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Experimental Study on Effects of Different Initial Water Supply and Cooling Conditions on Clay Freeze-Thaw Process: Postprint

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Abstract

To investigate the freeze-thaw characteristics of Xinjiang clay during water replenishment, unidirectional freeze-thaw model tests were conducted in the laboratory to analyze the spatiotemporal variation patterns of temperature, frost heave, and thaw settlement in unsaturated clay during unidirectional freeze-thaw processes. The results indicate that the freeze-thaw amount varies with temperature; in the early stage of freeze-thaw, temperature changes rapidly, and frost heave/thaw settlement begins to develop and gradually increases; in the later stage, temperature changes slow down and stabilize. Under both conditions, the thawing duration is shorter than the freezing duration, and soil samples with higher initial water content exhibit greater freeze-thaw duration, freezing/thawing depth, and frost heave/thaw settlement. The research results demonstrate that different initial water contents lead to variations in the water-ice phase transition and changes in soil moisture-heat dynamics, thereby resulting in different temperature fields and freeze-thaw amounts during the freeze-thaw process. The variation patterns of the freeze-thaw temperature field, freezing/thawing front, and frost heave/thaw settlement obtained from this study can provide theoretical references for the design, construction, operation, and maintenance of water conservancy projects in cold and arid regions.

Full Text

Experimental Study on the Influence of Different Initial Conditions of Water Replenishment and Refrigeration on Clay Freeze-Thaw Processes

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Abstract

To investigate the freeze-thaw characteristics of Xinjiang clay during water replenishment, a series of one-dimensional freeze-thaw model tests were conducted in the laboratory to analyze the spatiotemporal evolution of temperature, frost heave, and thaw settlement during the unidirectional freezing and thawing of unsaturated clay. The results demonstrate that freeze-thaw magnitude varies with temperature changes. During the early freeze-thaw stage, temperature changes rapidly while frost heave and thaw settlement begin to develop and gradually increase. In the later stage, temperature changes slow down and stabilize. Under both test conditions, the thawing duration was shorter than the freezing duration. Soil samples with higher initial water content exhibited greater freeze-thaw duration, freezing/thawing depth, and frost heave/thaw settlement magnitude. These findings indicate that differences in initial water content lead to variations in the water-ice phase transition and soil moisture-heat dynamics, which in turn cause differences in the temperature field and freeze-thaw magnitude during the process. The observed patterns of freeze-thaw temperature fields, freezing/thawing fronts, and frost heave/thaw settlement provide theoretical references for the design, construction, operation, and maintenance of water conservancy projects in cold and arid regions.

Keywords: clay; unidirectional freeze-thaw; moisture migration; temperature; freeze-thaw magnitude

Introduction

Frozen soil is defined as soil or rock with temperatures below freezing that contains ice [?]. Seasonal frozen soil regions account for a substantial portion of China' s territory [?]. Xinjiang' s unique geographical environment and climate, with winter lasting for several months [?], subjects hydraulic structures to repeated freeze-thaw cycles that cause seepage and significant water resource waste. Previous research [?] has shown that freeze-thaw damage in seasonal frozen regions is closely related to long-term freeze-thaw cycling and moisture migration during the freeze-thaw process.

Numerous scholars have investigated moisture migration and various factors affecting soil freeze-thaw behavior. Numerical studies include Harlan' s coupled hydro-thermal model [?], which laid the foundation for subsequent research, and studies on ice lens formation [?]. Sheng et al. [?] introduced a migration potential concept to account for moisture migration. Konrad and Morgenstern

[?] analyzed temperature fields and moisture content changes before and after freeze-thaw. Experimental studies have examined soil structure, temperature fields, moisture fields, and mechanical properties under varying moisture content, cold-end temperature, and dry density conditions in open systems [?]. Shoop [?] modeled experiments with different groundwater depths. Zhou [?] evaluated ice lens growth based on unfrozen water film pressure. Zhang et al. [?] identified moisture content gradient, soil-water potential gradient, and temperature gradient as the main driving forces for moisture migration in unsaturated soil during freeze-thaw. Zeng et al. [?] established a frost heave model simulating moisture migration and ice lens formation. Shi et al. [?] developed a coupled water seepage and heat convection model to determine temperature and velocity field changes during soil freeze-thaw.

While many studies have examined the effects of pre-freezing moisture content and external water sources on soil freeze-thaw, few have investigated indoor model tests where unsaturated samples undergo sufficient water replenishment during refrigeration. Most previous research has focused on homogeneous soil samples, whereas field conditions often feature a groundwater table dividing saturated soil below from unsaturated soil above. This study addresses this gap by conducting unidirectional freeze-thaw tests on Xinjiang silty clay under two conditions: (1) instantaneous water replenishment and refrigeration (uniform pre-freezing water content), and (2) water replenishment to saturate the lower soil before refrigeration. The experiments analyze temperature, water replenishment, frost heave, and thaw settlement to provide an experimental basis for frost heave mechanism research.

1. Materials and Methods

1.1 Test Material

The test soil was collected from typical frost-susceptible clay along a water diversion canal in Xinjiang. Basic physical properties were determined through conventional geotechnical tests, with particle size distribution shown in Table 1 . The soil has a liquid limit of 30.47%, maximum dry density of 1.62 $\mathrm{g \cdot cm^{-3}}$, and optimal moisture content of 15.68%, indicating strong frost susceptibility.

1.2 Test Apparatus

1.2.1 Refrigeration System

The system employs semiconductor refrigeration technology with a cold plate positioned above the test chamber. The chamber dimensions are 1 m × 0.5 m × 1.5 m, with heat transfer from top to bottom to achieve unidirectional freeze-thaw. The cold plate can reach -35°C. The chamber exterior is insulated with 5 cm thick rubber-plastic insulation boards, with 10 cm thick insulation on the bottom exterior. All joints and seams are sealed with specialized adhesive and polyurethane foam to ensure thermal performance.

1.2.2 Temperature Sensors

Temperature measurement and data acquisition were performed using a DL50-E8T recorder with thermistor waterproof probes (30 mm length). The measurement range is -50~110°C with $±0.3 ±$0.5°C accuracy, enabling stable, high-precision temperature monitoring at various soil positions.

1.2.3 Frost Heave/Thaw Settlement Measurement

Electronic dial indicators (range: -50~50 mm, accuracy: $±$0.02 mm) were mounted on universal stands to measure frost heave and thaw settlement.

1.2.4 Water Replenishment System

The system consists of a balance bottle and Mariotte bottle. The balance bottle’ s outlet connects to the chamber’ s inlet to stabilize the water surface and maintain continuous water supply. The Mariotte bottle is fixed to a stand with adjustable clamps to control height and maintain constant pressure for different groundwater levels. The apparatus is shown in Figure 1 [Figure 1: see original paper].

1.3 Test Procedure

Soil samples were air-dried, sieved, and prepared at 15.68% moisture content by adding water, mixing thoroughly, and curing for 24 hours. The prepared soil was placed into the chamber in layers (10 cm per layer), with each surface scarified to ensure bonding between layers. The final specimen measured 0.5 m × 0.5 m × 0.8 m, with 40 cm clearance between the soil surface and cold plate for air circulation. To investigate the effects of initial moisture conditions on temperature, frost heave, water replenishment, and thaw settlement, two test conditions were designed at the same groundwater level (40 cm depth): (1) instantaneous water replenishment with refrigeration, and (2) water replenishment to saturate the lower soil before refrigeration. Detailed conditions are shown in Table 2 .

Temperature sensors were installed at 10 cm intervals from the bottom. Five electronic dial indicators were placed on the soil surface to measure total frost heave and thaw settlement. All measurements were automatically collected and stored. The cold plate at the top enabled unidirectional freeze-thaw, while the Mariotte bottle provided continuous water replenishment from the bottom. Water replenishment was manually recorded from the Mariotte bottle scale.

2. Results and Analysis

2.1 Freezing Temperature Field

The temperature field evolution in both specimens exhibited three distinct stages (Figure 2 [Figure 2: see original paper]). **Stage 1 (Rapid Cooling, 0-50 h):** Large temperature gradients caused rapid cooling. Specimen No. 1 temperature decreased from ambient, with cold transferred sequentially from the top downward. **Stage 2 (Gradual Cooling, 50-200 h):** Temperature gradients decreased and changes became gradual. **Stage 3 (Stabilization,**

>200 h): Cooling rates approached zero, with stable temperatures below 0°C. At 390 h and 410 h, both specimens reached stable temperatures below the phase change point. Due to different initial moisture contents, the phase transition zones differed: Specimen No. 1 underwent water-ice phase change in the 80-65 cm range, while Specimen No. 2 had a larger phase change zone at 80-55 cm. Thus, initial moisture content differences caused phase transition variations, leading to different temperature fields.

2.2 Freezing Front

Figure 3 [Figure 3: see original paper] shows the freezing front progression. Both specimens exhibited two phases: **Phase 1** featured large fluctuations in the freezing front position, lasting 190 h for Specimen No. 1 and 160 h for Specimen No. 2, with final freezing fronts reaching 65 cm and 55 cm, respectively. **Phase 2** showed stable freezing front positions. The freezing front trend is determined by the temperature field. The 0°C isotherm reached 80 cm, 75 cm, 65 cm, and 55 cm at 6.4 h, 75 h, 165 h, and 290 h for Specimen No. 1, respectively. No negative temperatures appeared below 55 cm. For Specimen No. 2, the 0°C isotherm reached the same depths at 5.6 h, 60 h, 140 h, and 390 h. Specimen No. 2 had greater freezing depth due to higher initial moisture content. Under the same temperature gradient, higher initial moisture content required longer freezing time and resulted in deeper freezing depth. The stable freezing front represents equilibrium between positive and negative temperatures.

2.3 Frost Heave

Final frost heave values were 15.68 mm for Specimen No. 1 and 13.75 mm for Specimen No. 2 (Figure 4 [Figure 4: see original paper]). **Specimen No. 1** showed four stages: **Stage 1 (0-6 h)** with rapid freezing front movement but minimal moisture migration and negligible frost heave; **Stage 2 (6-184 h)** with active temperature and moisture changes, intense moisture redistribution, and rapid frost heave development; **Stage 3 (184-278 h)** with reduced temperature effects and slower frost heave growth; **Stage 4 (>278 h)** with stable temperature and water replenishment, where frost heave grew slowly until stabilization. **Specimen No. 2** showed two stages: **Stage 1 (0-48 h)** with slow total frost heave growth and small curve slope; **Stage 2 (48-410 h)** with faster, quasi-linear frost heave development and steeper curve slope. In both cases, initial high temperature gradients caused rapid surface cooling and in-situ freezing of pore water without significant moisture migration, resulting in minimal initial frost heave. Frost heave accumulated gradually during mid-to-late freezing stages. Differences in frost heave resulted from varying initial moisture content, which affected phase transition timing and ice content formation. Higher initial moisture content facilitated frost heave development.

2.4 Water Replenishment

Figure 5 [Figure 5: see original paper] shows water replenishment and frost heave curves for Specimen No. 1, with total replenishment of 2206 mL at test completion. Due to soil pores, external water replenishment began at 12 h. Rapid freezing front movement prevented water replenishment during 0-12 h. As the freezing front slowed (12-102 h), water migrated toward the cold end until the sample fully froze, with replenishment increasing continuously until stabilization at 102-390 h.

2.5 Thawing Temperature Field

Figure 6 [Figure 6: see original paper] shows thawing temperature distributions. **Stage 1 (0-20 h)** had large temperature gradients, with rapid temperature increase in chamber and surface (80 cm) temperatures. **Stage 2 (20-40 h)** showed slower temperature increases. The 65-75 cm layer temperature rose from negative values, with faster increase at 40-70 h and slower increase thereafter until stabilization. The 55-80 cm layer showed similar patterns, stabilizing after 70 h. The 5-55 cm layer temperature rose quickly in 0-40 h from initial positive temperatures. Total thawing time was 112 h for Specimen No. 1 and 140 h for Specimen No. 2, both shorter than freezing durations. Specimen No. 2' s higher initial moisture content produced more ice during freezing, requiring longer thawing time.

2.6 Thawing Front

Figure 7 [Figure 7: see original paper] shows thawing front progression, with black lines representing the 0°C isotherm. The 0°C isotherm reached 80 cm, 75 cm, 65 cm, 60 cm, and 50 cm at 6.4 h, 20 h, 40 h, 60 h, and 112 h for Specimen No. 1, respectively. For Specimen No. 2, it reached 80 cm, 75 cm, 65 cm, and 55 cm at 5.6 h, 18 h, 36 h, and 140 h. The 0°C isotherm stabilized at 50 cm for Specimen No. 1 and 55 cm for Specimen No. 2. Specimen No. 2' s thawing rate was slower than Specimen No. 1' s due to higher initial moisture content and greater ice formation during freezing.

2.7 Thaw Settlement

Final thaw settlement values were 10.23 mm for Specimen No. 1 and 8.86 mm for Specimen No. 2 (Figure 8 [Figure 8: see original paper]). Thaw settlement developed in three stages: **Stage 1** with no settlement as frozen soil warmed; **Stage 2** with rapid settlement growth; **Stage 3** with settlement stabilization. Specimen No. 2's higher initial moisture content produced more ice, resulting in greater thaw settlement when ice melted. At lower moisture contents, settlement primarily resulted from ice melting and volume reduction under gravity. At higher moisture contents, self-weight settlement dominated. These patterns align with previous research [**?**].

3. Conclusions

1) During freezing, higher initial moisture content leads to longer temperature field stabilization time, greater freezing depth, and larger frost heave. During thawing, higher initial moisture content results in longer thawing time and greater thaw settlement.
2) Freeze-thaw action involves coupled interactions among temperature, moisture, and displacement fields that gradually transition from dynamic to stable conditions.
3) For construction in cold regions, non-frost-susceptible or weakly frost-susceptible materials should be selected. High groundwater levels should be avoided, with drainage and waterproofing measures applied to submerged structures and insulation provided for frost-prone components.

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