Abstract: Loading/unloading tests and field emission scanning electron microscope (FESEM) tests were performed on undisturbed soft clay specimens to study the pore evolution under the loading/unloading process. The results showed that small pores (<0.2 µm) had intrinsic characteristics, and the distribution and the fragmentation fractal dimension of small pores were basically unchanged with pressure, while large pores (>0.6 µm) changed greatly under loading/unloading. The pore-size distribution was mainly influenced by large pores. The microstructure of soft clay before unloading has an influence on the change of the swelling index ($C_s$) and the pores evolution under unloading. $C_s$ increased as the surface fractal dimension of the pores and the area of large pores decreased, and the fragmentation fractal dimension of the pores increased under the loading process. The variations in fractal dimensions and large pore area increased under unloading. Moreover, the compression index ($C_c$) changed nonlinearly with the pore evolution under loading. Below 100 kPa, $C_c$ increased slightly with a small increase of the fractal dimensions and large pores area under loading. From 100 kPa to 400 kPa, $C_c$ increased to a peak value of 0.484, and the fractal dimensions and large pore area were the greatest under loading. Above 400 kPa, all of them changed slowly. Based on the evolution of pore fractal characteristics, the loading/unloading process could be divided into three stages: the natural structural stage, the structural adjustment stage, and the new equilibrium stage, which was important to study the loading/unloading properties of soft clay.

Keywords: soft clay; compression; swelling; pore evolution; fractal dimension

1. Introduction

Soft clays are widely distributed, with low strength, high sensitivity, and high compressibility [1,2]. Due to the rapid development of urbanization and the increase of population, it is inevitable to carry out a significant number of foundation pit engineering projects, including preloading treatments, and the excavation of foundations. The loading/unloading process may produce large deformation of soil, leading to safety problems.

The loading/unloading process was analyzed quantitatively by the finite element method [3] and constant rate of strain tests [4], showing that soil characteristics under the loading/unloading process behave elastically. The loading/unloading test can be exerted by an oedometer or apparatus to obtain the void ratio–stress curves with loading and unloading loops, which reflect the change of macroscopic mechanical properties of soil. Macro parameters like the compression and swelling indices of soil can be collected [5], reflecting the change of soil structural properties. Moreover, the loading/unloading process is controlled by the microstructure, which provides another method for studying the mechanical properties of clay [6].

SEM tests [7] are widely used, and is has been validated that the analysis of two-dimensional SEM images is consistent with the results from mercury injection tests [8,9] and CT scanning technology [10].
to study the microstructure evolution of soil [11,12]. The characteristics of pore shapes [13], sizes [14], and distribution [15] can be obtained from microscopic tests, reflecting the change of soil pores under the loading/unloading process. Research shows that the morphology and size distribution of pores have a strong influence on the microstructure of soft clay in Shanghai [16], and the pore sizes reduce as the plasticity increases [17]. Previous studies have indicated that the soil microstructure is closely related to the macroscopic mechanical properties of soil [18,19], where the mechanical properties of soil under consolidation or swelling are changed by the adjustment and evolution of soil microstructure [20]. It is necessary to study the relationship between microscopic parameters and macro-mechanical properties under the loading/unloading process.

The research objective was to study the evolution of pores under the loading/unloading process and to reveal the relationship between macro and micro properties, including the pore-size distribution and the fractal dimension characteristics of pores.

2. Experimental Program

2.1. Soil Sample

The soft clay samples were from the fourth soil layer, at 9–11 m depth, taken from the Pu Dong New Area of Shanghai. According to the Chinese standard [21], the physical properties of Shanghai soft soil were obtained by laboratory geotechnical tests. The results are shown in Table 1. The soft clay of the fourth layer in Shanghai is grayish-black in a soft-plastic state, characterized by high moisture content, high void ratio, and high compressibility. The main components of the soft clay are quartz and feldspar [22].

Table 1. Physical properties of soft clay.

| Density $\rho$ g/cm$^3$ | Water Content $\omega$ % | Specific Gravity $ds$ | Dried Density $\rho_d$ g/cm$^3$ | Porosity Ratio $e_0$ | Liquid Limit $I_L$ % | Plastic Limit $I_p$ % |
|-------------------------|------------------------|----------------------|-----------------------------|-------------------|----------------------|---------------------|
| 1.73                    | 45.7                   | 2.70                 | 1.18                        | 1.28              | 49.7                 | 23.5                |

2.2. Experimental Method

Oedometers were used to perform the loading/unloading tests, in which the loading process can reflect the consolidation characteristics, and the unloading process can reveal the swelling characteristics. The soil specimens were cylinders of 61.8 mm in diameter and 20 mm in height. The step method, regulated in the Standard for Soil Test Methods [21], was used, in which the first step load was 12.5 kPa, and the loading/unloading rate was 1 (shown in Table 2). The range of pressures was from 0 kPa to 1600 kPa, determined by the high-pressure situation of soft clay in practical engineering. Each loading/unloading step was applied for 24 h. Three parallel experiments were carried out for each case.

Table 2. The step load of the loading/unloading tests.

| The Step Load/kPa          |
|----------------------------|
| 1 0→12.5→25→50→25→12.5→0 |
| 2 0→12.5→25→50→100→50→25→12.5→0 |
| 3 0→12.5→25→50→100→200→100→50→25→12.5→0 |
| 4 0→12.5→25→50→100→200→400→200→100→50→25→12.5→0 |
| 5 0→12.5→25→50→100→200→400→800→400→200→100→50→25→12.5→0 |
| 6 0→12.5→25→50→100→200→400→800→1600→800→400→200→100→50→25→12.5→0 |

The step load of the FESEM scanning is shown in Figure 1. The FESEM images of the specimens at the end of each loading process were numbered $L_i$ ($i = 1, 2, 3, 4, 5, 6$), and at the end of each unloading
process were numbered \( U_i \) \((i = 1, 2, 3, 4, 5, 6)\). Soil samples were cut into 5 mm \( \times 3 \) mm \( \times 2 \) mm slices after immediate demolding at the end of each loading/unloading step, and subsequently freeze-dried in a lyophilizer for 24 h. The samples were then forced apart to observe the fracture surface by a secondary electron detector for FESEM, manufactured by Tescan Mira3 in the Czech Republic. Image-Pro Plus software was used for digital analysis. The 256-level greyscale images were converted into binary images by the threshold segmentation method, and the threshold was 80–110, determined by the combination of the Ostu and visual method [23]. Pores were shown in black, and were clearly distinguished from soil particles, in white, after segmentation, as seen in Figure 2. Image pixels were taken as the unit in Image-Pro Plus, which measures the image space according to the number and position of pixels. Then black parts were selected as the measurement objects, the diameter, perimeter, area, and roundness could be selected among the geometric and morphological parameters provided by Image-Pro Plus [24–26].

![Figure 1. Curves of \( e-p \) and the step load of the FESEM scanning.](image)

![Figure 2. The FESEM image and threshold image. (a) FESEM image; (b) threshold image.](image)

Previous studies have shown that a wide range of materials in the soil have self-similarity characteristics [27]. Fractal dimension theory was used in the analysis of pore-size distribution and shape complexity. The surface fractal dimension, \( D_s \) [28], and the fragmentation fractal dimension, \( D_f \) [27,29,30] were introduced, and the expressions were as follows:

\[
\ln L = \frac{D_s}{2} \ln A + C_1
\]

(1)

\[
\ln N(d) = -D_f \ln d + C_2
\]

(2)
where \( L \) is the perimeter of soil pore, \( d \) is the diameter of the pore, \( A \) is the area of the pore, which were converted from the pixels of a closed graph to the perimeter based on the setting scale in the software. \( N(d) \) is the number of the pores whose diameter was larger than \( d \), and \( C_1 \) and \( C_2 \) are constants calculated by expressions (1) and (2). The FESEM images with 50,000 times and 5000 times magnification were used to analyze the surface and fragmentation fractal dimension of the pores, respectively. \( D_s \) reflects the geometric complexity of the pore shapes. The larger the \( D_s \), the higher the geometric complexity of pore shapes. The value of \( D_s \) is related to the size difference of pores. The larger the \( D_s \), the smaller the size difference of the pores.

3. Experimental Results

3.1. The Compression and Swelling Indices

Curves of the void ratio \((\varepsilon)\) and the step load \((p)\) under each loading/unloading process of the soil samples are shown in Figure 3. The value of \( \varepsilon \) was obtained by the expression as follows [21]:

\[
\varepsilon_i = \varepsilon_0 - \frac{1 + \varepsilon_0}{h_0} \Delta h_i
\]

where \( \varepsilon_0 \) is the initial porosity ratio, \( h_0 \) is the initial height of the soil sample, \( \Delta h_i \) is the cumulative deformation of the soil sample under each loading process.

![Figure 3. \( e-p \) curves under the loading/unloading process.](image.png)

Each curve showed a change of \( \varepsilon \) when the specimens were loaded to a certain load and then unloaded to 0 kPa. The pre-consolidation pressure of soft clay was 88 kPa, by the Casagrand method, and the result agreed with the previous studies [31]. The slope of the unloading process at each step load was much smaller than that of the loading process, showing that the compression of soft clay cannot be fully swelled. The compression index, \( C_c \), and the swelling index, \( C_s \), are the critical parameters in the loading and unloading processes. \( C_c \) is defined as the slope of the linear part of the \( e-logp \) curve in the loading process, and \( C_s \) in the unloading process. \( C_c \) reveals the compressibility of soil, and \( C_s \) reveals the swelling property of soil [32]. The compression and swelling indices are shown in Figure 4.

The \( C_c \) of soft clay increased to the peak value of 0.494 at 400 kPa, and then gradually decreased to 0.403 at 1600 kPa. The compressibility of soft clay reached the maximum of 400 kPa. During the unloading process, the \( C_s \) of soft clay increased to a highest value of 0.097 at 400 kPa, and then changed from 0.097 to 0.082, revealing that the swelling property was enlarged as the step load of unloading increased to 400 kPa and then changed to a small degree.
The microstructure of clay underwent a significant change under the unloading process. At 800 kPa, the interaction between soil particles was characterized by face-to-face connection, while the shapes of the pores, between or inside the soil particles, were complicated. However, the microstructure of soft clay turned into a looser flocculent structure under the unloading process. The interaction between soil particles was displayed by face-to-face and face-to-edge types. The area of the large pores decreased, and the shapes of the pores became complicated. When the load ranged from 200 kPa to 400 kPa, soil particles broke into small aggregates. Large pores were collapsed into smaller ones, and were filled with dispersed soil particles. While the loose soil particles were gathered into massive ones under the unloading process, and edge-to-edge and edge-to-point connection types appeared. Pores were connected to develop larger ones, and the boundaries of pores were more apparent than those under the loading process. The microstructure of clay underwent a significant change under the unloading process. At 800 kPa, the interaction between soil particles was represented by face-to-face and face-to-edge types. The loose soil particles were squeezed into massive soil particles, and the boundaries of pores were more apparent than those under loading process. When it was unloaded, the microstructure of the clay changed into a flocculent one, that was much denser than that under 50 kPa. When it was 1600 kPa, the massive soil particles were squeezed into a much denser condition, and formed into a layered state. The area of large pores decreased, and the shapes of the pores became complicated. However, a flocculent and honeycomb structure was developed under the unloading process. The boundaries of the pores became ambiguous again.

The observation of FESEM images shows that it was the trend that the smaller pores were developed as the pressure increased under the loading process, and the complexity of pores shapes decreased and then increased. Under the unloading process, the microstructure of the soft clay changed significantly, comparing each loading step. It was necessary to analyze the micro parameters to describe the change of the microstructure.

3.2. FESEM Images and Pore Size Distribution

FESEM images are shown in Figures 5 and 6. When the loading pressure was lower than 100 kPa, the microstructure of the soft clay had a flocculent structure. The interaction between soil particles was characterized by face-to-face connection, while the shapes of the pores, between or inside the soil particles, were complicated. However, the microstructure of soft clay turned into a looser flocculent structure under the unloading process. The interaction between soil particles was displayed by face-to-face and face-to-edge types. The area of the large pores decreased, and the shapes of the pores became complicated. When the load ranged from 200 kPa to 400 kPa, soil particles broke into small aggregates. Large pores were collapsed into smaller ones, and were filled with dispersed soil particles. While the loose soil particles were gathered into massive ones under the unloading process, and edge-to-edge and edge-to-point connection types appeared. Pores were connected to develop larger ones, and the boundaries of pores were more apparent than those under the loading process. The microstructure of clay underwent a significant change under the unloading process. At 800 kPa, the interaction between soil particles was represented by face-to-face and face-to-edge types. The loose soil particles were squeezed into massive soil particles, and the boundaries of pores were more apparent than those under loading process. When it was unloaded, the microstructure of the clay changed into a flocculent one, that was much denser than that under 50 kPa. When it was 1600 kPa, the massive soil particles were squeezed into a much denser condition, and formed into a layered state. The area of large pores decreased, and the shapes of the pores became complicated. However, a flocculent and honeycomb structure was developed under the unloading process. The boundaries of the pores became ambiguous again.

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Figure 5. FESEM images of specimens $L_i$ with ×5000 magnifications. (a) $L_1$ (50 kPa); (b) $L_2$ (100 kPa); (c) $L_3$ (200 kPa); (d) $L_4$ (400 kPa); (e) $L_5$ (800 kPa); (f) $L_6$ (1600 kPa).

Figure 6. Cont.
The diameters of pores whose diameters were smaller than 0.2 µm or larger than 0.6 µm were regarded as the turning pore diameters. Pores smaller than 0.2 µm were defined as small pores, while pores ranged from 0.2 µm to 0.6 µm as medium ones, and bigger than 0.6 µm as large ones. The size distribution of small pores and the slope, k, of the fitting line below 0.2 µm were shown in Table 3, and was basically unchanged under the loading/unloading process. The correlation coefficient, $R^2$, was above 0.950. The change trend of the medium and large pore-size distribution is shown in Figure 8.

![Figure 6. FESEM images of specimens $U_i$ with ×5000 magnifications. (a) $U_1$ (50 kPa); (b) $U_2$ (100 kPa); (c) $U_3$ (200 kPa); (d) $U_4$ (400 kPa); (e) $U_5$ (800 kPa); (f) $U_6$ (1600 kPa).](image)

The method of obtaining the cumulative percentage of pore-size distribution is shown in Figure 7. The distribution of pores whose diameters were smaller than 0.2 µm or larger than 0.6 µm was linear to pore diameters. The change rate of the curves between 0.2 µm and 0.6 µm gradually slowed down. The diameters of 0.2 µm and 0.6 µm were regarded as the turning pore diameters. Pores smaller than 0.2 µm were defined as small pores, while pores ranged from 0.2 µm to 0.6 µm as medium ones, and bigger than 0.6 µm as large ones. The size distribution of small pores and the slope, k, of the fitting line below 0.2 µm are shown in Table 3, and was basically unchanged under the loading/unloading process. The correlation coefficient, $R^2$, was above 0.950. The change trend of the medium and large pore-size distribution is shown in Figure 8.

![Figure 7. Pore-size distribution (200 kPa). (a) Pore-size distribution of all pores; (b) pore-size distribution of small pores (<0.2 µm).](image)
The distribution of pore-size did not reflect well the change of large pores. For example, when the even large pores is broken into several pores including pores bigger than 0.6 \( \mu m \), the number of large pores increased, but the area might decrease. In this situation, the area percentages of pores would be used to calculate the distribution of large pores, as shown in Figure 9.

The percentage of large pores decreased to the minimum value of 4.082% at 100 kPa, and increased to 9.542% as the pressure increased to 1600 kPa under the loading process. However, the pore evolution analyzed by pore-size distribution contradicted the previous study [33], which showed that the percentage of large pores sharply decreased when the microstructure of soft clay rearranged. The distribution of pore-size did not reflect well the change of large pores. For example, when the even large pores is broken into several pores including pores bigger than 0.6 \( \mu m \), the number of large pores increase, but the area might decrease. In this situation, the area percentages of pores would be used to calculate the distribution of large pores, as shown in Figure 9.

### Table 3. Pore-size distribution and slope of the fitting line (<0.2 \( \mu m \)).

| \( P \) (kPa) | Loading | Unloading |
|---------------|---------|-----------|
|               | Percentage | \( k \) | \( R^2 \) | Percentage | \( k \) | \( R^2 \) |
| 50            | 67.013     | 4.737     | 0.955     | 67.829     | 4.833     | 0.978     |
| 100           | 70.469     | 4.859     | 0.962     | 68.726     | 4.860     | 0.975     |
| 200           | 70.915     | 4.731     | 0.965     | 69.231     | 4.751     | 0.990     |
| 400           | 68.046     | 4.639     | 0.958     | 65.625     | 4.854     | 0.963     |
| 800           | 69.799     | 4.846     | 0.950     | 68.601     | 4.941     | 0.987     |
| 1600          | 69.466     | 4.943     | 0.956     | 69.198     | 4.834     | 0.959     |

**Figure 8.** Pore-size distribution (>0.2 \( \mu m \)).

**Figure 9.** Area percentage of large pores (0.6 \( \mu m \)) under the loading/unloading process.
The area percentage of large pores underwent significant changes with pressure. Below 100 kPa, the microstructure was converted into the natural state, and the area percentage of large pores was high. As the pressure increased, the area percentage of large pores decreased to 91.087% under loading, while it decreased by 1.562% and 3.192% at 50 kPa and 100 kPa under unloading, respectively. From 100 kPa to 400 kPa, the area percentage of large pores sharply reduced to 84.771% under loading process, while it increased by 4.689 and 3.728 at 200 and 400 kPa under the unloading process, respectively. Above 400 kPa, the increase of area percentage of large pores slowed down. Under the loading process, the area percentage of large pores increased to 87.829%, while it increased slightly under the unloading process.

The distribution of small pores was basically unchanged, while that of large pores changed nonlinearly with pressure under the loading/unloading process. The pore-size distribution under loading/unloading was better analyzed by area percentage of large pores. The area percentage of large pores decreased to 84.771% until 400 kPa, and then increased under the loading process, while it decreased below 100 kPa, and then increased under each unloading process. However, further explanation is needed in combination with the following analysis.

3.3. Fractal Analysis

The surface and fragmentation fractal dimension of the pores of specimens $L_i$ and $U_i$ are expressed as $D_{L}^{D_{s}}$, $D_{U}^{D_{s}}$, $D_{L}^{D_{f}}$, and $D_{U}^{D_{f}}$, respectively, and the $D_{f}$ of small pores of specimens $L_i$ and $U_i$ as $D_{f}^{D_{s}}$ and $D_{f}^{D_{U}}$. The change of fractal characteristics under each unloading process was reflected by the variations in fractal dimensions of specimens $L_i$ and $U_i$, which were defined as $\Delta D_{s}$ and $\Delta D_{f}$:

$$\Delta D_{f} = D_{f}^{L} - D_{f}^{U}$$

$$\Delta D_{s} = D_{s}^{L} - D_{s}^{U}$$

If the value of $\Delta D_{s}$ or $\Delta D_{f}$ is positive, the fractal dimensions of the pores increase under unloading, otherwise they decrease. $D_{L}^{D_{s}}$, $D_{U}^{D_{s}}$, $D_{f}^{D_{s}}$, and $D_{f}^{D_{U}}$ are shown in Figure 10, and $\Delta D_{s}$ and $\Delta D_{f}$ are shown in Figure 11. The $D_{f}$ of small pores ranged from 1.120 to 1.160, and changed by a small degree. The distribution and size difference of small pores basically was unchanged with pressure, which can be seen as the intrinsic pore characteristics of soft clay. So that the properties of soft clay are mainly influenced by the large pores.

Figure 10. Fractal dimensions of specimens $L_i$ and $U_i$. 
Below 100 kPa, $D_s^{li}$ increased by 0.017 under loading, and $D_f^{li}$ increased from 1.442 to 1.477. The shapes of pores became complicated and the size difference of pores decreased under loading. The value of $\Delta D_f$ increased slightly while $\Delta D_s$ was negative and decreased by approximately 0.080 as the step load increased to 100 kPa. The shape complexity and the size difference of pores slightly increased under unloading.

As the pressure increased from 100 kPa to 400 kPa, $D_s^{li}$ decreased by 0.128 under the loading process. Moreover, $\Delta D_s$ increased to a positive value and then reached the maximum of 0.041 at 400 kPa. The pore shapes became less complicated under the unloading process, and the decrease of shape complexity under each unloading was further increased with the increase of the step load of $L_i$. The value of $D_f^{li}$ changed from 1.477 to 1.522 under loading, while $\Delta D_f$ increased from 0.081 to 0.223 under each unloading process. The size difference of pores reduced under the unloading process, while it increased under the unloading process, and the increase of pore size difference was enlarged with the increase of the step load of $L_i$.

Above 400 kPa, the value of the fractal dimensions changed to a small degree. $D_s^{li}$ gradually increased to 1.460, while $D_f^{li}$ slightly decreased to 1.443. $\Delta D_s$ changed from 0.004 to 0.027, and $\Delta D_f$ decreased from 0.223 to 0.069. The complexity of pore shapes increased as the step load of $L_i$ increased under the loading/unloading process. The size difference slightly increased under the loading process and decreased under the unloading process.

According to the analysis, small pores had intrinsic characteristics, so that the distribution and $D_f$ of the small pores were basically unchanged during loading/unloading. Based on the evolution of the $D_s$ and $D_f$ of pores, the loading/unloading process could be divided into three stages: the natural structural stage (<100 kPa), the structural adjustment stage (from 100 kPa to 400 kPa), and the new equilibrium stage (>400 kPa). The shape complexity and size difference of pores decreased under loading at the structural adjustment stage, while they increased when the soft clay was in the natural state or in a new balance. The shape complexity of pores under unloading changed in a similar trend with the loading process, while the size difference of pores increased under each unloading process.

4. Discussion

Soft clay has natural structural characteristics [34]. The compressibility of soft clay increased before the failure of the soil microstructure, and then maintained high compressibility [35,36]. The peak value of the compression index of Shanghai soft clay was at 400 kPa, which agreed with the previous research [37]. The microstructure of soft clay rearranged until 400 kPa, and then reached a new equilibrium. Wang and Gao [38] pointed out that surface fractal characteristics have a relationship with the adhesion between the interfaces for micron-sized particles. The larger the surface fractal
dimension, the higher the adhesion between particles. The contact between soil particles and the evolution of soil pores were the important manifestations of the soil microstructure failure.

At the natural structural stage, the microstructure of the soft clay recovered to the natural state, and maintained the properties of the soil skeleton; the size difference of pores and the area of large pores were the largest. The interaction between soil particles displayed a face-to-face type, where the adhesion between soil particles was strong. The $C_c$ of the soft clay was low and increased slightly. Under the unloading process, a low value of $C_s$ and little change in large pore distribution and fractal characteristics occurred, owing to the strong adhesion between soil particles and the high content of large pores at the end of each loading process.

The previous research showed that the collapse of large pores occurs first under the loading process, above the pre-consolidation pressure, leading to irrecoverable volume changes [39]. At the structural adjustment stage, the area percentage of large pores decreased sharply, in that the soil particles were broken into smaller aggregates and filled into pores. The $C_c$ of soft clay increased to the peak value of 0.464 at 400 kPa, where the breaking of the soil skeleton occurred. The adhesion between soil particles was weakened and the content of large pores decreased at the end of each loading process, leading to the great increase of $C_c$. The content of large pores increased and the adhesion between soil particles was weakened under the unloading process.

At the new equilibrium stage, the evolution of the pores slowed down. The adhesion between soil particles was enhanced, and the large pores were slightly increased under the loading process, while the $C_c$ of the soft clay decreased. The $D_s$ and the area percentage of large pores increased slowly and the $D_f$ decreased slightly under the loading process. The $C_s$ changed by a small degree, the adhesion between soil particles was enhanced, and the content of large pores increased under the unloading process.

According to the analysis above, $C_c$ changed nonlinearly with the pore evolution under the loading process, and the microstructure of the soft clay, before unloading, influenced the change of $C_s$ and pore evolution under each unloading process. When the $D_s$ and the area of large pores decreased, and the $D_f$ increased under loading, the $C_c$ increased greatly. When the $D_s$, $D_f$, and area of the large pores slightly changed under loading, $C_c$ changed by a small degree. When the $D_s$ and the area of large pores decreased, and the $D_f$ increased, under loading, $C_s$ increased to the peak value of 0.083, and the decrease of fractal dimensions and area of large pores increased under each unloading process.

5. Conclusions

Based on the fractal theory and microscopic analysis, the evolution of pores under loading/unloading process was investigated. The following conclusions can be drawn:

1. Small pores with diameters smaller than 0.2 $\mu$m had intrinsic characteristics, their $D_f$ and size distribution was basically unchanged with pressure. Large pores, bigger than 0.6 $\mu$m, changed greatly under loading/unloading, and the pore-size distribution was mainly influenced by large pores.

2. Based on the evolution of the fractal characteristics of pores, the loading/unloading process could be divided into three stages: the natural structural stage (<100 kPa), the structural adjustment stage (from 100 kPa to 400 kPa), and the new equilibrium stage (>400 kPa).

3. The state of microstructure of soft clay before unloading influenced the change of $C_s$ and the pore evolution under unloading. The $C_s$ increased greatly as the $D_s$ and large pore area decreased, and the $D_f$ increased, under loading; and the $\Delta D_s$, $\Delta D_f$, and large pore area increased under each unloading process.

4. The $C_c$ changed nonlinearly with the pore evolution under loading. Below 100 kPa, fractal dimensions and the area of large pores increased slightly under loading, and the $C_c$ changed by a small degree. From 100 kPa to 400 kPa, the $D_s$ and area of large pores decreased and $D_f$ increased, and $C_c$ increased greatly to the peak value of 0.464. Above 400 kPa, the change rates of the above parameters slowed down.
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