direction [0,N] of unit body. When the value of H_m is between 0-1, the arrangement direction of all structure unit body is in the same orientated region, and when H_m=1, unit body arrays randomly, and appearance probability is completely the same. The bigger the H_m is, the more disorder the unit body arrangement is.

As Table 4 shows, differences between k_V and k_H of silty clay, mucky silty clay and clay are not big, but since sand grain mucky soil has a modest layer of fine sand in between, its vertical permeability coefficient is far lower, even an order or two orders of magnitude lower, than horizontal permeability coefficient.

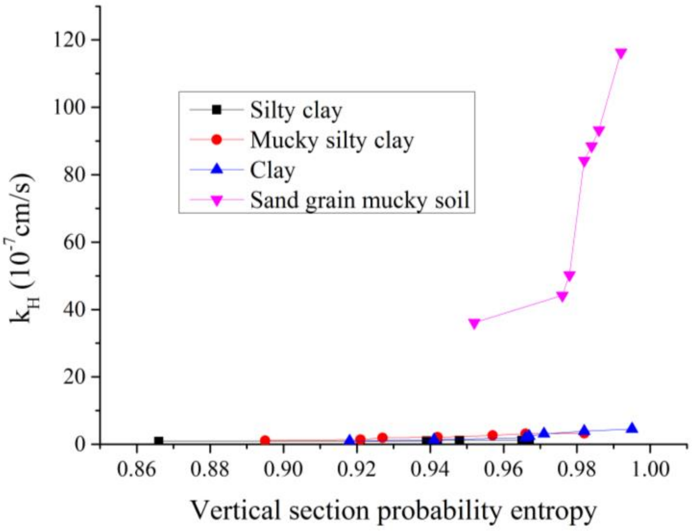
From Figure 10 and Figure 11, it can be seen that on both vertical and horizontal direction, the permeability coefficient of four types of soil decreases as probability entropy declines.

Compared with undisturbed samples, when p=400kPa, the permeability coefficient on horizontal direction of silty clay, mucky silty clay, clay and sand grain mucky soil decreases respectively 31.5%, 66.7%, 78.7%, and 68.9% . As permeability coefficients on horizontal direction of sand grain mucky soil are an order or two higher than that of the other three types of soil, in Figure 10 (a) curves k_H-H_m of the other three types of soil are almost horizontal lines. Figure10 (b) is the amplification of parts of the three curves. Except the nearly horizontal line of curve k_H-H_m of silty clay, curves k_H-H_m of mucky silty clay and clay have great fluctuations. When p=400kPa, permeability coefficient on vertical direction of four types of soil, compared with undisturbed samples, declines respectively 38.3%, 74.8%, 75%, and 75.9%, among which the drop of probability entropy of sand grain mucky soil is the biggest.

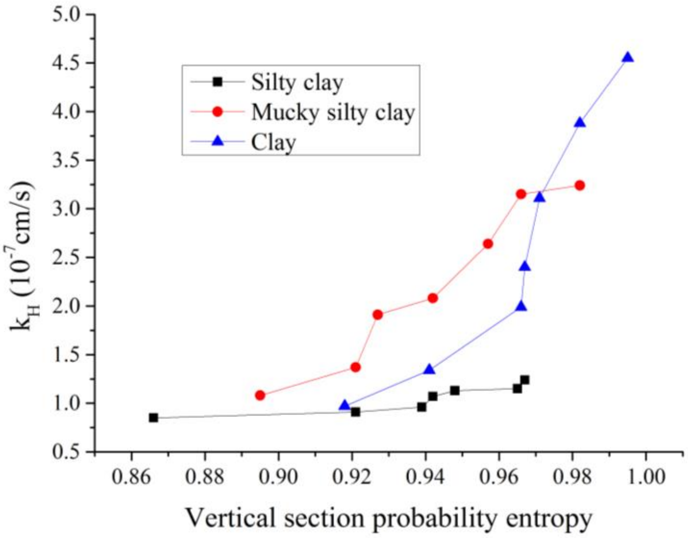
Table 4 Probability entropy of structure unit body and permeability coefficient of four types of soil

Samples	Consolidation pressure (kPa)	Probability entropy on vertical section	Probability entropy on horizontal section	Permeability coefficient(10^{-7}cm/s)	
				k_V	k_H
Silty clay	0	0.967	0.975	1.49	1.24
	25	0.965	0.974	1.37	1.15
	50	0.948	0.963	1.23	1.13
	100	0.942	0.924	1.10	1.07
	200	0.939	0.920	1.09	0.96
	300	0.921	0.898	0.98	0.91
	400	0.866	0.811	0.92	0.85
Mucky silty clay	0	0.982	0.997	3.85	3.24
	25	0.966	0.947	3.52	3.15
	50	0.957	0.933	3.11	2.64
	100	0.942	0.900	2.41	2.08
	200	0.927	0.859	1.33	1.91
	300	0.921	0.856	1.09	1.37
	400	0.895	0.851	0.97	1.08
Clay	0	0.995	0.992	3.68	4.55
	25	0.982	0.956	3.53	3.88
	50	0.971	0.952	2.81	3.11
	100	0.967	0.947	1.89	2.40
	200	0.966	0.885	1.42	1.99
	300	0.941	0.853	1.03	1.34
	400	0.918	0.848	0.92	0.97

Sand grain mucky soil	0	0.992	0.988	4.69	116.29
	25	0.986	0.951	4.17	93.25
	50	0.984	0.933	3.13	88.51
	100	0.982	0.863	2.62	84.18
	200	0.978	0.826	1.67	50.23
	300	0.976	0.825	1.24	44.17
	400	0.952	0.810	1.13	36.10



(a)Graph of curve kH-Hm



(b) Partial amplification graph of curve k_H-H_m

Fig. 10 Curve k_H-H_m of permeability coefficient on vertical section of four type of soil

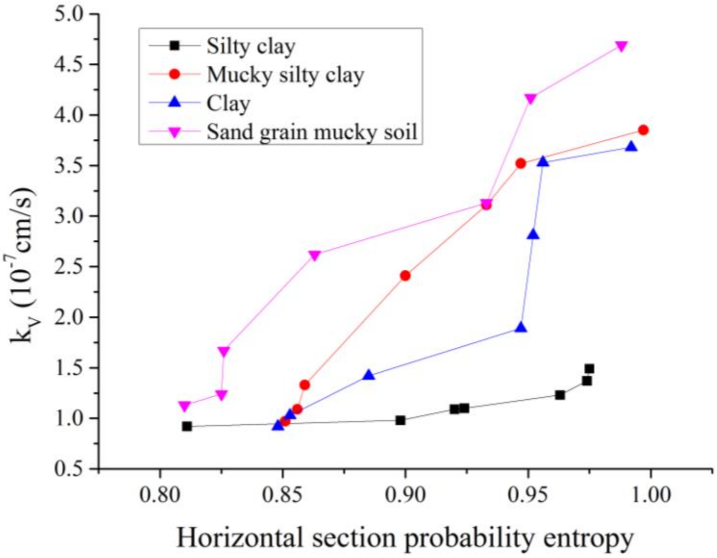


Fig.11 Curve k_V-H_m of permeability coefficient on horizontal section of four type of soil

5. Conclusion

This paper, by means of consolidation test and scanning electron microscope test, takes quantitative analysis of microstructural characteristics of sand grain mucky soil and the other three types of soil in Dongting Lake, and comparatively studies relations between surface void ratio, consolidation pressure and permeability coefficient of the four types of soil. Conclusions it draws are as follows:

1. The main microstructure of sand grain mucky soil is laminated structure, which is distinguished from clot-like structure and spongy structure of the other three types of soil;

2. Compared with the other three types of soil, with the increase of consolidation pressure, the equivalent diameter of sand grain mucky soil grows the fastest in the early stage while slows down significantly in the later stage, the decline of average roundness is the biggest, and the change of average shape factor and directionality are the smallest;

3. The compactibility of sand grain mucky soil grows fast, and the surface void ratio declines greatly in the early stage of consolidation. Then, as big pores turn into many small micropores, it becomes more difficult for structure unit body to adjust itself, so the decrease of surface void ratio slows down;

4. The k_H and k_V of sand grain mucky soil decrease with the decline of probability entropy.

Because of the modest layer of fine sand, the vertical permeability coefficient of sand grain mucky soil is far smaller than horizontal permeability coefficient, resulting big difference between curves k-H_m of horizontal section and vertical section.

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