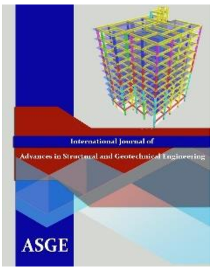

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Experimental Study on the Microstructure of the Lacustrine Soft Clay after Different Consolidation Deformations Based on SEM

Jianjun Gan

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Experimental Study on the Microstructure of the Lacustrine Soft Clay after Different Consolidation Deformations Based on SEM

Jianjun Gan [1]

[1] *Associate Professor, Jiangxi Engineering Research Center of Water Engineering Safety and Resources Efficient Utilization, Nanchang Institute of Technology, Nanchang, China;*
E-mail: ganjianjun@nit.edu.cn

ABSTRACT

In order to study the microstrcutrue of the lacustrine soft clay under different consolidation pressures, SEM and quantitative analysis of consolidation samples were carried out through GDS consolidation undrained tests with different consolidation pressures.
A different consolidation stress of 50 kpa, 100 kpa, 200 kpa, 400 kpa, 800 kpa, 1600 kpa and stress rate of 0.01 mm/min were used in this GDS test. The back pressure 10 kpa was unchanged, with different axial compression P1 (60 kpa, 110 kpa, 210 kpa, 410 kpa, 810 kpa, 1610 kpa) pressure of cylinder (76.2 mm diameter and 20 mm height) specimen was lasted 24 hours, while microstructure parameters of the specimen were obtained by using SEM image and the PCAS(Particles and Cracks Analysis System)s.
The results show that the boundary points of primary consolidation and secondary consolidation of lacustrine soft clay are not obvious at low consolidation pressure. The consolidation pressure increases, the slope of the fractal dimension of porosity rainfall curve is larger and the reduction rate is faster, and the probability entropy is above 0.96. When the consolidation pressure is larger than 400 kPa, with the increase of the consolidation pressure, the slope of the fractal dimension value change curve of porosity slows down. The average shape coefficient increases faster when the consolidation pressure is less than 400 kPa, while the fractal dimension decreases faster. The correlation coefficients between consolidation pressure and fractal dimension value of porosity, probability entropy, average shape coefficient and fractal dimension are all greater than 0.81, showing a high correlation.

Keywords: *Clay, Consolidation, GDS, Microstructure, Fractal, Poyanglake, China.*

1 INTRODUCTION

The Poyang Lake is the largest freshwater lake in China, which covers an area of 162,200 km2. There has three type of soft clay such as silt clay, silt and sandy silt soil with high compressibility, high moisture content and low strength. It has obvious consolidation settlement and rheological properties of uneven settlement in the upper structure, to lead to the instability of the cracking, piping and embankments, caused a great loss in [1]. Moreover, the annual variation range of water level in the Poyang Lake area is more than 10 m, and the stress environment of soft soil caused by the change of climate or lake level often causes great changes in the history of consolidation, resulting in a complex loading effect on the consolidation and settlement characteristics of soft soil layer.
Traditional soil mechanics considers that the consolidation characteristics of the soil are closely related to the microstructure of particles. Previous studies mostly used aqueous solution method, nuclear scanning method, X-ray diffraction method, SEM method and other methods to study the consolidation characteristics of coastal soft soil [2-4]. W.L.Kubiena has built an exact definition of the term the microstructure, whose used fabric description of soil matrix and the arrangement of the skeleton and their mutual relationship. R. Brewer has proposed the soil structure or structure, points out that the basic particles of forming composite particles and composite particles of itself and the corresponding pore size, shape and arrangement of the soil physical composition.

Shi Bin believed that the specific content of soil structure includes the following three aspects: morphological characteristics is the size, shape, surface characteristics and quantitative proportion of structural element body. The geometric characteristics, refers to the spatial arrangement of each element. The energy characteristics is the connection between the unit body characteristics [5].

J.b. Burland[6], Shen Zhujiang[7], Zhang Chenghou[8], Gong Xiaonan et al.[9] all studied the compression characteristics of soft clay. They concluded that the initial stage of the compression curve is very gentle, and when the pressure exceeds a certain value, a steep drop stage appears, which is close to the compression curve of the remolded soil. In other words, the compressibility of the soil is small in the range below the yield stress, and large in the range above the yield stress.

Recently, CT technology for detecting the internal structure of soil without damage has been adopted [10]. Through SEM image processing technology, Wang Qing et al.[11] proposed quantitative evaluation indexes of structural elements such as the morphology, orientation and pore characteristics of structural elements in cohesive soil microstructure. According to the nonlinear characteristics of soil mass, Li Xiangquan et al.[12] proposed 7 quantitative fractal indexes to characterize the microstructure state of soil mass, such as particle size fractal dimension and particle orientation fractal dimension, using fractal geometry theory. It was found that the change of microstructure elements of soft soil in the consolidation process were of an obvious stage.

Since the limited research on the effect of microstructure on the consolidation characteristics and consolidation coefficient of lacustrine soft clay. This study aims to investigate the effect of microstructural parameters and geometric parameters on the consolidation strength of lacustrine soft clay cylinder. The selected soft clay is considered as a typical soil sample of inland freshwater lacustrine soft clay. The consolidation pressure and microstructure of soft clay were studied[14-17].

2 MATERIALS AND METHODS

2.1 Materials

This test takes undisturbed soft clay spread over Poyang lake area, Jiangxi Province(China)，which cover about 162,2 million hectares, localized between the parallels 28° 22′ N and 29° 45′ N and the meridians 115° 47′ W and 116° 45′ E . The basic physical indexes of the soft clay are determined through basic laboratory soil test, see table 1.

Table 1 Physical and mechanical indexes of the typical soft soil in Poyang lake area

Depth/m	Water content/%	Gravity /G_s	Wet density/ g/cm^3	Dry density /g/cm^3	Prosity	Sr/%	W_L/ %	W_P/ %	I_p	I_L	Cc/MPa^{-1}	K ×10^{-5}m^3	Name
2.0-2.3	47.6	2.71	1.73	1.17	1.308	98.6	34.1	22.3	11.8	1.50	0.689	2.95	Silty clay
3.0-3.3	41.0	2.70	1.78	1.26	1.139	97.2	26.5	15.8	10.7	1.61	0.580	2.40	Silty clay
4.0-4.3	45.9	2.71	1.75	1.20	1.259	98.8	24.1	13.9	10.2	2.13	0.618	-	silt
5.0-5.3	39.5	2.71	1.81	1.30	1.089	98.3	25.4	14.9	10.5	1.60	0.588	-	silt
6.0-6.3	39.3	2.71	1.82	1.31	1.074	99.1	30.1	17.6	12.5	1.19	0.591	-	Silt with sand
12.5-12.8	46.7	2.70	1.75	1.19	1.263	99.8	38.3	21.1	17.2	1.00	---	-	Silt with sand
14.5-14.8	47.4	2.71	1.74	1.18	1.296	99.1	41.5	24.1	17.4	0.91	0.890	3.05	Silty clay
16.4-16.7	46.0	2.71	1.75	1.20	1.261	98.9	40.9	23.8	17.1	0.88	1.056	0.228	Silty clay

The basic laboratory soil test results show that the surface of the typical soft clay of the lake has a clay layer of about 1 ~ 2 m and a soft soil layer of 8 ~ 25 m following with main silt and silty soil. According to its permeability index, it is generally divided into two aquifers. The first weak permeable layer is silty clay with a depth of 0.5 ~ 8.7 m. The second layer is silty clay with fine sand and is buried 11.2 ~ 17.5 m deep. The foundation soil has the characteristics of "thousand-layer cake" of lacustrine facies sedimentation. Generally, soft soil is interlaced with fine sand, and local areas contain a fine sand lens. Because the permeability coefficient of soft soil layer is generally less than an order of magnitude of the permeability coefficient of the sand layer below, a natural weak permeable layer is formed. The natural moisture content of soft soil layer is greater than 39%, the pore ratio is greater than 1.18 with a characteristic of soft plastic ~ flow plastic shape. The clay layer of 2.6 ~ 10.1m thick is below the second sand layer, and the gravel layer of 0.8 ~ 11.5m thick is at the bottom.

2.2 Sampling and Testing

2.2.1 Test soil Sample and Preparation

In the consolidation test, 2.0-3.3m grayish-yellow silty clay samples were used. The initial pore ratio was 1.25, and the primary minerals in the sample included quartz and feldspar, accounting for 52%. Secondary minerals mainly include illite, kaolinite and chlorite, accounting for about 48%; Clay minerals are mainly illite (24.84%) and kaolinite (12.48), and montmorillonite (chlorite) is less (10.6%). Illite content is higher than chlorite content, indicating that the overall water stability of weak soil layer in this region is good [18].。

In the test, the original soil sample was prepared by the ring method. The soft soil in the middle part of the sample box was selected. The ring with a diameter of 76.2mm and a thickness of 20mm were used for sampling. In order to saturate the soil sample, the sample was placed in a bucket for 24 h（Fig.1）.

Sampling in Poyang lake (a) Consolidation test specimen (b) GDSACTS (c)

Fig. 1 The test sampling and test equipment

2.2.2 Test Equipment

The experiment adopted the Advanced Consolidation Testing System of GDSACTS (GDS Advanced Consolidation Testing System) introduced by Nanchang University of Engineering, which mainly includes consolidation pressure chamber, reverse pressure/axial pressure controller, sensor, data collector and GDSLAB data processing system, as shown in Fig. 2. The soil sample is placed in the consolidation pressure chamber, the ring cutter is placed in the guide ring, the upper and lower parts are respectively added with porous disc and filter paper, and pressurized by the back pressure/axial pressure controller. The data processing system automatically collects and records the test data through the sensor and its numerical collector[19].

The soil sample back pressure was to saturation before the consolidation, through the axial pressure controller to apply back pressure p1 and pressure controller to apply back pressure p2, so that the difference between the two is maintained in a small range, prevent soil pressure expansion deformation, the test used delta p = p1-p2 = 5kpa, each back pressure saturation for 2h. In order to ensure the soil sample to reach saturation, the use of saturation B to control, that is, when the bottom of the soil sample pore water pressure train u/ axial pressure and reverse pressure difference train p is greater than or equal to 0.95, can start the consolidation test; When the saturation B < 0.95, in the case of maintaining p =5 kPa constant, increase p1 and p2, then carry out reverse pressure saturation 2 h, and then calculate the saturation value, when the saturation B greater than or equal to 0.95 test could start.

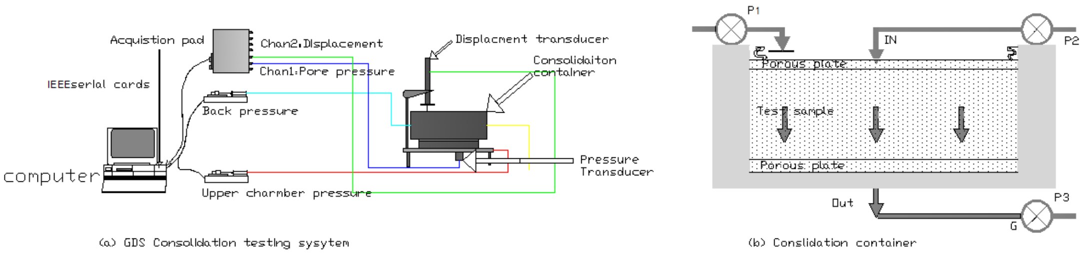

Fig. 2 GDS Advanced Consolidation Testing System

2.3 Methods

2.3.1 Test Methods

In order to study of the soft soil consolidation and secondary consolidation properties in different depth underground , consolidation stress of 50 kPa, 100 kpa, 200 kPa, 400 kPa, 800 kPa, 1600 kPa has been used in this test. In this test, the stress rate is 0.01 mm/min, the back pressure is 10 kPa unchanged, with different axial compression p1 (60 kPa, 110 kPa, 210 kPa, 410 kPa, 810 kPa, 1610 kPa) pressure, keep p2 for 10 kPa, The consolidation test was completed after the application time remained basically unchanged for 24 hours or 2 hours after deformation. In order to ensure the reliability of test results, three parallel tests were conducted for each group of consolidation tests, and the test data were sorted out by mathematical statistics.

2.3.2 SEM Methods

Scanning electron microscopy (SEM) was used to study the specimens under different consolidation pressures. Soil samples in the pad cut into 20 mm thick, thin slices of 5 mm x 5 mm wide, after - 70 ℃ low temperature freeze-drying after the cut with a sharp knife, put fresh face in the 500 ~ 5000 times were observed under scanning electron microscopy (SEM), the test is 500, 1000 and 2000 times magnification, and capture the SEM images, clear images of fetching SEM image was selected, then PCAS software (Particles and Cracks Analysis System, namely particle crack Analysis System) was used to analyzing the microstructure [20].

3. RESULT AND DISCUSSIONS

3.1 Deformation Characteristics

One of the most important characteristics to evaluate the consolidation characteristics is that the axial displacement changes have three stages with time. The displacement under different consolidation pressures(50 kPa，100 kPa, 200 kPa, 400 kPa, 800 kPa, 1600 kPa) as shown in Fig. 3: the first stage is a parabola segment(t<1 min); the second stage is an oblique line segment(t<10 min) and the third phase is a nearly horizontal line(t>10min) . It is basically close of the duration that in each consolidation pressures during the first stage with parabola stage. In the second stages, the displacement is different in each consolidation pressures, it is indicated that the slope of the time-displacement curve was increased fast follow the consolidation stress. Hence, the consolidation was finished first in the biggest pressure. But in the third stage, the displacement is increased slowly, although there was an increase in displacement with curing time, it will probably reflect that the pore of soft clay cannot be squeezed in the third stage.

In the six groups of constant strain rate consolidation tests, the final deformation of the soil sample is increased following the consolidation stress increased. The final deformation when the consolidation stress is 800kPa is basically close to 1600kPa, it is indicating that the primary consolidation and secondary consolidation of the sample are basically completed after the consolidation stress exceeds 800kPa. In terms of the consolidation time, during the same consolidation duration, the greater the consolidation stress, the greater the compression deformation value. After the consolidation stress of 6 groups of 50kPa, 100kPa, 200kPa, 400kPa, 800kPa and 1600kPa was applied for 24h, the final consolidation deformation values were: 0.4651mm, 0.589mm, 1.3002mm, 2.4132mm, 3.4071mm and 2.4446mm, respectively. It indicates that the total consolidation of soft clay increases with the consolidation stress, but when the consolidation stress exceeds 800kPa, the increased range of total consolidation decreases.

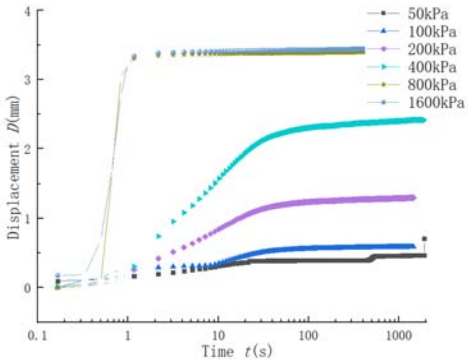

Fig. 3 Curve of time-displacement under different consolidation stresses

According to the consolidation deformation change of different consolidation stresses, when the soft soil in deep underground or the upper load is too large, the deformation will accelerate settlement of the foundation. Because of the soft clay in the area that has a sedimentary longer history, both primary consolidation and secondary consolidation properties of the soft clay could study its primary and secondary consolidation by graphical Casagrande[8]. Fig.3 shows the consolidation test curve of e ~ lgt, which can extend the intersection of the oblique line in the second stage and the near-horizontal line in the third stage under the action of various consolidation stresses at one point. The time corresponding to this point is the primary consolidation time.

As can be seen from Fig.4, the main consolidation time is related to tp50 > tp100 >tp200 >tp400 >tp800 >tp1600 with the increase of consolidation stress. It is indicating that the greater the consolidation stress, the shorter the main consolidation time tp. The curves under the action of consolidation stress at all levels are also different. With the increase of consolidation stress, the larger the ratio of the main consolidation compression amount to the total compression amount (primary consolidation ration), the smaller the proportion of the secondary consolidation. Therefore, the action time and deformation proportion of primary and secondary consolidation are very different, so it should be paid great attention to the calculation of consolidation settlement in practical engineering.

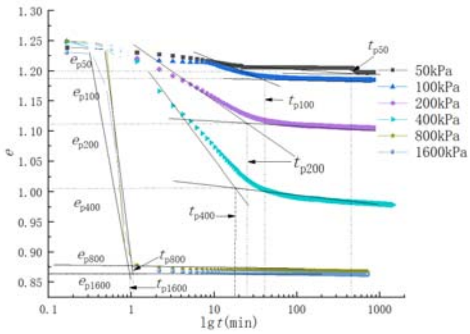

Fig. 4 Curve of e~lgt of the soft soil on different consolidation stresses

3.2 Secondary Consolidation

Secondary consolidation is the characteristic that soft clay will continue to compress and deform for a period of time after the main consolidation is completed[21]. People often use secondary consolidation coefficient to study the secondary consolidation of soft soil, i.e

$$C_\alpha = -\frac{\Delta e}{\lg t_2 - \lg t_1} \qquad (1)$$

In formula (1), C_α is the secondary consolidation coefficient, Δe is the increase in porosity ratio, t_1 and t_2 are refer to the time of primary and secondary consolidation respectively. According to Fig. 3, it can be seen that the main consolidation time t_1 of the soft clay is about 10min ~ 1000min under the action of 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa and 1600 kPa，and C_α is 0.001 ~ 0.015 respectively. Therefore, the secondary consolidation coefficient will be affected by load level and load history calculated if using this method, and corresponding secondary consolidation settlement calculation is larger. For example, when the first layer of soft soil in the study area of 8.2 m and 6.3 m is calculated with formula (1), the second soft soil initial void ratio e0 is 1.25, it can get the following results (table 2) by the formula (2).

$$S = \frac{H}{1+e_0} C_\alpha \lg(t_2 / t_1) \tag{2}$$

In equation (2), S is the secondary consolidation settlement and H is the thickness of the soil layer, where the symbolic significance is the same as equation (1).

It can be seen from Table 2 that the secondary consolidation characteristics of soft clay in the study area are close to the initial consolidation time and secondary consolidation coefficient. The secondary consolidation settlement S1 in the first condition(initial consolidation time t1 is 10 min and the secondary consolidation coefficient is 0.01) is more than 92% the second condition S2 (t1 is 200 min and the secondary consolidation coefficient is 0.001). Lei Huayang et al.[9] believed that the division of secondary consolidation obtained by Casagrande method did not have clear physical significance, and some scholars [10] believed that the final consolidation pressure determined the difference of secondary consolidation coefficient. However, the main reason for soil consolidation is the compression caused by dissipation of pore water pressure, and secondary consolidation is the creep of soil particle skeleton after the effective stress is basically unchanged. Therefore, whether it is primary consolidation or secondary consolidation, studying the microstructure characteristics of soil particles can indirectly reflect the consolidation characteristics of soft soil.

Table 2 The secondary consolidation settlement of the soft soil in Poayang lake area

Soil depth	t_1= 10min			t_1=200min			S_1/S_2(%)
	C_α	t_2	S_1/m	C_α	t_2	S_2/m	
First layer 8.7m	0.01	1a	0.183	0.001	1a	0.013	92.76
		10a	0.221		10a	0.017	92.27
		50a	0.248		50a	0.020	92.03
Second layer 6.3m	0.01	1a	0.132	0.001	1a	0.010	92.76
		10a	0.160		10a	0.012	92.27
		50a	0.180		50a	0.014	92.03

3.3 Microstructure

Scanning electron microscopy (SEM) was used to scan and photograph the samples under different consolidation pressures. Soil samples were cut into 20 mm thick, thin slices of 5 mm x 5 mm wide by the blade, then take it into the fridge after - 70 ℃ low-temperature freeze-drying, and cut the frozen soil with a sharp knife, put fresh face under scanning electron microscopy (SEM) with 500 ~ 5000 times and observed it. In this paper, 500, 1000 and 2000 times magnification was adoption, and images were captured by SEM. In the end, clear images of fetching SEM image was selected and analyzed by PCAS software (Particles and Cracks Analysis System, namely particle crack Analysis System).

Fig.5 and Fig.6 were shown that the soft clay in the study area has many types of spatial structures, including honeycomb structure, spongy structure and flocculent structure, as well as flake structure, skeleton structure and coagulation block structure. When the consolidation pressure is 50 kPa, the soft soil is mostly flocculent and skeleton structure (Fig.5 (a) & Fig.6(a)). After 100kPa, the soil grain framework is often flaky with large pores (d> 10 μm)(Fig.5 (b) & Fig.6 (b)). Under the effect of a solidification pressure of 200 kPa, the particle structure is in the form of a sheet, and the pore of the particles becomes smaller and the gap is changed into a medium pore (2.5 μm < d < 10 μm) (Fig. 5 (c) & Fig.6(c)).

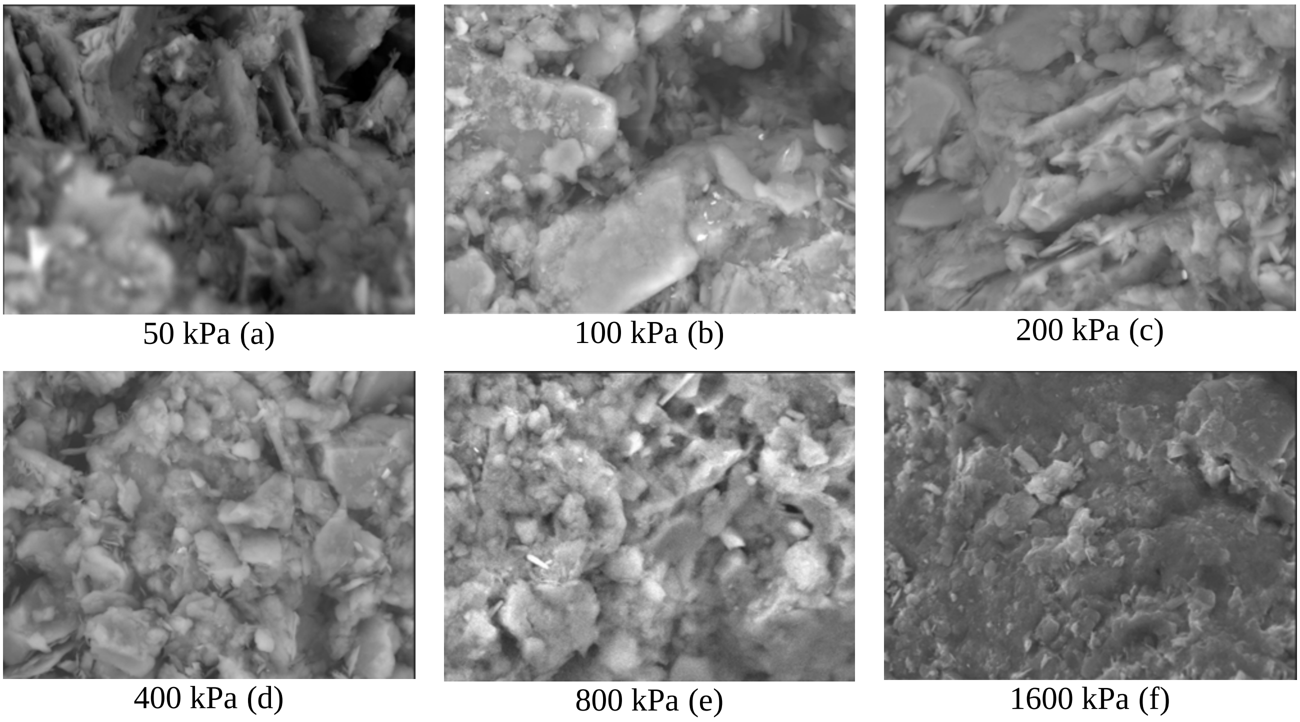

Fig.5 SEM image of soft clay under different pressures

After the consolidation pressure of 400kPa, the particles are extruded into granules, but there are still local medium and large pores (Fig. 5(d) & Fig.6(e)). After 800 kPa consolidation pressure, the porosity of the soft clay was squeezed between particles, it's particles and pores become more uniform, and it's pore number increasing (Fig. 5 (e) & Fig. 6 (f)). When the consolidation pressure reaches 1600kPa, the particles are extruded and agglomerated into blocks, but some strip-like penetrating fractures are also formed, indicating that the deposition history is relatively short (Fig. 5(f) and FIG. 6(l)) [11].

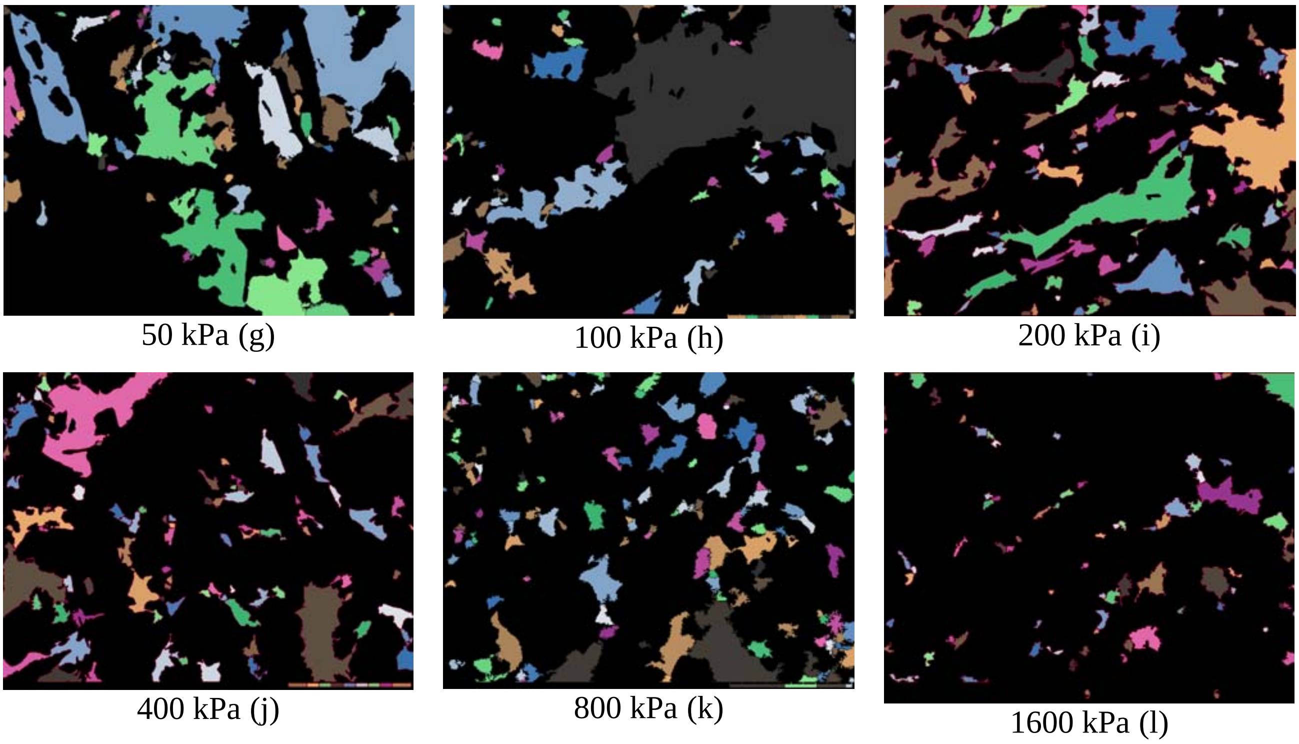

Fig.6 PCAS analyzed image of soft clay under different pressures

In order to investigate the distribution of the pore distribution in various directions, the SEM image is defined as a unit with an orientation of 0° ～180° , the average can be divided into 18 equal parts, and each equal to 0° , then the soil particle pore distribution of roses diagram as shown in Fig. 7. In this figure, the particles are arranged unevenly when consolidation stress is 50 kPa, and its orientation angle is concentrated in 0° to 30° . When the consolidation pressure is 100 kPa or 200 kPa, it' s particle arrangement do not have a unified arrangement, and its orientation angle is 40° ~ 145° . When the consolidation pressure is 400 kPa, particles continue to be compacted, and its orientation Angle is 100° ~ 160° . When the consolidation pressure increase to 800 kPa, the arrangement of particles becomes orderly and uniform. Under the consolidation pressure is 1600kPa, soil particles are compacted, but local new voids are formed. In general, with the increase in pressure, particles are compacted from large pores and gradually become medium pores and small pores, and the orientation of particles develops from non-uniformity to uniformity.

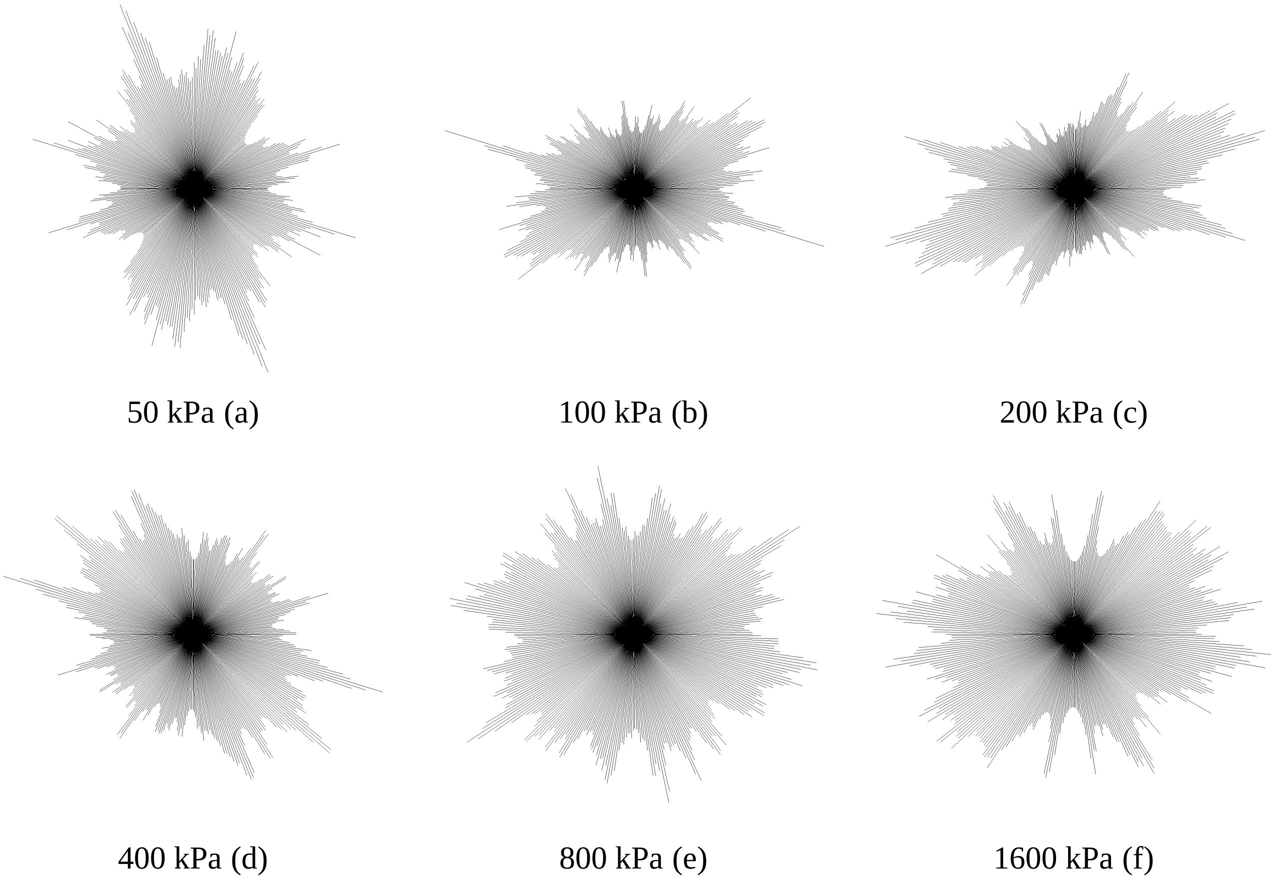

Fig.7 Rose diagram of the soft clay under different pressures

3.4 Consolidation Characteristics and Microstructure

3.4.1 Fractal dimension value and porosity

Fractal dimension of porosity refers to the distribution characteristics of *N* (*N*（≤r）)of the cumulative number of pores less than a certain pore (r), i.e

$$N（\leq r）=\int_{r}^{\infty} P(r)dr \propto r^{-D} \quad (3)$$

Where *D* is the volume dimension, and *P*(r) is the distribution density function of diameter r. Due to the total number of soil particles in a certain area is constant, so *N*（≤r） and *N*（≥r） has a certain corresponding relationship, assuming *V*(r) is a particle diameter less than the pore volume of r, *V* for sample pore volume, there is $V(r)/V \propto r^{b}$, if take the derivative of this formula, it can get

$$dV(r)/V \propto r^{b-1}. \tag{4}$$

If I differentiate PI (4), it will

$$dN(r) \propto r^{-D-1}. \tag{5}$$

Because of $V(r)=\frac{1}{6}\pi r^3 N(r)$,

$$dN(r) = \frac{1}{6}\pi r^3 dN(r) \propto r^3 r^{-D-1}. \tag{6}$$

It can be obtain by connecting vertical (4) and (6)，

$$D = 3\text{-}b \tag{7}$$

Therefore, the fractal dimension value can be obtained by using r as the abscissa and V(r)/V as the ordinate, drawing a log-log relationship curve and taking its stable slope b, the fractal dimension value of pore distribution can be obtained.

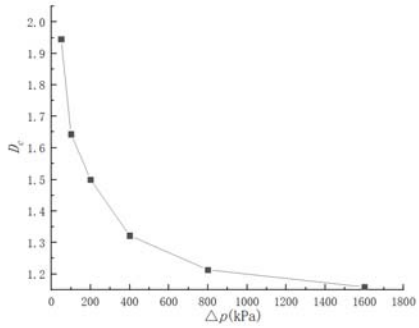

Fig.8 Variations of pore porosity fractal dimension under different pressures

Fig.8 shows the variation curve of the fractal dimension of the porosity with consolidation pressure. The larger of the porosity fractal value Dc, the worse the homogenization degree of porosity. By the Fig.8 show that with the increase of consolidation pressure, porosity fractal dimension values decrease gradually. Moreover, the consolidation pressure within 400 kPa pore fractal dimension value of the change of the slope is bigger, and consolidation pressure is greater than 400 kPa pore fractal dimension values decrease rate after the slowdown, it shows the porosity of homogenization in lacustrine facies soft clay have an increase of consolidation pressure tends to be stable. There is a negative correlation between the fractal dimension value of porosity and the consolidation pressure, and it is indicating that the greater the consolidation pressure of soft soil, the smaller the fractal dimension Dc of porosity will be.

3.4.2 Consolidation pressure and probabilistic entropy

The probabilistic entropy refers to the probability that the long axis of pores in soil particles is distributed at an Angle.It is used to describe and characterize the degree of directivity of particles or pores in soil, i.e

$$H_m = -\sum_{i=1}^{n} \frac{m_i}{M} \bullet \frac{\ln(m_i/M)}{\ln n} \tag{8}$$

In formula (8), H_m is the probability entropy, m_i is the number of equal parts of the *i* th in *n* equal parts along the pore long axis direction within 0～180°, *M* is the pore volume. The higher the probability entropy is, the more disordered the pore arrangement will be. And when the probability is so high, it gets messy.

The probabilistic entropy of typical soft soil in the study area changes with consolidation pressure as shown in Fig. 9. It can be seen from Fig. 9, the average probability entropy is above 0.92, which is generally disordered. With the increase of consolidation pressure, the arrangement of pores is more and more directional. Within 100kPa, the probability entropy decreases faster, which indicates that the pore changes are larger after the particles are squeezed. When the consolidation pressure is greater than 400 kPa, the probability entropy reduction rate is basically similar.It indicates that the rate of pore reduction slows down under the action of high consolidation pressure. The probability entropy is negatively correlated with the consolidation pressure, which means that the lower the probability entropy, the more stable the structure, the smaller the permeability, the smaller the pressure.

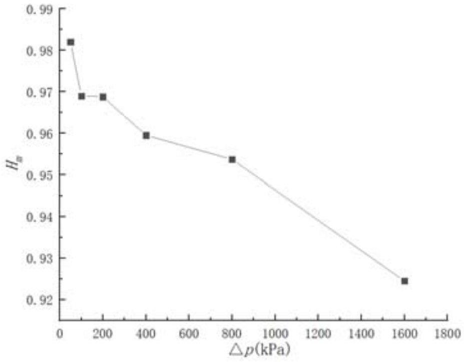

Fig.9 Variation of probability entropy under different pressures

3.4.3 Consolidation pressure and average shape coefficient

The average shape coefficient refers to the average ratio of the circumference of each particle or pore in the statistical area to the actual circumference, i.e.

$$F = \sum_{i=1}^{n} F_i / n \qquad (9)$$

In formula (9): F_i is the ratio of the circumference C_c of equal area of particles or pores to the actual circumference S_a of particles or pores, and n is the statistical number of particles or pores. The larger the average form factor, the more rounded the shape of its pores.

The average shape coefficient of typical Poyang lake soft soil is shown in Fig.11 which show that the average shape coefficient increases with the increase of consolidation pressure. The results indicate that with the increase of consolidation pressure, the shape of soil particles prone to round and the pore shape prone to round. It can be seen from the change curve that the average shape coefficient increases rapidly under the condition of low consolidation pressure (no more than 400kPa), indicating that the rate of particle pores becoming smooth is relatively fast at the initial pressure stage.Under the condition of high consolidation pressure (>400kPa), the slope of the curve becomes slow, it indicating that the pores of particles have been compressed and it is difficult to continue to be compacted. The average shape coefficient grows relatively slowly, indicating that the spatial arrangement of soil particles is getting closer and closer, and the permeability and compressibility of soil also decrease accordingly.

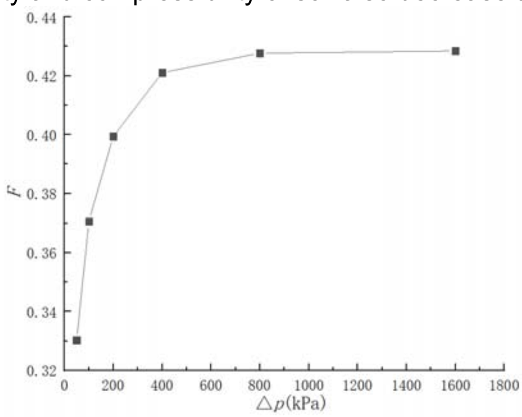

Fig.10 Variation curve of average shape coefficient under different pressure

3.4.4 consolidation pressure and fractal dimension

According to fractal geometry theory, pore fractal dimension refers to the quantitative index used to describe the non-uniform morphology of pore structure. Assuming that pores have irregular fractal characteristics, the following equation exists.

$$\text{Lg}\, L = D/2 \times \lg A + C \qquad (11)$$

In formula (11), L is the equivalent perimeter of the pore, D is the fractal dimension of the pore morphology, A is the equivalent area of the pore, and C is the constant value. In the form fractal dimension, it is simply called fractal dimension. The larger the fractal dimension, the more sophisticated the pore structure, and the rougher the spatial structure of the pores, the more uneven the morphology.

Fig. 10 shows the regularity of lacustrine soft soil changing with the consolidation pressure under different consolidation pressures. It can be seen from the figure that when the consolidation pressure increases from 50 kPa to 400kPa, the fractal dimension of lacustrine soft soil decreases rapidly, and it indicating that the pore size of lacustrine soft soil is basically irregular when the original soil or the initial pressure is applied. When a certain pressure is applied, the granular pore structure will change from irregular to smooth quickly. But，when the consolidation pressure is adjusted from 400kPa to 1600kPa, the fractal dimension decrease speed slows down, indicating that the degree of homogenization of the particle pores is close to the fixed value. Although the relationship between fractal dimension and consolidation pressure were positively correlated, the compression coefficient will not increase with the depth, this must be more attention in lacustrine facies soft soil survey.

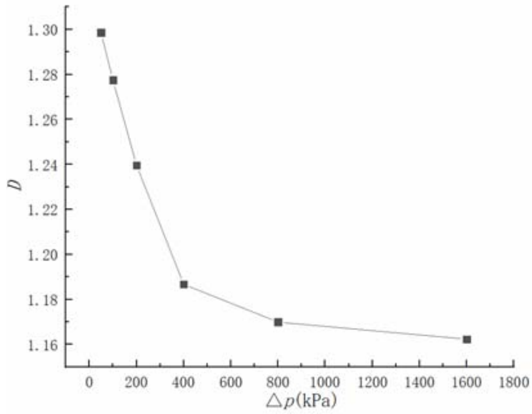

Fig.10 Variation curve of pore fractal dimension under different pressure

In order to study the correlation between the soft soil particle morphology and geometric characteristics under the action of consolidation pressure, binary polynomial fitting was carried out for the consolidation pressure and fractal dimension value of porosity, probability entropy, average shape coefficient and fractal dimension respectively. The results are shown in table 3, and the correlation coefficients are all greater than 0.81, which is highly correlated.

Table 3 Correlation analysis between consolidation pressure and microstructure parameters of soil particles

x	y	Correlation formula	R^2
porosity fractal dimension	Consolidation pressure	$y = 6E\text{-}7x^2\text{-}0.0014x+1.3009$	0.8776
probability entropy	Consolidation pressure	$y = 2E\text{-}9x^2\text{-}4E\text{-}5x+0.9771$	0.9508
average shape coefficient	Consolidation pressure	$y = 9E\text{-}8^{x2}+0.0002x+0.3453$	0.8171
pore fractal dimension	Consolidation pressure	$y = 1E\text{-}7x^2\text{-}0.003x+1.3009$	0.944

4 CONCLUSION

（1）When the consolidation pressure is low, the boundary points of primary consolidation and secondary consolidation of lacustrine soft soil are not obvious. With the increase of consolidation pressure, the primary consolidation ratio of lacustrine soft soil increases, the main consolidation time tp decreases, the secondary consolidation proportion decreases, and the relationship between the main consolidation time is $t_{p50}>t_{p100}>t_{p200}>t_{p40}0>t_{p80}0>t_{p160}0$. The secondary consolidation coefficient is greatly affected by consolidation pressure, the secondary consolidation coefficient calculated by Casagrande method will be affected by load level and loading history, and the corresponding secondary consolidation settlement calculation differs by more than 90%.

（2）When the consolidation pressure is low, the microstructure of the lacustrine soft soil is mainly flocculent and other irregular shapes. When the consolidation pressure increases to

400kPa, the granular structure of the soft soil becomes a structure with high uniformity such as flake and honeycomb, and the compressibility of the soil decreases.

（3）The pore arrangement characteristics of lacustrine soft soil particles had been changed by the consolidation pressure. With the increase of consolidation pressure, the pore changes from non-directional arrangement to directional arrangement. When the consolidation pressure is less than 400kPa, as the consolidation pressure increases, the slope of the fractal dimension of porosity rainfall curve is larger and the reduction rate is faster, and the probability entropy is above 0.96. When the consolidation pressure is more than 400kPa, as the consolidation pressure increases, the slope of the fractal dimension change curve of porosity slows down, the rate of decrease slows down, and the probability entropy decreases rapidly.

（4）The change of consolidation pressure is positively correlated with the geometric parameters of soil particles. The higher the consolidation pressure is, the higher the average shape coefficient is, and the lower the fractal dimension is. When the consolidation pressure is less than or equal to 400kPa, the average shape coefficient increases faster, while the fractal dimension decreases faster. When the consolidation pressure is > 400kPa, the average shape coefficient increases slowly with the increase of consolidation pressure, while the growth rate of fractal dimension slows down. The correlation coefficient between consolidation pressure and the fractal dimension value of porosity, probability entropy, average shape coefficient and fractal dimension is higher than 0.81, which is a high correlation.

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