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Implementation Report

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More Info:

The research is documented in Report FHWA/MT-20-008/9890-784
https://www.mdt.mt.gov/research/projects/deicing-geothermal.aspx

Principal Investigator
Mohammad Khosravi
mkhosravi@montana.edu
406.994.6122

MDT Technical Contact
Jeff Jackson
jejackson@mt.govjejackson@mt.gov
406.444.3371

MDT Research Project Manager
Emily Hawley,
ehawley@mt.gov;
406.444.2598

A FEASIBILITY STUDY OF ROAD CULVERT/BRIDGE DECK DEICING USING GEOTHERMAL ENERGY

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Introduction and Purpose

In Montana's cold climate, bridge decks are exposed to extreme winter conditions that lead to rapid snow and ice accumulation, frequent freeze–thaw cycles, and premature deterioration of concrete infrastructure. Traditional deicing methods, mainly based on salt applications, lose effectiveness below –9.4 °C and accelerate corrosion and joint degradation. This research project, led by Montana State University (MSU) and funded by the Montana Department of Transportation (MDT), explored the use of geothermal energy as a sustainable alternative for bridge deck deicing. Using ground-source hydronic systems, the project aimed to maintain surface temperatures above freezing, reduce freeze–thaw damage, and improve durability during early-age concrete curing.

The study employed laboratory experiments, numerical simulations, and machine learning (ML) tools to evaluate the feasibility of geothermal systems under Montana's climatic conditions. Results confirmed the system's ability to raise deck surface temperatures to above freezing under ambient conditions as low as –10 °C using a typical shallow geothermal inlet temperature of 10 °C. While effectiveness decreases at –20 °C without solar input or elevated fluid temperatures, partial mitigation was still observed. The findings suggest geothermal systems can play a significant role in increasing winter safety and extending bridge life. This report outlines four key implementation pathways to transition from laboratory evaluation to practical deployment.

Implementation Summary

The geothermal heating system proved effective in raising and maintaining bridge deck surface temperatures above 0 °C under ambient conditions ranging from 0 °C to approximately –10 °C using inlet fluid temperatures representative of Montana's shallow geothermal wells (around 10 °C). Seasonal analysis suggests that geothermal systems in Montana are most effective during early winter (October–November) and late winter/early spring (March–April), when ambient temperatures and solar radiation levels are more favorable. Under more extreme conditions, such as ambient temperatures near –20 °C, system performance declined without additional energy input, however, an increase in bridge deck temperature was still observed compared to the unheated condition. Consequently, during the peak winter months (December–February), the geothermal system alone may be insufficient during periods of severe cold or heavy snow accumulation and could require integration with supplemental measures, such as mechanical snow removal or external surface heating. A Montana-specific life-cycle cost-benefit analysis (LCCBA) would provide a more accurate understanding of system efficiency under different climatic, traffic, and design conditions, supporting data-driven decisions for future implementation.

Moreover, the current study focused on deicing performance (i.e., maintaining surface temperatures above freezing) and did not directly evaluate snow melting rates under varying snow loads. Additional testing is needed to characterize the system's snow-melting capabilities, particularly under low solar radiation and high snow accumulation which may be possible through mockup tests in the field under real weather conditions. These findings highlight the importance of a context-specific design and the potential role of hybrid systems for year-round reliability. To support practical application, this report outlines different phased implementation strategies, from life-cycle evaluation to pilot testing and full-scale deployment.

Implementation Recommendations

RECOMMENDATION 1*: LLCBA for Deployment Prioritization*

While this project demonstrated the technical feasibility of geothermal bridge deck deicing systems, a LCCBA framework is essential to guide practical decision-making and prioritize deployments across Montana. Although an LCCBA framework has not yet been developed for this project, a foundational study by Habibzadeh-Bigdarvish et al. (2019) provides a valuable reference point. Their scenario-based analysis quantified benefits related to corrosion prevention, improved safety, reduced maintenance, and enhanced traffic flow. Results indicated that bridges with higher Average Annual Daily Traffic (AADT) volumes, particularly those exceeding 15,000 vehicles/day, achieved benefit-cost ratios greater than 2.5, underscoring the importance of strategic site selection.

Building on this prior work, the proposed next step is to is to develop a Montana-specific LCCBA framework that incorporates real-world bridge inventory data, soil thermal properties, regional energy pricing, and construction costs (new vs. retrofit) specific to Montana, and combine the data with performance metrics from Habibzadeh-Bigdarvish et al.'s study. The framework will be expanded from the ML models already developed as part of this current study to predict thermal behavior and system response under variable environmental and design conditions. Integrating ML with economic modeling will result in a robust, adaptive tool for estimating lifecycle costs, return on investment, and operational performance across a wide range of scenarios.

RECOMMENDATION 2: *Experimental Evaluation of External Heating Systems*

The current study focused on an internal geothermal heating system, which is best suited for integration into new bridge construction. However, for existing bridges where retrofitting internal tubing is not feasible, alternative solutions, such as external surface-mounted heating systems, should also be explored. To address this, a follow-up experimental effort is planned at MSU's Subzero Research Laboratory, where an external heating system resembling the design investigated by Yu et al. (2020) will be installed on the existing bridge deck model. This setup will enable comparison between internal and external configurations in terms of surface heating efficiency, installation feasibility, and control responsiveness under simulated Montana winter conditions. The results from these experiments will also support numerical model calibration, enhancing the ability to predict system performance at field scale across a variety of retrofit scenarios.

RECOMMENDATION 3: *Mock-Up Field Experiments at Sites with Different Ground Temperatures*

To bridge the gap between laboratory testing and full-scale deployment, mock-up field sections are proposed at two locations representing different geothermal conditions: one with a ground temperature of approximately 10 °C, typical of shallow geothermal wells across Montana, and another with a ground temperature near 50 °C, located in proximity to geothermal hotspots. The first site will enable validation of system performance under widely available subsurface conditions, while the second will test the upper performance limits of the system with elevated fluid temperatures. At both locations, scaled bridge deck sections will be constructed and instrumented with internal (for new bridges) and external (for existing bridges) geothermal heating systems, as well as surface temperature and environmental sensors. These systems will be operated over one or more winter seasons to monitor surface temperature response, energy consumption, snow and ice accumulation, and durability-related factors. The data collected will be used to validate numerical models. These validated results will, in turn, be integrated into the machine learning and ML/LCCBA framework to improve predictive accuracy and support data-driven decision-making for broader implementation. These mock-up tests will also provide practical insight into constructability, maintenance requirements, and operational responsiveness under real weather conditions, with particular attention to snow accumulation prevention and melting. Findings from these tests will support refinement of design standards, including recommended inlet fluid temperature ranges, tubing configurations, insulation approaches, and strategies for integrating geothermal systems in sites exposed to variable solar and wind conditions.

RECOMMENDATION 4: *Full-Scale Implementation on an Operational Bridge*

Following the mock-up validation, the next step is to implement the geothermal deicing system on a full-scale, operational bridge. This deployment would serve as a demonstration project for statewide use and allow evaluation of the system under real-world traffic loading, environmental exposure, and long-term maintenance conditions. The selection of a suitable bridge site can be informed by the ML-assisted LCCBA framework discussed earlier, incorporating factors such as traffic volume, geothermal potential, and regional climate data.

The full-scale installation would include embedded tubing during construction or externally retrofitted systems, a heat exchange loop connected to a ground source or shallow borehole field, and control systems for real-time monitoring. Performance metrics will include surface temperature maintenance, deicing speed, thermal strain reduction, and maintenance tracking over at least two winter seasons.

This implementation will provide MDT with field data necessary to develop specifications for future deployments and assess long-term economic viability, safety impact, and durability improvements.

MDT Response:

MDT is planning to hold a workshop with division administrators, MDT staff and engineers, particularly from the Maintenance and Operations divisions, as well as MSU researchers to further discuss the recommendations, with a focus on field implementation. The workshop goals will be exploring suitable bridges and funding opportunities., with more emphasis on recommendation 1 and 2After the workshop, a suitable bridge will be sought to test this research in Montana. If successful, it might be utilized across the state (when conditions are appropriate) to help save money and improve safety.