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Research Article

# Evolution of Mechanical Behaviors and Microstructure of Tianjin Binhai Cohesive Soil during Freeze-Thaw Cycles

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The variation of soil structure and mechanical damage caused by freeze-thaw cycles results in degradation of engineering properties and engineering geological problems, such as deformation, cracking, and even project accidents. In this study, the freeze-thaw cycle tests, unconfined compressive strength tests, scanning electron microscope (SEM) tests, and nuclear magnetic resonance (NMR) tests were carried out to find out the effects of freeze-thaw cycles on the mechanical behaviors and microstructure properties of Tianjin Binhai cohesive soil. The results show that the original structure of the cohesive soil has been destroyed after the first freeze-thaw cycle, resulting in severe loss of compressive strength by 84.2%. The axial stress-strain response showed a strain-hardening behavior transitioned to a strain-softening behavior after 15 freeze-thaw cycles. The unconfined compressive pressure, sensitivity, and void ratio showed the same corresponding reaction with the increase of freeze-thaw cycles. The effects of freezing and thawing on void ratio were weakening with the increase of consolidation pressure, since the void expansion and contraction were limited with smaller void sizes. The frost-heaving force during the freezing process increased the compaction of the soil structure, and face to face contact became the main contact formation, which led to a reduction in void ratio. This study provides technical guidance for evaluation on the mechanical properties and engineering stability of cohesive soil in seasonally frozen areas and technical support for artificial ground freezing treatment on underground construction of the west coast of Bohai Bay.

## 1. Introduction

Tianjin is the economic center of the Bohai Bay Area, the largest port city, and an international comprehensive transportation hub in the north. The economic construction of Tianjin and the west coast of Bohai Bay is inseparable from the construction of infrastructure such as railways and highways, and the engineering geological problem of freeze-thaw damage of cohesive soil cannot be avoided [1–3]. The west coast of the Bohai Bay Area belongs to the seasonal frozen area. The freezing in winter and the thawing in spring will weaken the mechanical properties of the soil. What is more, the artificial ground freezing method is a good reinforcement method and has been widely applied in underground constructions of China coastal areas, where the soft soil is widespread [4]. Therefore, the weakening of soil mechanical properties caused by freeze-thaw cycles must be considered in the construction of foundations, embankments, and underground constructions in coastal areas.

Freeze-thaw cycles are important factors that attack the strength properties of soil mass, reducing the strength of all kind of soils [5]. Water migration and phase transition between fluid water and ice lenses lead to the variation of the internal microstructures in soil, mainly affecting the engineering properties of soil mass [6–8]. Kamei et al. [9] proposed that the unconfined compressive strength decreased with freeze-thaw cycles and the structure and void volume of soil varied the most in the first freeze-thaw cycle. Liang et al. [10] found that the influence of freeze-thaw cycles on shear strength of expansive soil was not significant after exceeding a threshold of the cycles. The strength and elastic modulus of the soil gradually decreased and stabilized as the number of freeze-thaw cycles increased [11]. The strength and deformation properties of soil during freezing and thawing process were determined by the connection form between soil particles and the degree of water-ice transformation [12]. The uniaxial compressive strength decreased after various freeze-thaw cycles, especially for the first six cycles. Finally, the mechanical properties were altered [13]. Deng et al. [14] revealed that the change of microstructure had a good corresponding relationship with the mechanical properties under the action of freeze-thaw cycles. Changizi et al. [15] found that the reduction in soil shear strength was negligible after 9 to 12 freeze-thaw cycles, where the soil structure reached a stable condition. The strength decreased by 30-35% with both unreinforced and fiber-reinforced samples, after 15 freeze-thaw cycles [16].

The freeze-thaw process can significantly influence the pore network of soil and induce changes in soil particle stability, which in turn changes the hydraulic properties [17, 18]. The energy input and output on soil during freezing and thawing strongly affects the bonding and arrangement of particle connections and soil structures [19, 20]. Freeze-thaw cycle changes the porosity, the pore shapes, and the pore sizes, resulting in cumulative damage to the soil mass. Common methods for analysis on soil structure are scanning electron microscope (SEM) tests, mercury intrusion porosimetry (MIP), and nuclear magnetic resonance (NMR) tests, which put an effort to evaluate the relationship of pore size distribution and microstructure of soil mass [21, 22]. During freezing process, water migrates from the unfrozen section, generating ice lenses in the soil. Then, during the thawing process, the melting of the ice lenses leads to the development of cracks in soils [23–25]. Chamberlain and Blouin [26] concluded that there was an increase in permeability in fine-grained dredged soil after freeze-thaw cycles, which stated a result of crack formation and arrangement of soil particles. Guo et al. [27] found that when the number of freeze-thaw cycles exceeded a critical number, the effective void ratio and hydraulic conductivity of the compacted soil may decrease. After freeze-thaw cycles, the water volume expanded in the pores, and the internal structure was destroyed; two cycles would aggravate this damage [28]. Gao et al. [29] visualized that soil macropores transformed into smaller ones during the freeze-thaw process. Freezing lenses due to the process of thermal cycles increase the number of micropores, expanded soil porosity, and formed microcracks within the soil mass [30, 31].

Researches on the failure mechanism and microstructures under the effect of freeze-thaw cycles of all kinds of soils are reported recently. However, there are very limited studies related to the relationship of mechanism and microstructure influenced by freeze-thaw cycles based on Tianjin Binhai cohesive soil. This work further investigates the unique features of freeze-thaw cycles effecting on the mechanical behaviors and microstructure of a cohesive soil collected from Tianjin Binhai dredger filling area. It conducted freeze-thaw cycle tests, unconfined compressive strength tests, SEM tests, and NMR tests to study the strength variations and microstructure changes under the freezing and thawing. The effect of freeze-thaw cycles on soil microstructure has been explored and the inherent relationship between soil mechanical property degradation and structural damage was revealed. The research results will enrich the strength theory of the Tianjin Binhai cohesive soil affected by freeze-thaw cycles and provide theoretical support for artificial ground freezing method applying in the dredger filling area and the prevention and control of engineering disasters of coastal cohesive soils.

## 2. Materials and Method

*2.1. Samples and Their Geological Background.* The cohesive soil investigated in this study was collected from the coast in Tianjin Binhai dredger filling area, Tianjin, China, which is a seasonal frozen area (Figure 1). The climate type of Tianjin belongs to the temperate monsoon climate, which is featured by hot and concentrated rainfall in summer and cold and dry in winter. In the past 70 years, the average minimum temperature in winter is about -10°C, and the minimum temperature extreme value reaches to -17.8°C; the average temperature in spring is about 18°C. The layers in the coastal plain are composed typically of river alluvium and marine deposits. The vertical strata follow a sequence of the Holocene Formation $Q_4$, the Late Pleistocene Formation $Q_3$, the Middle Pleistocene Formation $Q_2$, and the Early Pleistocene Formation $Q_1$ [32]. The artificial ground-freezing method is widely used in geological engineering, and the design value for the average frozen temperature of the freezing method ranges from -25 to -15°C [33]. The soil samples were drilled from the dredger filling area at a depth of 7 m to 16 m by using thin-walled earth picker, recorded and preserved by thin-walled stainless steel tubes, 100 mm in diameter and 300 mm in length. Both ends of these tubes were sealed with wax and stored in a humidity room. The soils contain yellow-brown clay, clayey sand, gray mucky clay, and gray-green fine sand, with high moisture content, high void ratio, and low permeability [34]. The basic index properties of this soil are tested and summarized in Table 1.

According to the demand of the unconfined compressive strength test, consolidation test, SEM test, and NMR test, four sizes of soil samples were made based on the Standard for Soil Test Method (GB/T 50123-1999). Samples were trimmed from the core of the soil mass with a wire saw. One size is a column of 39.1 mm in diameter and 80 mm in height, one is of 61.8 mm in diameter and 20 mm in height, one is a cube of 10 mm × 10 mm × 10 mm, and one is of 50 mm × 50 mm × 50 mm, respectively. Two parallel experimental group tests were conducted to minimize error caused by experimental chance for each test.

*2.2. Application of Freeze-Thaw Cycles.* Based on the local annual temperature range and the requirement of the artificial ground freezing method in Tianjin Binhai Area, the specimens were firstly frozen at -20°C for 12 h and then allowed to thaw at 20°C for 12 h as one cycle [35, 36]. Specimens for all kinds of sizes were wrapped in a plastic film for moisture equilibrium and were directly placed in the temperature and humidity control chamber (DR-2A type) undergoing freezing and thawing stages. To reveal the evolution and final status of the structure and mechanical properties of soil mass, the specimens were subjected to 0, 1, 2, 3, 5, 7, 9, 11, 13, and 15 cycles. Further, the specimens were tested at a room temperature of 20°C.

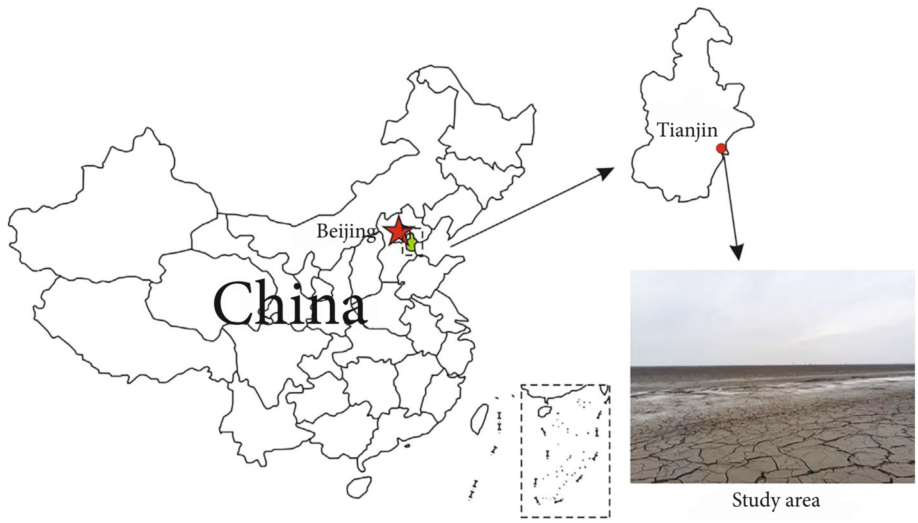



Figure 1: Location of the tested cohesive soil.

Table 1: Basic index properties of the tested cohesive soil.

| Properties | Natural moisture content (%) | Density (g/cm$^3$) | Specific gravity | Void ratio | Liquid limit (%) | Plastic limit (%) | Plasticity index | Liquid index | Unconfined compressive strength (kPa) | Standard number for each test |
|---|---|---|---|---|---|---|---|---|---|---|
| Cohesive soil | 51.70 | 1.73 | 2.75 | 1.41 | 63.60 | 33.70 | 24.60 | 0.92 | 55.70 | 2 |

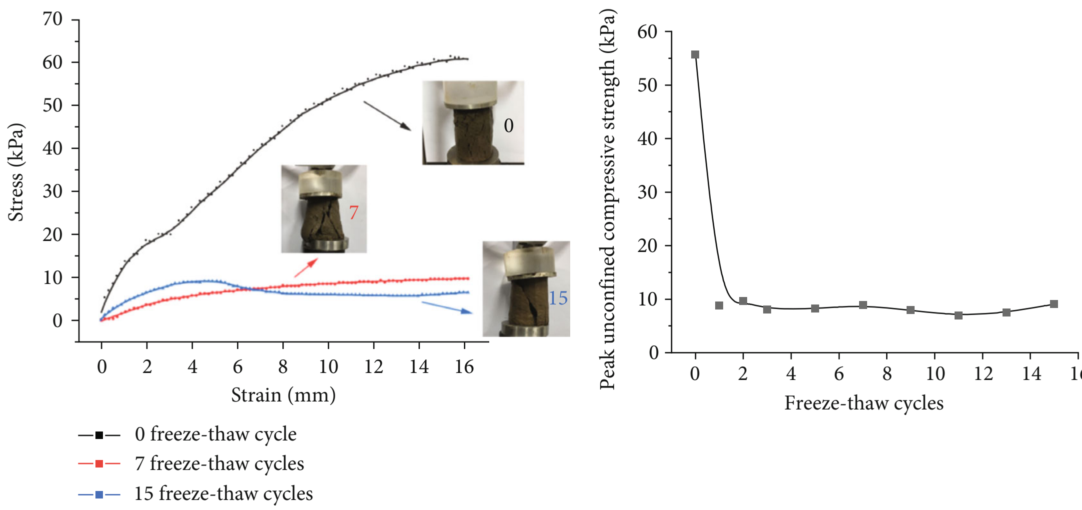
*2.3. Unconfined Compressive Strength Test.* Unconfined compressive strength tests of specimens with different freeze-thaw cycles have been performed to investigate the evolution characteristics of the mechanical properties. The sample was placed on the lower pressing plate, and the handwheel was rotated to make the sample just contact with the upper pressing plate. Adjust the reading of axial displacement meter and axial dynamometer to zero. The shear rate was controlled at 2.4 mm/min during the tests according to the Standard for Soil Test Methods (GB/T50123-2019), and the test was terminated when the strain reached 20%. Records were done with an interval of 0.5% strain when the total strain was less than 3% and an interval of 1% after 3% of total strain. An YZ-1SZ-3-B1S triaxial compressive strength machine was used for the unconfined compressive strength tests, which have been performed on all specimens.

*2.4. NMR and SEM Tests.* NMR refers to the resonance transition phenomenon of atoms with spin magnetic moments caused by electromagnetic waves within a constant magnetic field. Hydrogen atoms of free water in soil can produce NMR phenomena. The fluid in the porous medium has special NMR relaxation characteristics, and the NMR relaxation time (T2 spectrum) can be used to analyze the physical properties of the fluid in the soil sample. By testing the T2 spectrum of the saturated samples after each freeze-thaw cycle, the evolution of pore volume and pore size can be analyzed, which would reflect the pore distribution characteristics. T2 spectrum was tested for both drying samples and saturated samples. Then, the saturated samples were frozen for 12 h, melted for 12 h, and then vacuumed for the first freeze-thaw cycle. The T2 spectrum and weight was tested by then. NMR tests were performed on specimens subjected to 0, 1, 2, 3, and 5 freeze-thaw cycles by repeating the former steps. A MesoMR23-060H-I machine has been used for the NMR tests.

A narrow focused high-energy electron beam is used to scan the specimen. The interaction between the beam and the specimen provides various kinds of information of physical properties. The information is collected, amplified, and reimaged to get detailed information on microstructural characteristics, such as pore types and connection properties. SEM tests were performed on untreated specimens and specimens subjected to 1 and 2 freeze-thaw cycles. All samples have been cut into cubes of 10 mm × 10 mm × 10 mm when they were air-dried to semi-solid state by lyophilization. Before the test, the fresh section was made and pasted on the sample plate. All samples were coated with gold when they had dried for good electrical conductivity. Then, the sample was placed in the sample chamber and evacuated. A FEI Quanta 200 machine was used for the SEM tests. The enlargement factor is chosen as 5000 by referring to [4, 30].

## 3. Results and Discussion

*3.1. The Effects of Freeze-Thaw Cycles on Compressive Strengths.* After freeze-thaw cycles, the relationship between the unconfined compressive strength and the number of freeze-thaw cycles is shown in Figure 2(a). The stress-strain behavior transitioned from strain-hardening as stress increases with strain (0 freeze-thaw cycle and 7 freeze-thaw cycles) to strain-softening as crest appeared during this increasing (15 freeze-thaw cycles). It indicates that soils with more numbers of freeze-thaw cycles




(a) (b)

Figure 2: Relationship between the unconfined compressive strength and the freeze-thaw cycles: (a) stress-strain behavior and (b) peak strength versus freeze-thaw cycles.

are more likely to behave strain-softening phenomenon. Zhang et al. [37] found that the failure mode of soil samples changed from brittle failure to plastic failure after increasing the numbers of freeze-thaw cycles.

According to Figure 2(b), the unconfined compressive strengths show significant deterioration. After the first freeze-thaw cycle, the value of compressive strength reduced by 84.2%. However, after the first cycle, the strength deterioration rate decreased, and the strength values stayed in a range of 7.5 kPa to 9 kPa for the rest cycles. This can be stated that during freeze-thaw processes, internal texture of the soil specimens has reached a dynamic balance. Water in the void of the soil froze, then the ice volume expansion damaged the texture of the soil mass, and thawing process resulted in the reduction of the unconfined compressive strength. After the first cycle, the void decreased with the rearrangement, where the pore water decreased. The ice volume expansion for the next freeze-thaw cycles reduced, resulting in less reduction of the compressive strength. Benoit [38] and Wu et al. [39] also proved that the greatest changes in relative value occurred after the first freeze-thaw cycle with further changes being significant but of smaller value. Jamshidi et al. [40] found a reduction in the unconfined compressive strength of cemented soils when they were exposed to 3 freeze-thaw cycles.

The sensitivity of a clay is defined as the ratio of undisturbed strength and the remolded strength as

$$S_t = \frac{c}{c_r}, \tag{1}$$

where $S_t$ is the sensitivity of the soil sample, $c$ is the strength of undisturbed soil (kPa), and $c_r$ is the strength of remolded soil (kPa).

Sensitivity is a function of the relative looseness of packing of the particles [41]. According to Figure 3, the sensitivity of the original soil specimen was 2.1. However, after the freeze-thaw cycles, the sensitivity decreased dramatically, and the value reduced to below 1. Both freezing-thawing effect and artificial remold could be regarded as the process of endowing soil with a new structure. In general, the sensitivity of soil is larger than 1, which means that the strength of the artificial remolded soil sample deteriorates after the original balance structure is destroyed. It also indicates that the artificially remolded soil structure is obviously inferior to the natural soil structure. However, after the influence of freeze and thaw cycles, the structure of the soil body was damaged more seriously than that of the remolded one, where the sensitivity drops below 1. This tendency shows a great damage in the structure by freeze-thaw influences, the degree of damage caused by freezing and thawing was even greater than that of the remolded function.

*3.2. The Effects of Freeze-Thaw Cycles on Soil Pore Networks and Void Ratios.* The results showed that the effects caused by freeze-thaw cycles on soil pore networks were significant, inducing changes in soil aggregate stability and hydraulic properties. The void ratio showed a decrease after the first, second, and third freeze-thaw cycles and then stayed stable through the next several cycles. After the third freeze-thaw cycle, the void ratio with no consolidation pressure stayed stable (Figure 4(a)). Under the influence of freezing and thawing process, the soil structure was damaged. After different consolidation pressure applied after freeze-thaw cycles, the variation of void ratio caused by freezing and thawing weakened with the increase of consolidation pressures (Figure 4(b)). When the pressure rose to 400 kPa, the relationship between the void ratio and the freeze-thaw cycles tended to be a flat line. The influence of freezing and thawing on the characteristics of the voids decreased, when these voids in the soil sample were compressed by applying higher pressure. It indicates that the change of void ratio caused by freezing and thawing can be almost offset under such consolidation pressure.

The freeze-thaw cycles can be divided into repeated processes of frost-heave and thaw-settlement. During this process,

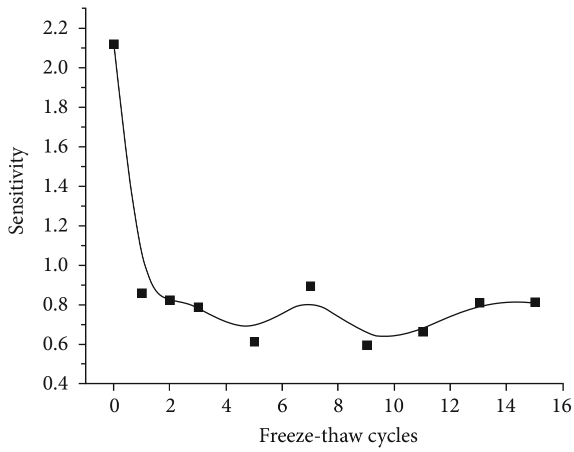



Figure 3: Variation of sensitivity under different freeze-thaw cycles.

water molecules gradually expand the pores during the frost-heave stage, resulting in an increasing trend of the void ratio. Some unconnected small pores in the cohesive soil are connected and form larger pores. After thaw-settlement process, water precipitates from the connected pores, the soil particles collapse, and the contact formation leads to a reduction in both void ratio and specific surface area. Due to the precipitation of water, the increasing trend of void ratio caused by frost-heave effect would also decrease, and the effect of thaw-settlement caused by the collapse of soil particles will also decrease. The effects of frost-heave and thaw-settlement during the freeze-thaw cycles can be regarded as a dynamic system. With the increase number of freeze-thaw cycles, a dynamic equilibrium system gradually formed. The test results show that the void ratio gradually stabilized within a small interval after the 3 freeze-thaw cycles.

This result is in accord with the results in the study of Chamberlain and Gow [42], in which they studied four kinds of soils and found that in all cases of fine-grained soils, freeze-thaw cycles caused significant structural changes in consolidated clay slurries, which in turn caused decreasing in void ratio and great increasing in vertical permeability. In this study, specimens were dominated by a flocculated clay matrix, in which the sand or silt grains were not in contact but were floating in the matrix. In this situation, both the compressibility and the permeability were controlled by the arrangement of the clay particles. The collapse and rearrangement of the clay packets caused by freezing and thawing led to a more dispersed structure, resulting in a reduction in void ratio. Chamberlain and Gow [42] pointed that there was little or no change in void ratio after freezing and thawing if coarser sand or silt grains controlled the packing. Meanwhile, in Tang and Yan's study [4], both the equivalent void ratio and the total pore area decreased after freeze-thaw test, indicating that the pore volume decreased and a thaw settlement on a macroscopic existed.

*3.3. The Effects of Freeze-Thaw Cycles on Microstructures.* The SEM pictures are shown in Figure 5. Based on the SEM tests and combined with lab tests, the SEM images showed the most obvious changes after 0, 1, and 2 freeze-thaw cycles. The variation became weak after 2 freeze-thaw cycles. Therefore, SEM images of 0, 1, and 2 cycles were used for analysis in this part. Cohesive soil has the properties of high water content, high porosity, and low permeability. The study soil layers contain various thin layers of silt sand, fine sand, and silt, due to the coastal sedimentary environment. Fine-grained soils predominate the structure, which leads to a relatively low permeability. During freeze-thaw cycles, the change of temperature led to the internal structure of the soil to be rebuilt. The arrangement of soil particles became loose, and the originally unconnected small pores are gradually connected, forming large and connected pores. The permeability was increased by those connected pores.

Before freeze-thaw cycles, the soil particles were granular, forming an untidy pile, which indicated that it had a flocculent structure. Point to point contact and point to edge contact accounted a large amount of the connections between soil particles. There were a large number of small pores. Most of these pores were not connected. After the first freezing process, ice lens was formed due to water migration. The frost-heaving force increased the compaction of the soil body, and those soil particles were flattened and arranged finally. The bonding and arrangement of particle connections and soil structures were strongly affected by energy inputting and outputting on soil during freezing and thawing. After the first freeze-thaw cycle, face to face contact was replaced with point to point contact, becoming the main contact formation between soil particles, which led to a reduction in the specific surface area, indicating that the void ratio decreased. The melting of the ice lenses led to the development of cracks in soils, remolded the soil texture, resulting in a decrease on soil strength.

Figure 6 shows the relationship between relaxation time and pore volume ratio under different freeze-thaw cycles. Before freezing and thawing, only one main wave crest existed, indicating that there was no macropore in the original soil specimen. After the fifth freeze-thaw cycles, the changes for each cycle were slight, so only the first 5 freeze-thaw cycles were displayed in the results section. There were two wave crests during 1-5 cycles; crest 1 was the main crest, distributed in the range of 0.001-1 ms; crest 2 distributed during 10-10000 ms. With the increase of freeze-thaw cycles, the main crest had an obvious tendency to move to the right along the relaxation time. It means that the relaxation time corresponding to the wave crest extends and the pore diameter corresponding to the crest increases gradually. The peak intensity of crest 1 reduced and that of crest 2 rose as the crest shifted to the right.

In the first and second freeze-thaw cycles, the pores in the soil were still mainly micropores, with a small amount of medium and macropores increasing. With the increase of freeze-thaw cycles, the wave crest continued to move to the right, indicating that the pore diameter gradually increased. The increasing of cycles led to the intensification of expansion of small pores and the generation of more medium pores and macropores. The results show that damage occurred under freezing and thawing process, the damage degree increased with the increase of freeze-thaw cycles. The freezing-thaw damage of soil is a cumulative process. However, the total crest area stated the pore volume ratio decreased after the freezing and thawing.

With the increase of freeze-thaw cycles, the ratio of small pores decreased, and the large pores increased. After the

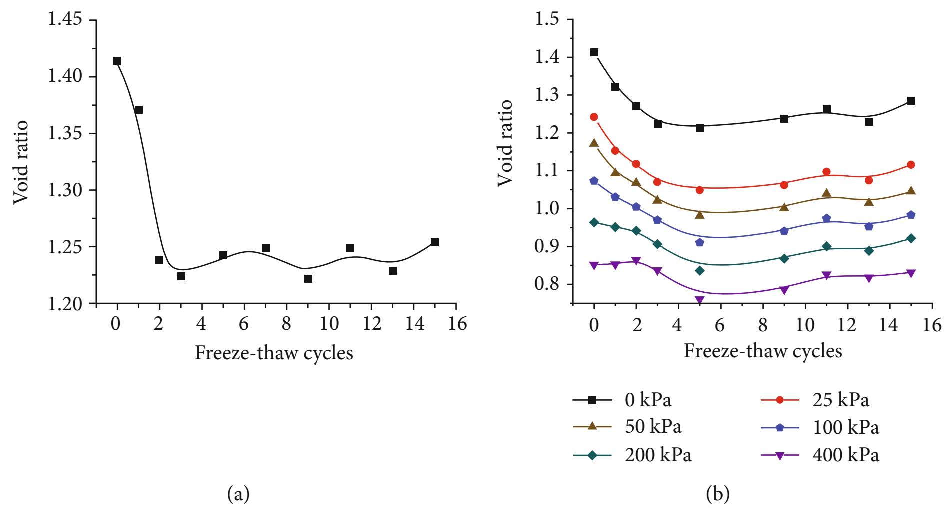



FIGURE 4: Variation of void ratio with different freeze-thaw cycles: (a) 0 kPa and (b) 0–400 kPa.

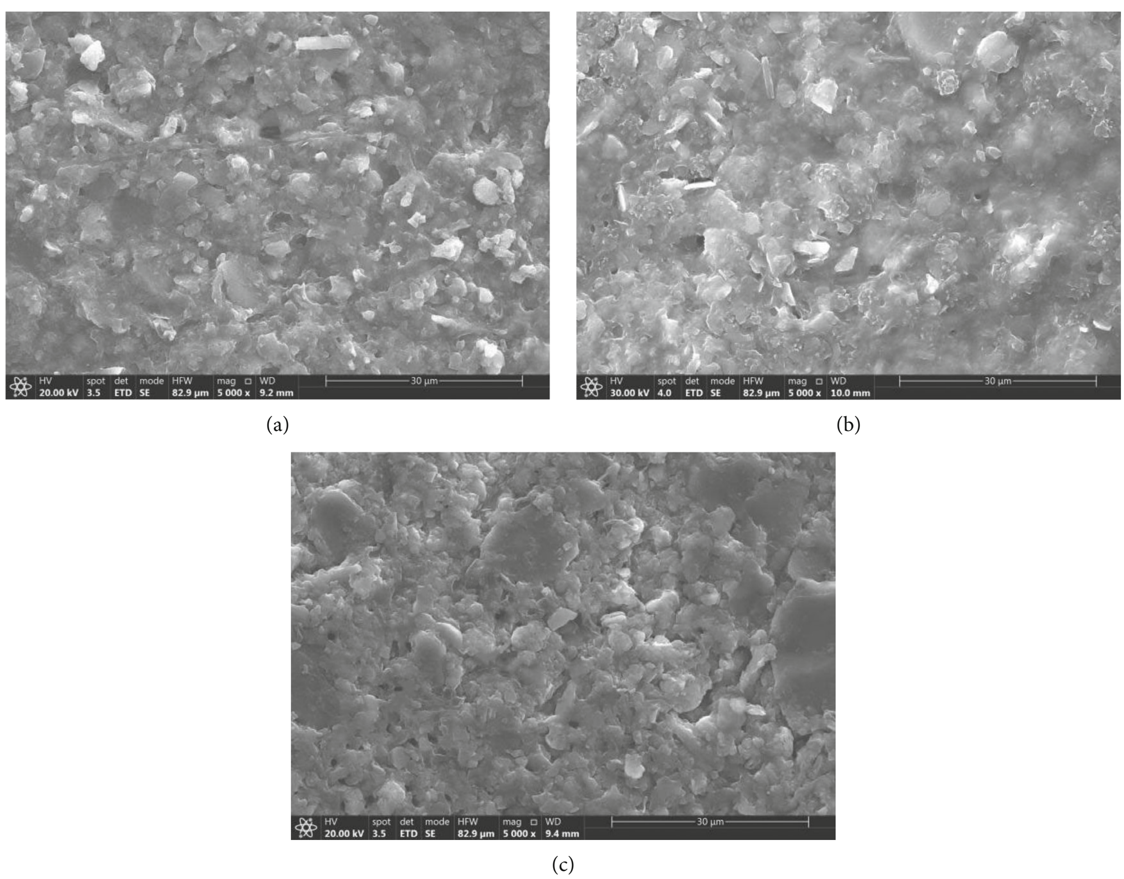



FIGURE 5: Microstructure with SEM test: (a) 0 freeze-thaw cycle, (b) after 1 freeze-thaw cycle, and (c) after 2 freeze-thaw cycles.

specimens subjected to the freeze-thaw effect, the proportion of pores with a diameter of 0-0.1 $\mu$m has decreased from 25% and 55% (0 cycle) to 20% and 50% (1, 2, 3, and 5 freeze-thaw cycles), respectively; the pores with a pore size in the range of 0.1-1 $\mu$m has increased from 20% to 30% (Figure 7). A small amount of large pore size in the range of 16-100 $\mu$m appeared after freezing and thawing cycles.

During the freeze-thaw processes, the volume change caused by water molecules in the soil mass during the frost heave process forced the pores to change. The original

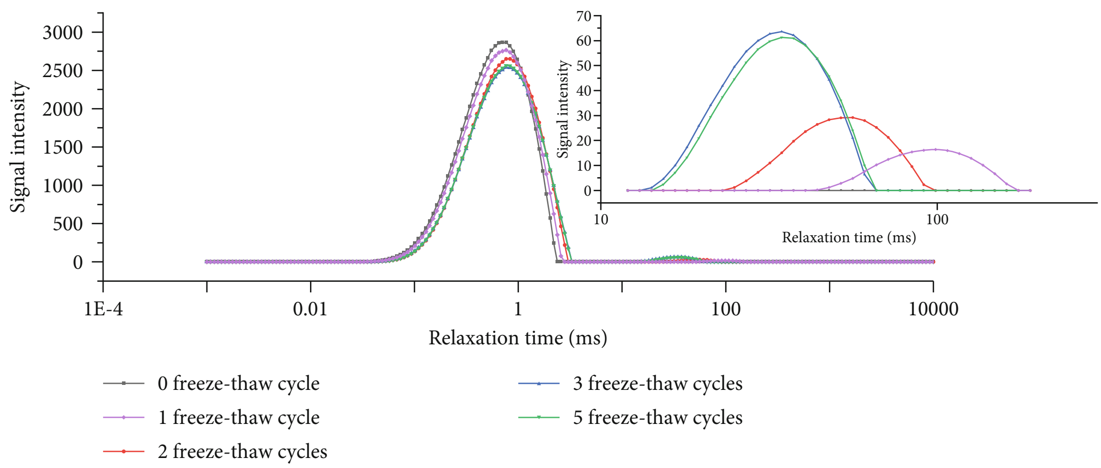



FIGURE 6: Variation of T2 spectrum with different freeze-thaw cycles.

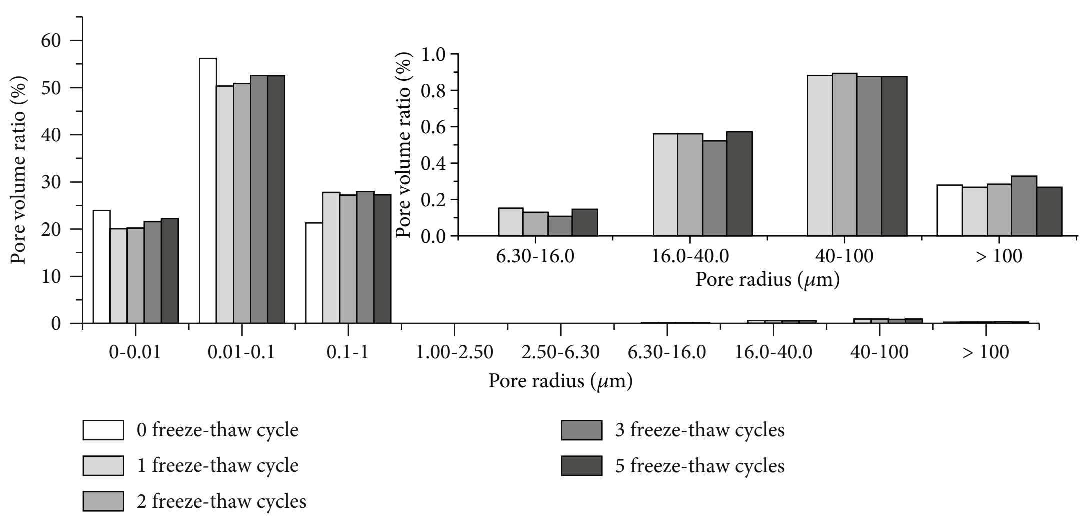



FIGURE 7: The proportion of accumulated pore volume with different freeze-thaw cycles.

structure of the cohesive soil was destroyed, which changed the stability of the soil, resulting in severe loss of compressive strength at the macroperspective after the first freeze-thaw cycle. The proportion of pore size in the range of 0.01-0.1 $\mu$m decreased after the freeze-thaw cycle, but the proportion basically remained above 50%, maintaining its dominant position. The mechanical property shows that the permeability has increased but not greatly improved, and the moisture content has decreased but was finally stabilized at a high water content standard of 40%. The results show that there is a correlation between the microstructural changes and the mechanical properties under freeze-thaw cycles.

There may be some possible limitations in this study. Suction is one of the important properties in cohesive soils. Soil strength is derived from soil suction. This study did not include the relationship between the variations of suction versus freeze-thaw cycles. This part will be considered in the future study of cemented reinforce soils.

## 4. Conclusion

The influence of freeze-thaw cycles on the mechanical behaviors and microstructure of the Tianjin Binhai cohesive soil was investigated through unconfined compressive strength tests, SEM tests, and NMR tests in this study. Depending on the test results obtained from the current study, the following conclusions can be made.

(1) The unconfined compressive strength of the soil responded significantly to freeze-thaw cycles. The strength value decreased by 84.2% after the first cycle and stayed at a range of 7.5 kPa to 9 kPa for the next few cycles for a stable state

(2) The axial stress-strain response showed a strain-hardening behavior transitioned to a strain-softening behavior after 15 freeze-thaw cycles. It indicated that

the structure of the soil damaged significantly with shear zones existing and being unstable

(3) The increasing of cycles leads to the intensification of expansion of small pores and the generation of medium pores and macropores. But the influence of freezing and thawing on void expansion weakened when there was an increase in consolidation pressure

(4) On a micro level, the void ratio and total pore area were all reduced, due to the aggregation of soil particles and face to face contact domination after freeze-thaw cycles. During the freeze-thaw cycles, large pores increased, some microcracks were generated, and small pores were connected

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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