

ARTICLE

Smart Maintenance Technology and Its Application for Subgrade Frost Heave Diseases on Roads in Cold Regions

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ARTICLE INFO

Article history

Received: 17 April 2025

Accepted: 12 June 2025

Published Online: 30 June 2025

Keywords:

Cold regions

Road subgrade

Frost heave

Smart maintenance

Information monitoring

Predictive maintenance

ABSTRACT

Roads in cold regions are often affected by frost heave, resulting in structural damage such as cracking, uplift, and subsidence, which seriously undermines road stability and traffic safety. Traditional maintenance methods, characterized by delayed response and low efficiency, are inadequate for the complex and dynamic nature of frost heave in these regions. This study begins with an analysis of the mechanisms and distribution of frost heave-related subgrade diseases, examining how frost heave deteriorates road performance and identifying the limitations of current maintenance techniques. In response, this paper introduces the concept of “smart maintenance” enabled by advances in information technology and intelligent sensing. Key components of smart maintenance—including multi-source monitoring, data analysis, predictive modeling, and intelligent decision-making—are explored to develop a refined, data-driven, and automated maintenance management system. Through case studies, the paper validates the technical advantages and practical effectiveness of smart maintenance in predictive interventions, structural regulation, and disaster early warning. The findings suggest that smart maintenance significantly improves efficiency, reduces operational costs, and extends service life of roads in cold regions, thus demonstrating strong application potential.

1. Introduction

The frequent occurrence of seasonal frost heave in cold regions poses a major threat to the performance and structural safety of road infrastructure. As road networks expand in northern and high-altitude regions of China, frost heave-related diseases have become increasingly severe,

characterized by high frequency, persistence, and concealment. These issues not only raise maintenance costs but also compromise road service quality and safety.

Conventional road maintenance practices, relying primarily on manual inspections and reactive repairs, suffer from delayed responses and lack the capacity for timely risk control in the face of sudden or structural damage

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caused by frost heave. In light of this, the integration of smart technologies in road maintenance has emerged as a promising solution. The rise of the Internet of Things (IoT), remote sensing, big data analytics, and intelligent algorithms has enabled the construction of maintenance systems capable of real-time monitoring, trend forecasting, and dynamic intervention.

This paper focuses on the characteristics and impacts of subgrade frost heave diseases in cold regions, explores the architecture and core technologies of smart maintenance systems, and analyzes their application in real-world scenarios. The objective is to provide theoretical guidance and practical insights for sustainable road maintenance in cold climates.

2. Causes and Characteristics of Frost Heave Diseases in Cold Region Roadbeds

The formation of frost heave diseases in road subgrades is influenced by climate fluctuations, hydrological conditions, soil types, and construction quality. During the freezing season, moisture within the subgrade freezes and expands, creating upward pressure that leads to surface uplift and cracking. When thawing occurs, the melted layer loses bearing capacity, resulting in surface deformation and subsidence. The repetition of this freeze-thaw cycle accumulates internal stresses, threatening the long-term stability of the road structure.

Frost heave is especially prevalent in fine-grained soils such as silt and clay, which exhibit high water content and capillary action conducive to ice formation. Drastic temperature variations are a major exacerbating factor; in northern China, winter temperatures often fall below -30°C , with frost depths exceeding 2 meters. Inadequate drainage systems, insufficient compaction, and improper construction timing further aggravate frost-related damages.

Common manifestations include longitudinal cracks, surface bulges, and localized depressions. In severe cases, frost lenses may form, leading to structural displacement and reduced surface smoothness, ultimately compromising driving safety. These damages are cyclical and cumulative; without timely intervention, they can escalate rapidly, underscoring the necessity for accurate identification and effective treatment.

3. Limitations of Traditional Maintenance Approaches

In current practice, maintenance of cold-region roads is largely dependent on manual inspections and reactive repair strategies. While these methods provide basic remediation, they fall short in responsiveness and precision,

particularly when dealing with complex frost heave phenomena. Specific limitations include:

Delayed Detection: Reliance on visual inspection and vehicle-mounted sensors makes it difficult to identify latent or early-stage structural damage. By the time surface deformation is observed, internal frost damage may already be severe, missing the optimal intervention window.

Limited Data Utilization: A lack of systematic data collection and historical analysis results in arbitrary maintenance decisions. Repair actions are often experience-driven and lack the support of a lifecycle-based maintenance strategy.

Simple Technical Means: Traditional repair techniques—such as cold patching, refilling, or partial reconstruction—are ineffective against deep-layer frost damage or structural instability. Harsh winter conditions further hinder timely repair operations.

Fragmented Management: Maintenance responsibilities are often distributed among various agencies, leading to communication gaps, long response times, and inefficient resource allocation.

To overcome these challenges, there is a pressing need for a smart, technology-driven maintenance system capable of proactive identification, precise intervention, and dynamic risk management.

4. Architecture and Key Technologies of Smart Maintenance Systems

Smart maintenance systems integrate sensing, communication, data analytics, and intelligent control technologies to establish a closed-loop management platform encompassing monitoring, analysis, decision-making, and execution. The system includes the following components:

(1) Multi-Source Sensing and Data Acquisition

Sensors—including ground temperature probes, soil moisture sensors, strain gauges, fiber-optic temperature cables, LiDAR, and UAV-based photogrammetry—are deployed to capture real-time data on subgrade temperature, moisture, structural deformation, and environmental changes. The fusion of diverse data sources enhances monitoring accuracy and provides a robust foundation for analysis.

(2) Big Data Platform and Disease Analysis Models

Utilizing edge computing and cloud platforms, massive sensor datasets are processed, cleaned, and analyzed. Advanced algorithms such as data mining, time-series forecasting, and AI-driven modeling enable trend analysis and risk prediction of frost-related diseases. Comparison with historical data allows for rapid diagnosis of recurring issues.

(3) Intelligent Warning and Response Mechanisms

Based on a multi-index evaluation framework, early warning models are developed with tiered alert thresholds. Once abnormalities are detected, the system automatically triggers alerts and pushes notifications to management platforms and maintenance crews, ensuring prompt intervention and improved hazard preparedness.

(4) Smart Decision-Making and Maintenance Optimization

After locating and assessing the severity of frost heave damage, the system recommends optimal intervention strategies, matching resources and repair methods accordingly. Maintenance plans are dynamically adjusted based on weather conditions, resource availability, and traffic control constraints, enhancing scientific planning and operational flexibility.

The adoption of smart maintenance transforms management from experience-based to data-driven, providing a powerful tool for addressing frost-related challenges in cold-region roads.

5. Practical Applications of Smart Maintenance in Cold Regions

Several pilot projects in Heilongjiang, Inner Mongolia, and Xinjiang have implemented smart maintenance systems in highways, national roads, and municipal streets, yielding positive outcomes.

In one case, a provincial highway integrated a frost heave risk monitoring system using soil temperature and moisture sensors, fiber-optic cables, and UAV patrols to monitor high-risk segments. Real-time analysis enabled early detection of subgrade bulging, allowing maintenance crews to preemptively conduct layered grouting and insulation sealing, preventing large-scale cracking.

Another project utilized automated laser scanning and 3D reconstruction to assess post-thaw deformation across a highway. Historical monitoring data supported the development of a frost heave evolution model, facilitating the identification of high-risk zones and precise targeting of maintenance resources. The results showed a 40% reduction in response time, 60% increase in repair efficiency, and a 30% decrease in annual maintenance costs.

Nonetheless, challenges remain, such as inadequate cold resistance of sensors, unstable data transmission in extreme temperatures, and high integration costs. Future improvements should focus on optimizing hardware resilience, lowering deployment costs through modular designs, and enhancing overall system robustness and adaptability.

6. Conclusion

Frost heave-induced subgrade diseases in cold-region roads present a formidable challenge due to their complexity, hidden nature, and rapid progression. Traditional reactive maintenance models are no longer sufficient. Smart maintenance technologies—powered by sensor networks, big data, predictive modeling, and intelligent decision-making—offer a proactive, efficient, and cost-effective alternative.

This paper analyzes the mechanism of frost heave, outlines the limitations of conventional maintenance, and proposes a smart maintenance system tailored to the needs of cold-region roads. Real-world applications demonstrate significant improvements in efficiency, accuracy, and resource utilization.

To realize the full potential of smart maintenance, further efforts are needed to standardize system components, enhance integration with BIM/CIM platforms, and establish coordinated management frameworks. In parallel, research should focus on adapting technologies to extreme climates and improving system durability. With continued innovation and policy support, smart maintenance will play an increasingly vital role in ensuring the resilience and sustainability of road infrastructure in cold regions.

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ARTICLE

Construction Technology of Self-Anchored Suspension Bridges

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ARTICLE INFO

Article history

Received: 18 April 2025

Accepted: 15 June 2025

Published Online: 30 June 2025

Keywords:

self anchored suspension bridge

Prefabricated bridge piers

Steel box girder

Steel truss bridge tower

Cable construction

Steel bridge deck paving

ABSTRACT

As a special type of building, the industrialization of bridges is imperative in the context of the new industrialization era. The specific focus of bridge industrialization is to promote prefabricated construction technology in bridge construction. Based on the construction experience of the Dongta Bridge spanning the Hun River in Shenyang City, this article summarizes the construction techniques of prefabricated segmental assembled piers, continuous steel box girders, steel truss bridge towers, cables, and steel bridge deck paving for self anchored suspension bridges, providing experience for similar bridge construction in the future.

1. Project Overview

The Dongta Bridge over the Hun River in Shenyang is a key project in the comprehensive improvement plan of "one river and two banks" in Shenyang. It is the largest single span suspension bridge in the Shenyang area and has been put into use, becoming a local landmark building. The operation diagram of the Dongta Bridge over the Hun River in Shenyang is shown in Figure 1. The main bridge of Dongta Bridge over Hunhe River in Shenyang City is a five span continuous steel truss bridge tower self anchored suspension bridge, with a span arrangement of (40+90+220+90+40) m and a total steel consumption of

20000 tons.



Figure 1 Operation diagram of Dongta Bridge over Hun River in Shenyang City

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DOI: <http://doi.org/10.26549/frac.v8i1.33844>

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