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Research Article

Experimental Study on the Rheology and Cryo-Mechanism of Pile-Frozen Soil Interface

Qiang Gao,[1,2] Zhi Wen,[1,3] Zhiwei Zhou,[1] Wei Ma,[1] Anatoli Brouchkov,[2] Rui Shi,[1] and Yasheng Li[1,4]

[1]*State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*Lomonosov Moscow State University, Moscow 109807, Russia*
[3]*School of Civil Engineering, Lanzhou Jiao Tong University, Lanzhou, Gansu 730100, China*
[4]*University of Chinese Academy of Sciences, Beijing 100049, China*

Correspondence should be addressed to Zhi Wen; wenzhi@lzb.ac.cn

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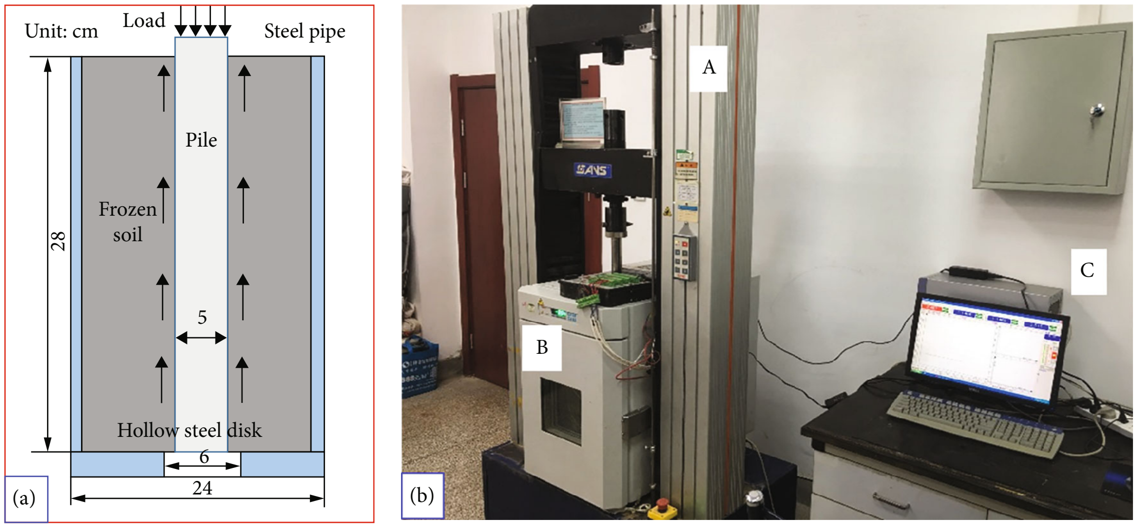
The rheological behavior of a pile-frozen soil interface can accelerate pile settlement in pile foundation engineering and deteriorate the bearing capacity of the pile in cold regions. This is the core basis for guiding the design of pile engineering and judging the service life of pile foundations. However, it is unclear how the rheological process is affected by the factors which determine the ad-freeze strength at the pile-frozen soil interface. In this paper, based on a series of Multistage Loading Creep Test (MLCT) for pile-frozen Qinghai-Tibet clay soil interface and microscopic observations of frozen soil, the rheological process and the cryo-mechanism of the interface were analyzed. The results showed that the decrease in soil temperature reduce the interface's instantaneous deformation value and creep rate, which results from the temperature-dependent rheological behavior of ice. The trend also occurs in the soil with coarser particles and the pile with a rough surface. The presence of massive ice in frozen soil benefits the bearing capacity of the interface at a high temperature of -1°C. However, it can considerably increase the interface's creep rate due to the influence of the rheological properties of ice at a relatively low temperature of -5°C. Either thick lenticular ice lens or chaotic reticulate cryo-structures in the frozen soil surrounding a pile will enhance the interface's rheological properties. The interface exhibits the lowest instantaneous deformation value and the slowest creep rate for frozen soil with the massive cryo-structure, which is formed with optimum moisture content. From an engineering viewpoint, the settlement of a pile foundation can be reduced by controlling its instantaneous deformation or restraining its creep rate.

1. Introduction

A pile is the most common deep foundation type of bridges, houses, transmission lines, and other geotechnical engineering projects. The frictional resistance of soil acting on the side surface of the pile bears the upper load of the pile foundation. The magnitude of the friction is determined by the shear mechanical properties of the pile-soil interface. The ad-freeze bond strength at the pile-frozen soil interface usually accounts for almost the majority of its total bearing capacity and contributes to the far greater bearing capacity of piles in permafrost regions than that of piles in general areas. Numerous experimental investigations on the interface shearing characteristics have been carried out to clarify the displacement behavior of the pile [1–7]. However, engineering practices have shown that the bearing performance of pile foundations deteriorates in permafrost regions, and the settlement of pile foundations is gradually aggravated over their service life nonetheless ([8–11]. Some researches have shown that the time-dependent settlement of a pile is dominated by the rheology of the pile-frozen soil interface ([12–14]. Investigations describing the long-term creep behavior of pile foundations cannot be utilized without reliable verification results from laboratory tests. Therefore, the rheological processes, as well as the cryo-mechanism of the interface between the pile and frozen soil, are the core basis



(a) (b)

Figure 1: Pile-frozen soil structure (a) and creep testing apparatus (b). (A) Material testing machine. (B) Thermostats. (C) Data collection system for displacement and load.

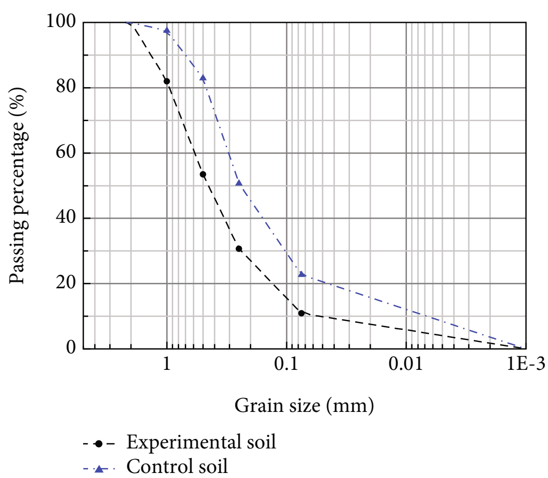


Figure 2: Grain distribution of the clay.

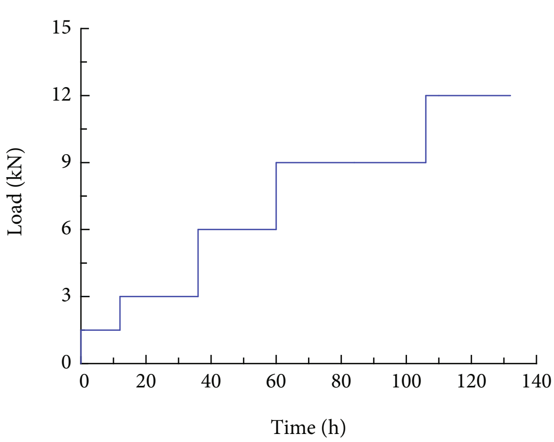


Figure 3: Loading method of the MLCT.

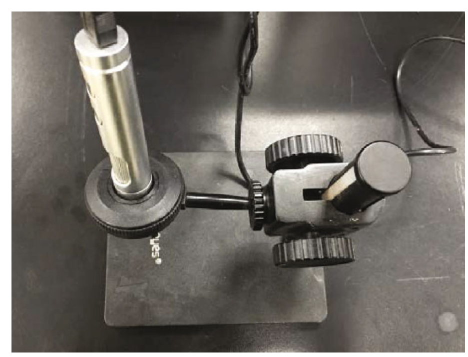


Figure 4: Cryo-structure observation system for frozen soil surrounding a pile.

for guiding the design and judging the service life of a pile foundation.

Rheology refers to the plastic flowing properties of materials under an external force. Studies on it have mainly focused on the relationship among stress, deformation, deformation rate, and viscosity [15]. Generally, the rheology of frozen soil is characterized by creep, stress relaxation and long-term strength reduction ([16–18]. Similarly, the rheology of a pile foundation has always been investigated by characterizing the creep behavior of the pile-frozen soil interface. The creep behavior depends on the properties of the pile and surrounding frozen soil. The former includes its material and surface roughness, and the latter includes soil quality, particle dispersion, moisture content, temperature, salinity, and freeze-thaw process [19–21]. Biggar and Kong [22] found that the time index for the time-dependent deformation of piles is independent of the load but dependent on the pile surface according to a series of field tests of piles in the Arctic area, Canada. The index also decreases as the salinity in frozen soil increases [23]. Stelzer

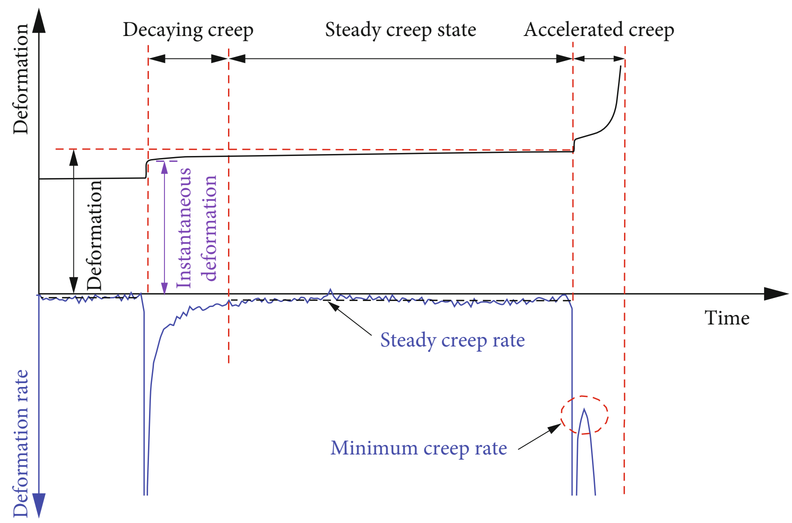


Figure 5: Basic principles of the multistage loading creep test (MLCT).

and Anderson [24] studied the relationship between creep parameters and main influencing factors, including the loading modes, pile roughness, ice content, and particle dispersion through steel model piles. As a strongly viscous material, ice in frozen soil plays a very important role in the rheology of pile foundations. Morgenstern et al. [13] proved that a prediction of the flow velocity of a pile foundation in ice and ice-rich frozen soil based on the ice flow criterion was consistent with test results. The bearing capacity of piles in frozen soil is even one order of magnitude larger than that in ice under the same strain rate [21]. Apart from the decrease in the instantaneous bearing capacity of the pile, the time-dependent settlement of the pile is aggravated under the background of climate warming. Nixon [25] and Abdulghader and Mohammad [12] all found that the creep rate of piles in frozen ground increases as the ground temperature increases. The latest research has found that the mechanical property of the interface during shear creep are strengthened first and then obviously damaged with the increase of shear stress [26].

To investigate the cryo-mechanism of the creep behavior for frozen soil, a combination of creep tests and cryo-structure has been widely adopted [27, 28]. As a multicomponent geomaterial with mineral particles, ice inclusions, unfrozen water, and gas, frozen soil has distinctive mechanical properties different from those of unfrozen soil. The mechanical properties of frozen soil are temperature- and rate-sensitive due to the viscosity of ice and the phase transition between ice and unfrozen water. Many researchers have found that the rheological properties of frozen soil are dependent on the cryo-structure, thickness, and orientation of segregation ice ([29–31]. Although CT technology with the nanoscale resolution has been used in studying the creep behavior of frozen soil, those studies mainly focused on revealing the internal deformation process, rather than the influence of cryo-structure on creep. The ad-freeze strength of the pile-soil interface is mainly determined by ice cementation, which is extremely similar to that in frozen soil. The rheological characteristics of a pile-soil interface are closely related to the cryo-structure of the frozen soil surrounding the pile. Few efforts have been made to reveal the core mechanism of the rheological properties of pile foundations. In this paper, a model creep test of a pile-soil interface was designed, and a series of creep tests with different temperatures, moisture contents, particle dispersions of soil, and pile surfaces were conducted. The creep features as well as key parameters, i.e., steady creep rate and instantaneous deformation, were analyzed. Then, microscopic observation of the dissected frozen soil surrounding the pile was further performed, and the relationship between the cryo-structure of the frozen soil and the interface's rheological behavior was investigated.

2. Experiment

2.1. Pile-Frozen Soil Structure Preparation and Testing Apparatus. A material testing machine and a temperature-adjustable incubator were combined to perform a shear creep test for a pile-frozen soil structure. The accuracy of the temperature control in the incubator was ±0.05°C. A photograph of the testing apparatus is shown in Figure 1. Three-step process was required for the initial preparation of the pile-frozen soil structure. First, a concrete pile (diameter of 5 cm and length of 33 cm) was prepared. Second, soil samples prepared with different moisture contents (37%, 27%, and 20%) were placed in a sealed box for more than 24 hours to keep the moisture uniform. Typical clay obtained from the Beiluhe area in the Qinghai-Tibet Plateau was used in this experiment. The grain size distribution of the clay is listed in Figure 2. The liquid and plastic limits of the clay are 35% and 21%, respectively. For comparative purposes, a control clay with another particle gradation was also prepared for the control tests, as shown with the blue line in Figure 2. Finally, the concrete pile was vertically fixed in the center of a steel pipe (diameter of 24 cm, height of 28 cm, and wall thickness of 1 cm). A round hole (diameter of 6 cm) in the center of a bottom plate was reserved to ensure that the concrete pile was only subjected to side

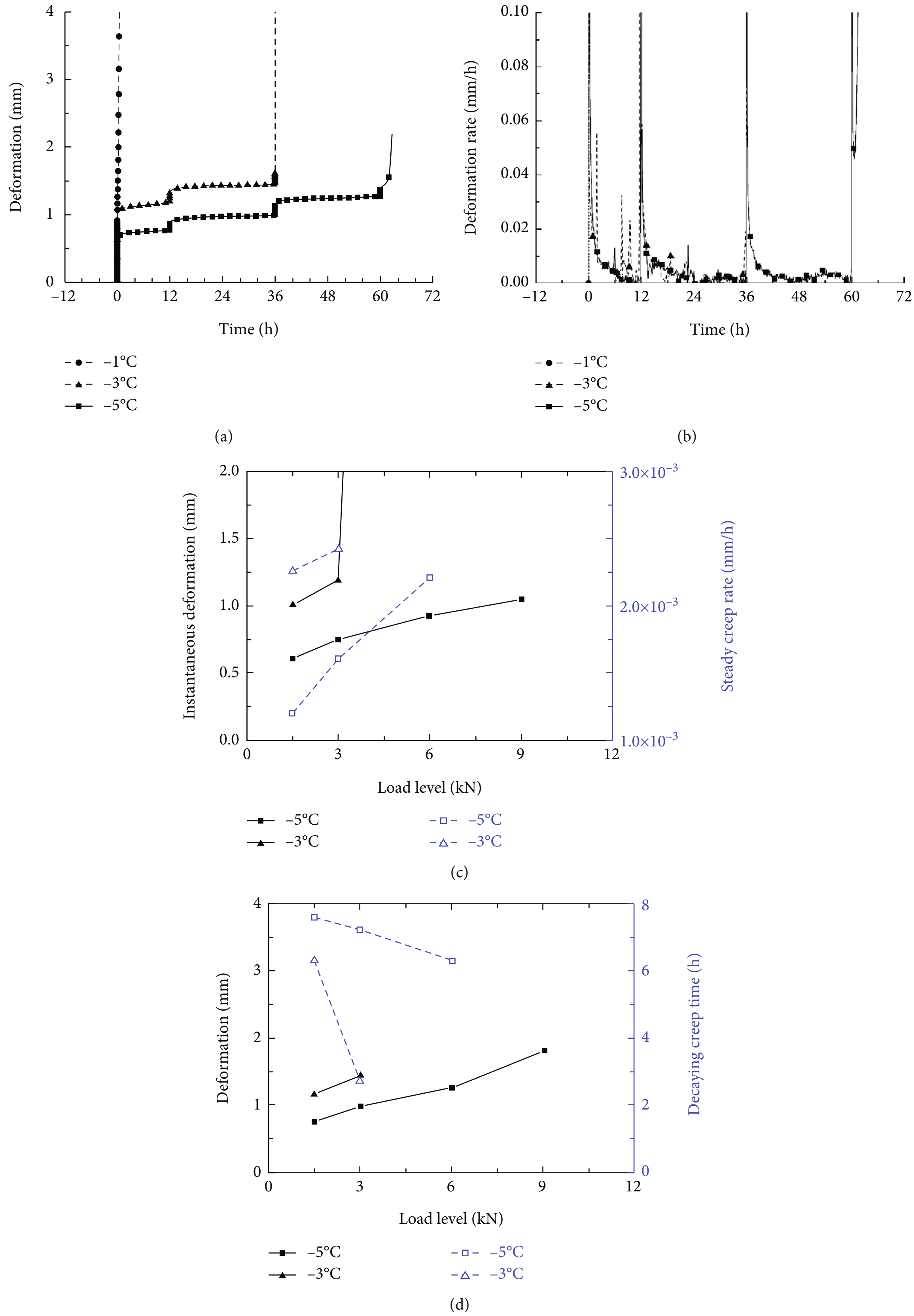
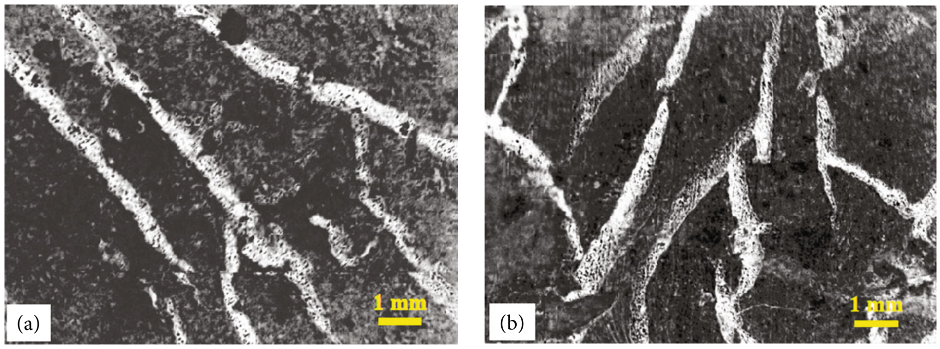


Figure 6: Creep parameters of the pile-frozen soil interface subjected to different given temperatures.



(a) (b)

Figure 7: Macroscale images of a frozen soil cryo-structure with a moisture content of 37% at temperatures of -5°C in (a) and -3°C in (b).

resistance under the load at the pile top. The soil sample was filled in the pipe layer by layer, which was then placed in a temperature-controlled refrigerator with an accuracy of ± 0.05°C for rapid freezing. Once the pile-soil structure was completely frozen, the refrigerator was adjusted to the test temperature and kept constant for more than 24 hours. A layered freezing method, adding water to the pipe with 2 cm in thickness each time and freezing until the pipe is completely filled with ice, was adopted in the preparation of pile-ice structures. Before the loading test, the testing structure was quickly moved to the incubator and kept for more than 12 hours at the testing temperature. Due to the long duration of sample preparation and testing, all samples were covered with clear plastic wrap to prevent sublimation of the water in the frozen soil and ice.

2.2. Testing Methods. In general, the period of the rheological test should be sufficiently long to ensure that a complete creep curve can be obtained. The Multistage Loading Creep Test (MLCT) was conducted due to its high efficiency and small discretization among the different test results. The method can not only shorten the test cycle but also obtain the influence of shear stress level on interface creep law. According to conventional shear tests of pile-frozen soil structures (temperature of -3°C, and moisture content of 37%), the shear strength and deformation characteristics of the pile-frozen soil structure were experimentally investigated. The loading procedures, including the loading values and corresponding durations, were carefully designed as shown in Figure 3. In particular, in order to obtain the relationship between stable creep rate and load level, the duration of each load level in MLCT increases with the increase of load level. To observe the cryo-structure of the frozen soil surrounding the pile, the structure was quickly dissected in cold storage after the end of the MLCT. A Supereyes device was used during the microscopic observation (Figure 4). Binary treatment of the micrographs was carried out and the test results and the character of separated ice in the micrographs were contrastively analyzed to explore the relationship between the cryo-structure of the frozen soil and the rheological characteristics of the structure to reveal the core cryo-mechanism of the time-dependent deformation at the pile-frozen soil interface.

3. Test Results and Analysis

The deformation process of the pile in the MLCT at a small loading level, shown in Figure 5, can be divided into three stages: the instantaneous deformation stage, decaying creep stage, and steady creep stage. The deformation rate of the pile abruptly increases when the next load level is applied, and then gradually decreases in the second stage. The shear modulus of the pile-soil interface can be obtained through the instantaneous deformation, which is a key index for judging the carrying capacity and stiffness behavior of a pile foundation. The deformation rate of the pile decays exponentially once the load is kept constant. The endpoint of the decaying creep stage is defined as the deformation point at which the creep rate is less than 1% of the creep rate at the onset of constant load. The decaying creep time is defined as the time from loading to the endpoint. The steady creep rate represents the average value in the steady creep stage. It should be noted that the steady creep rate is the most important index for characterizing the rheological property at the pile-soil interface, and it is also the key basis for judging the time-dependent displacement of the pile foundation over the service life of the structure. Once the load reaches a certain level, accelerating creep occurs. At this stage, the deformation rate rapidly increases until the pile-frozen soil interface is destroyed. Therefore, four important parameters, the instantaneous deformation value, final deformation value, steady creep rate, and decaying creep time, were selected to quantificationally describe the creep characteristics of the pile-soil structure.

3.1. Influence of Temperature on the Rheology of the Pile-Soil Structure. Figures 6(a) and 6(b) provide the development features of the deformation and deformation rate of the pile at different temperatures. The moisture content of frozen soil surrounding the pile is 37%. The deformation value of the pile during the MLCT significantly decreases as the temperature gradually decreases from -1°C to -5°C. The interface was destroyed under the first level load of 1.5 kN at -1°C, while it appeared under the fourth level load of 9 kN for the pile at -5°C. The increase of unfrozen water in ice and the decrease of ad-freeze strengths at the pile-frozen soil interface as the temperature approaches 0°C may be the

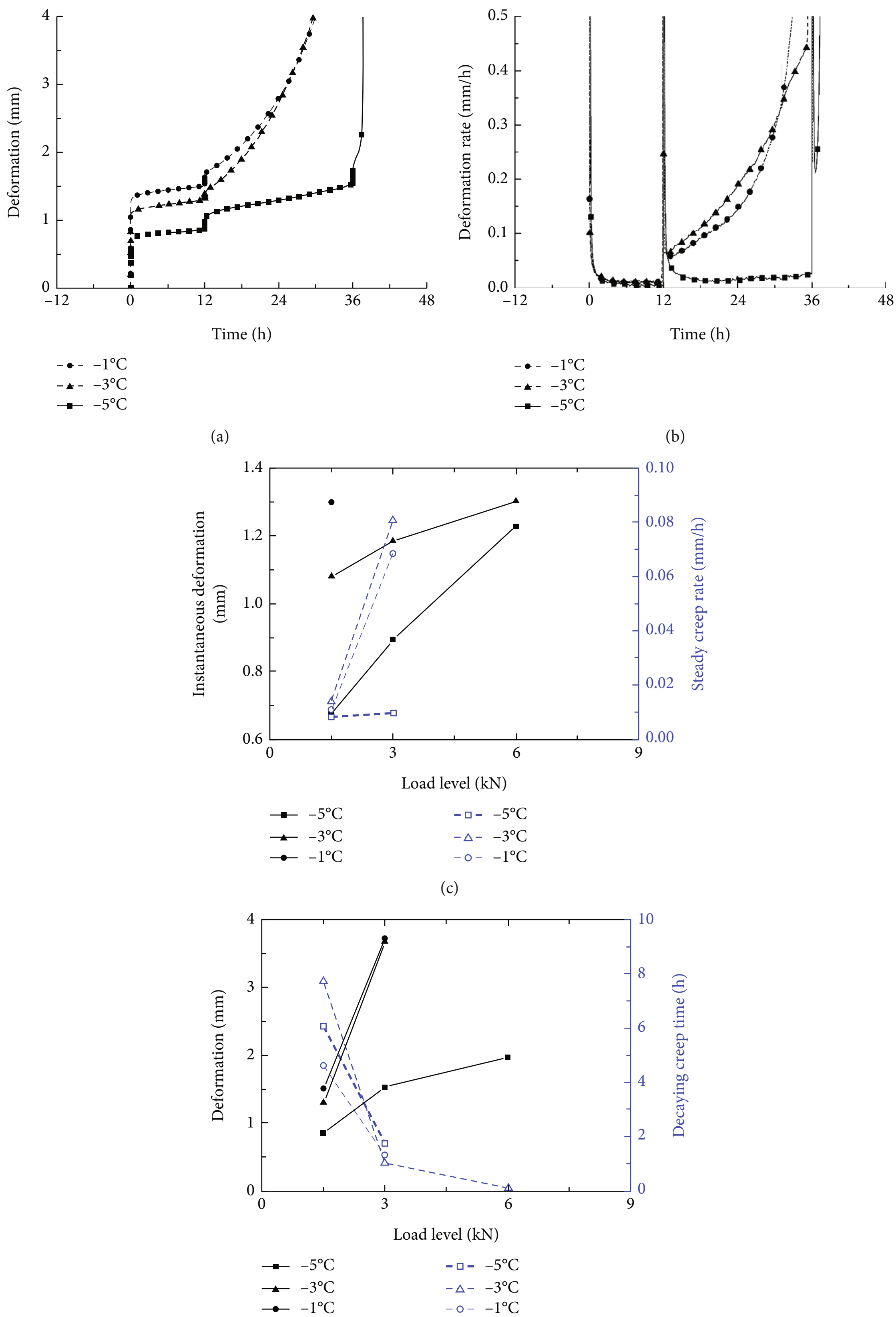


Figure 8: Creep parameters of ice-pile interfaces subjected to different given temperatures.

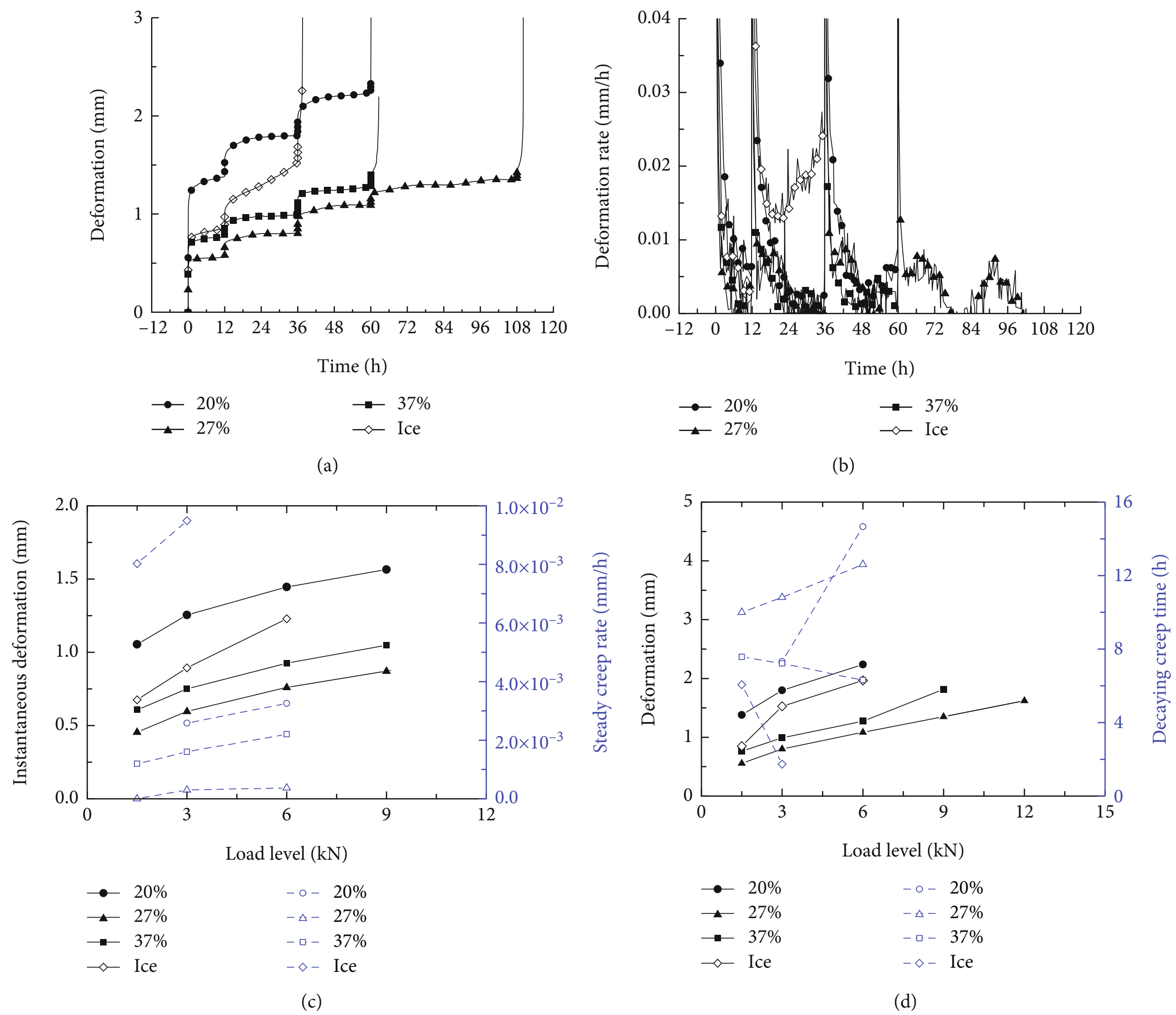
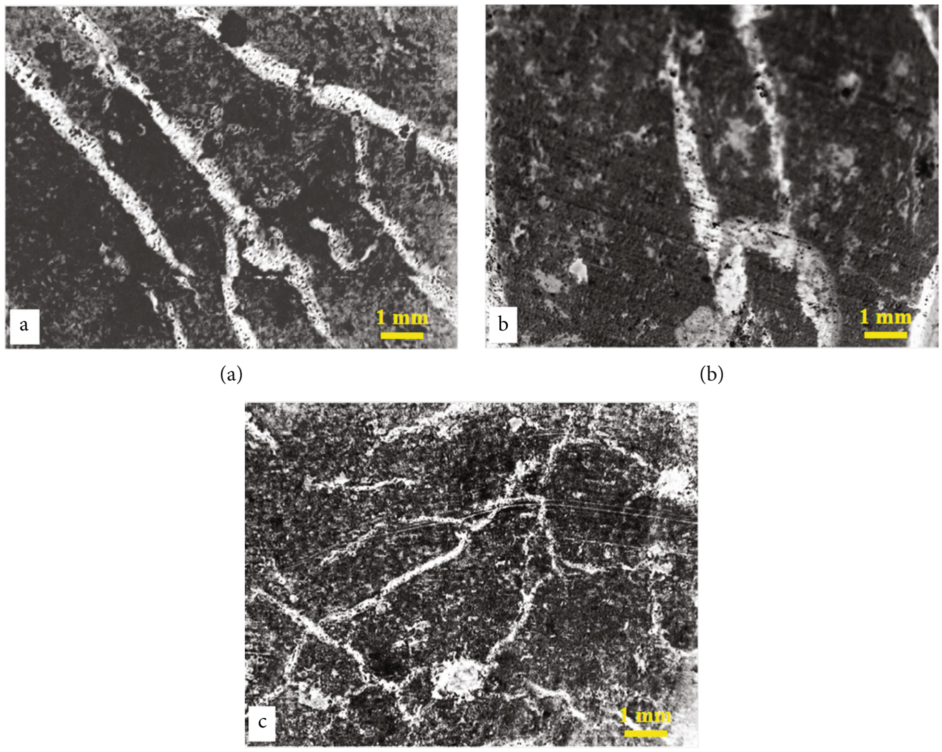


Figure 9: Creep parameters of interfaces between pile and frozen soil with different moisture contents.

main reason for this result. Therefore, the temperature has a severe effect on controlling the deformation of the pile.

Figures 6(c) and 6(d) show the variations in instantaneous deformation value, final deformation value, steady creep rate, and decaying creep time with load level. These figures indicate that with the increase in load level, the instantaneous deformation value, final deformation value, and steady creep rate gradually increase, while the decaying creep time gradually decreases. Compared with the result at -5°C, the instantaneous deformation value, creep deformation value, and steady creep rate is greater, while the decaying creep time is shorter at -3°C. This implies that temperature affects not only the time-independent deformation stage of the pile in the initial loading process but also the rheological characteristics at the creeping stage. The closer the temperature is to the transformation zone, the more obvious the rheology is.

Past experiences have shown that under a high load level, the rheological performance is intrinsically determined by the combined effects of the microstructural evolution and dislocation behavior [32]. The existence of ice and unfrozen water in frozen soil results in significant differences in the mechanical properties from those in rock and unfrozen soil. The micromechanics of the deformation process in frozen soil consists of dislocation and aggregations of skeleton particles, redistribution of the ice content, and migration of unfrozen water. In particular, the ice-a prominent viscous material and cryo-structure in frozen soil have a significant influence on the rheological behavior of frozen soil. The rheological properties of the pile-frozen soil interface are closely related to the cryo-structure surrounding the pile. Figure 7 shows the macroscale image of the cryo-structure in frozen soil with a moisture content of 37% surrounding the pile. The images, in which white stripes represent segregation ice, show a large number of lenticular ice lenses existing in frozen soil. According to Figures 6 and 7, it turns out that the creep features of the results at different temperatures are significantly different, although the macrocryo-structure of frozen soils is similar for frozen soils with the same moisture content, which may be induced by the same



(a) (b) (c)

Figure 10: Macrocryo-structure of frozen soils with different moisture contents of 37% (a), 27% (b), and 20% (c) surrounding a pile at a given temperature of -5°C.

freezing process during the preparation stage of the pile-frozen soil structure before loading tests. It is reasonable to speculate that the effect of temperature on the strength and stiffness of ice in frozen soil directly determines the rheological properties of the pile.

Figure 8 shows the creep result of the pile-ice interfaces under different temperatures. According to the figure, the temperature's effect on the creep of the pile-ice structure is consistent with that on ice creep obtained in the past [33], which is also similar to that on the pile-frozen soil structure. However, some differences should be further noted. A higher steady creep rate and a shorter decaying creep time can be observed for the pile-ice structure compared to the pile-frozen soil structure with 37% moisture content. The closer the temperature is to the phase transformation zone, the more obvious the steady creep rate responds to the increasing load. The reason is that the increase of temperature promotes the transformation of ice from solid to fluid, which strengthens the viscous property of frozen soil. The results shown in Figures 6–8 directly prove that the existence of a large amount of segregation ice in frozen ground with high ice content is the core factor controlling the rheological characteristics of the pile. Decreasing temperature can significantly reduce the creep rate and deformation value. In addition, the pile-frozen soil structure is nearly destroyed at -1°C, while the pile-ice structure has small deformation even with a relatively high creep rate at the same temperature. This result is also verified by the conclusion that ice creeps at a slower rate than frozen soil for temperature range from -1°C to -2°C [27]. The lower freezing temperature and much higher unfrozen water in frozen soil than in ice lead to the above conclusions.

3.2. Influence of Moisture Content on the Rheology of Pile-Frozen Soil Structure. Figure 9 shows the creep results of pile-frozen soil structures with different moisture contents at-5°C. It shows that the trend of the indexes is the same as those in Figure 6. A particular rule is that the decaying creep time does not significantly decrease with increasing load except for ice. The influence of the moisture content on the rheology is also different from the temperature. For frozen soil with moisture content of 27%, the structure has minimum deformation during the test. The instantaneous deformation, final deformation, and steady creep rate all first decrease and then increase as the moisture content increases, while the opposite occurs for the decaying creep time. The pile-ice structure exhibits the highest steady creep rate, but its deformation value is not the largest. The results indicate that there is an optimal moisture content corresponding to the minimum creep rate and deformation. The creep rate of the pile-ice interface is nearly an order of magnitude higher than that of the pile-frozen soil interface with 27% moisture content. The influence of the moisture content on the rheological effect of a pile foundation is similar to the results for frozen soil with different moisture contents [16].

To further investigate the effect of moisture content on the rheological behaviors of the structures, microscale images of the cryo-structure of frozen soil with different

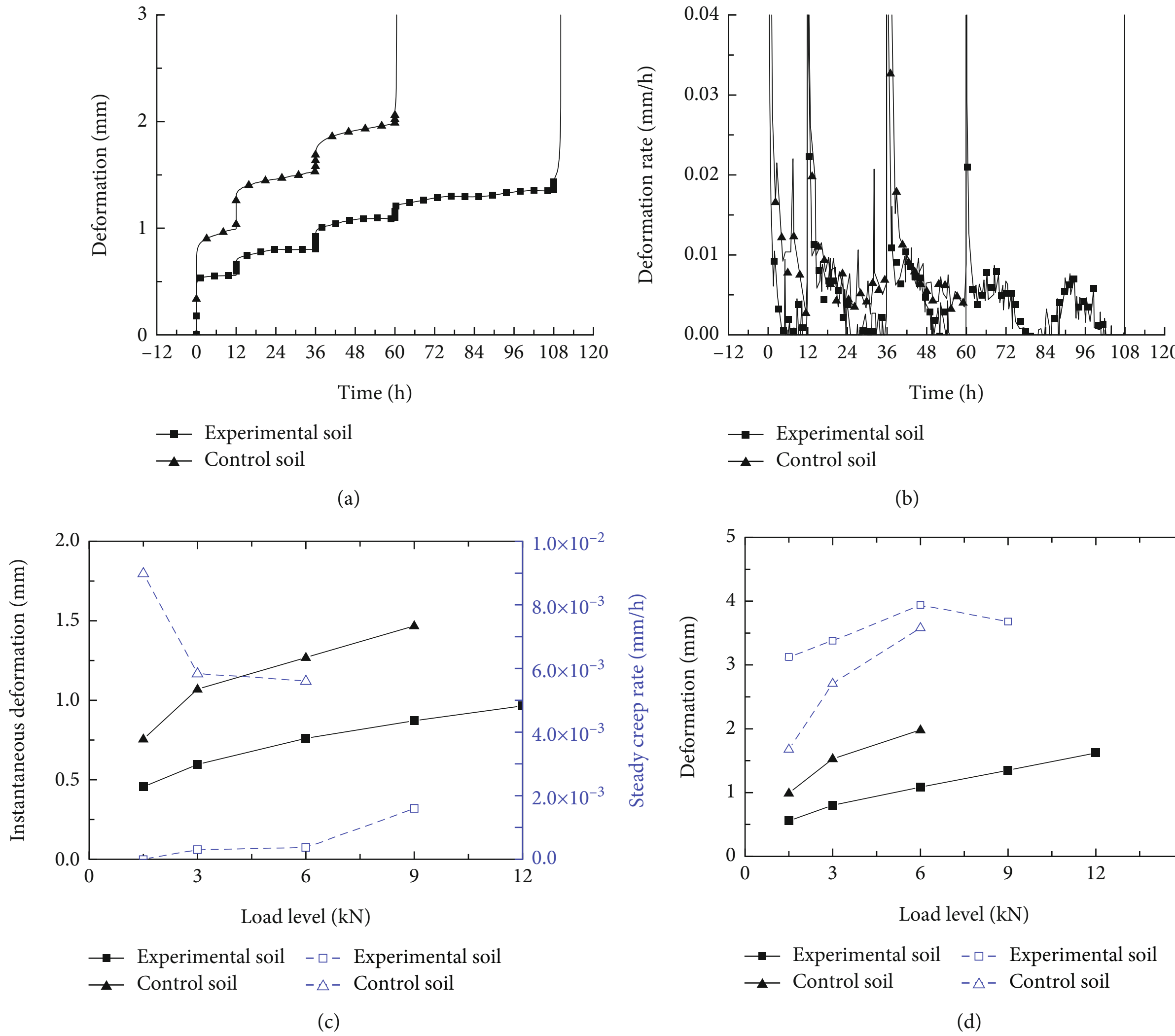
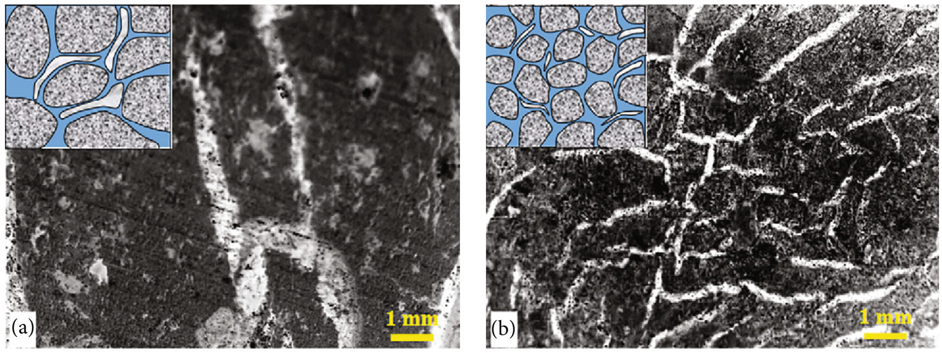


Figure 11: Creep parameters of interfaces between pile and frozen soil with different grain distribution.

moisture contents surrounding piles are shown in Figure 10. It demonstrates that the cryo-structures of frozen soil vary significantly with the moisture content, especially for thickness and dispersion of the segregated ice. For oversaturated soil, part of the free water freezes and condenses into ice lenses first, and residual water can easily migrate to the ice lenses [31]. The thicker ice lenses abounding in frozen soil reduce the strength of the frozen soil and increase its creep rate. For soil with relatively low moisture content, however, free water will freeze into ice in-situ to form a chaotic reticulate cryo-structure due to the soil particles impeding the migration of water without a through channel. A large amount of schlieren ice or mesh ice in frozen soil will lead to an increase in interface's creep rate. The result leads to significant increase in the contact area between soil particles and separated ice. Under the external load, the shear stress in the pile-frozen soil structure causes the weak soil-ice interface to slide more easily due to the interface effect. When the moisture content is probably 80%~90% of the saturated water content, a massive cryo-structure probably appears in frozen soil. The massive cryo-structure will impose restrictions on the rheology of the pile-frozen soil interface. Therefore, the cryo-structure of the frozen soil surrounding the pile has an important influence on the rheology of pile-frozen soil structure, and the thickness and dispersion of ice lenses in frozen soil both have excellent stimulus effects on the instantaneous deformation and creep behaviors of the interface.

3.3. Effect of Soil Particle Gradation on the Rheology of the Pile-Soil Interface. To study the influence of solid particles on the rheology of the structure, another soil with different particle gradation, as shown in Figure 2, was selected as a control group in the MLCT at -5°C. Test results in Figure 11 show that the deformation curve of the pile-frozen soil structure with the experimental soil is far below that of the control group. The former sample was destroyed under a load of 12 kN, while the latter sample was destroyed under a load of 9 kN. Compared to the control group, the steady creep rate of the structure with the experimental soil is much smaller. Therefore, it is concluded that soil with more finer particles can increase the creep rate and deformation. Microscale images of frozen



(a) (b)

Figure 12: Macrocryo-structures of frozen soils with particle dispersions 2 (a) and 1 (b) surrounding a pile.

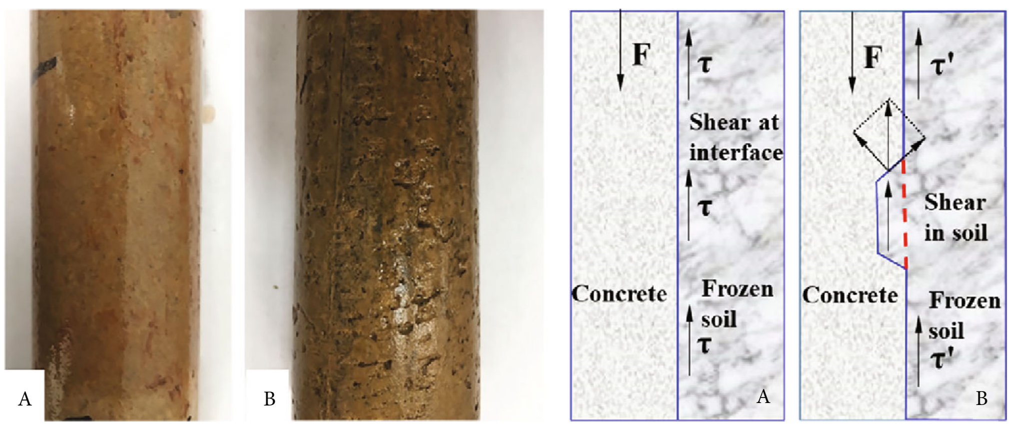


Figure 13: Piles with different roughness used in MLCT.

soil are shown in Figure 12 to clearly illustrate the effect of the finer particles on the rheology of the pile-frozen soil interface. Observation shows that a finer granular soil corresponds to a chaotic reticulate cryo-structure, which results in a higher creep rate and a larger deformation. The reason is that it is easier for fine and dispersed porous soil to form a chaotic reticulate cryo-structure during freezing without water migration. For coarse-grained soil, the carrying capacity of particles and ice dominates resistance to the external load, while for fine-grained soil, the resistance mainly depends on the friction among soil particles and ice-soil interfaces. In addition, regardless of the fact that the difference in unfrozen water between the two tests also affects the rheology of the structure, the results show that the influence of the cryo-structure on the rheological properties of the interface is decisive, and the influence of unfrozen water could be relatively ignored here.

3.4. Effect of Pile Surface on the Rheology of the Pile-Soil Interface. It is well known that the bearing capacity of a pile can be greatly increased by increasing the roughness of the pile foundation. However, the effect of roughness on the rheology of pile foundations is a new topic. Some previous efforts have found that during the construction of the cast-in-place bored piles widely used in the Qinghai-Tibet Plateau, the hydration heat released by concrete will melt and heat-erode the frozen soil surrounding the borehole, resulting in an increase in the surface roughness of the pile [1]. Therefore, two piles with different surfaces were selected for a comparative study of the influence of pile roughness on the rheology of the pile-ice interface at -5°C (Figure 13). According to the results in Figure 14, pile "B" with a rougher surface exhibits a rheological failure process under a load of 12 kN, which is far greater than the value of 6 kN for pile "A". The creep rate of the former is much lower than that of the latter, although there are no obvious differences between the instantaneous deformation feature. This indicates that a pile with a rougher surface could increase the resistance to pile rheology despite the surrounding ice with obvious viscosity. The reasons may be a transformation from shear stress to normal stress at the pile-ice interface as well as the shift of the shear plane from the pile-ice interface to the ice surrounding pile for the pile with a rougher surface. The latter reason is based on the fact that the freeze strength at the pile-ice interface is generally smaller than that of the materials composing the structure. Moreover, it can be inferred that a rougher pile will more obviously restrain the rheology of the pile-frozen soil structure than that of the pile-ice structure.

4. Discussion

In this paper, the creep behavior of pile-soil structures was studied by combining MLCT and microobservations of

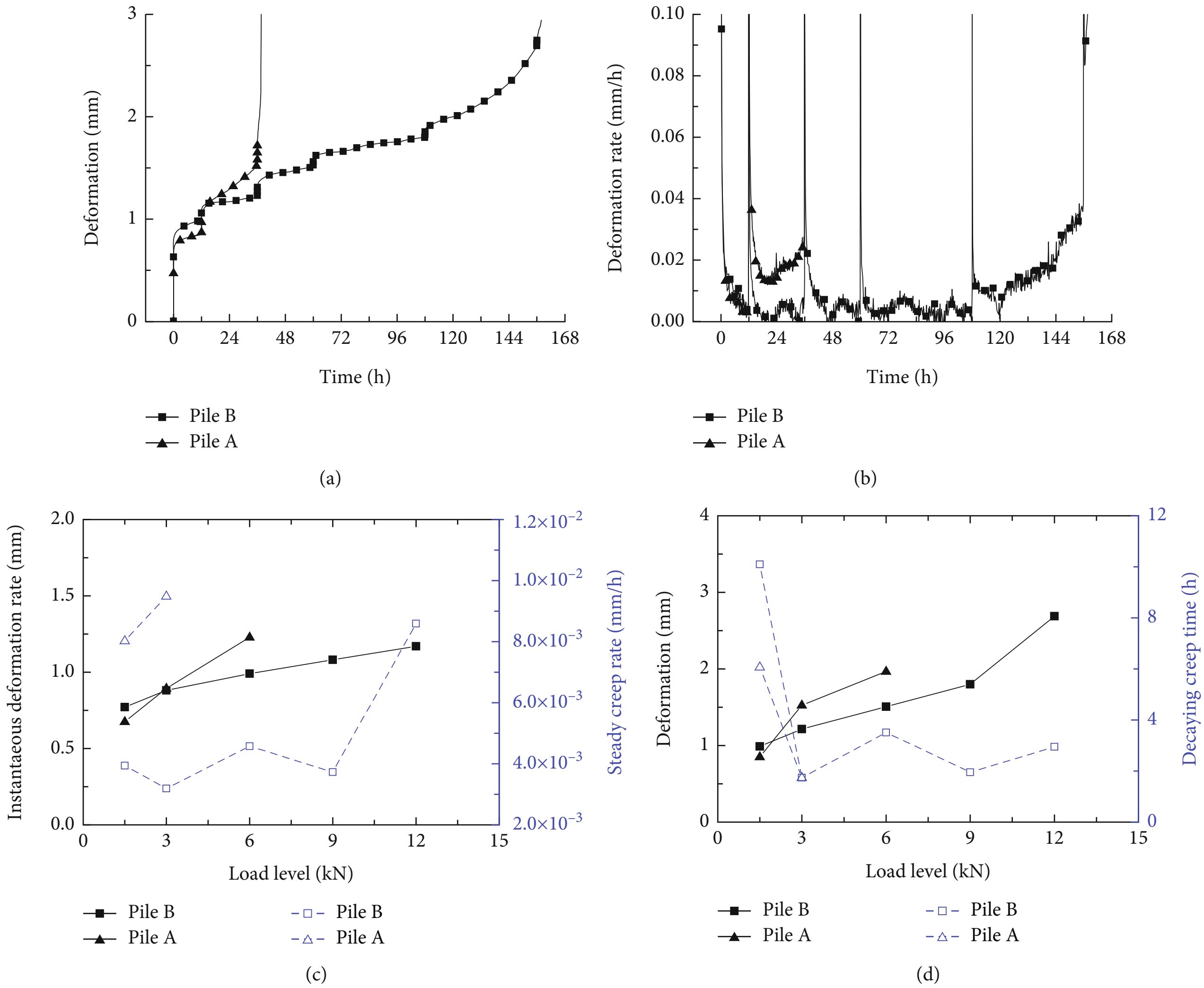


Figure 14: Creep parameters of interfaces between frozen soil and piles with different roughness.

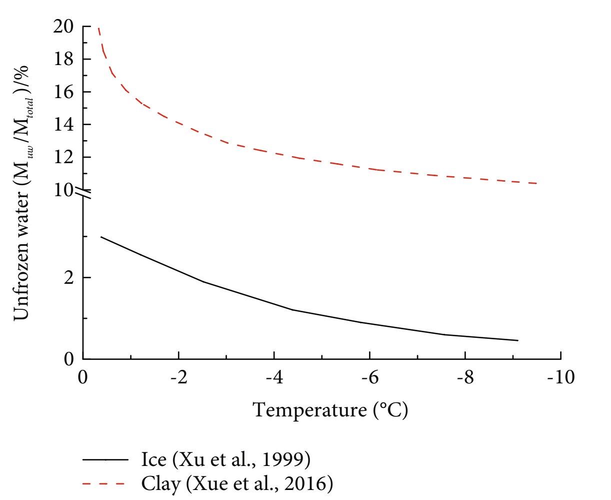


Figure 15: Variation curves of unfrozen water content in soil and ice with temperature.

frozen soil. The results showed that the temperature, moisture content, particle gradation of frozen soil, and pile surface all have marked impacts on the rheology of the pile-frozen soil structures. The effect of temperature on unfrozen water content and ice strength in frozen soil surrounding piles is the core mechanism controlling the rheological properties of the pile-frozen soil interface. For the pile-frozen soil interface in the zone near phase transformation, the degree of ice cementation and the unfrozen water content control the strength and creep characteristics of the pile-frozen soil interface. With the increase in temperature, the unfrozen water content in clay increased significantly, and the magnitude and degree of increase were higher than those in ice crystals (Figure 15) [34, 35]. The lubricating effect from higher unfrozen water content and smaller ice cementation capacity results in lower bearing capacity and higher rheological properties of the pile-soil interface. At the same temperature, the presence of a large amount of ice in frozen soil will reduce the deformation and inhibit the creep performance of the pile-soil interface. For the pile-frozen soil interface far away from phase transformation, structural material

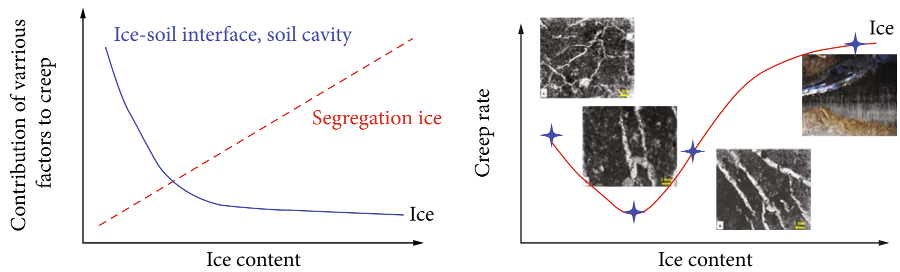


FIGURE 16: Effect of ice content on creep behavior of pile-frozen soil interface at a low temperature.

in frozen soil, segregation ice, and cryo-structure determines the rheology of the pile-soil interface. Both the thick layers of segregated ice in frozen soil with high ice content and the increase of segregated ice and soil interface due to the presence of highly dispersed thin segregated ice in frozen soil with low ice content increase transient and creep deformation rates and improve the creep performance of the pile-frozen soil interface. Therefore, there is an optimum moisture content corresponding not only to the minimum instantaneous deformation but also to the minimum creep rate (Figure 16). Once the moisture content exceeds the optimum value in frozen soil, the instantaneous deformation increases, and the creep rate significantly increases. The settlement of a pile foundation can be reduced from an engineering viewpoint by controlling the instantaneous deformation or restraining the creep rate.

5. Conclusions

A series of MLCT for pile-frozen soil/ice structures were conducted, and the cryo-structures of the frozen soil surrounding the piles were observed to investigate the rheology and mechanism of the pile-frozen soil/ice interfaces. Some conclusions are summarized as follows:

(1) The creep at pile-frozen soil interface is easier to enter the stable stage, and the steady-state average rate gradually increases as the external load level increases. Higher temperature, smoother interface, and finer soil particles will all improve the rheological properties of the interface. The temperature-dependent rheology of ice directly produces a marked impact on the creep process of the pile-frozen soil interface

(2) The existence of massive ice in frozen soil is beneficial to the bearing capacity of piles for high-temperature (-1°C) frozen soil. However, it can considerably increase the creep rate, deteriorate the bearing capacity of the pile-frozen soil interface for low-temperature (-5°C) frozen soil

(3) The rheology of pile-frozen soil interface is closely related to the cryo-structure of the low-temperature frozen soil. Either thick lenticular ice lenses or chaotic reticulate cryo-structures in the frozen soil surrounding piles will enhance the rheological properties of the pile-soil interface. The pile-frozen soil interface exhibits the lowest instantaneous deformation value and slowest creep rate for frozen soil with an optimum moisture content, which corresponds to a massive cryo-structure

(4) The settlement of piles can be reduced by controlling the instantaneous deformation or restraining the creep rate from an engineering viewpoint. Cooling the pile foundation or increasing the mutual embedding between pile side and surrounding frozen soil can effectively reduce the deformation and deformation rate of pile foundation

Data Availability

The original data in this paper are from experiments.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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