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Treatment Technology and Engineering Application of Settlement Distress in Permafrost Subgrades in Alpine Regions of Tibet

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Abstract

Permafrost and seasonal frozen soils are widely distributed in the alpine regions of Tibet. Under the combined effects of climate warming and engineering disturbances, the thermal stability of frozen ground has continuously deteriorated, resulting in increasingly severe pavement and subgrade distresses, including subgrade settlement, pavement cracking, and shoulder deformation, which significantly threaten highway operational safety and service performance. Existing studies have primarily focused on the mechanisms of frozen-subgrade distress formation and individual treatment measures, whereas research on distress diagnosis systems and integrated treatment technologies for engineering maintenance applications remains relatively limited. Based on a settlement remediation project for a highway permafrost subgrade in an alpine region of Tibet, this study established a diagnostic and decision-making framework for settlement distress in frozen-soil subgrades and proposed a synergistic treatment technology integrating thermal insulation, drainage improvement, and foundation reinforcement. By developing a distress classification standard and a comprehensive evaluation index system, accurate matching between distress types and treatment schemes was achieved. Combined with insulation layer installation, drainage system optimization, and grouting reinforcement, field implementation and long-term monitoring were conducted to evaluate treatment effectiveness. The results indicate that the maximum settlement of the distressed section decreased from 168 mm to 42 mm, while the annual settlement rate was reduced from 56 mm·a^{-1} to 12 mm·a^{-1}, corresponding to a settlement control efficiency of 75%. The proposed synergistic treatment technology effectively improved the thermal regime, moisture condition, and structural stability of the subgrade, thereby significantly mitigating the development of settlement distress. The study establishes a comprehensive technical framework for the treatment of settlement distress in frozen-soil subgrades in the alpine regions of Tibet and provides valuable engineering references for highway maintenance and distress remediation in similar cold-region permafrost areas.

Keywords

Alpine regions of Tibet; frozen-soil subgrade; settlement distress; synergistic treatment; thermal insulation; engineering application

1. Introduction

The Tibet Autonomous Region is located in the interior of the Qinghai–Tibet Plateau, where high elevations, low temperatures, and complex freeze–thaw environments have resulted in the widespread distribution of permafrost and seasonal frozen ground. In recent years, with the continuous expansion and improvement of transportation infrastructure, a large number of highways have been constructed across alpine permafrost regions [1]. However, under the combined influences of climate warming and engineering disturbances, the thermal stability of frozen ground has progressively declined, leading to reductions in subgrade bearing capacity and inducing various engineering distresses, such as subgrade settlement, pavement cracking, and shoulder deformation. These issues severely affect highway operational safety and service life [2]. Therefore, investigating effective treatment technologies for settlement distress in frozen-soil subgrades within the alpine regions of Tibet and developing practical remediation approaches are of considerable engineering significance.

Extensive studies have been conducted worldwide on distress problems associated with frozen-soil subgrades. Regarding distress formation mechanisms, researchers have investigated the effects of temperature-field variations and permafrost degradation on foundation deformation [3]. Based on engineering practices associated with the Qinghai–Tibet Railway and Qinghai–Tibet Highway, previous studies have systematically revealed the mechanisms of subgrade deformation induced by permafrost degradation, groundwater activity, and thermal disturbances caused by engineering construction [4]. In terms of monitoring and assessment, existing research has primarily employed indicators such as ground temperature, settlement, and moisture content to analyze distress development patterns and establish corresponding monitoring and evaluation methodologies [5]. Concerning treatment technologies, various remediation measures—including insulation boards, thermosyphons, ventilated embankments, drainage systems, and grouting reinforcement—have been developed and successfully applied in transportation infrastructure projects located in cold regions [6].

Overall, current studies mainly focus on the mechanism analysis of frozen-subgrade distress and the evaluation of individual treatment techniques, whereas research on distress diagnosis systems and treatment-selection frameworks tailored to engineering maintenance requirements remains relatively insufficient. Furthermore, for settlement distress caused by the coupled effects of permafrost degradation, groundwater activity, and reduced foundation bearing capacity in the alpine regions of Tibet, single treatment measures often fail to achieve satisfactory performance.

Consequently, mature integrated treatment technologies and engineering validation studies are still lacking.

To address these issues, this study was conducted based on a highway permafrost-subgrade settlement remediation project in an alpine region of Tibet. A diagnostic and decision-making framework for frozen-subgrade settlement distress was established to achieve accurate matching between distress characteristics and treatment strategies. Furthermore, a synergistic treatment technology integrating thermal insulation, drainage regulation, and foundation reinforcement was proposed, and its effectiveness was evaluated through engineering implementation and field monitoring. The findings provide technical support and practical guidance for the remediation of highway settlement distress in Tibet and other alpine permafrost regions with similar environmental conditions.

2. Diagnosis and Treatment Decision-Making System for Settlement Distress in Frozen-Soil Subgrades

To address the complex mechanisms and insufficient targeting of existing treatment measures for settlement distress in frozen-soil subgrades in the alpine regions of Tibet, a classification system, diagnostic indicators, and treatment decision-making framework were established based on field investigations and monitoring data collected from representative distressed sections. The proposed framework enables accurate matching between distress types and corresponding treatment strategies.

2.1. Classification System for Settlement Distress

Field investigations revealed that settlement distress in frozen-soil subgrades is primarily manifested as pavement cracking, shoulder subsidence, and differential settlement. The severity of distress is closely related to the magnitude and development rate of settlement. Based on cumulative settlement, the distress classification criteria shown in Table 1 were established.

Table 1 Classification Criteria for Settlement Distress in Frozen-Soil Subgrades

Distress Level	Settlement (mm)	Distress Characteristics	Recommended Measures
Level I	< 50	Localized cracks and minor subsidence	Drainage maintenance
Level II	50–150	Differential settlement	Thermal insulation + drainage
Level III	> 150	Extensive settlement	Comprehensive treatment

2.2. Development of Diagnostic Indicators

Considering that settlement in frozen-soil subgrades is jointly affected by thermal, hydrological, and deformation factors, a comprehensive evaluation system was established using cumulative settlement, settlement rate, active-layer thickness, and moisture content as assessment indicators. The distress evaluation index is expressed as:

$$I = \sum_{i=1}^{n} \omega_i X_i \quad (1)$$

where: I = distress evaluation index; ω_i = weighting coefficient of indicator i; X_i = normalized value of indicator i. The weighting coefficients assigned to each indicator are presented in Table 2. Based on the calculated evaluation index, the distress condition is classified into three categories: Stable: I < 0.40; Developing: 0.40 ≤ I < 0.70; Severe: I ≥ 0.70.

Table 2. Weighting Coefficients of Diagnostic Indicators

Indicator	Cumulative Settlement	Settlement Rate	Active-Layer Thickness	Moisture Content
Weight	0.35	0.25	0.20	0.20

2.3. Establishment of the Treatment Decision-Making Process

Based on field investigations and comprehensive distress evaluation results, a treatment decision-making framework for settlement distress in frozen-soil subgrades was developed, as illustrated in Fig. 1. Differentiated treatment measures corresponding to various distress levels are summarized in Table 3. To evaluate treatment effectiveness, the settlement control ratio was introduced:

$$\eta = \frac{S_0 - S_t}{S_0} \times 100\% \quad (2)$$

where:η= settlement control ratio (%); S_0 = settlement before treatment; S_t = settlement after treatment.

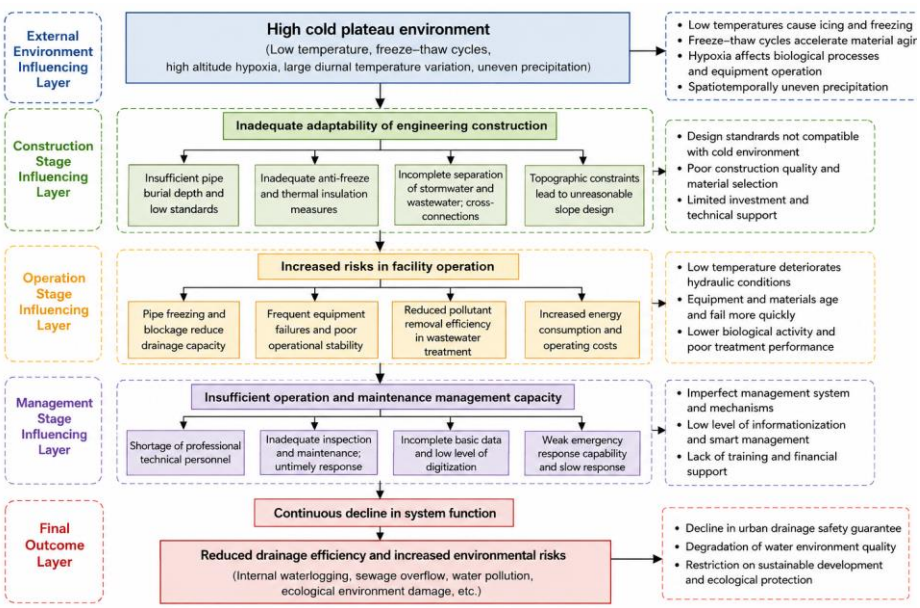


Figure 1. Decision-making framework for the treatment of settlement distress in frozen-soil subgrades.

Table 3. Correspondence between Distress Levels and Treatment Measures

Distress Level	Level I	Level II	Level III
Primary Cause	Poor drainage	Permafrost degradation	Permafrost degradation and insufficient bearing capacity
Treatment Measure	Drainage improvement	Thermal insulation + drainage	Thermal insulation + drainage + reinforcement

3. Synergistic Treatment Technology Integrating Thermal Insulation, Drainage Improvement, and Foundation Reinforcement

Settlement distress in frozen-soil subgrades in the alpine regions of Tibet is generally induced by the combined effects of permafrost degradation, groundwater activity, and reduced foundation bearing capacity. For Level II and Level III distress, a single treatment measure is often insufficient to ensure long-term stability. Therefore, a synergistic treatment technology integrating thermal insulation, drainage improvement, and foundation reinforcement was proposed. By simultaneously regulating the thermal regime, moisture condition, and stress field of the subgrade, comprehensive mitigation of settlement distress can be achieved.

3.1. Overall Technical Concept

The overall concept of the proposed synergistic treatment technology can be summarized as follows: Permafrost degradation → Thermal insulation → Groundwater activity → Drainage improvement → Bearing-capacity reduction → Foundation reinforcement → Settlement control. Among these measures, thermal insulation is employed to reduce heat transfer into the subgrade and maintain the thermal stability of frozen ground. Drainage improvement is adopted to mitigate the adverse effects of groundwater on permafrost thawing, while foundation reinforcement is used to enhance bearing capacity and overall structural stability.

3.2. Thermal Insulation Technology

To mitigate thaw-settlement induced by permafrost degradation, extruded polystyrene (XPS) insulation boards were installed at the top of the subgrade bed in distressed sections. The thickness of the insulation layer was determined according to local freezing depth and thermal stability requirements and generally ranged from 5 to 10 cm. The thermal conductivity was required to be no greater than 0.030 $W \cdot m^{-1} \cdot K^{-1}$, while the compressive strength was required to be at least 300 kPa. The insulation layer effectively reduces external heat transfer into the frozen ground and slows the deepening of the active layer.

3.3. Drainage Improvement Technology

Field investigations indicated that most distressed sections suffered from blocked side ditches and groundwater accumulation. To reduce subgrade moisture content, interception ditches, side ditches, and longitudinal blind drains were installed along

both sides of the roadway, forming an integrated drainage system. The principal design parameters were as follows: Side-ditch width ≥ 0.6 m; Side-ditch depth ≥ 0.8 m; Blind-drain diameter ≥ 200 mm; Drainage gradient = 2%–3%. A well-designed drainage system effectively reduces moisture content within the subgrade and weakens hydrothermal coupling effects.

3.4. Foundation Reinforcement Technology

For sections classified as Level III settlement distress, grouting reinforcement was adopted to improve foundation bearing capacity. Grout was injected into loose soil layers through predrilled boreholes to fill voids and improve soil structure. Cement grout was generally used, with a water–cement ratio ranging from 0.8 to 1.0. The grouting pressure was typically 0.3–0.5 MPa, and the spacing between grouting holes was generally 1.5–2.0 m. Grouting reinforcement enhances soil compactness and overall stability, thereby reducing long-term deformation.

3.5. Analysis of the Synergistic Treatment Mechanism

The three treatment measures act respectively on the thermal field, moisture field, and stress field of the subgrade. Their synergistic mechanism can be summarized as follows:Thermal insulation → Control of permafrost degradation; Drainage improvement → Reduction of moisture content; Foundation reinforcement → Enhancement of bearing capacity; Combined action → Effective control of subgrade settlement; Specifically, thermal insulation slows active-layer development and permafrost degradation; drainage measures reduce the influence of groundwater on thawing processes; and foundation reinforcement restores bearing capacity and structural integrity. Through their combined action, effective mitigation of settlement distress is achieved.

In summary, the proposed synergistic treatment technology simultaneously improves thermal stability, hydrological stability, and structural stability of frozen-soil subgrades, providing a solid technical foundation for subsequent engineering applications and performance evaluations.

4. Engineering Application and Performance Evaluation

To verify the engineering applicability and effectiveness of the proposed synergistic treatment technology, a field application was conducted in a highway settlement remediation project located in an alpine permafrost region of Tibet. The effectiveness of the integrated treatment strategy was evaluated through construction implementation, long-term monitoring, and performance assessment.

4.1. Engineering Implementation and Monitoring Program

The study section is located within a high-altitude permafrost region of Tibet at an elevation of approximately 4,500 m. The mean annual air temperature is below 0°C.

Influenced by freeze–thaw cycles and groundwater activity, significant settlement distress had developed within the subgrade. Field investigations showed that the maximum settlement reached 168 mm, accompanied by severe longitudinal and transverse pavement cracks as well as shoulder subsidence.

According to the proposed diagnostic system, the section was classified as Level III settlement distress. Consequently, the integrated treatment scheme consisting of thermal insulation, drainage improvement, and foundation reinforcement was adopted. The construction sequence included: Distress investigation → Pavement excavation → Installation of insulation layer → Construction of drainage facilities → Grouting reinforcement → Pavement restoration. The major implementation parameters are presented in Table 4. Following construction, the pavement structure was restored and a long-term monitoring program was initiated. Settlement monitoring points, ground-temperature monitoring points, and moisture-content monitoring points were installed within the treated section.

Table 4. Engineering Implementation Parameters

Item	Insulation Thickness (cm)	Side-Ditch Depth (m)	Blind-Drain Diameter (mm)	Grouting Pressure (MPa)	Grouting Hole Spacing (m)
Value	8	0.8	200	0.4	1.5

4.2. Analysis of Settlement-Control Performance

The monitoring results summarized in Table 5 indicate that the settlement rate was significantly reduced after treatment. The settlement control ratio proposed in this study was adopted to evaluate remediation effectiveness. The results demonstrate that the maximum settlement decreased substantially after treatment, and the settlement control ratio reached 75%, satisfying engineering performance requirements. Meanwhile, monitoring data indicated that the insulation layer effectively slowed active-layer development, the drainage system reduced subgrade moisture content, and grouting reinforcement improved foundation stability. Overall, the integrated treatment technology achieved remarkable remediation performance.

Table 5. Settlement Monitoring Results

Indicator	**Before Treatment**	**After Treatment**
Maximum Settlement (mm)	168	42
Annual Settlement Rate ($mm \cdot a^{-1}$)	56	12
Settlement Control Ratio (%)	—	75

4.3. Comprehensive Benefit Analysis

Field implementation and monitoring results demonstrate that the proposed synergistic treatment technology achieved substantial technical and engineering benefits.

From a technical perspective, the thermal insulation measure effectively reduced heat transfer into the frozen ground, thereby slowing active-layer development and permafrost degradation. Drainage improvement enhanced drainage conditions and reduced the adverse effects of groundwater activity on subgrade stability. Foundation reinforcement improved bearing capacity and overall structural integrity. Through the combined action of these measures, comprehensive regulation of the thermal, moisture, and stress fields was achieved, significantly mitigating settlement development.

From an engineering perspective, the post-treatment settlement rate decreased substantially, while pavement cracking and shoulder deformation were effectively controlled. Long-term stability of the subgrade was markedly improved. Monitoring results indicated stable operational performance without significant new settlement or structural damage, demonstrating the durability and adaptability of the proposed technology.

From an economic perspective, the proposed treatment strategy maximized the utilization of the existing subgrade structure, reducing the need for extensive excavation, replacement, and reconstruction works. Consequently, construction costs were reduced. Furthermore, effective control of long-term settlement significantly lowered future maintenance requirements and life-cycle maintenance expenditures.

From a social perspective, the technology shortens remediation periods, minimizes disruptions to traffic operations during construction, and enhances roadway safety and service quality. It therefore contributes positively to transportation reliability, regional economic development, and the long-term operation of critical infrastructure in Tibet.

Overall, the proposed synergistic treatment technology exhibits excellent technical feasibility, engineering applicability, and promotion potential, providing valuable guidance for the remediation of settlement distress in highways located within Tibet and other alpine permafrost regions.

5. Conclusions

To address settlement distress caused by permafrost degradation in the alpine regions of Tibet, this study established a diagnostic and treatment decision-making system for frozen-soil subgrade settlement distress based on field investigations and monitoring data from a highway remediation project. A synergistic treatment technology integrating thermal insulation, drainage improvement, and foundation reinforcement was proposed and validated through engineering application. The major conclusions are as follows:

(1) Settlement distress in frozen-soil subgrades in the alpine regions of Tibet primarily manifests as pavement cracking, shoulder subsidence, and differential settlement. Its development is jointly influenced by permafrost degradation,

groundwater activity, and reduced foundation bearing capacity. A three-level distress classification system based on cumulative settlement was established, enabling quantitative evaluation and hierarchical identification of settlement distress.

(2) A comprehensive diagnostic framework was developed using cumulative settlement, settlement rate, active-layer thickness, and moisture content as evaluation indicators. A treatment decision-making process comprising distress investigation, indicator diagnosis, distress classification, treatment selection, and engineering implementation was established, enabling accurate matching between distress types and treatment strategies.

(3) A synergistic treatment technology integrating thermal insulation, drainage improvement, and foundation reinforcement was proposed. Thermal insulation mitigates permafrost degradation, drainage measures reduce groundwater influence, and foundation reinforcement enhances bearing capacity. These measures act on the thermal, moisture, and stress fields of the subgrade, respectively, thereby improving thermal stability, hydrological stability, and structural stability in a coordinated manner.

(4) Engineering application results demonstrated significant treatment effectiveness. The maximum settlement decreased from 168 mm to 42 mm, while the annual settlement rate was reduced from 56 mm·a^{-1} to 12 mm·a^{-1}. The settlement control ratio reached 75%. Monitoring results confirmed that the insulation layer effectively restrained active-layer development, drainage facilities improved moisture conditions, and grouting reinforcement enhanced foundation stability.

(5) Comprehensive benefit analysis indicated that the proposed technology effectively controls settlement development in frozen-soil subgrades, reduces long-term maintenance demand, and improves highway service performance and operational safety. The technology exhibits strong engineering applicability and considerable potential for widespread implementation in Tibet and other alpine permafrost regions.

In conclusion, the diagnostic and treatment decision-making framework developed in this study, together with the proposed synergistic treatment technology integrating thermal insulation, drainage improvement, and foundation reinforcement, provides an effective solution for settlement distress in frozen-soil subgrades in the alpine regions of Tibet. The proposed approach is of considerable practical significance for improving highway maintenance and distress remediation practices in alpine permafrost regions.

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