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MONTANA
Department of Transportation

Project Summary Report
FHWA/MT-20-008/9890-784

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

https://www.mdt.mt.gov/research/projects/deicing-geothermal.aspx

Introduction

In cold regions such as Montana, bridge decks are exposed to extreme winter conditions that lead to rapid snow accumulation, frequent freeze–thaw cycles, and accelerated concrete deterioration. Traditional deicing methods, including salt-based chemicals and mechanical snow removal, become ineffective below −9.4 °C and contribute to structural degradation through corrosion and cracking. As an alternative, this research explored the feasibility of using geothermal energy, specifically ground-source hydronic systems, for bridge deck deicing and the mitigation of concrete deterioration in Montana. Led by Montana State University (MSU) and funded by the Montana Department of Transportation (MDT), the project represents the first comprehensive evaluation of such systems under Montana's environmental conditions.

The overarching goal was to determine whether geothermal energy could maintain bridge deck surface temperatures above 0 °C during winter events, reduce freeze–thaw cycling, and improve concrete durability during early-age curing and under thermal stress. This project is a critical step in evaluating sustainable, low-maintenance alternatives for improving winter road safety and extending infrastructure lifespan in Montana.

What We Did

The research approach employed a multidisciplinary approach including literature review, surveys, laboratory testing, numerical modeling, and machine learning analysis.
Literature Review: Domestic and international case studies from Japan, Switzerland, China, and the U.S. were reviewed to evaluate existing geothermal bridge and roadway systems. Key aspects such as thermal performance, system configurations, and long-term maintenance were analyzed to inform design parameters appropriate for Montana conditions.

• *Surveys:* A targeted survey was distributed to MDT personnel to assess current deicing practices, associated costs, and limitations. Survey responses identified corrosion, joint deterioration, and early-age cracking as recurring maintenance concerns, reinforcing the need for alternative deicing solutions.

• *Laboratory Testing:* A scaled concrete bridge deck model embedded with geothermal piping was constructed and tested in the Subzero Research Laboratory (SRL) at MSU to evaluate the system's thermal performance under simulated winter conditions. The system operated with an inlet fluid temperature of 8°C, and testing was conducted across ambient temperatures ranging from 0 °C to –20 °C and solar radiation intensities from 0 to 490 W/m². Two controlled weather scenarios were used: a Synthetic Scenario (Figure 2a) with four distinct stages involving step changes in ambient temperature (–10 °C and –20 °C) and solar radiation (on/off), and a Daily Fluctuation Scenario (Figure 2b) simulating diurnal cycles, where ambient temperature varied from –5 °C to 10 °C and solar radiation gradually ramped up and down to a peak of 490 W/m². These scenarios allowed evaluation of the system's performance under both static and dynamic thermal loading conditions.

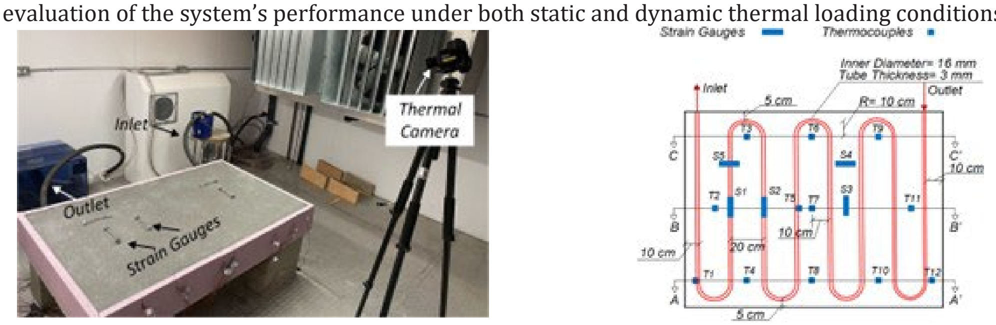

Figure 1. **Bridge deck model (left) and instrumentation schematic (right), with thermocouple and strain gauge locations shown**

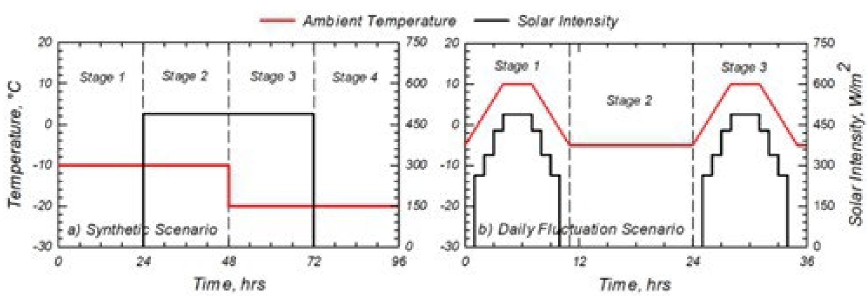

Figure 2. Weather scenarios: (a) Synthetic Scenario and (b) Daily Fluctuation Scenario.

An additional experimental setup was developed to assess the geothermal system's potential to mitigate early-age thermal cracking during cold-weather concrete curing. A representative portion of the bridge deck model was cast and cured under controlled conditions in the SRL at MSU. One specimen was cured with the geothermal system operating at an inlet fluid temperature of 8 °C, while the other was cured without heating. The chamber temperature was maintained at 3 °C throughout the curing period, which is the highest ambient temperature at which the Cold Hydrodynamics Chamber (CHC) can sustain a constant fluid temperature of 8 °C.

• *Numerical Modeling:* A validated COMSOL model was used to simulate more than 2,300 system configurations, evaluating the effects of inlet fluid temperature, ambient air temperature, solar intensity, and wind speed on system performance. Results indicated that inlet temperatures ≥10 °C are generally sufficient to prevent ice bonding at ambient temperatures down to –10 °C. For more severe conditions (–15 °C to –20 °C), inlet temperatures of at least 35–50 °C are required to achieve effective deicing.

• *Machine Learning Analysis:* Figure 3 summarizes the machine learning model development process for training and evaluating the prediction models. Simulation data were used to train two machine learning models, one to predict time-to-deicing effectiveness and a second to predict full temperature profiles under varying environmental conditions. This analysis enables rapid feasibility assessments of geothermal deicing systems at potential bridge sites throughout the state.

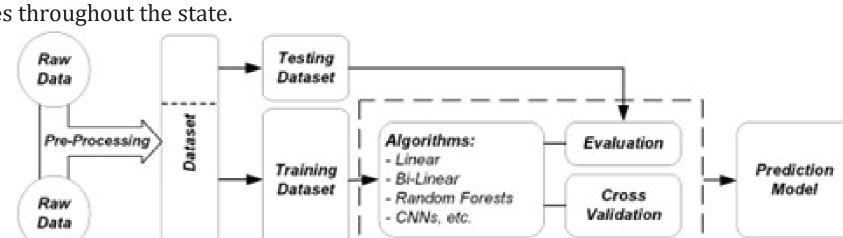

Figure 3: Machine learning model development process

What We Found

• *Feasibility and Temperature Range:* The geothermal system effectively maintained bridge deck surface temperatures above freezing under multiple ambient temperature scenarios (Figure 4a). With an inlet fluid temperature of 10 °C, representative of shallow geothermal wells in Montana, the system effectively kept bridge deck surface temperatures above 0 °C during ambient conditions of –5 °C and –10 °C (Stages 1–3 on Figure 2a). At –20 °C ambient temperature (Stages 5–6 on Figure 2a), the top surface temperatures approached 0 °C with the system operating, and minimum temperatures remained several degrees higher than in the unheated case, demonstrating reduced freezing severity even under extreme conditions. These results confirm that geothermal systems can provide effective deicing at ambient temperatures as low as –10 °C, with partial mitigation benefits still present at –20 °C. Performance further improves when combined with solar radiation, especially in the day length is longer.

• *Thermal Stress Mitigation:* Simulations showed that geothermal heating reduced thermal gradients and associated strains. In restrained bridge decks, this reduction helps lower the risk of flexural cracking. Even under extreme gradients, most temperature differentials remained within the AASHTO design limits. Figure 4b illustrates strain responses due to thermal movement across ambient conditions. The geothermal system significantly reduced thermal strain fluctuations in all stages. For instance, during the –10 °C and –20 °C scenarios, the average strain with the system remained closer to zero, while the unheated case experienced larger compressive strain (up to –250 με), indicating greater thermal contraction. Overall, the system reduced strain magnitudes by approximately 30–50% compared to the unheated deck, depending on the stage. These reductions in thermal movement imply a lower risk of stress-induced cracking, particularly in restrained decks. Maintaining more stable strain profiles across temperature swings helps protect structural integrity and extend the service life of bridge decks in cold climates.

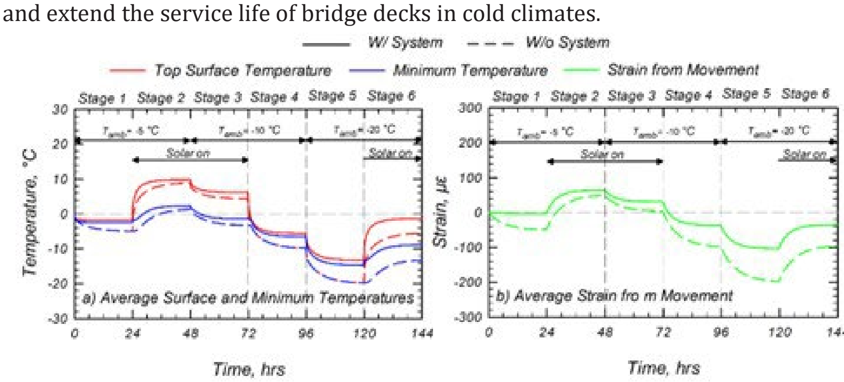

Figure 4. (a) Average surface and minimum temperature and (b) average strain from thermal movement for 10 °C inlet temperature

• *Concrete Deterioration Mitigation (Quantitative & Qualitative):* Early-age thermal shrinkage is a major contributor to concrete cracking, especially during winter curing. The geothermal system was tested for its ability to reduce temperature drops during the critical period of early-age curing. With an inlet fluid temperature of 8 °C, the concrete stabilized at 4–5 °C internally, compared to about 2 °C in unheated control specimens, a ~2–3 °C reduction in thermal gradient that reduced contraction potential (Figure 5).

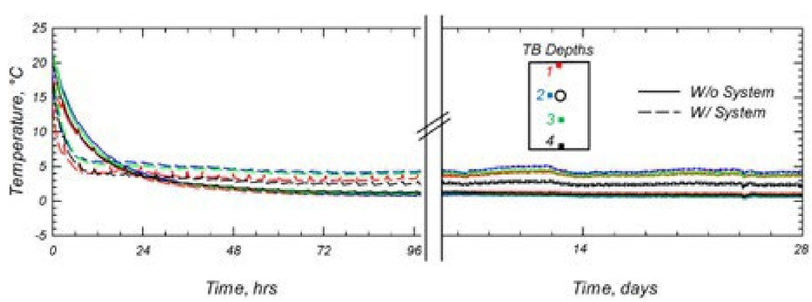

Figure 5. Thermocouple results of models with system and without system at each depth

• *Sensitivity Analysis:* Sensitivity analyses demonstrated that ambient temperature consistently exerted the greatest influence on system performance metrics, including surface temperature, internal concrete temperature, thermal strain, and vertical thermal gradients. Without solar radiation, ambient temperature shifts produced up to 11.5°C variation in surface temperature and 12.2°C in internal temperature, compared to 2–3°C variations from inlet fluid temperature and tube spacing. For thermal strain, ambient temperature shifts caused variations of up to 100με, compared to ~35–40με from inlet temperature and tube spacing. Vertical thermal gradients were the least sensitive metric, varying less than 0.5°C across all parameters, particularly under solar radiation. These results indicate that ambient temperature and inlet fluid temperature are the most critical design parameters for effective system design, with tube spacing exerting a more moderate effect on near-surface behavior.

• *Machine Learning–Based Analysis*: Two machine learning models were developed using results from over 2,300 numerical simulations to support rapid assessment of geothermal system performance. Model 1 predicted the time required for the bridge deck surface to reach 0 °C (i.e., effective deicing), while Model 2 provided continuous surface temperature predictions under varying design and environmental inputs. Inputs included ambient temperature, solar radiation, inlet fluid temperature, pipe spacing, and wind speed. These models offer a computationally efficient tool for evaluating system feasibility and optimizing designs for Montana's diverse climate conditions.

What the Researchers Recommend

This study demonstrates that geothermal bridge deck deicing systems have strong potential to enhance winter safety and reduce long-term infrastructure deterioration in cold regions like Montana. The system effectively maintained surface temperatures above freezing and reduced freeze–thaw cycles, particularly when inlet fluid temperatures were at or above 10 °C and ambient temperatures were below –10 °C.

Performance further improved with solar radiation, confirming the method's feasibility in a range of winter conditions. However, the system's effectiveness declined in extreme cold temperatures (e.g., –20 °C ambient) unless higher, atypical inlet temperatures (e.g., 35–50 °C) were available. Additionally, while the system reduced thermal shrinkage and strain, it could not fully eliminate the potential for thermal stresses or cracking under the conditions tested.

Sensitivity and machine learning analyses identified ambient temperature and inlet fluid temperature as the most critical factors influencing system performance. Tube spacing had a smaller but still measurable effect near the surface, while wind speed and solar radiation played secondary roles that can enhance or limit effectiveness under specific conditions. Further, pilot-scale implementation is recommended to validate system performance under field conditions and support the development of statewide design standards.

More Info:

The research is documented in Report
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