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Study on Deformation Characteristics and Treatment Techniques of Building Foundations in High-Cold and High-Altitude Regions of Tibet

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Abstract

In high-cold and high-altitude regions of Tibet, foundation soils of building engineering projects are prone to settlement deformation and stability degradation under the combined effects of freeze–thaw cycles, temperature variations, and building loads. In this study, the deformation characteristics and treatment techniques of building foundations in such environments are investigated. Based on regional engineering geological conditions and the physical and mechanical properties of foundation soils, the deformation behavior of foundations subjected to freeze–thaw cycles and building loads is analyzed, the influencing factors are discussed, and the applicability of various foundation treatment techniques, including replacement cushion layers, composite foundations, pile foundations, and thermal insulation measures, is evaluated. The results indicate that foundation soils in high-cold regions of Tibet exhibit significant freeze–thaw sensitivity. Freeze–thaw cycles alter soil structures, reduce soil strength, and increase compressibility, while building loads further accelerate settlement development, resulting in long-term and cumulative deformation characteristics of foundations. Appropriate foundation treatment measures can effectively improve bearing capacity and reduce settlement risks. Among these methods, composite foundations, pile foundations, and thermal insulation measures demonstrate better performance in controlling long-term deformation. The findings provide a reference for foundation design and deformation control of building engineering projects in Tibet and other similar high-cold regions.

Keywords

Tibet region; high-cold and high-altitude environment; foundation deformation; freeze–thaw cycle; foundation treatment

1. Introduction

Located on the Qinghai–Tibet Plateau, Tibet is characterized by high altitude, low temperature, intensive freeze–thaw processes, and complex geological conditions

[1]. With the continuous development of urban construction and infrastructure projects in this region, higher requirements have been imposed on the bearing capacity, deformation control, and long-term stability of building foundations. However, under high-cold and high-altitude conditions, foundation soils are simultaneously affected by freeze–thaw cycles, temperature variations, water migration, and building loads, which may induce frost heave, thaw settlement, settlement deformation, and reduction in bearing capacity [2], thereby threatening the safety of building structures. Therefore, investigating foundation deformation characteristics and treatment technologies for building engineering in high-cold regions is of great engineering significance.

Extensive studies have been conducted on geotechnical engineering problems in cold regions. Previous research has demonstrated that freeze–thaw cycles can modify the internal structure of soils, resulting in reduced strength and increased compressibility, and are therefore regarded as critical factors affecting foundation stability in cold regions [3]. The combined effects of temperature variations, groundwater conditions, and building loads influence permafrost degradation and settlement development, causing foundation deformation to exhibit significant time-dependent and complex characteristics [4]. At present, various treatment technologies, including replacement cushion layers, composite foundations, pile foundations, and thermal insulation measures, have been widely applied in cold-region engineering. However, the mechanisms governing long-term deformation control under the unique environmental conditions of Tibet require further investigation [5].

Therefore, this study focuses on building foundations in high-cold and high-altitude regions of Tibet. The regional engineering geological conditions and foundation soil characteristics are analyzed, the deformation behavior of foundations under freeze–thaw cycles and building loads is investigated, and the deformation control effects of different treatment techniques are evaluated. The results provide a reference for foundation design and treatment of building engineering projects in Tibet and other similar cold-region environments.

2. Engineering Geological Conditions and Foundation Soil Characteristics in High-Cold and High-Altitude Regions of Tibet

To investigate the deformation behavior of building foundations under high-cold environmental conditions, the regional engineering geological conditions and fundamental properties of foundation soils are first analyzed. The unique climatic environment and complex geological conditions of Tibet determine that regional soils exhibit significant freeze–thaw sensitivity and deformation characteristics.

2.1. Characteristics of Regional Natural Environment

Located in the southwestern part of the Qinghai–Tibet Plateau, Tibet belongs to a

typical high-cold continental climate region, characterized by high altitude, low temperature, long freezing periods, and intensive freeze–thaw cycles. Influenced by temperature variations and water migration, ice–water phase transitions occur within soils, resulting in structural adjustment and changes in engineering properties.

The freeze depth is mainly affected by freezing conditions, active layer thickness, and groundwater conditions, which can be expressed as:

$$Z_f = \sqrt{\frac{2\lambda \Delta T t}{L\rho}} \tag{1}$$

where Z_f represents the freezing depth (m); λ represents the thermal conductivity of soil (W/(m·℃)); Δ represents the temperature difference (℃); t represents freezing duration (s); L represents the latent heat of soil freezing (J/kg); and ρ represents soil density (kg/m^3).

During freeze–thaw cycles, the freezing and melting of pore water alter the bonding conditions between soil particles, thereby affecting the bearing capacity and deformation characteristics of foundations.

2.2. Geological Structure and Soil Composition

The geological structure of Tibet is complex, with widespread Quaternary alluvial deposits, glaciofluvial deposits, residual slope deposits, and bedrock layers. Shallow foundation soils commonly consist of silt, silty clay, sandy soil, and gravel soil. The typical stratigraphic structure is presented in Table 1. Among these soil types, silt and silty clay exhibit strong water retention capacity and are highly susceptible to frost heave caused by ice crystal accumulation during freezing. After thawing, structural degradation and thaw settlement may occur, making these soils critical targets for foundation deformation control.

Table 1. Typical Stratigraphic Characteristics of Building Sites in High-Cold Regions

Layer	Soil type	Main engineering characteristics
Surface layer	Miscellaneous fill or topsoil	Loose structure and high compressibility
Shallow layer	Silt and silty clay	Strong freeze–thaw sensitivity and prone to deformation
Intermediate layer	Sandy gravel layer	High permeability and relatively high bearing capacity
Deep layer	Bedrock or dense soil layer	Good stability and suitable as foundation bearing strata

2.3. Basic Physical and Mechanical Parameters of Foundation Soils

The physical and mechanical parameters of foundation soils are important indicators for evaluating foundation stability. Typical soil parameters are listed in Table 2.

Table 2. Main Physical and Mechanical Parameters of Foundation Soils

Soil type	Natural water content (%)	Void ratio	Compression coefficient (MPa^{-1})	Cohesion (kPa)	Internal friction angle (°)
Silty clay	18–28	0.75–1.05	0.25–0.45	18–35	12–22
Silt	15–25	0.65–0.90	0.20–0.35	10–25	18–28
Sandy gravel soil	8–15	0.40–0.65	0.10–0.20	0–10	28–38

As shown in Table 2, silty clay and silt exhibit relatively high compressibility, and their engineering properties are significantly affected by environmental variations. Foundation settlement can be calculated using one-dimensional consolidation theory:

$$S = \frac{C_c H}{1 + e_0} \log \frac{p_0 + \Delta p}{p_0} \tag{2}$$

where S represents foundation settlement (mm); C_c represents compression index; H represents thickness of the compressible layer (m); e_0 represents initial void ratio; p_0 represents initial effective stress; and Δp represents additional stress.

In summary, the engineering properties of foundation soils in high-cold regions of Tibet are jointly controlled by soil composition, temperature, moisture conditions, and freeze–thaw cycles.

3. Deformation Characteristics of Building Foundations under High-Cold Environmental Conditions

The engineering properties of foundation soils in high-cold and high-altitude regions of Tibet are significantly influenced by temperature variation, water migration, and soil structure. Compared with foundations in non-frozen regions, foundation deformation under combined freeze–thaw cycles and building loads exhibits cumulative and long-term characteristics.

3.1. Influence of Freeze–Thaw Cycles on Foundation Soil Deformation

Freeze–thaw cycling is one of the key factors affecting foundation stability in cold regions. During the freezing stage, pore water forms ice crystals and generates frost heaving pressure, increasing the spacing between soil particles. During thawing, ice crystals melt, causing soil structural loosening, and some pores cannot recover, resulting in irreversible deformation. With increasing freeze–thaw cycles, the internal structure of soil gradually deteriorates, characterized by reduced strength and increased compressibility.

The freeze–thaw deformation ratio can be expressed as:

$$\varepsilon_f = \frac{H_i - H_0}{H_0} \times 100\% \tag{3}$$

where ε_f represents the freeze–thaw deformation ratio (%); H_i represents the height of soil sample after freeze–thaw cycles (mm); and H_0 represents the initial height of soil sample (mm).

Under freeze–thaw cycles, soil deformation generally experiences three stages: rapid development, stable variation, and cumulative deformation, as shown in Figure 1. During the initial freeze–thaw stage, soil structural adjustment is significant and deformation increases rapidly. With increasing cycle numbers, the deformation rate decreases, but cumulative deformation continues to develop. Therefore, foundation design in high-cold regions should consider not only initial bearing capacity but also long-term freeze–thaw deformation effects.

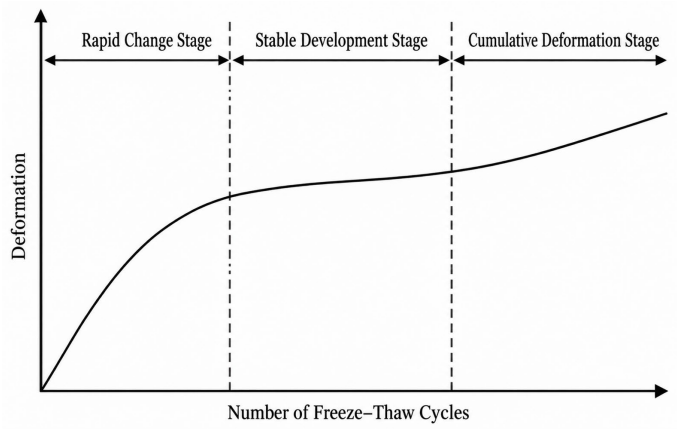


Fig 1. Development process of soil deformation under freeze–thaw cycles

3.2. Characteristics of Foundation Settlement under Building Loads

In addition to environmental factors, building loads are another important factor affecting foundation deformation in high-cold regions. Building loads alter the original stress state of the ground and induce soil compression deformation. When freeze–thaw processes weaken soil structures, external loads further accelerate pore compression and particle rearrangement, thereby intensifying settlement development.

Foundation settlement can be calculated using the layer summation method:

$$S = \sum_{i=1}^{n} \frac{m_i \Delta p_i H_i}{E_i} \tag{4}$$

where S represents total foundation settlement (mm); m_i represents the settlement correction coefficient of layer i; Δp_i represents additional stress in layer i (kPa); H_i represents thickness of layer i (m); and E_i represents compression modulus of layer i (MPa).

The deformation characteristics of foundations under building loads are shown in Table 3. It can be observed that foundation settlement in high-cold regions is controlled not only by initial loading conditions but also by long-term environmental variations. Therefore, the development trend of foundation settlement under freeze–thaw environments should be fully considered during foundation design.

Table 3. Deformation Characteristics of Foundations under Building Loads

Deformation stage	Main mechanism	Deformation characteristics
Initial stage	Rapid soil compression induced by foundation loading	High settlement rate
Consolidation stage	Pore water dissipation and structural adjustment	Continuous settlement development
Long-term stage	Freeze–thaw cycles and creep effects	Accumulated deformation

3.3. Analysis of Factors Influencing Foundation Deformation

Foundation deformation in high-cold regions of Tibet results from the combined effects of multiple factors. The main influencing factors are summarized in Table 4. Among them, temperature variation controls freeze–thaw processes, water content affects frost heave and thaw settlement, while building loads accelerate soil compression deformation after freeze–thaw damage. Therefore, foundation deformation in high-cold regions exhibits significant multi-factor coupling characteristics, requiring targeted treatment measures.

Table 4. Main Influencing Factors of Foundation Deformation

Influencing factor	Mechanism	Influence on deformation
Temperature variation	Controls freeze–thaw processes and frozen soil state changes	Most significant influence
Water content	Affects ice crystal formation and thaw settlement	Increases deformation risk
Soil structure	Determines compression and shear resistance characteristics	Influences deformation capacity
Building load	Alters foundation stress conditions	Accelerates settlement development

4. Foundation Treatment Techniques and Deformation Control Performance

Because natural foundations are prone to frost heave, thaw settlement, and cumulative settlement under long-term freeze–thaw environments, adjusting only the foundation design parameters is insufficient to meet long-term stability requirements. Therefore, appropriate foundation treatment techniques should be adopted according to regional environmental conditions to improve bearing capacity and control deformation.

4.1. Analysis of Common Foundation Treatment Methods in High-Cold Regions

Currently, commonly used foundation treatment methods for building engineering in high-cold regions of Tibet mainly include replacement cushion layers, composite foundations, pile foundations, and thermal insulation measures.

(1) Replacement Cushion Method

The replacement cushion method involves removing shallow frost-susceptible soils and replacing them with sand and gravel materials to reduce frost heave and thaw settlement effects. This method is suitable for treating shallow weak soils.

The bearing capacity of the improved composite foundation after replacement can be

expressed as:

$$f_{spk} = mf_{pk} + (1-m)f_s \quad (5)$$

where f_{spk} represents the characteristic bearing capacity of the composite foundation after replacement (kPa); m represents the replacement area ratio; f_{pk} represents the characteristic bearing capacity of the replacement material (kPa); and f_s represents the characteristic bearing capacity of the original foundation soil (kPa).

(2) Composite Foundation Technology

Composite foundation technology improves the overall stiffness of foundations by installing reinforcement elements and is widely applied in building projects requiring strict settlement control. Its bearing capacity can be calculated as:

$$f_{spk} = mf_{pk} + \beta(1-m)f_s \quad (6)$$

where β represents the bearing capacity contribution coefficient of soil between reinforcement elements. This method can effectively reduce foundation settlement and improve overall stability. It is suitable for buildings subjected to relatively high loads or projects with stringent deformation control requirements.

(3) Pile Foundation Technology

Pile foundations transfer building loads to deeper stable soil layers or bedrock, effectively avoiding shallow freeze–thaw sensitive zones. In high-cold regions, pile foundations can not only enhance vertical bearing capacity but also reduce the influence of freeze–thaw cycles on foundation stability.

The bearing capacity of pile foundations can be expressed as:

$$Q_u = Q_s + Q_p \quad (7)$$

where Q_u represents the ultimate bearing capacity of the pile foundation (kN); Q_s represents shaft resistance; and Q_p represents pile-tip resistance.

However, it should be noted that changes in the properties of frozen soils surrounding piles under freeze–thaw conditions may affect the mobilization of shaft resistance. Therefore, pile foundation design should fully consider the influence of long-term temperature variations.

(4) Thermal Insulation Measures

Thermal insulation techniques control permafrost melting and deformation development by reducing fluctuations in foundation temperature and decreasing the frequency of freeze–thaw cycles. Common measures include installation of insulation boards, construction of ventilated layers, and optimization of foundation embedment depth.

The commonly used foundation treatment methods and their applicable characteristics in high-cold regions are summarized in Table 5.

Table 5. Main Foundation Treatment Methods and Applicable Characteristics in High-Cold Regions

Treatment Method	Main Function	Applicable Conditions	Deformation Control Effect
Replacement cushion layer	Improvement of shallow soil properties	Shallow frost-susceptible soils	Good
Composite foundation	Enhancement of foundation stiffness	Weak soils and medium-to-high load buildings	Good
Pile foundation	Improvement of bearing capacity	Thick weak layers or permafrost regions	Excellent
Thermal insulation measures	Reduction of freeze–thaw effects	Continuous and seasonal permafrost areas	Effective in long-term control

4.2. Evaluation of Deformation Control Effects of Different Treatment Methods

Different foundation treatment methods exhibit significant differences in deformation control performance. The replacement cushion method mainly reduces compressive deformation by improving shallow soil properties and provides effective control of shallow frost heave problems. Composite foundations improve overall foundation stiffness and effectively reduce settlement under building loads. Pile foundations reduce the influence of freeze–thaw sensitive soils by transferring loads to deeper stable layers and are suitable for projects requiring strict deformation control.

The deformation control effect of different treatment methods can be evaluated using the settlement reduction ratio:

$$\eta = \frac{S_0 - S_1}{S_0} \times 100\% \tag{8}$$

where η represents the settlement reduction ratio (%); S0 represents the foundation settlement before treatment (mm); and S1 represents the foundation settlement after treatment (mm). The comparison of deformation control effects among different treatment methods is shown in Table 6.

Table 6. Comparison of Deformation Control Effects of Different Foundation Treatment Methods

Treatment method	Improvement of bearing capacity	Settlement control capability	Long-term stability
Replacement cushion layer	Relatively high	Good	General
Composite foundation	High	Good	Relatively good
Pile foundation	High	Excellent	High
Thermal insulation measures	Indirect improvement	Significant long-term effect	Excellent

Comprehensive analysis indicates that foundation treatment for building engineering in high-cold and high-altitude regions of Tibet should be selected according to engineering loads, geological conditions, and freeze–thaw environmental characteristics. For shallow frost-susceptible foundations, replacement cushion layers or thermal insulation measures can be adopted. For

buildings requiring strict settlement control, composite foundations or pile foundations are more appropriate. In practical engineering, combined treatment methods can be implemented to improve long-term foundation stability.

5. Conclusions

This study focuses on the deformation, settlement, and stability degradation problems of building foundations in high-cold and high-altitude regions of Tibet under long-term freeze–thaw environments. Based on regional engineering geological conditions and foundation deformation characteristics, the deformation behavior and treatment technologies of building foundations were analyzed. The main conclusions are as follows:

(1) Due to the combined effects of low temperature, freeze–thaw cycles, and complex geological conditions, foundation soils in high-cold and high-altitude regions of Tibet exhibit significant environmental sensitivity. Freeze–thaw processes alter internal pore structures and particle arrangements, reducing soil strength and increasing compressibility, thereby increasing the risks of foundation settlement and deformation. Therefore, temperature variations, moisture conditions, and soil property changes should be fully considered in foundation design to ensure long-term stability.

(2) Foundation deformation of building engineering in high-cold environments results from the combined effects of freeze–thaw cycles, building loads, and groundwater conditions. Freeze–thaw cycles control soil structural degradation, building loads accelerate compression deformation, and water conditions influence frost heave and thaw settlement. Foundation deformation exhibits significant cumulative and long-term evolutionary characteristics; therefore, conventional deformation evaluation methods developed for non-frozen regions should be modified according to regional environmental conditions.

(3) For building engineering in high-cold regions of Tibet, foundation treatment technologies including replacement cushion layers, composite foundations, pile foundations, and thermal insulation measures can effectively improve foundation performance. Replacement methods reduce shallow frost susceptibility, composite foundations and pile foundations enhance bearing capacity and reduce settlement, while thermal insulation measures mitigate freeze–thaw effects. In practical engineering applications, appropriate combined treatment schemes should be selected based on geological conditions, building load levels, and deformation control requirements.

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