

Study on Influencing Factors of Bearing Performance of Pile Foundations in High-Altitude Permafrost Environments and Their Engineering Applications

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Abstract

High-altitude permafrost regions are characterized by low temperatures, intense freeze-thaw cycles, and pronounced temperature sensitivity. Changes in the permafrost environment can easily lead to the deterioration of the mechanical properties of soils, thereby affecting the long-term bearing performance and engineering stability of pile foundations. To clarify the variation law of pile foundation bearing performance and its major influencing factors under permafrost conditions, this study focuses on the pile-soil interaction mechanism and engineering application issues in high-altitude permafrost areas. First, the characteristics of the high-altitude permafrost environment and their effects on the mechanical behavior of pile foundations are analyzed, and the mechanisms by which freezing action, freeze-thaw cycles, and temperature variation influence shaft freeze-bond resistance and pile-tip bearing capacity are elucidated. Second, the effects of the physical and mechanical properties of frozen soil, temperature variation, freeze-thaw cycles, structural parameters of pile foundations, and loading conditions on the bearing performance of pile foundations are discussed. Finally, in combination with the engineering application characteristics in permafrost regions, key issues in the design, construction, and long-term service of pile foundations are analyzed. The results indicate that ground temperature variation and freeze-thaw cycles are the primary factors affecting the long-term stability of pile foundations. Permafrost degradation weakens the freezing effect at the pile-soil interface, thereby reducing shaft resistance and the overall bearing capacity. Therefore, in the construction of pile foundation projects in high-altitude permafrost regions, environmental changes, structural parameters, and long-term service effects should be comprehensively considered, and reasonable design and protective measures should be adopted to improve the safety and reliability of foundation engineering. The findings of this study can provide a reference for the optimization of pile foundation design and engineering application in high-altitude permafrost regions.

Keywords

High-Altitude Permafrost; Pile Foundation; Bearing Performance; Freeze–Thaw Cycle; Pile–Soil Interaction; Engineering Application

1. Introduction

With the continuous advancement of transportation, energy, and infrastructure development in western China, high-altitude permafrost regions have gradually become important areas for major engineering construction. The Qinghai–Tibet Plateau and other alpine regions are characterized by low temperatures, intensive freeze–thaw cycles, and fragile ecological environments. As a typical temperature-sensitive geomaterial, the physical and mechanical properties of permafrost vary significantly with temperature changes [1–2]. Variations in temperature, ice–water migration, and freeze–thaw processes within permafrost environments can induce changes in soil strength and the accumulation of deformation, thereby affecting the long-term stability of foundation structures. Therefore, investigating the bearing characteristics of foundation systems in high-altitude permafrost environments is of significant theoretical and engineering importance.

Pile foundations, owing to their high bearing capacity and effective deformation control capability, have been widely applied in bridges, roads, and building structures in permafrost regions [3,4]. However, pile foundations in permafrost environments are significantly affected by the unique mechanical behavior of frozen soils. Under frozen conditions, frozen bonding develops between the surrounding soil and the pile surface, enhancing the shaft resistance of piles. With increasing freeze–thaw cycles and rising temperatures, the frozen soil structure gradually deteriorates, weakening the pile–soil interface interaction and reducing the bearing performance of pile foundations [5]. In addition, factors such as frozen soil properties, temperature variation, freeze–thaw effects, and pile structural parameters have significant influences on the mechanical behavior of pile foundations [6]. Although considerable progress has been achieved in the study of pile foundation bearing performance in permafrost regions, the high-altitude permafrost environment involves complex multi-factor coupling effects, and the long-term evolution mechanism of pile foundation bearing performance under service conditions remains insufficiently understood. Therefore, systematically identifying the key factors affecting pile foundation bearing performance is essential for improving the reliability of engineering design in permafrost regions.

This study focuses on the bearing performance of pile foundations in high-altitude permafrost environments. The characteristics of the permafrost environment and pile–soil interaction mechanisms are analyzed, and the effects of frozen soil properties, temperature variation, freeze–thaw cycles, and structural parameters on

pile foundation bearing performance are investigated. Furthermore, key issues related to pile foundation design and engineering applications in permafrost regions are summarized based on engineering cases, providing references for infrastructure construction in cold regions.

2. Characteristics of High-Altitude Permafrost Environment and Pile Foundation Interaction Mechanism

2.1. Characteristics of High-Altitude Permafrost Environment

High-altitude permafrost regions are generally characterized by low temperatures, intensive freeze–thaw cycles, and significant seasonal temperature variations, with subsurface soils remaining in a frozen or partially frozen state for long periods. Permafrost is a multi-phase geomaterial composed of soil particles, ice, water, and gas, and its engineering properties are jointly governed by temperature, moisture conditions, and stress state. It exhibits strong temperature sensitivity, with its strength and deformation characteristics varying significantly with the degree of freezing.

As shown in Table 1, seasonal temperature variations result in repeated freeze–thaw processes within the active layer, while the stability of the underlying permafrost layer is primarily controlled by long-term ground temperature variations, which directly determine the long-term service performance of engineering foundations. Ice content is one of the critical factors influencing the mechanical behavior of frozen soils. When temperature decreases, pore water freezes into ice crystals, enhancing soil cementation and improving soil strength. Conversely, increasing temperature causes ice melting and structural degradation of frozen soils. Therefore, permafrost generally exhibits higher bearing performance under lower temperatures and higher ice contents, whereas its strength gradually decreases with increasing temperature and decreasing ice content.

Table 1. Main Engineering Characteristics of High-Altitude Permafrost and Their Effects

Characteristics of permafrost environment	Main manifestations	Effects on pile foundations
Low-temperature environment	Long-term soil freezing	Enhances pile–soil frozen bonding effect
Freeze–thaw cycles	Repeated ice–water phase transitions	Causes soil structural damage
Variation in ice content	Ice crystal formation and melting	Alters soil strength
Increase in ground temperature	Permafrost degradation	Reduces long-term bearing performance

2.2. Mechanism of Pile Foundation Behavior in Permafrost Environments

As illustrated in Figure 1, the bearing performance of pile foundations in high-altitude permafrost environments is mainly contributed by shaft resistance and pile-tip resistance, and its load-bearing mechanism differs significantly from

that under normal temperature conditions. Due to the freezing effect of permafrost, a frozen bonding layer develops between the surrounding soil and the pile surface, resulting in strong pile–soil interface interaction. Under permafrost conditions, the frozen shaft resistance is a critical component governing the bearing capacity of pile foundations.

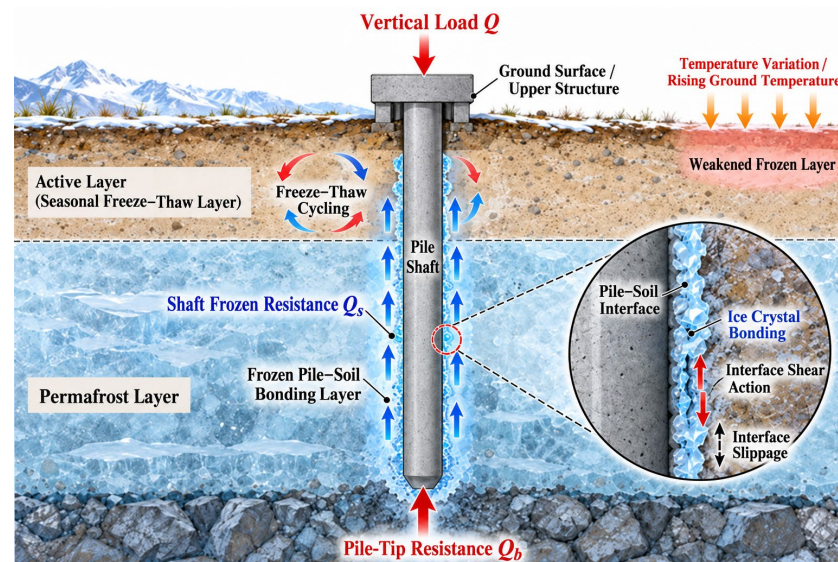


Fig 1. Schematic diagram of pile foundation interaction mechanism in permafrost environments

As presented in Table 2, under frozen conditions, a frozen bonding zone forms around the pile, and the frozen bonding force along the pile shaft can effectively restrict pile displacement and enhance the bearing capacity. However, under long-term freeze–thaw cycles, the frozen bonding structure gradually deteriorates, leading to softening of the pile–soil interface and reduction of shaft resistance.

Table 2. Comparison of Pile Foundation Interaction Characteristics under Frozen and Thawed Conditions

State	Characteristics of pile–soil interaction	Bearing performance
Frozen state	Enhanced pile–soil frozen bonding	High shaft resistance
Freeze–thaw stage	Interface changes induced by ice–water phase transition	Fluctuating bearing performance
Thawed state	Degradation of frozen layer and weakening of interface	Reduced bearing capacity

In addition, pile–soil interface behavior is affected by temperature gradients, loading conditions, and soil deformation characteristics. Increasing external loads enhances the shear interaction at the pile–soil interface. When the applied stress exceeds the shear strength of the interface, slippage may occur, resulting in increased pile foundation settlement. Therefore, the bearing performance of pile foundations in permafrost environments is governed by the coupled effects of environmental conditions, soil properties, and structural parameters.

In summary, high-altitude permafrost environments exhibit significant temperature

sensitivity and time-dependent characteristics. Variations in permafrost conditions directly influence pile–soil interface interaction and foundation bearing capacity. Understanding the characteristics of the permafrost environment and the mechanical behavior of pile foundations provides an essential basis for further investigating the influencing factors of bearing performance and engineering applications.

3. Analysis of Influencing Factors on the Bearing Performance of Pile Foundations in High-Altitude Permafrost Environments

3.1. Influence of Physical and Mechanical Properties of Frozen Soil

The physical and mechanical properties of frozen soil are fundamental factors controlling the bearing performance of pile foundations. Parameters such as ice content, soil density, particle composition, and freezing strength have significant effects on pile–soil interface behavior.

When the ice content is relatively high, the frozen soil forms a strong ice-cemented structure after freezing, which enhances the shear strength of the soil and the frozen bonding strength along the pile shaft, thereby improving the bearing capacity of pile foundations. However, as temperature increases and ice crystals melt, the soil structure deteriorates, pore water content increases, and shear strength decreases, resulting in a reduction in shaft resistance.

The shear strength of frozen soil can generally be expressed as:

$$\tau_f = c_f + \sigma_n \tan \varphi_f \quad (1)$$

where τ_f represents the shear strength of frozen soil; c_f represents the frozen cohesion; σ_n represents the normal stress; and φ_f represents the frozen internal friction angle. Among these parameters, frozen cohesion is an important indicator reflecting the freezing effect of soil, and its magnitude is closely related to temperature and ice content.

3.2. Influence of Temperature Variation

Temperature is a critical factor controlling the variation of frozen soil mechanical properties. When temperature decreases, the degree of soil freezing increases, resulting in higher ice content and the formation of a stronger frozen layer around the pile, which enhances shaft resistance. Conversely, increasing temperature causes permafrost degradation, reduces the thickness of the frozen layer, and weakens the pile–soil interface strength.

The relationship between the bearing performance of frozen soil and temperature can generally be expressed as:

$$R = f(T) \quad (2)$$

where R represents the bearing performance indicator of frozen soil, and T

represents the frozen soil temperature.

3.3. Influence of Freeze–Thaw Cycles

Freeze–thaw cycles are one of the primary factors responsible for the degradation of pile foundation performance in permafrost regions. Repeated freezing and thawing processes alter the pore structure of frozen soil, induce frost heave and thaw settlement, and cause damage to the pile–soil interface. As shown in Table 3, the effects of freeze–thaw cycles on pile foundations mainly include: (1) reducing the frozen bonding strength along the pile shaft; (2) weakening the shear strength of the pile–soil interface; (3) increasing pile foundation settlement deformation; and (4) reducing long-term bearing stability.

Table 3. Effects of Freeze–Thaw Cycles on Pile Foundation Performance

Freeze–thaw stage	Soil variation characteristics	Effects on pile foundations
Initial freezing	Formation of ice crystals and structural enhancement	Increased shaft resistance
Repeated freeze–thaw cycles	Adjustment of pore structure	Reduced interface strength
Long-term thawing	Ice disappearance and soil softening	Decreased bearing capacity

3.4. Influence of Pile Foundation Structural Parameters

In addition to environmental factors, structural parameters of pile foundations are also important factors affecting bearing performance. Parameters including pile length, pile diameter, pile type, and material properties can alter pile–soil stress transfer behavior. Increasing pile length enlarges the effective interaction area between the pile and surrounding soil, thereby improving the contribution of shaft resistance. Increasing pile diameter enlarges the pile-tip bearing area and enhances pile-tip resistance. However, in permafrost environments, the design of pile length and diameter should also consider construction disturbance, heat transfer effects, and economic efficiency.

3.5. Influence of Loading Conditions

In practical engineering applications, pile foundations are generally subjected to combined actions of vertical loads, horizontal loads, and long-term cyclic loads. Increasing load levels enhances shear deformation at the pile–soil interface. When the applied load exceeds the shear strength of the interface, slippage failure may occur.

Furthermore, long-term cyclic loading accelerates the structural degradation of frozen soil and induces cumulative deformation of pile foundations. Therefore, the effects of loading types and long-term loading behavior should be comprehensively considered in the design of pile foundations in permafrost regions.

In summary, the bearing performance of pile foundations in high-altitude permafrost environments is governed by multiple factors. Temperature variation and freeze–thaw cycles are the key controlling factors affecting long-term stability,

while frozen soil properties, structural parameters, and loading conditions determine the pile–soil interaction process and bearing capacity. A comprehensive understanding of these influencing mechanisms is essential for ensuring the safe operation of pile foundations in permafrost regions.

4. Engineering Applications of Pile Foundations in High-Altitude Permafrost Regions

4.1. Overview of Engineering Regions and Permafrost Conditions

High-altitude permafrost regions are mainly distributed in the cold areas of western China and are characterized by the coexistence of continuous permafrost and seasonal frozen soils. These regions generally experience low mean annual air temperatures, relatively thick permafrost layers, and significant variations in subsurface temperature fields affected by climate change.

As shown in Table 4, during engineering construction in permafrost regions, pile foundations are usually designed to penetrate through the active layer and extend into relatively stable permafrost layers. The frozen bonding effect of permafrost is utilized to enhance the shaft bearing capacity of piles. However, when regional temperatures increase or the near-surface thermal environment is disturbed, permafrost degradation may occur, resulting in a reduction in frozen bonding strength around piles and affecting foundation stability.

Table 4. Main Engineering Influencing Factors of Pile Foundations in High-Altitude Permafrost Regions

Influencing factors	Engineering manifestations	Effects on pile foundations
Permafrost temperature	Increase in ground temperature and variation in freezing depth	Reduction in frozen bonding strength
Ice content	Ice melting and structural changes	Weakening of pile–soil bonding
Freeze–thaw cycles	Seasonal repeated freezing and thawing	Increasing settlement deformation
Construction disturbance	Alteration of surface thermal conditions	Accelerating permafrost degradation

4.2. Characteristics of Pile Foundation Engineering Applications

The design of pile foundations in high-altitude permafrost regions generally follows the principle of “reducing disturbance and maintaining permafrost stability.” Compared with pile foundations in non-permafrost regions, engineering applications in permafrost areas place greater emphasis on controlling thermal disturbance during construction and considering temperature variations during long-term service.

Currently, commonly used pile foundation types in permafrost regions mainly include cast-in-place piles, precast piles, and thermosyphon piles. Cast-in-place piles exhibit strong adaptability to complex geological conditions; precast piles can reduce construction disturbance due to their rapid installation; and thermosyphon piles utilize natural temperature differences to achieve active cooling, thereby

helping maintain permafrost stability.

The bearing capacity of pile foundations is mainly provided by shaft frozen resistance and pile-tip resistance. Therefore, pile foundation design should consider the time-dependent variation of frozen soil strength. In practical engineering applications, design approaches should not rely solely on short-term frozen strength but should incorporate the influence of permafrost degradation on long-term bearing performance.

4.3. Analysis of Long-Term Service Performance

During long-term service in high-altitude permafrost regions, pile foundations mainly experience increased settlement deformation and reduced bearing capacity. Engineering monitoring results indicate that in areas undergoing permafrost degradation, increasing ground temperature gradually weakens the frozen layer surrounding piles, reduces shaft resistance, and increases pile head settlement. The long-term stability of pile foundations can be expressed as:

$$S = f(T, N, t) \quad (3)$$

where S represents pile foundation settlement; T represents permafrost temperature; N represents the number of freeze-thaw cycles; and t represents service time.

It can be observed that temperature variation, freeze-thaw cycles, and service duration are important factors controlling the long-term deformation behavior of pile foundations.

To improve the stability of pile foundations in permafrost regions, the following measures are commonly adopted: (1) Optimizing pile embedment depth to ensure that pile tips penetrate into stable permafrost layers; (2) Applying insulation measures to reduce heat transfer from the ground surface into deeper soil layers; (3) Strengthening permafrost protection during construction and minimizing disturbance; (4) Establishing long-term monitoring systems to evaluate the evolution of permafrost conditions and pile foundation performance.

4.4. Engineering Implications

Engineering practices in permafrost regions demonstrate that environmental conditions are the dominant factors controlling the long-term performance of pile foundations. Traditional design methods based on the assumption of stable soil layers cannot fully represent the behavior of pile foundations in permafrost environments. Therefore, temperature variations and long-term degradation effects of permafrost should be comprehensively considered.

Future pile foundation construction in permafrost regions should focus on the following aspects: (1) Strengthening long-term monitoring of permafrost environments to characterize ground temperature variations; (2) Developing pile

foundation design methods considering freeze–thaw effects; (3) Applying active or passive thermal insulation measures to improve permafrost stability; (4) Combining operational monitoring data to predict the long-term performance of pile foundations.

In summary, engineering applications of pile foundations in high-altitude permafrost regions require comprehensive consideration of environmental factors, structural parameters, and long-term service effects. A thorough understanding of the influence of permafrost conditions on pile–soil interaction mechanisms is essential for improving the reliability and adaptability of pile foundation design.

5. Conclusions

This study investigated the bearing performance of pile foundations in high-altitude permafrost environments by analyzing permafrost characteristics, pile–soil interaction mechanisms, and major influencing factors. Furthermore, key issues related to the long-term service behavior of pile foundations in permafrost regions were discussed based on engineering applications. The main conclusions are summarized as follows:

- (1) High-altitude permafrost environments exhibit significant temperature sensitivity and time-dependent characteristics. Variations in permafrost temperature, ice–water migration, and freeze–thaw processes alter soil structures and mechanical properties, thereby affecting the long-term stability of pile foundations. Among these factors, permafrost degradation and thaw settlement are important causes of reduced pile foundation bearing performance.
- (2) The bearing capacity of pile foundations in permafrost environments is mainly provided by shaft frozen resistance and pile-tip resistance. Under frozen conditions, frozen bonding develops between surrounding soil and pile surfaces, enhancing shaft bearing performance. However, increasing temperature and intensified freeze–thaw cycles gradually weaken the frozen layer and pile–soil interface strength, resulting in degradation of bearing performance.
- (3) Frozen soil properties, temperature variations, freeze–thaw cycles, pile structural parameters, and loading conditions are the main factors affecting pile foundation bearing performance. Temperature variation and freeze–thaw cycles have particularly significant effects on long-term service behavior, while pile length, pile diameter, and structural type mainly control bearing capacity and deformation characteristics.
- (4) Engineering applications in high-altitude permafrost regions indicate that design and construction processes should fully consider environmental changes and long-term service effects. By selecting appropriate pile foundation types, reducing construction disturbance, and implementing thermal protection measures, the stability and reliability of foundation structures can be effectively improved.

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