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Experimental Study on Clogging Characteristics of Silt Soft Soil in Nansha District of Guangzhou

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Abstract

The silt soft soil in Nansha District of Guangzhou was the softest soft soil in China. It had the characteristics of high natural water content, high compressibility, long consolidation time, and complex layered distribution of soil layers. These characteristics formed the clogging characteristics of silt soft soil, which greatly increased the construction difficulty and hindered the construction progress. Therefore, based on the basic physical and mechanical properties of silt soft soil in Nansha District of Guangzhou, this paper evaluated the clogging characteristics of three silt soft soil areas in Nansha District of Guangzhou through long-term permeability test, and carried out scanning electron microscope test to explore the influence of different parameters and microstructure on the clogging difficulty of silt soft soil. The results showed that the silt soft soil Zone I and Zone II (shallow layer) in Nansha District of Guangzhou were divided into slight siltation levels, and the silt soft soil Zone III (deep layer) was mild siltation level. Large pores were widely distributed in shallow silt soft soil, while the continuity of large pores in deep silt soft soil was poor. The migration of fine particles that failed to establish contact with surrounding particles in the soil blocks the small pores of seepage and thus produces siltation.

Keywords

Silt Soft Soil, Clogging Characteristics, Permeability Coefficient, Microstructure

1. Introduction

Saturated soft soils of marine, delta, lacustrine and fluvial facies are widely distributed in coastal areas, inland plains and mountainous areas of China. Understanding the clogging characteristics of soft soils is helpful for the determination of theoretical models and parameters of soft soils, analysis and calculation, engineering design and construction [1]. The soft soil in the Pearl River Delta is mainly formed by the gradual deposition of waves and tidal hydrodynamics in the inner coast. It belongs to Quaternary sediments. The soil layer is mostly water-rich silt, muddy clay and fine sand. Due to its unique geological and geographical characteristics, the soft soil in the Pearl River Delta has become the softest soft soil encountered in the projects reported in China. It has the characteristics of low bearing capacity, large deformation after loading, obvious time effect and strong interaction with buildings [2] [3]. Compared with other regions in China, the silt soft soil in Nansha District of Guangzhou is the softest soft soil. It has the characteristics of high natural water content, high compressibility, long consolidation time and complex layered distribution of soil layer. These characteristics make it the silty soft soil with the most obvious clogging.

The Mesozoic Yanshan period in Nansha District of Guangzhou caused the activation of the platform, thus forming faults in different directions. The main faults include Shawan fault, Hongqi fault, Shiziyang fault depression and Wanqingsha fault depression. The basement is composed of Paleozoic metamorphic rock series [4]. The Yanshan period biotite granite is distributed in Huangshanlu of Nansha District and Dashanxu of Huangge, which has a large distribution area. The continental conglomerate, glutenite, sandstone and argillaceous siltstone deposited in the Mesozoic fault basin are distributed in the Dahushan and Xiaohushan of the Shiziyang and the Shibaluohan of Tanzhou. The Lower Paleozoic Sinian metamorphic rocks are distributed from Tangkeng to Ronger Mountain in Nansha Forest Farm, and the Caledonian mixed granites are distributed in the deep bay of Nansha district [5]. Studying the clogging characteristics of silt soft soil is helpful to solve the problem of roadbed filling and settlement, such as the southern Dagang sewage treatment plant project.

The clogging characteristic is that under the action of seepage, particulate matter accumulates or deposits on the surface or internal pores of porous media, hindering the channel of water flow, resulting in a decrease in the water conductivity of porous media, that is, a decrease in permeability [6]. This phenomenon often occurs in silt soft soil, which seriously increases the difficulty of construction and hinders the construction progress [7]. Therefore, based on a series of physical and mechanical properties such as particle size, colloidal particle size, consolidation coefficient, compression modulus, shear strength and permeability coefficient of silt soft soil in Nansha District of Guangzhou, a long-term permeability test was carried out in this paper. According to the proportion of the decrease of permeability coefficient of silt soft soil in the process of permeability test, an evaluation standard was proposed for the silting characteristics of silt soft soil, and the silt grade evaluation was carried out. Further, the microstructure of silt soft soil was analyzed by scanning electron microscopy, and the influence of different parameters and microstructure on the difficulty of silt soft soil clogging was discussed, so as to infer the main reason of silt soft soil clogging. Long-term permeability test is helpful to understand the permeability characteristics of soil, which is closely related to the clogging characteristics. The scanning electron microscope test can visually show the microstructure changes of the soil, and the clogging characteristics are also closely related to the microstructure of the soil.

2. Analysis of Basic Physical Properties of Silt Soft Soil in Nansha District of Guangzhou

2.1. Project Overview

The Nansha area is basically distributed with silt soft soil. The soft soil layer is distributed in a large area of thick layers, and the local distribution is intermittent. The soft soil type is mainly the silt and muddy soil of the Henglan Formation and the Denglongsha Formation. The thickness of the silt layer in the Nansha area gradually increases from northwest to southeast, up to 50 m thick, and the upper part of the soft soil is covered with a layer of 2 - 3 m thick artificial dredger fill.

The samples taken in this experiment are from the southeast of Nansha District, as shown in Figure 1. According to the histogram data of the area, the thickness of the silt soft soil layer in Zone I and Zone II is about 9 - 12 m, which is mostly distributed and shallow, and the buried depth is about 2 m. The lower part of the silt layer is mostly distributed with thick silt clay layer or silty clay layer. The thickness of the silt soft soil layer in the Zone III is about 30 m, and the buried depth is 2 m. Thin silty clay layers are distributed in the lower part of the silt layer. The collection area and depth of borehole soil samples are shown in Table 1.

Figure 1. Sampling site and sample diagram: (a) Sampling site; (b) Drilling samples.

Table 1. Characteristics of sample collection area.

Drilling number	Soil sample depth (m)	Characteristics of silt layer	Belonging region
BNS112	7.70 - 7.90	The silt is distributed in the shallow layer, the buried depth is shallow, about 2 m, and the thickness is about 10 m.	Zone I
BNS113	8.50 - 8.70		
BNS116	9.70 - 9.90		

Continued

BNS133	8.40 - 8.60	The thickness of the silt is small, the buried depth is about 2 m, and the thickness is about 9 - 12 m.	Zone II
BNS139	3.20 - 3.40		
BNS152	15.50 - 15.70	The thickness of the silt is large, about 30 m.	Zone III
BNS155	19.70 - 19.90		
BNS156	23.70 - 23.90		
BNS158	10.80 - 11.00		
BNS167	34.30 - 34.50		

2.2. Characteristics of Physical and Mechanical Properties

The indoor physical and mechanical tests were carried out on the obtained 10 borehole samples, and the results are shown in Table 2 and Table 3.

Table 2. Basic physical indexes of silt soft soil.

Drilling number	Consistency index		Natural state indicators			
	Liquid limit (%)	Plastic limit (%)	Water content (%)	Dry density (g/cm^3)	Void ratio	Degree of saturation (%)
BNS112	57.21	35.18	66.23	0.93	1.84	94.42
BNS113	57.46	33.21	67.32	0.93	1.86	95.32
BNS116	56.28	34.21	66.84	0.89	1.85	95.24
BNS133	58.02	34.68	68.32	0.90	1.82	94.23
BNS139	57.64	35.02	65.25	0.95	1.83	94.03
BNS152	56.92	35.97	68.23	0.97	1.86	93.98
BNS155	58.12	35.06	64.23	0.96	1.80	94.56
BNS156	57.46	36.45	68.36	0.92	1.85	95.32
BNS158	58.36	34.21	66.27	0.94	1.84	94.23
BNS167	56.21	34.56	62.70	1.01	1.62	97.23

Table 3. Basic mechanical indexes of silt soft soil.

Drilling number	Sensitivity	Consolidation index			Shear index	
		compressibility (MPa^{-1})	Compressive module (MPa)	Consolidation coefficient (10^{-3} cm^2/s)	Cohesion (kPa)	Internal friction angle (˚)
BNS112	5.04	0.89	3.50	0.773	6.8	4.87
BNS113	5.02	0.92	3.62	0.801	7.2	5.32
BNS116	4.77	0.93	3.51	0.790	7.4	4.75
BNS133	4.56	0.84	3.56	0.763	6.4	5.67

Continued

BNS139	4.67	0.87	3.49	0.762	6.8	5.48
BNS152	5.93	0.90	3.48	0.776	6.7	4.65
BNS155	4.51	0.91	3.42	0.752	7.0	4.56
BNS156	5.22	0.93	3.56	0.776	7.3	4.75
BNS158	5.16	0.89	3.56	0.790	7.0	4.92
BNS167	6.00	0.96	3.75	0.702	7.2	14.30

The thickness of the silt soft soil layer in the Nansha area gradually becomes thicker from northwest to southeast. Through the test and comparison of the physical and mechanical properties of the test samples in three areas (sampling zones I, II, and III), it can be seen that the physical and mechanical properties of the silt soft soil at the shallow position (samples BNS112-BNS158) have a high degree of similarity, while the silt soft soil at the deep position (sample BNS167) has a certain difference from the shallow position. The silt soft soil in the deep position is mainly characterized by low void ratio, low water content, high saturation, low consolidation coefficient and permeability. At the same time, the deep soil sample has a large shear strength index and high sensitivity, which also indicates that it has high consolidation pressure and long consolidation time.

According to the physical and mechanical properties of silt soft soil, its large water content and large pore ratio not only reflect the interaction between mineral composition and medium in soil, but also reflect the shear strength and compressibility of silt soft soil. The larger the water content is, the smaller the shear strength of silt soft soil will be, and the greater the compressibility will be. The water content of the sample BNS167 is low, and the saturation is high, indicating that the particles in the sample occupy more space, and the pore content is low. The lower pore content may make the drainage channel less, resulting in weakened seepage, which is prone to clogging.

Therefore, the basic characteristics of silt soft soil in Nansha District of Guangzhou can be generally described. The water content is high, the water content is about 60% - 70%, and the average water content is 67.37%. The natural void ratio is large, the void ratio is about 1.6 - 1.9, and the average void ratio is 1.6; the soil is close to saturation, and the saturation is between 94% and 100%, with an average of 94.5%. The horizontal permeability coefficient is about 10^{-4} - 10^{-6} cm/s. The shear strength is low and the internal friction angle is small. The compressibility is high, and the average compression coefficient is 0.89 Mpa^{-1}. It can be inferred from the results that the shallow soft soil (3.2 m - 23.9 m) and the deep soft soil (34.3 m - 34.5 m) in Nansha area should be formed in two different geological historical periods, and their sedimentary environments are different. Combined with the existing engineering geological exploration data, the shallow silt should be the Quaternary Denglongsha Formation deposit, while the deep silt should be the Quaternary Henglan Formation deposit [8].

3. Analysis of Clogging Characteristics of Silt Soft Soil

3.1. Analysis of the Variation of Permeability Coefficient with Time

In this paper, a long-term permeability test is set up to study the clogging difficulty of silt soft soil in Nansha District of Guangzhou [9]. The test instrument is shown in **Figure 2**. Its pressure can reach 1000 kPa, and the standard sample diameter is 50 mm.

Figure 2. Schematic diagram of permeability test instrument.

The sample was kept in the seepage state, and the variation curve of the permeability coefficient of the sample with time was observed and recorded. At the same time, the proportion of 0 - 1 um particles in the upper and lower particles of the soil sample after the penetration test was tested. Because the test results of the shallow position of the silt soft soil in this area are similar, the test results of the BNS133 sample and the deep position BNS157 sample were compared and analyzed. The results were shown in **Figure 3**.

It can be seen from the results that in the process of infiltration, the permeability coefficient of the sample will decrease with time, and the downward trend will gradually decrease. Finally, the change curve of the permeability coefficient with time will show a gradually downward concave curve. The initial permeability coefficient of shallow muddy soft soil (BNS133) is larger than that of deep muddy soft soil (BNS167). When the infiltration time is 1 - 30 days (the test period is 50 days), the decrease rate of the permeability coefficient of the silty soft soil in the deep position is slightly larger than that in the shallow layer. When the infiltration time is 30 - 50 days, the decline rate of the permeability coefficient in the deep and shallow parts is reduced, but the decline rate of the permeability coefficient in the deep part is still greater than that in the shallow part. It can be seen that the muddy soft soil in the deep part is more likely to be clogged during the drainage consolidation process.

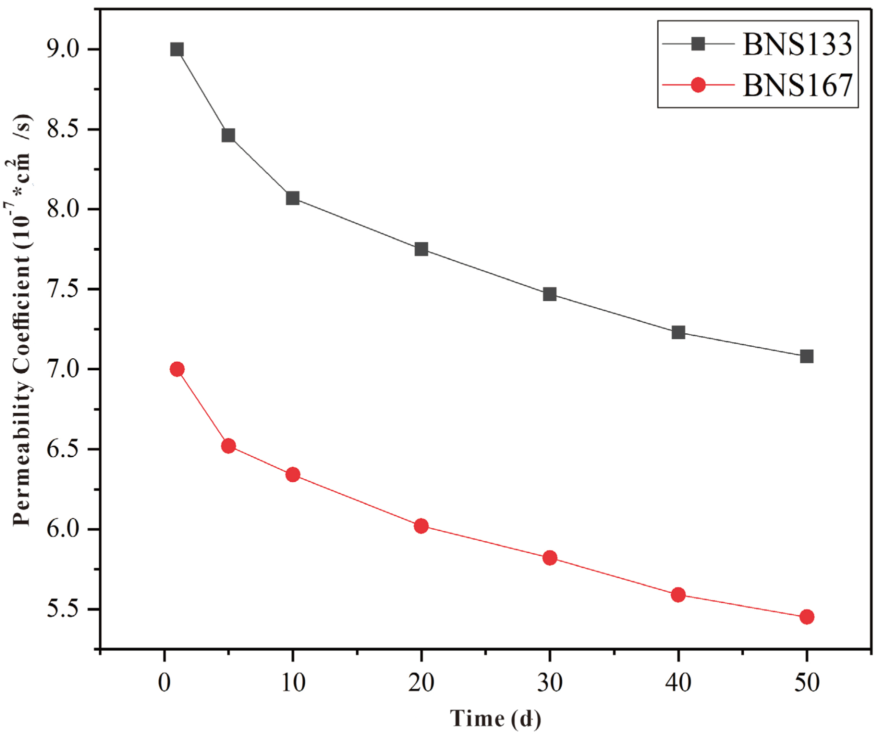

Figure 3. The relationship curve between permeability coefficient and time.

3.2. Classification of Clogging

In order to facilitate the engineering application and the evaluation of sludge clogging characteristics, an evaluation criterion for the clogging characteristics of muddy soft soil is proposed in this paper according to the proportion of the decrease of permeability coefficient of muddy soft soil in the process of permeability test. According to the test results and the standard, the clogging characteristics of the three muddy soft soil areas in this paper are evaluated [10]. Among them, the muddy soft soil at the bottom of Zone III is mild silted up, and the muddy soft soil in Zone I and Zone II is slightly silted up. In combination with the test done, under the condition of continuous infiltration for 50 days, the clogging is now divided into 5 grades, as shown in Table 4.

Table 4. Classification of clogging level.

Clogging level	Characteristic
Severe	The permeability coefficient decreased to less than 10% of the original value
Heavy	The permeability coefficient decreased to 10% - 30% of the original value
Moderate	The permeability coefficient decreased to 30% - 60% of the original value
Mild	The permeability coefficient decreased to 60% - 80% of the original value
Slight	The permeability coefficient decreased to more than 80% of the original value

3.3. Analysis of the Migration Law of Particles in the Seepage Process

The particle size of BNS167 and BNS133 samples before and after the test was tested at both ends of the water head. In this experiment, a laser particle size analyzer was used. The model was Malvern Mastersizer 3000, and the corresponding professional supporting software was used to analyze the test results. The instrument is shown in Figure 4.

Figure 4. Schematic diagram of laser particle size analyzer instrument.

The results showed that the particles with a diameter of 0 - 1 um before the penetration test of BNS167 sample account for about 7.30% of the total particles. After the penetration test, the particles with a diameter of 0 - 1 um at the upper head end accounted for about 7.00% of the total particles, and the particles with a diameter of 0 - 1 um at the lower head end accounted for about 7.42% of the total particles. Before the penetration test, the particles with a diameter of 0 - 1 um in the BNS133 sample accounted for about 10.00% of the total particles. After the penetration test, the particles with a diameter of 0 - 1 um at the upper head end accounted for about 9.72% of the total particles, and the particles with a diameter of 0 - 1 um at the lower head end accounted for about 10.14% of the total particles. Therefore, it can be seen that the fine particles migrate in the direction of low water head with the permeable water flow components, which will reduce the permeability coefficient of the silt soft soil and gradually lead to the silt soft soil clogging.

Through the analysis of the results of the long-term permeability test of the two samples, it can be seen that the decrease rate of permeability coefficient of the two soil samples is similar, which is between mild clogging and slight clogging. BNS133 is slight clogging, and BNS167 is mild clogging. The content of fine particles in the BNS133 sample is high, and the number of seepage migration is large.

The proportion of pores in the sample is high and there are many large pores, which makes the overall permeability of the soil sample better. More pores and widespread macropores also make it difficult for fine particles to fill pores, so that the BNS133 sample is less likely to produce clogging than the BNS167 sample.

4. Microstructure Analysis of Silt Soft Soil

4.1. Test Process

The previous analysis results and the research results of scholars all reflect that the clogging characteristics of silt soft soil are closely related to its microstructure changes [11]. Therefore, the microstructure of the sample was observed by scanning electron microscopy (SEM), and the pore content, particle contact and contact mode of the obtained SEM image were analyzed by PCAS software (particle and fracture image recognition and analysis system), so as to explore the influence of microstructure change on the clogging characteristics of silt soft soil [12]. The type of scanning electron microscope is ΣIGMATM, the maximum magnification is 100,000 times, and the resolution is 1.3 nm. The test process is shown in Figure 5. Because the microstructure of shallow silt soft soil in Nansha District of Guangzhou is similar, the shallow typical sample BNS133 and the deep sample BNS167 were analyzed.

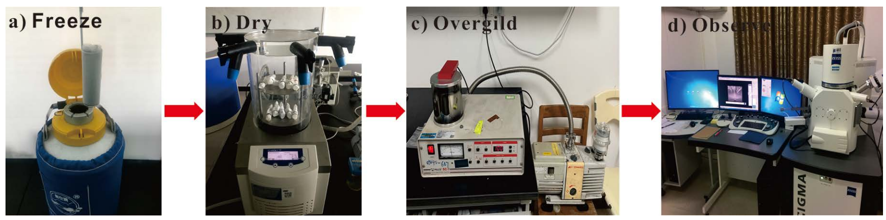

Figure 5. Scanning electron microscope test process.

4.2. Test Result Analysis

The scanning electron microscope image of BNS133 sample was shown in Figure 6, and the energy spectrum analysis was carried out, as shown in Figure 7. From the results, it can be seen that the particle size of the shallow silt soft soil sample in this area is about 100 um - 300 um, and the shallow silt soft soil contains many large particle mineral crystals, and the maximum particle size of the crystal can reach 150 um. It can be known from the energy spectrum analysis that there are large-grained minerals with a particle size greater than 50 um in the sample. The large particles are mostly quartz crystals, while the fine-grained minerals are mostly aluminosilicates. At the same time, Mg, Na, Cl, Fe and other elements are filled or replaced in the mineral lattice.

The PCAS software was used to binarize the sample BNS133. The results are shown in Figure 8, in which black represents pores and other colors represent soil particles. According to the binary image, there are 217 particles in the sample BNS133, of which 10% are 0 - 1 um particles and 93% are 0 - 4 um particles. The area of pores in the soil sample is large, and there are many large pores, and the overall permeability is preliminarily evaluated. The distribution of BNS133 particles in the direction of 80˚ - 110˚ is relatively small, which is about half of the number of particles in other directions. The pore arrangement direction is mostly concentrated in the two regions of −45˚ and −25˚. The soil sample has a large area of pores and good overall permeability.

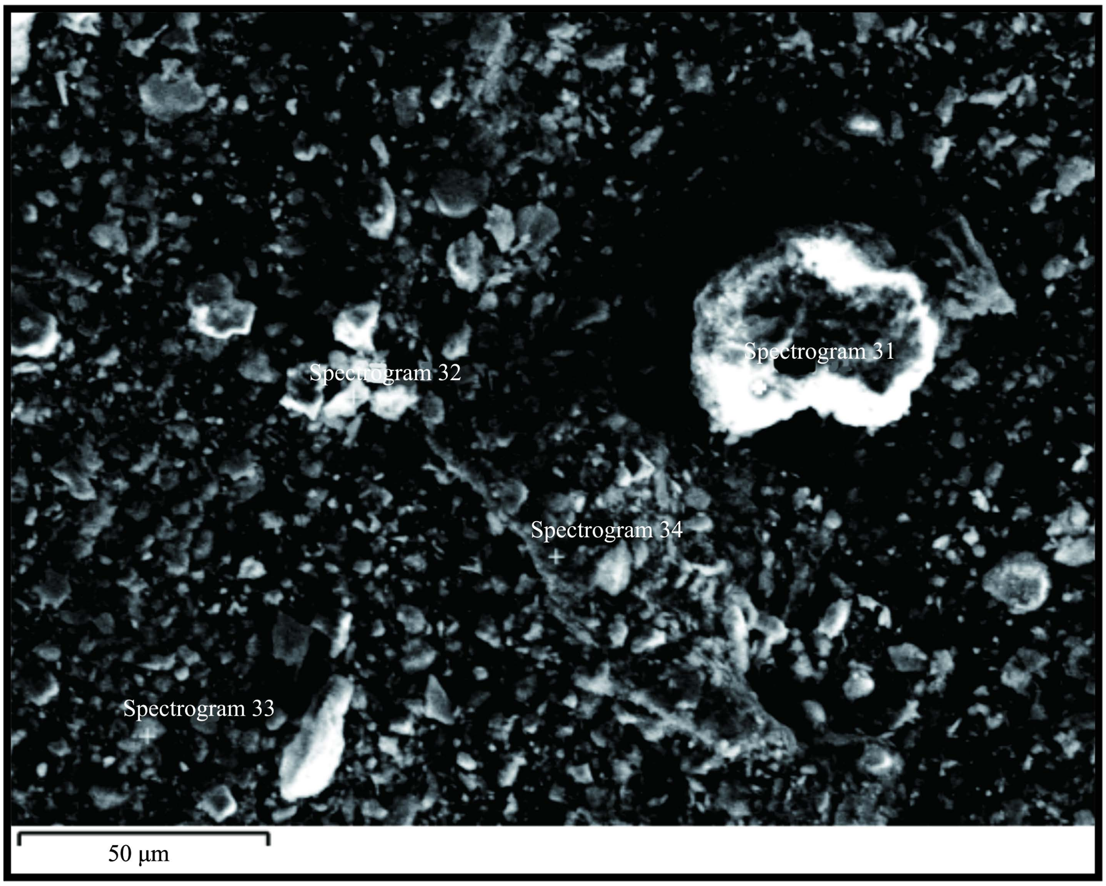

Figure 6. SEM image of BNS133 sample.

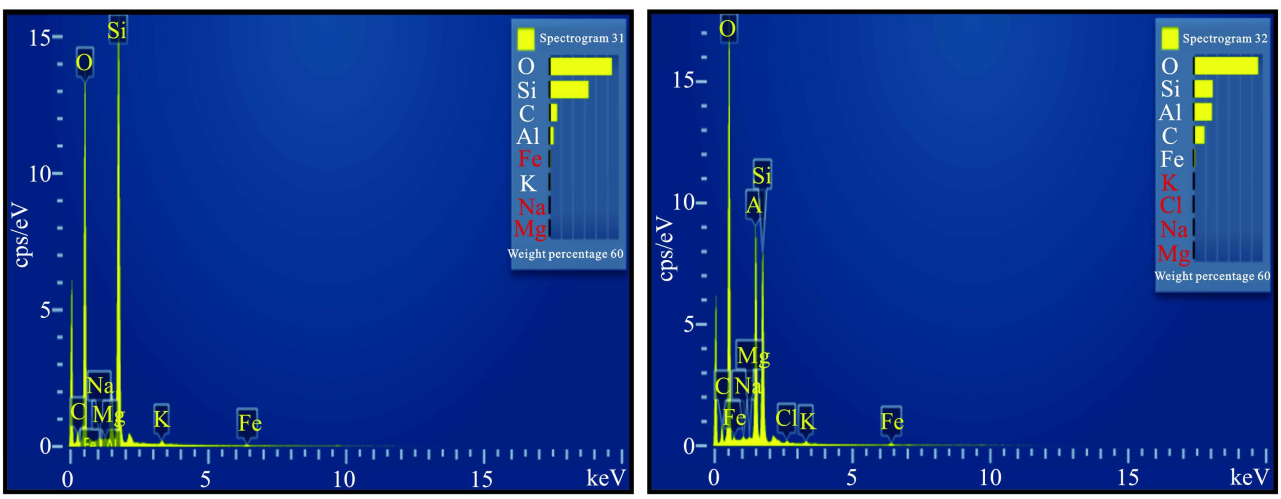

Figure 7. Energy spectrum analysis of BNS133 sample.

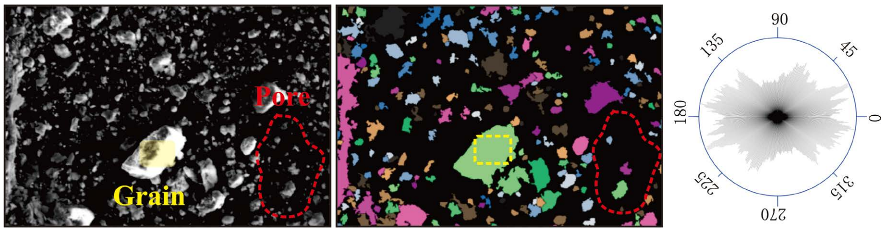

Figure 8. SEM image, binary image and particle distribution direction of BNS133 sample.

The scanning electron microscope image of the BNS167 sample was shown in **Figure 9**, and the energy spectrum analysis was carried out, as shown in **Figure 10**. It can be seen from the results that there are large particles of crystalline minerals in deep silt soft soil, and the maximum diameter of minerals can reach 200 um. Compared with the BNS133 sample, the colloidal particles in the BNS167 sample are closer to the sphere and have higher roundness. Through energy spectrum analysis, it can be known that deep silt soft soil is rich in metal oxides and silicates. The bright bands in the structure are mostly silicates and carbonates or organic matter, and the dark bands are mostly organic matter filling or carbonaceous cementation.

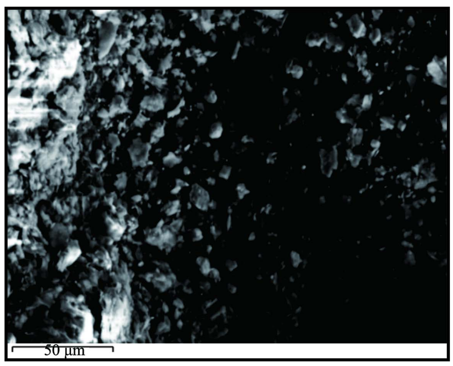

Figure 9. SEM image of BNS167 sample.

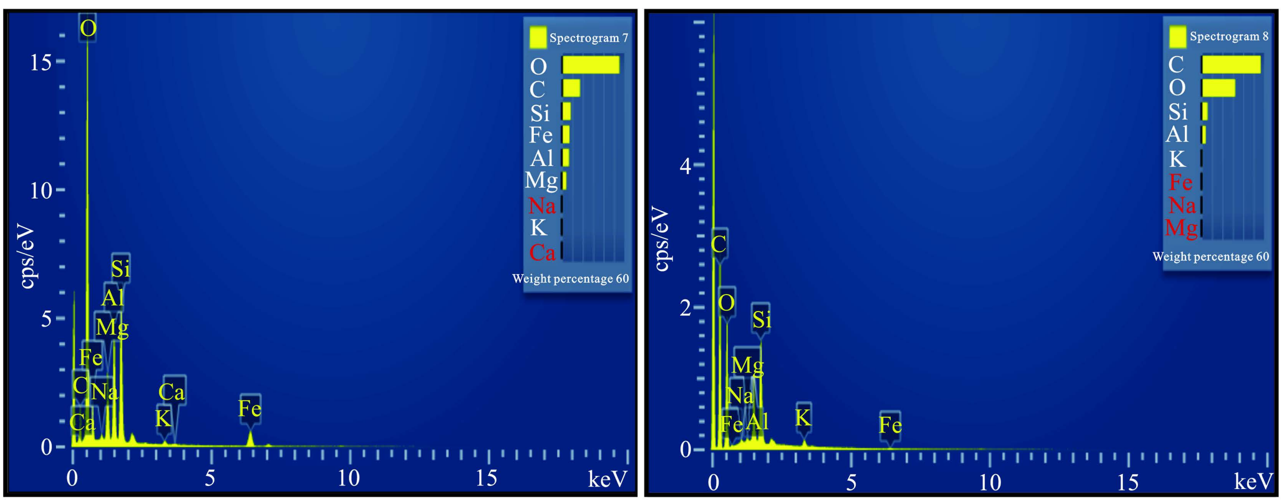

Figure 10. Energy spectrum analysis of BNS167 sample.

The scanning electron microscope image of the sample BNS167 was further binarized, and the results were shown in Figure 11. The results show that the average particle size of the soil is 2.9 um, the average area of the particles is 6.3 um^2, and the number of particles of 1 - 5 um accounts for about 87.3% of the total. The average shape coefficient of the particles is 0.559, and the roundness is high. Compared with the shallow silt soft soil, the content of small particles in 0 - 1 um of BNS167 sample is more, accounting for about 7.3% of the total particles. The particles and pores are highly consistent in the arrangement direction. The number of particles and pores distributed in the direction of −30˚ to −10˚ is the largest, which is about 2.5 times that of the particles distributed in the direction of 90˚. It can be seen that the soil samples have obvious anisotropy in different directions. In particular, the permeability coefficient of the particles in the direction of −30˚ to −10˚ is much larger than that in the vertical direction.

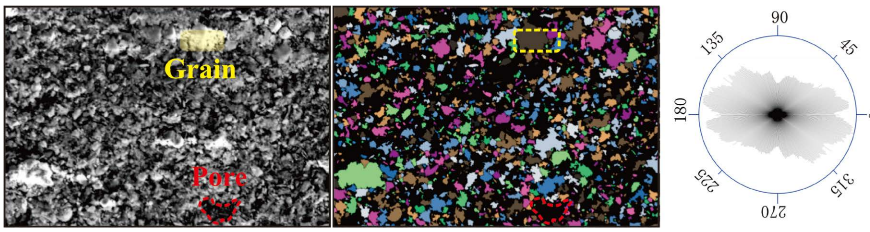

Figure 11. SEM image, binary image and particle distribution direction of BNS167 sample.

4.3. Analysis of the Relationship between Microstructure and Clogging Characteristics

In the samples of Nansha area, the average diameter of particles is between 2.2 - 2.6 um, and the diameter of particles is mainly between 1 - 5 um, accounting for more than 90% of all particles. The composition of the particles is mainly composed of some small clastic minerals. The mineral components are mainly quartz, carbonate, aluminosilicate, and contain metal elements such as Fe, Na, Mg, and Ti. The silt layer in the Zone III is thicker, and the large particle mineral crystals are widely distributed in the silt soft soil. The large particle mineral crystals are mainly quartz and calcite, and the small particle crystals are mainly silicate, aluminosilicate and carbonate. At the same time, it contains Na^+, Mg^{2+}, K^+, Fe^{2+} and a very small amount of Fe^{3+}, indicating that the deep silt soft soil should be in a weak oxidizing environment [13] [14]. The silt soft soil particles and pores in Zone III have good consistency in the arrangement direction. It can be seen that the seepage coefficient of the soil in this direction will be much larger than that in other directions. The internal particles are mostly connected by cementation to form colloidal particles. The size of the colloidal particles is between 100 um and 350 um, and the roundness of the colloidal particles is high. The cementation between the internal particles is carbonaceous cementation or organic matter cementation. There are also honeycomb structures in some cemented particles. The particles less than 1 um in Zone III account for about 7.3% of the total number of particles. These particles are mostly distributed in pores, which fail to form a relatively strong contact relationship with the surrounding particles, and are easy to flow with the seepage of water, and then accumulate to form clogging somewhere.

The silt layer in zone I and zone II are thinner, and the particle composition is also dominated by a small particle mineral. The small particle size is mostly in the range of 0 - 4 um, accounting for about 93% of the number of medium particles. Large particle mineral crystals are widely distributed in silt soft soil. The maximum particle size of mineral crystals can reach 200 um. The main component of large particles is SiO_2, and a very small part is TiO_2. The composition of small particles is complex, mostly aluminosilicate. Na^+, Mg^{2+}, K^+, Fe^{2+} and Ti^{4+} are replaced or filled in the lattice of minerals. The small particles are cemented or there are pores. The way of cementation is mostly organic cementation or carbonaceous cementation. The particles are mostly cemented into colloidal particles. The particle size is 100 um - 300 um. The roundness of the colloidal particles is higher, but not as high as that of the deep silt soft soil layer. In the part that does not form colloidal particles, the particles are mostly in the form of loose material. Among them, the particles of 0 - 1 um account for about 10.0% of the total number of particles. Many small particles fail to form cementation or other connections with the surrounding soil. This kind of small particles is easy to move with the direction of water flow during the infiltration process, and then accumulate together to produce blockage. However, due to the existence of large pores in the soil samples in this area, the soil samples in zone I and zone II are not easy to produce clogging for the samples in zone III.

5. Conclusions

The following are the main conclusions of this study:

1) The silt soft soil in Nansha District of Guangzhou had the characteristics of high water content, large void ratio, large saturation, small shear strength of soil, small horizontal permeability coefficient, high consolidation coefficient and poor mechanical properties. Compared with shallow silt soft soil, deep silt soft soil had lower void ratio, lower water content, higher saturation, smaller permeability coefficient, smaller consolidation coefficient and larger shear strength, which indicated that it had been subjected to high consolidation pressure and longer consolidation time. The shallow silt soft soil was deposited in the Quaternary Denglongsha Formation, while the deep silt soft soil was deposited in the Quaternary Henglan Formation.

2) The permeability coefficient of the zone II sample (BNS133) decreased from the initial 0.9×10^{-6} cm^2/s to 0.71×10^{-6} cm^2/s at the end of the test, and the reduction rate was 19%. The permeability coefficient of the zone III sample (BNS167) decreased from the initial 0.7×10^{-6} cm^2/s to 0.54×10^{-6} cm^2/s at the end of the test, and the reduction rate was 22%. According to the evaluation standard of silt soft soil clogging characteristics, areas I and II were divided into slight clogging levels, and the area III was mild clogging level.

3) Through the study of the microstructure of muddy soft soil in Nansha area, it was found that the average particle diameter of muddy soft soil in this area is 2.2 - 2.6 um, and most of them were 100 - 300 um, and all of them were carbonaceous cementation. The content of particles with particle size of 0 - 1 um in the silt soft soil of zone I and zone II was more (10% of the total number of particles). In zone III, there were fewer particles of 0 - 1 um (accounting for 7% of the total), and the content of fine particles in the upper muddy soft soil (7%) was smaller than that in the lower muddy soft soil (7.3%). Macropores were widely distributed in shallow silt soft soil, while the continuity of macropores in deep silt soft soil was poor.

4) According to the change of the number of fine particles near the upper and lower water heads after the permeability test, it was seen that the migration of fine particles that fail to establish contact with the surrounding particles in the soil blocks the small pores of the seepage and thus produces clogging. The number of small particles that did not form colloidal particles, the number and continuity of large pores, and the microstructure of organic matter and particles in the soil were all very important factors affecting silt clogging.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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