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Research on the Mechanisms of Frost Heave and Thaw Settlement, Influencing Factors, and Engineering Prevention and Control Technologies

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Abstract

Frost heave and thaw settlement are core problems restricting the construction and safe operation of infrastructure in cold regions. This phenomenon widely exists in seasonal frozen soil and permafrost regions, which will lead to uneven deformation of engineering structures, cracks, and even safety accidents. Based on the systematic analysis of the physical process of frost heave and thaw settlement, this paper expounds the development of classical theories such as capillary theory and frozen fringe theory, and discusses the key influencing factors including soil properties, water content, temperature gradient and engineering load. On this basis, a comprehensive technical system for frost heave and thaw settlement prevention and control is constructed from three aspects: engineering measures, material improvement and intelligent monitoring. Combined with typical engineering cases in seasonal frozen soil areas and plateau permafrost areas, the application effect of various prevention and control technologies is verified. Finally, the future research directions in the fields of multi-field coupling mechanism, intelligent prevention and control equipment and full life cycle management are prospected.

Keywords

Frost Heave and Thaw Settlement; Frozen Soil; Water Migration; Engineering Prevention and Control; Multi-field Coupling.

1. Introduction

Frozen soil is a special soil body containing ice, which is widely distributed in the world, accounting for about 25% of the global land area. China is one of the countries with the largest frozen soil distribution in the world, with seasonal frozen soil accounting for 53.5% of the national land area, and permafrost mainly concentrated in the Qinghai-Tibet Plateau and high-latitude areas in Northeast China. With the continuous advancement of national strategies such as the "Belt and Road Initiative" and the development of the western region, a large number of major infrastructure projects such as railways, highways and oil and gas pipelines have been built and planned in cold regions.

Frost heave and thaw settlement are the most prominent engineering geological problems in cold regions. When the soil temperature drops below the freezing point, the pore water freezes into ice, and the volume expands by about 9%, causing the soil particles to be squeezed and the soil volume to increase, resulting in frost heave. When the temperature rises above the freezing point, the ice melts into water, and the soil structure loses the support of ice and collapses, resulting in thaw settlement. This cyclic process of freezing and thawing will cause serious damage to engineering structures. For example, the Qinghai-Tibet Highway has suffered from severe uneven deformation due to frost heave and thaw settlement, with maintenance costs as high as tens of millions of yuan every year. In some residential buildings in Northeast China, wall cracks and foundation tilting have occurred due to improper foundation treatment, seriously threatening the safety of residents.

Therefore, carrying out in-depth research on the mechanism, influencing factors and prevention and control technologies of frost heave and thaw settlement has important theoretical significance and practical value for ensuring the safety and stability of infrastructure in cold regions, reducing engineering maintenance costs and promoting the sustainable economic and social development of cold regions.

2. Basic Mechanism and Theoretical Development of Frost Heave and Thaw Settlement

(1) Physical Process of Frost Heave and Thaw Settlement

The freezing and thawing of soil is a complex physical process involving water phase change, heat transfer and soil structure change. In the freezing stage, when the soil temperature gradually decreases to below the freezing point, the liquid water in the pores begins to crystallize into ice crystals. Due to the difference in density between ice and water, the volume expansion generates extrusion force on soil particles, causing initial frost heave. With the continuous progress of freezing, under the drive of temperature gradient, unfrozen water migrates to the freezing front, continuously freezes on the surface of existing ice crystals, and gradually forms ice lenses. The formation of ice lenses further occupies the pore space of the soil, intensifying the frost heave deformation.

In the thawing stage, the ice in the frozen soil gradually melts into liquid water. Under the action of gravity and pore pressure, the melted water is discharged from the soil. The soil structure that was originally expanded by ice loses its support and collapses, and the soil particles readjust their contact relationship. Under the action of self-weight and overlying load, the skeleton structure undergoes compression deformation, resulting in thaw settlement. Due to the heterogeneity of soil, the frost heave and thaw settlement process shows complex spatial and temporal variation characteristics, and the fine particle content area usually has more significant frost heave and thaw settlement phenomena.

(2) Classical Theoretical System

The research on frost heave mechanism has experienced a development process from simple to complex, and has formed three classic theoretical systems.

The capillary theory proposed by Everett in 1961 is the earliest theory to explain the frost heave phenomenon. This theory holds that capillary pores in fine-grained soil are the key places for water migration and frost heave. Under the action of surface tension, capillary water forms a meniscus, and the freezing of water at the meniscus generates capillary pressure, which drives the surrounding unfrozen water to migrate to the ice nucleus, causing the ice nucleus to grow and the soil to frost heave. However, this theory cannot explain the formation mechanism of discontinuous ice lenses and underestimates the frost heave pressure in fine-grained soil[6].

In order to make up for the shortcomings of capillary theory, Miller proposed the frozen fringe theory in 1978. This theory holds that there is a special region called "frozen fringe" between the freezing front and the bottom surface of the warmest ice lens, which has the characteristics of low water content, low moisture conductivity and no frost heave. The low moisture conductivity of the frozen fringe hinders the migration of water, causing water to accumulate near the frozen fringe. When the water pressure exceeds a certain threshold, a new ice lens is formed. This theory successfully explains the formation mechanism of discontinuous ice lenses and reveals the internal relationship between water migration and frost heave pressure[5].

With the deepening of research, scholars have combined the heat conduction equation with Darcy's law to establish a water migration and energy balance model, realizing the quantitative analysis of water migration and volume deformation during the freezing-thawing process. The thermal-hydraulic-mechanical (THM) coupling model comprehensively considers the interaction between temperature field, water field and stress field, and the simulation accuracy can reach more than 90%. Chinese scholar Xu Xuezu proposed a nonlinear analytical solution for thaw depth, which considers the nonlinear characteristics of soil during thawing and provides an important theoretical basis for engineering design[4].

3. Analysis of Key Influencing Factors of Frost Heave and Thaw Settlement

(1) Internal Factors: Inherent Properties of Soil

Soil texture and particle composition are the most important internal factors affecting frost heave sensitivity. Fine-grained soils such as silt sand and cohesive soil have small particle size, large specific surface area and complex pore structure, which are conducive to water adsorption and capillary rise, so they have high frost heave sensitivity. Studies have shown that the frost heave rate of silt sand and cohesive soil can reach 10%-30% under the same freezing conditions. In contrast, coarse-grained soil has large pore size and small specific surface area, and water is easy to drain, so its frost heave property is low. However, when the fine particle content in coarse-grained soil exceeds 15%, its frost heave property will be significantly enhanced, and the frost heave rate may rise to 5%-10%[1].

Water content is a key factor determining the frost heave potential of soil. When the soil water content is low, the number of ice crystals formed during freezing is small, and the frost heave amount is relatively small. With the increase of water content, the frost heave amount increases nonlinearly. When the water content exceeds the optimal water content, the pores are gradually filled with water, and water migration is restricted, leading to the formation of large ice lenses in local areas, resulting in a sharp increase in frost heave amount. For example, when the soil water content increases from 20% to 30%, the frost heave amount can increase from 5mm to 20mm[2].

Initial compaction degree also has an important impact on frost heave and thaw settlement. Soil with insufficient compaction has high porosity, which provides more channels for water migration, leading to uneven frost heave. During the thawing process, the destruction of pore structure and the rearrangement of soil particles will lead to larger thaw settlement. Improving the initial compaction degree of soil can effectively reduce porosity, restrict water migration, and reduce the harm of frost heave and thaw settlement[3].

(2) External Factors: Environment and Load Conditions

Temperature gradient plays a crucial role in the frost heave process, which affects the downward movement rate of the freezing front and water migration. Rapid cooling will increase the temperature gradient and accelerate the downward movement of the freezing front, making water have no time to fully migrate, resulting in frost heave concentrated on the surface layer, which is easy to cause surface soil cracking and uplift. The frequency of freeze-thaw cycles also has a significant impact on soil structure. Frequent freeze-thaw cycles will gradually destroy the soil structure, increase porosity, reduce soil strength and stability, and increase the thaw settlement coefficient year by year. In areas where the annual freeze-thaw cycles exceed 50 times in the Qinghai-Tibet Plateau, the subgrade settlement rate is 15% higher than that in single cycle areas[7].

Groundwater level and drainage conditions are important external factors affecting frost heave and thaw settlement. High groundwater level provides a continuous water source for the freezing front, intensifying the frost heave phenomenon. Poor drainage conditions will cause melted water to stay in the soil, making the soil in a saturated state, softening the soil and reducing its strength, which is easy to cause sudden thaw settlement disasters. Statistics show that more than 80% of road diseases in seasonal frozen soil areas are related to groundwater infiltration[8].

Engineering load and structural form also affect the frost heave and thaw settlement characteristics. Engineering load changes the stress distribution of soil, inducing local frost heave force concentration. Rigid structures such as concrete pipelines have poor deformation resistance, and are prone to cracking and damage under the action of frost heave and thaw settlement. Flexible structures such as steel corrugated pipes have good deformation capacity, which can release stress through their own deformation and reduce the incidence of diseases. Studies have shown that the disease rate of drainage systems using steel corrugated pipes is more than 60% lower than that of concrete pipe[10].

4. Engineering Prevention and Control Technology System for Frost Heave and Thaw Settlement

(1) Engineering Measures: From Passive Response to Active Control

Foundation treatment and structural optimization are the most basic engineering measures. The replacement method replaces frost heave sensitive soil with low frost heave materials such as graded sand and gravel and fly ash to reduce the frost heave sensitivity of the foundation. According to engineering experience, the replacement depth in seasonal frozen soil areas is usually 1.2-1.5 times the freezing depth. Thermal insulation measures reduce the influence of external temperature on the foundation by laying thermal insulation materials such as expanded polystyrene (EPS) board and polyurethane thermal insulation layer. Monitoring data show that after laying the thermal insulation layer, the freezing depth of the Harbin-Dalian high-speed railway subgrade has been reduced by 30%, and the thaw settlement amount is controlled within 5mm[3].

Drainage and water regulation measures avoid water accumulation in the foundation by dredging groundwater and melted water. Blind ditches and seepage wells are common drainage facilities. The Siberian Railway in Russia has adopted deep drainage blind ditches to lower the groundwater level to 2m below the freezing depth, reducing the frost heave disease rate by 70%. The heat pipe technology is an active cooling method, which uses the gas-liquid two-phase circulation of ammonia to transfer heat from the underground to the atmosphere, reducing the foundation temperature. The Qinghai-Tibet Railway has widely adopted heat pipe technology, maintaining the soil temperature below -0.5°C and ensuring the stability of the subgrade[1].

(2) Material Improvement: R&D and Application of Functional Materials

Mineral admixture modification improves soil properties by adding active minerals such as metakaolin and silica fume. These active minerals undergo pozzolanic reaction with water and cementitious materials in the soil to generate gel substances such as calcium silicate hydrate, which fill soil pores, improve soil cementation, and inhibit water migration. Studies have shown that when the content of metakaolin and silica fume is 8%-10%, the frost heave amount of clay can be reduced by 25%-30%[2].

Nanomaterials and chemical admixtures have shown unique advantages in soil improvement. Nano-SiO_2 particles can fill soil micropores due to their extremely small particle size and huge specific surface area, improving soil compactness and freeze-thaw resistance. After 50 freeze-thaw cycles, the strength and stability of soil added with nano-SiO_2 particles can still be maintained at a high level. Polypropylene fiber, as a common chemical admixture, can enhance the toughness of soil and reduce crack development. After 50 freeze-thaw cycles, the compressive strength retention rate of fiber-modified soil is 40% higher than that of plain soil[2].

(3) Intelligent Monitoring and Prediction Technology

Distributed optical fiber monitoring technology can real-time perceive soil temperature and strain changes through fiber Bragg grating (FBG), with temperature accuracy up to 0.1℃ and strain accuracy up to 10με. This technology has been widely used in the frozen soil subgrade monitoring of the Qinghai-Tibet Railway, providing all-weather monitoring and early warning for the safe operation of the railway[1].

Big data and machine learning models provide new methods for frost heave and thaw settlement prediction. Based on historical freeze-thaw data and meteorological parameters, models such as LSTM and random forest are constructed to accurately predict the trend of frost heave and thaw settlement. In the subgrade settlement prediction of seasonal frozen soil areas in Northeast China, the prediction error of the LSTM model can be controlled within 5%, providing a scientific basis for engineering maintenance and management[9].

5. Typical Engineering Application Cases

(1) Road Engineering in Seasonal Frozen Soil Areas: A Case Study of Northeast China

Northeast China is a typical seasonal frozen soil area, with long and cold winters and short and warm summers. Roads in this area face serious frost heave and thaw settlement problems. In winter, the rapid freezing of subgrade soil leads to road bulges with heights of 15-30cm. In spring, the thawing of frozen soil causes road pits and boiling mud, seriously affecting driving safety and comfort. The disease rate increases exponentially with the number of freeze-thaw cycles[8].

In order to solve these problems, engineers have adopted a combined scheme of "subgrade moisture retention + structural strengthening". This scheme includes laying a 5cm thick EPS thermal insulation layer, replacing the base with graded crushed stone, and selecting high-toughness asphalt mixture for the surface layer. The EPS thermal insulation layer reduces the subgrade freezing depth by 30%-40%, the graded crushed stone improves the drainage condition of the subgrade, and the high-toughness asphalt mixture enhances the deformation resistance of the road surface. Practice has shown that this scheme has extended the service life of roads from the original 5 years to more than 12 years, significantly reducing maintenance costs[9].

(2) Railway in Plateau Permafrost Area: A Case Study of Qinghai-Tibet Railway

The Qinghai-Tibet Railway traverses the permafrost area of the Qinghai-Tibet Plateau, with an average altitude of more than 4000m, an annual average temperature below -5℃, and a permafrost thickness of 10-30m. The thaw settlement coefficient is as high as 15%-20%, which brings huge challenges to railway construction. Traditional concrete structures are difficult to adapt to such complex geological and climatic conditions, and are prone to cracking and damage[1].

In order to solve the world-class problem of "building a railway on tofu", the Qinghai-Tibet Railway has adopted a comprehensive technology of "heat pipe + steel corrugated pipe + thermal insulation layer". Heat pipes actively cool the foundation to maintain the stability of permafrost; steel corrugated pipes adapt to soil deformation through their own flexibility; thermal insulation layers reduce heat infiltration and keep the frozen soil in a frozen state. Through the application of this comprehensive technology, the Qinghai-Tibet Railway has successfully realized safe and stable operation, providing valuable experience for global cold region railway construction[10].

6. Conclusion and Prospect

(1) Research Conclusion

Frost heave and thaw settlement is a complex process involving multi-field coupling of soil, water and heat, and its core mechanism can be described by capillary theory, frozen fringe theory and THM coupling model. Soil properties, water content, temperature gradient and engineering load are the key factors affecting frost heave and thaw settlement. Fine-grained soil has high frost heave sensitivity, and the increase of water content and temperature gradient will significantly intensify frost heave deformation.

At present, a relatively complete technical system for frost heave and thaw settlement prevention and control has been formed at home and abroad, including engineering measures such as foundation treatment and thermal insulation, material improvement technologies such as mineral admixtures and nanomaterials, and intelligent monitoring and prediction technologies based on distributed optical fiber and machine learning. These technologies have been successfully applied in typical projects such as roads in seasonal frozen soil areas and railways in plateau permafrost areas, achieving good prevention and control effects.

However, there are still some shortcomings in the current research. The multi-field coupling constitutive model considering chemical action and microbial activity needs to be improved, the influence mechanism of long-term freeze-thaw cycles on soil microstructure is not yet fully clear, and the full life cycle risk assessment system for infrastructure in high-altitude permafrost areas is lacking.

(2) Future Prospect

In terms of theory, future research should focus on constructing a multi-field coupling constitutive model that comprehensively considers factors such as salt migration and microbial activity, improving the dynamic description of the whole process of frost heave and thaw settlement, and deeply exploring the micromechanical mechanism of freeze-thaw cycles on soil structure evolution.

In terms of technology, research and development of intelligent prevention and control equipment and environmentally friendly improved materials will become the development direction. Adaptive temperature control and drainage systems can realize precise control of frost heave and thaw settlement, and bio-based polymer admixtures can reduce the environmental impact while improving soil performance.

In terms of engineering, it is necessary to establish a full life cycle monitoring database for infrastructure in frozen soil areas, combine digital twin technology to realize real-time monitoring, accurate prediction and active prevention and control of frost heave and thaw settlement disasters, and provide more reliable theoretical support and technical solutions for infrastructure construction in frozen soil areas along the "Belt and Road Initiative".

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