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Analysis of Freeze Damage in Drainage Pipe Networks in Cold High-Altitude Regions and Engineering Mitigation Practices

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Abstract

Drainage pipe networks in cold high-altitude regions are continuously affected by low temperatures, frozen ground, and freeze–thaw cycles, making them susceptible to ice blockage, frost-heave deformation, joint cracking, and manhole freezing, which compromise the safe and stable operation of drainage systems. Existing studies have primarily focused on frozen-soil mechanisms or individual anti-freezing measures, while systematic research on freeze-damage diagnosis, integrated mitigation strategies, and effectiveness verification throughout the entire engineering process remains limited. Therefore, based on the operational characteristics of drainage systems in cold high-altitude regions, this study adopts an integrated approach combining field investigation, risk identification, indicator-based evaluation, and engineering validation to systematically analyze the characteristics and causes of freeze damage in drainage pipe networks. A freeze-damage risk identification framework consisting of environmental, engineering, and operational factors is established. Furthermore, a whole-process anti-freezing technical system featuring "source prevention–process control–operation assurance" is proposed, together with a hierarchical and integrated mitigation scheme. Engineering practice demonstrates that, after implementing zoned and graded anti-freezing measures, the number of freeze-damage incidents during the freezing period in the treated area decreased from 12 to 2, achieving a freeze-damage improvement rate of 83.3%. The internal temperature of high-risk pipeline sections was maintained above 0°C, and the winter operational stability of the drainage system was significantly enhanced. The research establishes a closed-loop framework integrating freeze-damage risk diagnosis, mitigation measure selection, and operational performance evaluation, providing practical guidance for the planning, design, rehabilitation, operation, and maintenance of drainage pipe networks in cold high-altitude regions.

Keywords

Cold High-Altitude Regions; Drainage Pipe Network; Freeze-Damage Mitigation; Risk Identification; Engineering Practice

1. Introduction

With the continuous advancement of urbanization and infrastructure development in western China, the scale of drainage system construction in cold high-altitude regions, including the Qinghai–Tibet Plateau, western Sichuan Plateau, and northwestern alpine mountainous areas, has expanded rapidly [1]. Influenced by factors such as low temperatures, frozen ground, large diurnal temperature variations, and seasonal freeze–thaw cycles, drainage pipe networks in these regions are prone to problems including ice blockage, frost-heave deformation, joint cracking, and manhole freezing during operation. These issues not only reduce the conveyance capacity of drainage systems but may also trigger secondary hazards such as sewage overflow, road subsidence, and environmental pollution, thereby posing significant threats to the safe operation of urban infrastructure [2]. Consequently, investigating the mechanisms of freeze damage and corresponding engineering mitigation measures for drainage pipe networks in cold high-altitude regions is of considerable practical significance for ensuring stable system operation and enhancing infrastructure resilience.

To date, extensive research has been conducted worldwide on freeze damage affecting underground pipelines in cold regions. Existing studies can generally be categorized into three aspects. First, research on frozen-ground environments and frost-heave mechanisms has focused on the impacts of ground temperature variations, freeze–thaw cycles, and soil frost-heave characteristics on underground structures, providing a theoretical basis for pipeline freeze-protection design [3]. Second, studies on anti-freezing technologies for drainage pipelines have explored optimization of burial depth, application of thermal insulation materials, electric heat-tracing technologies, and improvements in pipeline structural design, leading to the development of various freeze-protection measures [4]. Third, practical investigations of municipal engineering projects in cold regions have summarized freeze-damage problems encountered during drainage system operation and documented corresponding mitigation experiences, thereby verifying the applicability and effectiveness of relevant technical measures [5]. Overall, existing research has mainly focused on frozen-soil environmental analysis or individual anti-freezing technologies [6]. However, comprehensive research frameworks addressing systematic diagnosis of freeze-damage causes, development of whole-process prevention and control systems, and evaluation of engineering effectiveness for drainage pipe networks in cold high-altitude regions remain insufficient, limiting their applicability under complex engineering conditions.

In light of these challenges, this study investigates the operational characteristics of drainage engineering systems in cold high-altitude regions. First, regional environmental conditions and typical freeze-damage characteristics of drainage pipe networks are analyzed, and a framework for freeze-damage diagnosis and risk identification is established. Second, considering the entire lifecycle of planning and

design, construction, and operation and maintenance, a drainage pipe network anti-freezing technical system based on the concept of "source prevention–process control–operation assurance" is developed, and integrated engineering mitigation schemes targeting different types of freeze damage are proposed. Finally, through a practical engineering case study, the effectiveness of the proposed measures is validated, and a methodology for selecting mitigation measures that balances technical reliability and economic efficiency is established. The findings provide technical references for the planning, design, construction, operation, and management of drainage pipe networks in cold high-altitude regions, while also offering valuable engineering experience for freeze-damage mitigation in similar environments.

2. Characteristics and Causative Analysis of Freeze Damage in Drainage Pipe Networks in Cold High-Altitude Regions

To clarify the occurrence patterns of freeze damage in drainage pipe networks in cold high-altitude regions and provide a basis for the development of subsequent anti-freezing technical systems, it is necessary to conduct a systematic analysis of regional environmental conditions, freeze-damage manifestations, and influencing factors, and to establish a freeze-damage risk identification framework.

2.1. Analysis of Regional Environmental Characteristics

Cold high-altitude regions are characterized by high elevations, low temperatures, long freezing periods, and large diurnal temperature variations. Winter minimum temperatures often fall below −20°C, while soil freezing depths can reach 1.5–3.0 m, resulting in drainage pipe networks being exposed to prolonged low-temperature conditions. Furthermore, intense solar radiation and frequent freeze–thaw cycles create a complex subsurface thermal environment, thereby increasing the risk of freeze damage within pipe networks. The severity of low-temperature conditions can be represented by the freezing index:

$$F = \sum_{i=1}^{n} (0 - T_i) \tag{1}$$

where: F = freezing index (°C·d);T_i= average daily temperature on day i (°C); n = number of consecutive days with temperatures below 0°C. A larger freezing index indicates a higher risk of freeze damage. The freeze-damage formation process is illustrated in Fig.1.

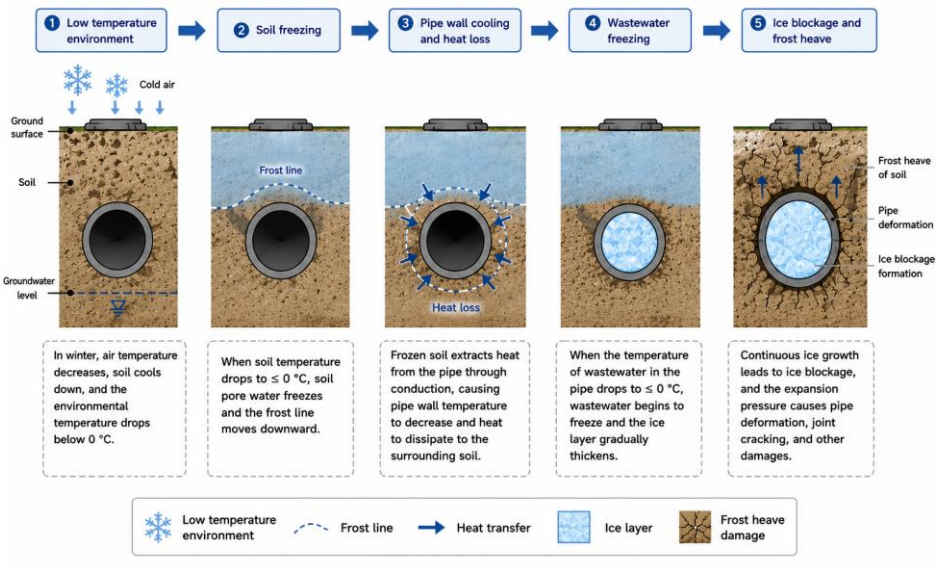


Figure 1. Schematic Diagram of the Freeze-Damage Formation Process

2.2. Typical Manifestations of Freeze Damage in Drainage Pipe Networks

Based on the operational characteristics of drainage systems in cold regions, freeze damage in drainage pipe networks mainly occurs in the forms of ice blockage, frost-heave deformation, and structural damage, as summarized in Table 1. Ice blockage is commonly observed in pipeline sections with low flow rates or insufficient gradients; frost-heave damage is primarily manifested as pipeline uplift and misalignment; structural damage includes joint cracking and frost-induced deterioration of manholes.

Table 1. Typical Types of Freeze Damage in Drainage Pipe Networks.

Freeze-Damage Type	Main Manifestation	Impact
Ice blockage	Ice formation within pipelines	Reduced drainage capacity
Frost-heave damage	Pipeline deformation and uplift	Impeded drainage performance
Joint frost cracking	Leakage and cracking	Reduced structural integrity
Manhole freezing	Ice accumulation within manholes	Increased operation and maintenance difficulty

2.3. Freeze-Damage Mechanisms and Influencing Factors

Freeze damage in drainage pipe networks results from the combined effects of natural environmental conditions, engineering design factors, and operational management practices. Natural environmental factors primarily include extreme low temperatures, freezing depth, and freeze–thaw cycles. Engineering factors mainly involve insufficient burial depth, inadequate pipeline gradients, and the absence of thermal insulation measures. Operational factors include insufficient wastewater flow, prolonged system shutdown periods, and inadequate maintenance.

The interaction of these factors contributes to the occurrence and development of freeze damage within drainage systems.

2.4. Establishment of a Freeze-Damage Risk Identification System

Based on the foregoing analysis, a freeze-damage risk identification system was established, consisting of three categories of factors: environmental factors, engineering factors, and operational factors, as shown in Fig. 2.

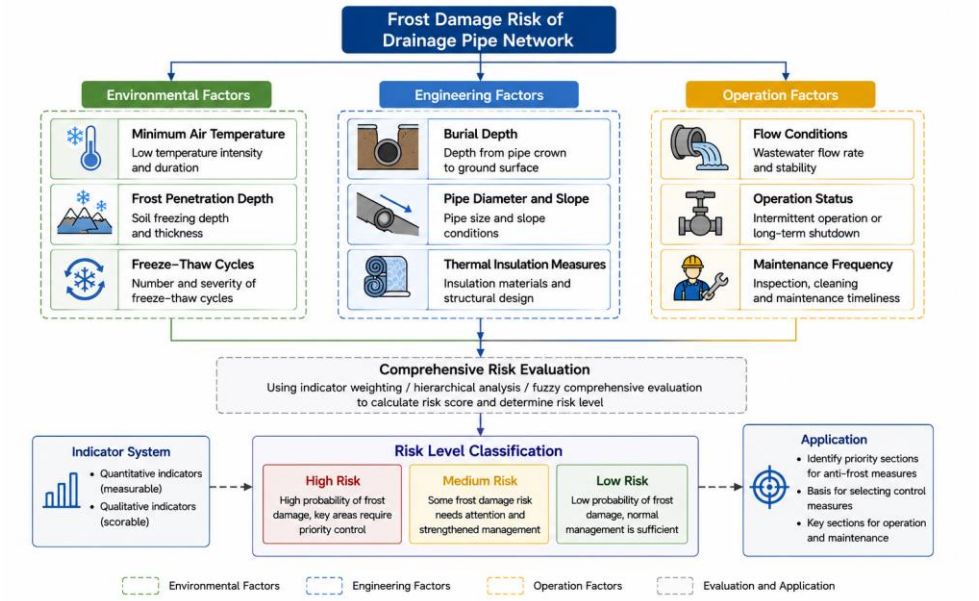


Figure 2. Freeze-Damage Risk Identification Framework

According to the combined influence of these factors, freeze-damage risks within drainage pipe networks can be classified into three levels: high, medium, and low. Pipeline sections characterized by insufficient burial depth and low flow rates under severe low-temperature conditions are generally categorized as high-risk areas and should be prioritized for anti-freezing interventions. The proposed risk identification framework provides a foundation for the subsequent development of a whole-process anti-freezing technical system and the selection of appropriate engineering mitigation measures.

3. Development of a Whole-Process Anti-Freezing Technical System for Drainage Pipe Networks

Based on the established freeze-damage risk identification framework, effective freeze-damage mitigation should not rely on a single measure. Instead, control strategies should be implemented throughout the entire project lifecycle—including planning and design, construction, and operation and maintenance—to form the technical framework of "source prevention–process control–operation assurance," as illustrated in Fig. 3.

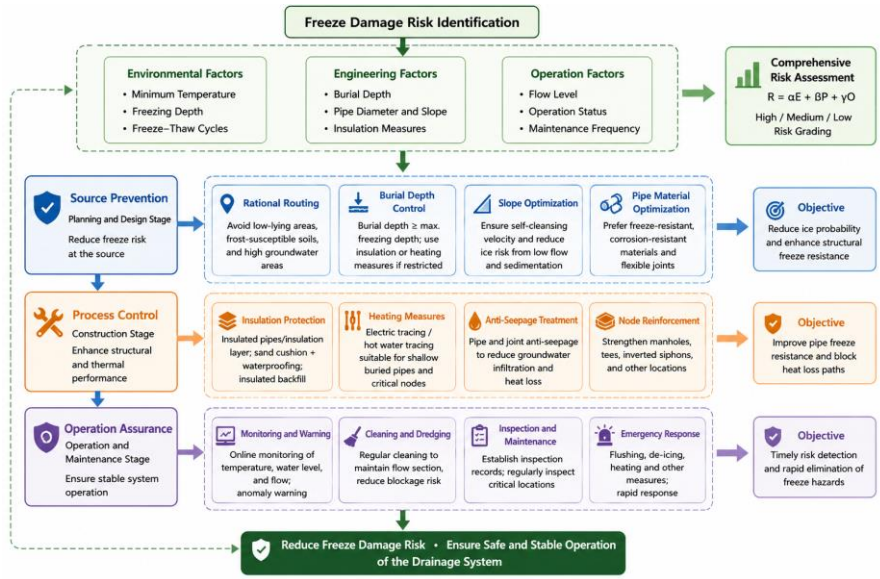


Figure 3. Framework of the Whole-Process Anti-Freezing Technical System

3.1. Overall Framework of the Technical System

The whole-process anti-freezing technical system is founded on risk classification and aims to reduce the probability of ice formation within pipelines while enhancing structural frost resistance. The anti-freezing control level of a pipeline section can be expressed by the comprehensive freeze-damage risk index:

$$R = \alpha E + \beta P + \gamma O \tag{2}$$

where: R = comprehensive freeze-damage risk index; E = environmental risk factor; P = engineering risk factor; O = operational risk factor;α, β, andγ = weighting coefficients. According to the value of R, pipeline sections can be categorized into high-, medium-, and low-risk classes, each corresponding to appropriate mitigation measures.

3.2. Source Prevention Measures

Source prevention measures are primarily implemented during the planning and design stages. First, pipeline routes should avoid low-lying waterlogged areas, highly frost-susceptible soils, and zones with high groundwater levels. Second, pipeline burial depths should be determined according to the local maximum freezing depth. Where burial-depth requirements cannot be satisfied because of terrain constraints or conflicts with existing utilities, thermal insulation layers or active heat-tracing systems should be installed simultaneously. In addition, pipeline gradients should be designed to maintain self-cleansing flow velocities, thereby minimizing the risk of ice formation caused by low-flow stagnation.

3.3. Process Control Measures

Process control measures are mainly implemented during the construction phase. For high-risk pipeline sections, a combined approach consisting of insulated pipes, sand bedding, and impermeable backfill is recommended. For frost-prone locations, including shallow-buried pipelines, inverted siphon sections, and manhole inlet/outlet connections, electric heat tracing or hot-water heat-tracing systems may be installed. Heat-tracing technologies have already been applied in cold-region shallow-buried pipelines. Previous engineering studies have demonstrated that appropriate control of heat-tracing temperatures can effectively prevent pipeline freezing.

3.4. Operational Assurance Measures

Operational assurance focuses on pre-winter inspections, operational monitoring, and emergency response to freeze-damage incidents. Inspection records should be established for critical pipeline sections. Low-flow pipelines, terminal sections, and manholes should be regularly cleaned to remove accumulated sediments that reduce hydraulic capacity. Temperature, water-level, and flow-monitoring devices may be installed at high-risk locations. When pipeline temperatures approach 0°C or abnormal increases in water levels are detected, flushing, ice-removal, or heat-tracing measures should be activated promptly.

3.5. Integrated Engineering Mitigation Scheme

Pipeline sections with different risk levels should adopt differentiated mitigation measures, as shown in Table 2.

Table 2. Integrated Freeze-Damage Mitigation Measures for Drainage Pipe Networks.

Risk Level	Applicable Pipeline Sections	Recommended Measures	Management Requirements
High Risk	Shallow-buried, low-flow, ice-prone sections	Enhanced insulation, heat tracing, reinforced critical nodes	Online monitoring and prioritized inspections
Medium Risk	Typical pipeline sections in cold regions	Insulated pipes, optimized backfill, regular cleaning	Specialized winter inspections
Low Risk	Adequately buried and operationally stable sections	Routine seepage control and maintenance	Periodic inspections

In summary, the whole-process anti-freezing technical system translates freeze-damage risk assessment results into engineering decision-making criteria, achieving a closed-loop process from risk diagnosis to mitigation implementation and providing a technical basis for subsequent engineering validation.

4. Engineering Practice and Verification of Mitigation Effectiveness

To verify the engineering applicability of the proposed whole-process anti-freezing technical system, a drainage pipe network rehabilitation project in a cold high-altitude town was selected as a case study. The effectiveness of the mitigation

measures was evaluated following the procedure of risk diagnosis–scheme design–construction implementation–operational assessment.

4.1. Project Overview

The project area is located at an average elevation of approximately 3,600 m. The winter minimum temperature is about −25°C, and the seasonal freezing depth is approximately 2.0 m. The rehabilitation project involved municipal sanitary sewer trunk and branch pipelines with a total length of approximately 4.8 km. Freeze damage was particularly severe in shallow-buried sections, low-gradient sections, and areas with a high density of manholes. Prior to rehabilitation, the drainage network experienced frequent winter problems, including ice blockage, manhole icing, and joint leakage, which adversely affected continuous system operation.

4.2. Freeze-Damage Investigation and Risk Diagnosis

Field investigations combined document review, CCTV inspection, manhole surveys, and analysis of winter operational records. The results indicated that freeze damage was primarily concentrated in pipeline sections with burial depths less than the maximum freezing depth, gradients below design requirements, and relatively low winter flow rates. To quantitatively evaluate mitigation performance, the freeze-damage improvement rate was introduced:

$$\eta = \frac{N_0 - N_1}{N_0} \times 100\% \tag{3}$$

where: η= freeze-damage improvement rate (%); N_0=number of freeze-damage incidents before mitigation; N_1 = number of freeze-damage incidents after mitigation. The engineering diagnostic procedure consisted of: Data collection → Field investigation and CCTV inspection → Freeze-damage identification → Risk classification → Mitigation measure selection → Operational performance evaluation

4.3. Design and Implementation of Mitigation Measures

Based on the risk assessment results, the drainage network was divided into high-, medium-, and low-risk zones. As shown in Table 3, high-risk sections adopted a combined strategy of insulated pipes, electric heat tracing, and reinforced manhole insulation. Medium-risk sections employed thermal insulation layers, sand bedding, and impermeable backfill, while low-risk sections focused primarily on sediment removal and routine maintenance. Previous studies on cold-region engineering have demonstrated that thermal insulation materials, active heat-tracing systems, and monitoring-based early-warning approaches are effective methods for reducing freeze-damage risks. Heat-tracing solutions have also proven feasible for shallow-buried pipelines.

Table 3. Implementation Plan for Anti-Freezing Measures

Risk Level	Main Problems	Implemented Measures	Key Control Focus
High Risk	Shallow burial, ice blockage, manhole freezing	Insulated pipes, electric heat tracing, manhole insulation	Temperature monitoring and emergency activation
Medium Risk	Insufficient gradient, localized stagnation	Insulation layers, sand bedding, impermeable backfill	Backfill quality control
Low Risk	Sediment accumulation, unstable operation	Cleaning, inspections, maintenance	Maintaining hydraulic capacity

4.4. Analysis of Operational Performance

Following implementation, the system was monitored throughout an entire freezing season. The results showed that the internal temperatures of high-risk pipeline sections remained generally above 0°C, while ice accumulation in manholes was substantially reduced. Winter drainage performance remained stable throughout the monitoring period. Prior to mitigation, 12 freeze-damage incidents occurred during the freezing season within the study area. Following implementation, this number decreased to 2. According to Equation (3), the calculated freeze-damage improvement rate reached 83.3%. Moreover, the adoption of risk-based mitigation measures avoided the excessive investment associated with applying uniformly high anti-freezing standards across the entire network, thereby achieving an effective balance between technical reliability and economic efficiency. These results demonstrate that the proposed whole-process anti-freezing technical system is well suited to practical drainage engineering applications in cold high-altitude regions.

5. Conclusions

This study addressed common winter operational problems in drainage pipe networks located in cold high-altitude regions, including ice blockage, frost-heave deformation, joint cracking, and manhole freezing. Considering factors such as regional low-temperature conditions, freeze–thaw cycles, pipeline burial depth, gradient, and operational flow rates, research was conducted on freeze-damage mechanisms, risk identification, development of an anti-freezing technical system, and engineering validation. With a strong emphasis on engineering applications, a freeze-damage risk identification framework incorporating environmental, engineering, and operational factors was established. A whole-process anti-freezing strategy based on the concept of "source prevention–process control–operation assurance" was proposed and validated through a practical drainage network rehabilitation project. The principal conclusions are as follows:

(1) Freeze damage in drainage pipe networks within cold high-altitude regions results from the combined effects of low temperatures, insufficient burial depth, inadequate pipeline gradients, low flow rates, and insufficient maintenance. Shallow-buried, low-flow, and water-retaining pipeline sections are particularly susceptible to freeze damage and should be prioritized for mitigation.

(2) The proposed comprehensive freeze-damage risk index model quantitatively

integrates environmental, engineering, and operational factors and classifies pipeline sections into high-, medium-, and low-risk categories, thereby providing a rational basis for selecting mitigation measures.

(3) The proposed whole-process anti-freezing technical system enables continuous control throughout planning and design, construction, and operation and maintenance. Source prevention focuses on route optimization, burial-depth control, and gradient design; process control emphasizes insulation, seepage prevention, heat tracing, and node reinforcement; operational assurance prioritizes monitoring, early warning, cleaning, inspections, and emergency response.

(4) Engineering application results demonstrate significant mitigation effectiveness. After implementing risk-based mitigation measures, freeze-damage incidents within the study area decreased from 12 to 2 during the freezing season, corresponding to an improvement rate of 83.3%. Internal temperatures of high-risk pipeline sections remained above 0°C, while manhole icing and pipeline ice-blockage events were substantially reduced.

(5) Compared with applying uniformly high anti-freezing standards throughout the entire network, the proposed zoned, risk-based, and integrated mitigation strategy can reduce unnecessary investment while maintaining technical reliability, offering favorable economic performance and strong potential for wider engineering application. Overall, the findings of this study provide valuable references for the freeze-protection design, rehabilitation, operation, and management of drainage pipe networks in cold high-altitude regions.

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