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Research Article

Measurement of Excess Pore-Water Pressure in Frozen Soil at Subfreezing Temperatures Close to 0°C

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Response of pore-water pressure has crucial effect on the engineering geological performance of permafrost ground. However, there is a dearth of literature on the measurement of pore-water pressure in frozen soils due to challenges with regard to technical and operational method. To validate the generation of pore-water pressure and to reveal its variation property in frozen soils at subfreezing temperatures close to 0°C, a miniature pressure transducer was utilized to conduct a number of confined compression tests. Double-wall structure avoided damage to the transducer during frozen soil sampling. The transducer at sample bottom perceived a pressure fluctuation as varying air pressure imposed on sample surface, proving the connectivity among the pores in frozen soils with a hysteretic effect on pressure transmission. Pore-water pressure experienced a progressive increase followed by a slow dissipation under invariable load and temperature conditions when water drainage was permitted, while a monotonic increase in pressure was observed for an undrained sample. With decreasing temperature, a smaller peak and a more dilatory dissipation were displayed. When the sample was exposed to a stepwise warming process, a similar performance for the pressure was obtained with abrupt rise at the turning point of temperature.

1. Introduction

Total stress behaviors have always been applied in the mechanical analysis and the engineering design of frozen soils which are considered a completely solid material [1–3]). The preservation of an appreciable quantity of unfrozen water, however, makes the frozen soil a porous medium, especially at subfreezing temperatures close to 0°C [4, 5]. When saturated frozen soil is compressed, pore-water pressure (PWP) increases as in thawed soils, signifying that the total stress does not represent the actual stress borne by solid phase. Therefore, utilizing the effective stress theory to analyze the mechanical behavior of saturated frozen soils is more accurate than using the total stress theory. Experiments illustrated that the soils at a frozen state still have a substantial permeability for unfrozen water to migrate down the pore pressure gradient [6–8]. This results in the rise in effective stress over time that alters the deformation and strength behavior of the frozen soil. To evaluate the effective stress behavior, measurement of the PWP within saturated frozen soils is required. However, ice-water phase change occurs in soils at subfreezing temperatures which makes the PWP measurement more complicated than in thawed soils. Great efforts have been made by researchers on how to measure the PWP variation in freezing or thawing soils, which deepens the understanding of the mechanism of hydrothermal migration and the mechanical behavior during freezing and thawing processes [9–16]. Meanwhile, increasing attentions have been paid by more and more scientists on the measuring method of PWP in frozen soils which is of great significance to the deformation and strength properties under applied load [1, 17–21].

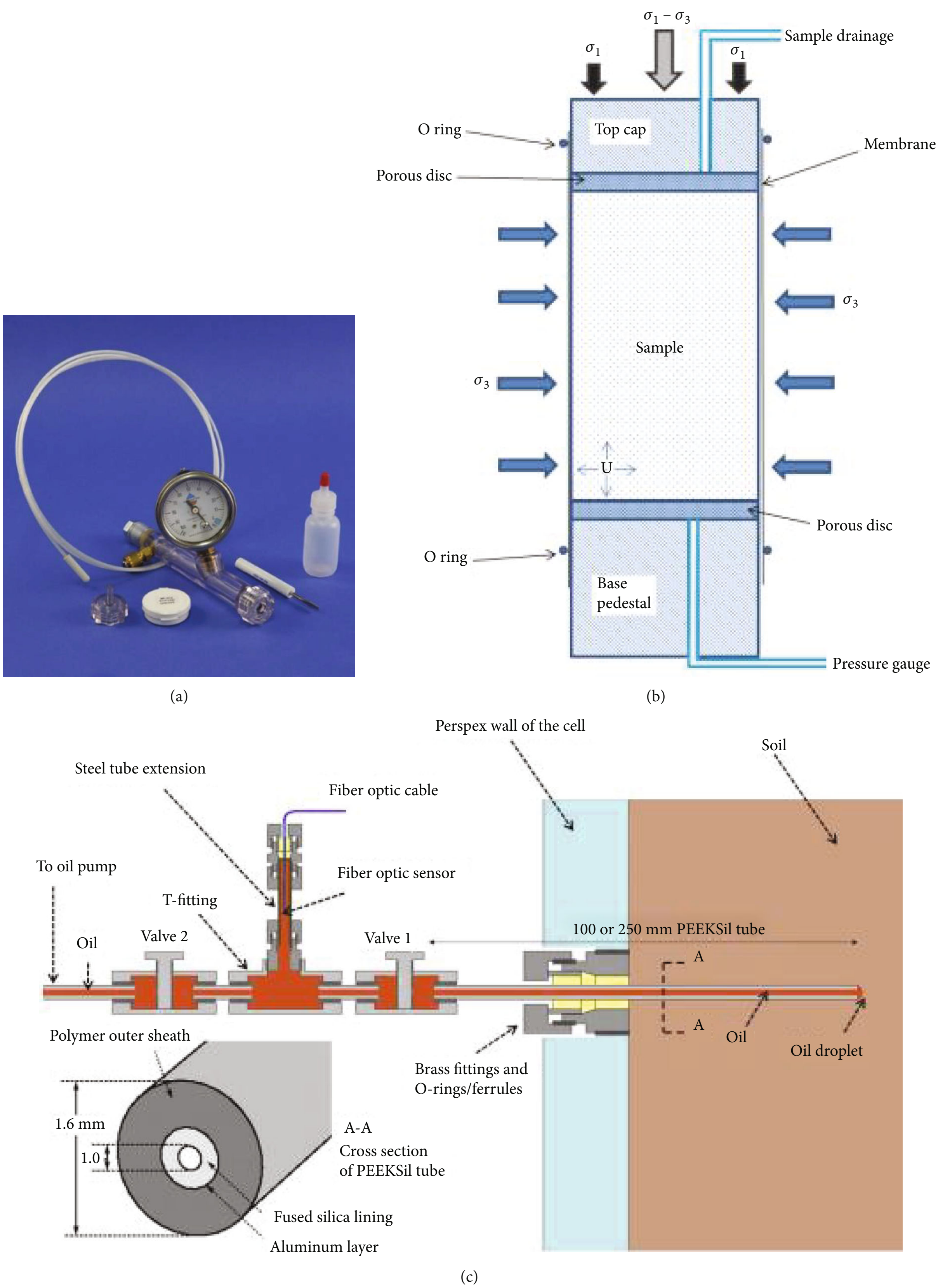

Figure 1: Continued.

(d)

Figure 1: Four methods to measure PWP in freezing, thawing, and partially frozen soils. (a) Tensiometer, (b) porous disc, (c) filter-less rigid piezometer [18], and (d) miniature pressure transducer.

Table 1: Publication on PWP measurement in freezing, thawing, and frozen soils.

Measurement methods	Device structure	Literatures
Tensiometer	A porous cup inserted in soil connects to a pressure sensor via a tube	[9, 10, 12, 13, 16]
Porous disc or ring transfer device	A porous disc or lateral ring connects to pressure gauge via a tube	[14, 17, 22, 23, 25]
Filter-less rigid piezometer	A filter-less rigid tube connects to fiber-optic pressure sensor	[18]
Miniature pressure transducer	A miniature pressure sensor with a porous filter on the sensing plane	[21, 20, 26, 27]

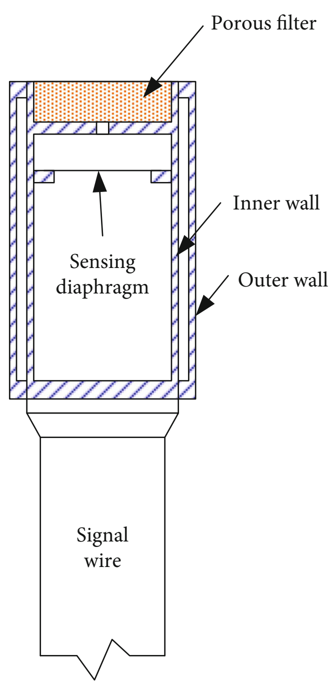

Figure 2: Miniature pressure transducer.

2. Methods of Pore-Water Pressure Measurement

Scientists and engineers have focused on the measurement of PWP in freezing, thawing, or partially frozen soils for decades. Various laboratory investigations have been performed using several measuring methods. These ways could generally be classed into four kinds: tensiometer, porous disc or ring transfer device, filter-less rigid piezometer, and miniature pressure transducer, as shown in Figure 1 and Table 1. (a) Tensiometer is a device that consists of a porous cup, a flexible tube, and a pressure transducer (Figure 1(a)). It is commonly used to measure pore pressure drop in freezing soil by inserting the porous cup into soil [9, 10, 12, 13, 16]. (b) Porous disc is a conventional structure assembled in a triaxial apparatus or oedometer (Figure 1(b)), which transfers liquid pressure via a channel to a pressure transducer [14, 17, 22–24]. Eigenbrod et al. [25] modified this structure to a lateral porous ring connecting a transducer through a flexible tube, which could measure the pressure at various levels. (c) A filter-less rigid piezometer designed by Kia [18] consists of a small diameter tube and a fiber-optic pressure sensor (Figure 1(c)). The tube tip without filter was directly inserted into frozen soil for receiving a faster response and a more accurate variation of PWP. (d) A miniature pressure transducer has a very small size that assembles sensing diaphragm and porous filter within a rigid housing (Figure 1(d)). It can be directly installed in soil to keep the interspace between sensing diaphragm and soil as small as possible [20, 21, 26, 27].

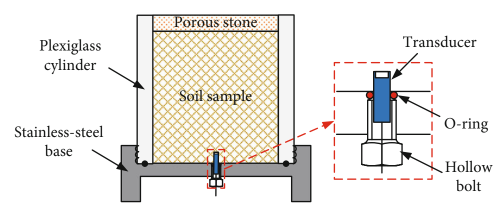

Figure 3: Laterally confined compression cell.

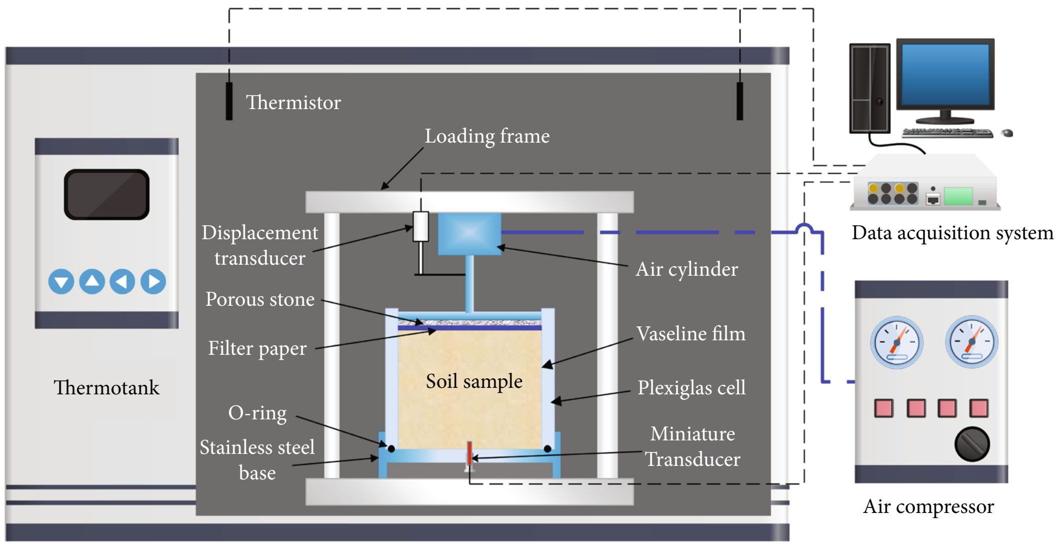

Figure 4: Test system.

Table 2: Physical parameters of the soil.

Classification symbol	Values
Specific gravity (g/cm^3)	2.71
Plastic limit (%)	18.1
Liquid limit (%)	29.6
Uniformity coefficient, C_u	7.5
Gradation coefficient, C_c	0.37
Thawing point (°C)	-0.05

The authors have attempted all the methods mentioned above to access the excess PWP variation in frozen soils induced by an external load at subfreezing temperatures close to 0°C. The first three devices, however, failed to receive the pressure for possibly multiple reasons. When there was a long pressure transmission tube or channel, it was difficult to completely exclude air bubbles from the liquid medium within the tube or channel, which might result in failure or inaccuracy in pressure transmission. In addition, the sealing of measuring system is another important issue that needs attention. When frozen sample was placed on a porous disc, the interspace between them was compressed upon loading, causing an excess liquid pressure transmitting to the transducer which did not represent the real PWP within the frozen sample. A problem of pressure transfer channel clogging was faced when a filter-less piezometer was inserted into frozen soil to measure the PWP. The miniature pressure transducer was proven to measure the excess PWP in frozen soil effectively and to reveal their variation behaviors [20, 21]. During sampling preparation, however, the transducer structure inserted into the sample was extremely vulnerable to the huge frost heave pressure when the sample was quickly frozen under the condition of unallowed volumetric deformation, causing the damage of sensing diaphragm [28]. To solve this problem, we proposed an improved structure of miniature pressure transducer and elaborated on the detailed procedures of confined compression tests to observe the variation of the PWP of frozen soil.

3. Test Apparatus and Procedures

3.1. Improved Miniature Pressure Transducer. The pressure transducer proposed in our study was improved from a commonly miniature sensor, consisting of stainless steel cylindrical housing, porous filter, and sensing diaphragm. Double-wall structure with a layer of thin gap was designed for the housing, as shown in Figure 2. When saturated soil is frozen to prepare testing sample, the outer wall of the transducer resists frost heave pressure occurred within the sample. The gap between the walls admits the tiny deformation of the outer wall and avoids the deformation of the inner wall that may destroy the sensing diaphragm.

The transducer has a size of 10 mm in diameter and 20 mm in height. The porous filter is fixed on the tip of the housing and works to prevent soil particles from blocking the channel of PWP transmission. Prior to installation in the testing cell, the porous filter as well as the space behind within the transducer is filled with silicone oil and deaired in a vacuum desiccator. Liquid water pressure in frozen soil was transferred via the silicone oil to the sensing diaphragm. Signal wire was covered by a flexible transparent tube to prevent water from entering into the interior of the transducer. The transducer could measure within a range of -100 to +500 kPa with an accuracy of ±0.1% of reading and a temperature drift of ±0.02% of reading per °C.

3.2. Test Apparatus. To check the performance of the improved transducer, a series of confined compression tests were carried out using a special designed cell modified from an ordinary oedometer (Figure 3). The cell consists of

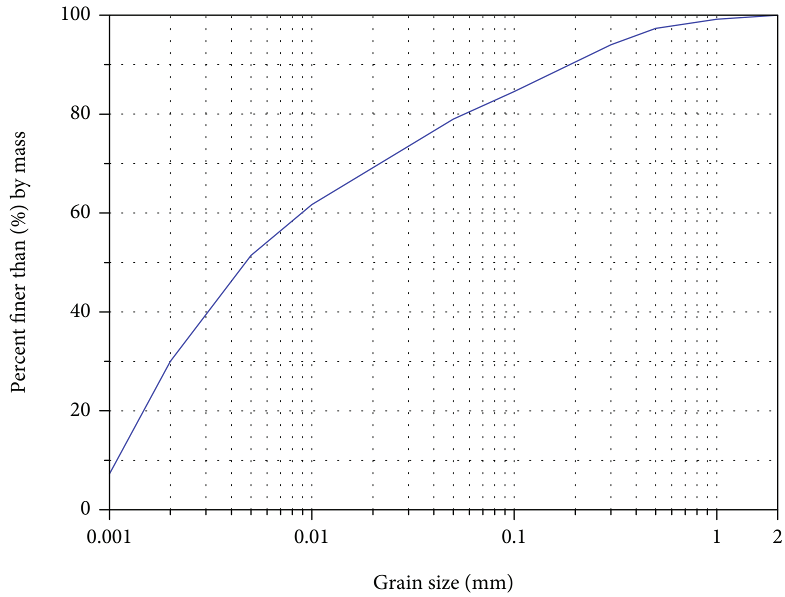

Figure 5: Soil grain size distribution.

100 mm thickness, 62 mm inner diameter, plexiglass cylinder, and a stainless steel base. These two parts are threaded together with an O-ring to assure the sealing between them. A hollow bolt is used to attach the transducer tightly on the base, keeping the tip 10 mm higher than the surface. The vertical movement of the transducer was allowed when the sample was compressed, preventing the transducer from a concentrated stress. Soil surface was allowed to drain water using a porous stone and a filter paper during testing.

A loading frame with an air cylinder powered by an air compressor supplies the required load of the tests, as illustrated in Figure 4. A thermotank modified by the State Key Laboratory of Frozen Soil Engineering, China, is used to control the test temperature with an accuracy of approximately ±0.05°C that is received in real time by four thermistors around the compression cell. Sample temperature is controlled by the ambient temperature within the thermotank. The room where the apparatus is placed is controlled to a constant temperature, 15°C, to reduce the effect of ambient temperature on soil specimens.

Sample displacement was recorded using a TR-100 linear variable differential transformer (LVDT) provided by Novotechnik Siedle Group, Germany. The LVDT had a range of 50 mm and a nonlinearity of ±0.15% of reading. The data including temperature, PWP, and soil displacement are recorded continuously using a DT500 data acquisition system produced by Thermo Fisher Scientific Ltd., Australia.

3.3. Soil Specimen Preparation. Qingzang silty clay obtained from Beilu River Basin on the Qinghai–Tibetan Plateau was tested in the study. The physical parameters and the grading curve of the soil are shown in Table 2 and Figure 5, respectively. Wet soil was prepared by mixing dry soil and water at a given mass ratio of 1 : 0.16 and was sieved through 2 mm diameter mesh to make the sample more uniform (Figure 6(a)). Then, the wet soil was placed into a plastic package for 24 hours for fully soaking soil particles. Vaseline® was scribbled on the inside wall of the cell prior to sample compaction to minimize soil-cell friction (Figure 6(b)). A designed amount of wet soil was filled in the cell with the miniature pressure transducer installed beforehand (Figure 6(c)) and was compacted to a desired height according to the required dry density (Figure 6(d)). The sample was then saturated with water in a vacuum vessel with no deformation allowed (Figure 6(e)). All specimens were prepared to the size of 62 mm in diameter and 30 mm in height. Finally, the cell was rapidly frozen in a -30°C freezer for at least 12 hours to ensure the sample is fully frozen, with no frost heave allowed.

3.4. Test Procedures. During the freezing process of the samples in the freezer, the liquid water within the sample could not be frozen immediately and would migrate outward to the sample surface in the early freezing stage. The migrated water accumulated on the sample surface and formed an ice layer that blocked the drainage of unfrozen water during the testing stage. To provide a drained condition, 2.0 ml saline water at a concentration of 6% was sprayed on the frozen sample surface before the testing cell was placed in the thermotank. On the contrary, a rubber membrane was laid on the sample to create a strictly undrained condition. The sample was kept in the thermotank adjusted to a desired temperature more than 12 hours prior to initiating the tests, which proved that the sample had reached the stable thermal state. A constant load was then imposed on the sample. Figure 5 shows the temperature variation within the thermotank. It varied by ca. ±0.03°C around the required value (Figure 7), suggesting a satisfactory temperature condition. Five tests under different conditions were conducted, as

Figure 6: Sample moulding procedure.

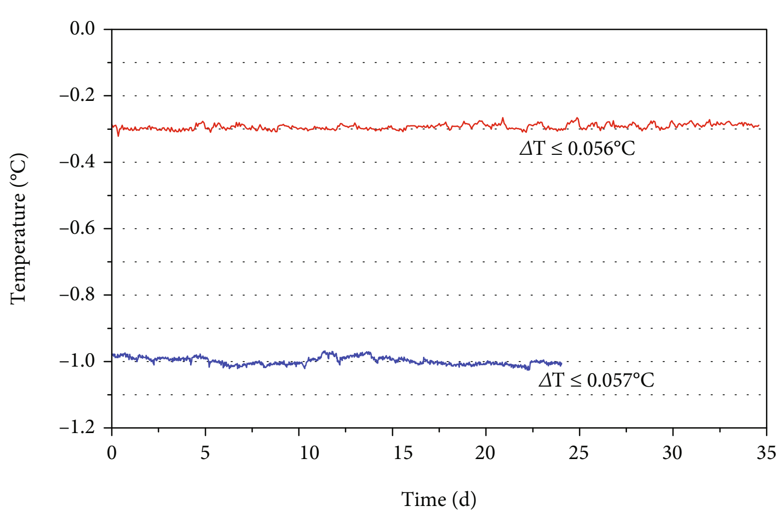

Figure 7: Temperatures variation in the box.

Table 3: Test conditions for each sample.

Test no.	Conditions
KY-01	Dry density 1.7 g/cm^3, temperature -1.0°C, air pressure loading, and drained condition
KY-02	Dry density 1.7 g/cm^3, temperature 5.0°C, air pressure loading, and drained condition
KY-03	Dry density 1.7 g/cm^3, temperature -0.3°C, weights loading 200 kPa, and drained condition
KY-04	Dry density 1.7 g/cm^3, temperature -0.3°C, weights loading 200 kPa, and undrained condition
KY-05	Dry density 1.7 g/cm^3, temperature -0.5°C, weights loading 200 kPa, and drained condition
KY-06	Dry density 1.7 g/cm^3, increasing temperature, weights loading 200 kPa, and drained condition

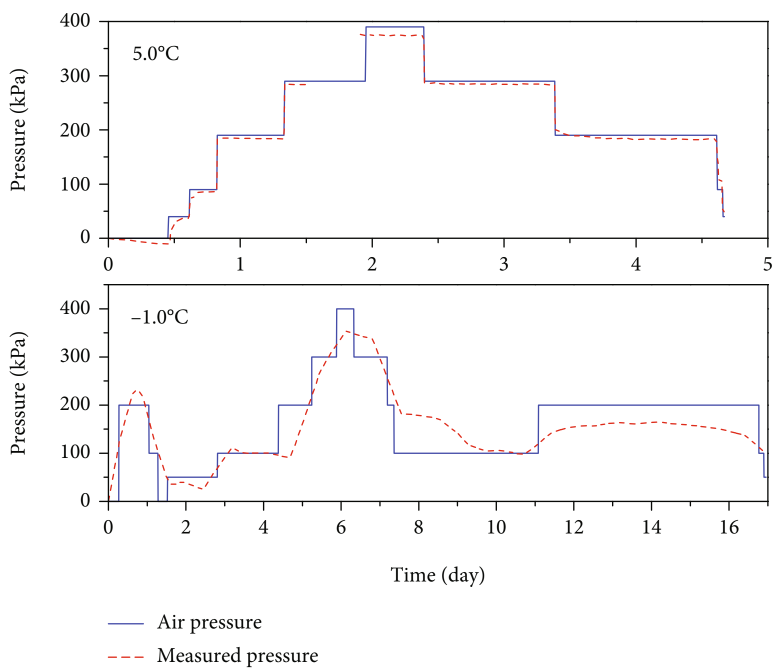

Figure 8: Connectivity test result for frozen soil at 5°C and -1.0°C (KY-01 and KY-02).

listed in Table 3, to declare the applicability of the improved transducer in frozen soil.

4. Results and Discussions

4.1. Continuity of Water Phase in Frozen Soil. Unfrozen water exists at the particle surface and the ice particle interface, even at very low temperature [28]. The continuity of the pore-water phase was an assurance that liquid water can transmit hydrostatic pressure in saturated frozen soil [18]. The water phase in frozen soils is categorized as the bound water around soil particles since the free water is frozen to ice at subzero temperatures. Some researchers proposed that the bound water cannot transmit the water pressure in unfrozen soils because of the electrical attraction of soil particles. Mitchell and Soga [29] argued that the viscosity and diffusion behaviors of the bound water are basically the same as free water. Furthermore, Li [30] concluded through triaxial tests on saturated clay that the bound water had an ability to transfer hydrostatic pressure, but it might attenuate the initial pressure level when the soil was subjected to a large confining pressure. We checked the continuity of saturated frozen soils by applying air pressure on sample surface and monitoring the corresponding PWP response. When the transducer detects the water pressure induced by air pressure, the unfrozen water is considered continuous. Figure 8 provides the examples of continuity verification for soils at 5°C and -1.0°C. The measured pressure presents a well agreement with applied air pressure with a very small deviation for unfrozen sample. For frozen sample at -1.0°C, the variation of measured pressure roughly accords with that of air pressure but shows a significantly delaying trend. The test result proved the continuity of bound water in saturated frozen soil, but a hysteretic character was exhibited in the transmission of the liquid pressure probably due to the minimal thickness and the viscosity of liquid water film. We should point out that the application of air pressure may lead to the compression of soil mass that induces an increase in pore pressure and brings doubt to the result of continuity testing. However, the connectivity of the pores in frozen soil can still be verified in a great extent by comparison with subsequent test results. Certainly, a more

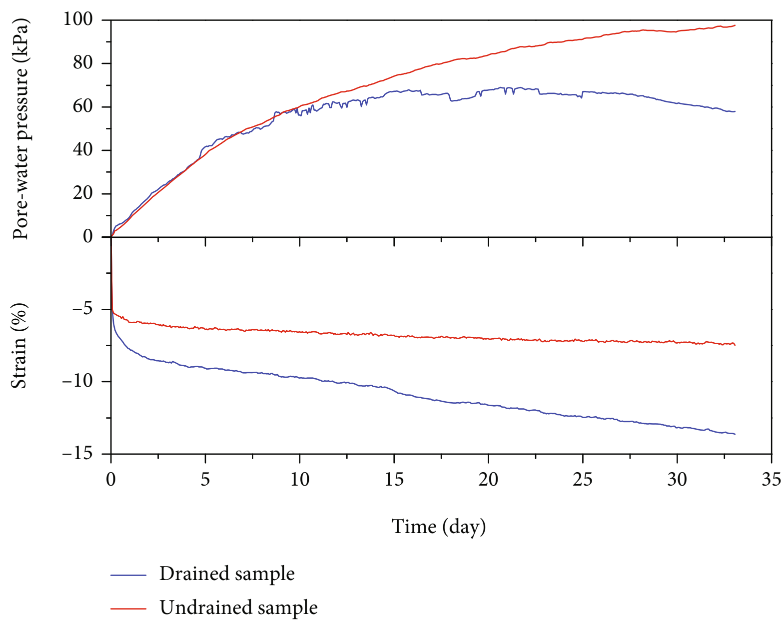

Figure 9: Effect of drainage conditions on test results (KY-03 and KY-04).

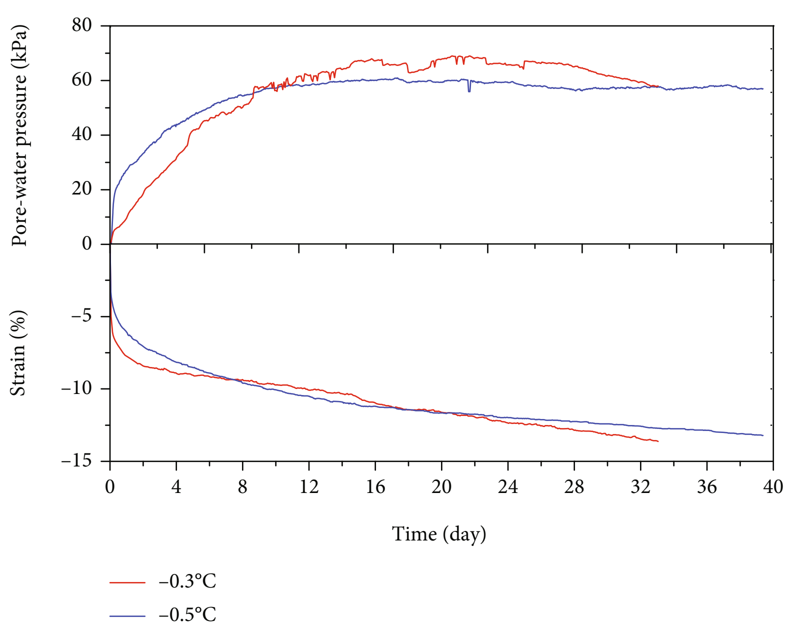

Figure 10: Effect of soil temperatures on test results (KY-03 and KY-05).

reliable method is still needed to perform in the future for better understanding of the pressure transmission or continuity of the bound water.

4.2. PWP Variation at Constant Temperatures. Figure 9 plots the PWP responses and the strains for drained and undrained samples at -0.3°C. Very pronounced responses of the pressures were observed under both drainage conditions. For drained sample, the PWP experienced a progressive increase up to a peak value, 70 kPa, followed by a slow release of the pressure. By contrast, a monotonic increase in the pressure was observed for undrained sample, approaching 100 kPa by the end of the test. Recorded axial strain was substantially a volumetric strain caused by the lateral confinement of the cell, which underwent a progressive increase with a nearly linear trend. The trend had not levelled off at the test end, indicating that the deformation did not reach a residual state and that changes in the structure were still ongoing. Even though at a frozen state, drainage condition still imposed a great impact on the amount of volumetric strain, manifesting a much larger strain for the drained sample. The authors assumed that overburden stress was mainly

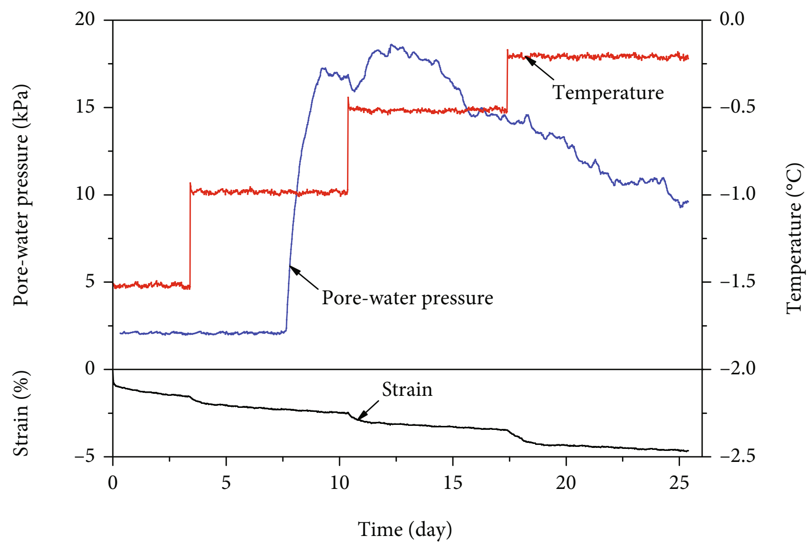

Figure 11: Pore-water pressure variation with warming temperature (KY-06).

undertaken by soil particles and ice at initial time and was partially transferred to liquid water as pore compactions caused by ongoing volumetric compression. When the sample was admitted to drain, the pore water could be expelled from the substantially open soil system to cause the PWP release to proceed simultaneously with the pressure rise, accompanied by a continuous volume shrink of equal quantity to expelled water volume. Once the soil system was closed, the liquid water could not flow out of the soil, showing a monotonic rise of the PWP caused by soil creep deformation.

Pore-water pressure variations at different temperatures showed similar trends with some differences in peak value and dissipation process, as shown in Figure 10, both increasing and falling stages exhibited on the curves of PWP for the tests KY-03 at -0.3°C and KY-05 at -0.5°C. At a higher temperature for KY-03, the sample contained a larger amount of unfrozen water [7] which took more stress transferred from solid matrix. Then, a larger value of the peak point on the PWP curve was received. In addition, KY-03 had a larger hydraulic conductivity in response to a higher soil temperature [21], causing a faster dissipation. Corresponding to the above processes, KY-03 seemed to develop a volumetric deformation at a larger strain rate than KY-05.

4.3. PWP Variation with Warming Temperature. Figure 11 plots the PWP variation with step increasing temperature under a constant load. The curves show that the PWP had no response at initial time to loading, possibly caused by pretty low temperature of -1.5°C. Then, after the temperature warmed to -1.0°C, the pressure increased rapidly to the first peak, 17 kPa, followed by a falling trend. As the temperature further increased to -0.5°C, another rising stage of the pressure with a small amplitude occurred again. Afterwards, the PWP presented a continuous falling trend, even though the temperature increased again to a relatively higher level, -0.25°C. There was a stepped increment in displacement with stepwise warming of temperature. The sharp compression of the sample seemed to not give a birth of abrupt rise of the PWP, possibly because the sample contained some air bubbles that affected the compaction against the liquid pore water.

5. Conclusion

Based on the study, some useful conclusions can be drawn as follows:

The miniature pressure transducer was available in measuring the PWP in frozen soil. Double-wall structure avoided damage to the transducer during frozen soil sampling. It could be experimentally confirmed that there was a connectivity among the pores in frozen soil but was of a hysteretic character in pressure transmission.

Under a constant load, PWP experienced a progressive increase followed by a slow dissipation when unfrozen water was allowed to discharge, while a monotonic increase was observed for an undrained sample. The difference in volumetric strain might imply a consolidation deformation caused by pore water expulsion.

Frozen sample at a lower temperature showed a markedly different performance in PWP with a smaller peak and a slower dissipation. When the temperature was stepwise increased, PWP showed a similar performance to that at a constant temperature but with an abrupt rise after the temperature rise.

Data Availability

The data was obtained through our experiments.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Authors' Contributions

Hu Zhang provided the test data. Suiqiao Yang wrote the main content of the manuscript. Huijun Jin suggested the structure design of the paper and edited the language. Mengxin Liu gave some discussion ideas and checked the grammar of the text.

Acknowledgments

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