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Field Scale Study of a Shallow Geothermal Inter-Seasonal Energy Storage System for Bridge Deicing

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ABSTRACT: Shallow geothermal energy systems integrated with borehole thermal energy storage (BTES) offer sustainable solutions for bridge deck deicing while reducing dependency on chemical agents and electrical heating. This study evaluates a full-scale inter-seasonal heat storage system deployed on an in-service bridge in Arlington, Texas, utilizing the bridge deck as a solar thermal collector for winter deicing operations. The BTES comprises eight ground heat exchangers extending 91.45 m in depth, arranged hexagonally with 3.35 m spacing—40% closer than conventional designs—to maximize thermal interference and storage density. During a 15-day summer experiment, hydronic loops embedded in the bridge deck experiencing 40-45°C surface temperatures transferred solar thermal energy to subsurface storage while providing structural cooling. Distributed temperature monitoring at 15.24, 45.72, 76.20, and 83.82 m depths revealed heat accumulation with initial shallow-zone concentration followed by downward thermal migration, exhibiting diurnal oscillations corresponding to solar radiation cycles. Post-injection analysis demonstrated depth-dependent thermal decay rates, with enhanced shallow dissipation indicating surface heat losses and optimization opportunities for insulation strategies. While successfully demonstrating heat injection and short-term retention, the abbreviated monitoring period precludes quantitative assessment of inter-seasonal storage efficiency and winter deicing performance, necessitating full annual cycle evaluation. The dual-function system providing summer bridge cooling while storing thermal energy represents an advancement in climate-resilient transportation infrastructure. These preliminary findings establish critical design parameters for BTES-supplemented bridge deicing systems and empirical validation for deployment in freeze-susceptible regions, though extended monitoring and comprehensive energy balance analysis remain essential for quantifying system performance metrics and economic viability.

KEYWORDS: Shallow geothermal, borehole thermal energy storage, field study, solar energy collector.

1 INTRODUCTION

Climate change brings new challenges in the design, construction, and operation of transportation. One such challenge is the icing of pavement on bridges and approach slabs, which is responsible for reducing driver safety and increasing road accidents due to frequent extreme cold weather events in North Texas, U.S.

To address this challenge, a full-scale shallow geothermal energy-supplemented bridge deicing system was deployed on an in-service bridge in Arlington, Texas, USA, for bridge deicing purposes (Figure 1a and b). The construction and operational performance of the system can be found in Deshmukh et al. (2025).

Since the bridge surface absorbed solar radiation in the summer, it presented a unique opportunity in the study, where the heat in summer could be stored in the subsurface (Borehole Thermal Energy Storage-BTES) and utilized in winter for bridge deicing purposes and enhancing the energy efficiency of the bridge deicing operation.

(a)

(b)

Figure 1. (a) Bridge site in Arlington, Texas, U.S. (b) Bridge heating loops installed under the bridge deck.

BTES has been successfully used on several shallow geothermal energy systems to improve their energy output by 30-50% (Chapuis & Bernier, 2009; Sibbitt et al., 2012; Baser & McCartney, 2015; Behbehani & McCartney, 2022). The primary principle of BTES involves the storage of surplus thermal energy during periods of abundance for subsequent extraction during periods of demand.

A similar strategy was deployed on a full-scale bridge deicing system supplemented by a shallow geothermal system where solar heat was collected and stored in the subsurface. Since the pavement temperature frequently rises to 40-45°C in Arlington, Texas, U.S., it presents an opportunity for the shallow geothermal energy-based systems to store the energy in the subsurface during and utilize the energy in winter. The bridge deck acts as a solar heat collector, where the energy from the hot pavement is stored underground. The operation also serves a secondary purpose of cooling the bridge structure and preventing structural damage to the bridge by reducing thermal stresses.

This study presents field field-scale experiment performed during summer 2024 on an in-service bridge acting as a solar heat collector and an instrumented BTES, which stored energy in the subsurface. This study is a step toward using a bridge as a solar heat collector and utilizing the energy stored in the summer for potential bridge deicing operations to improve driver safety in the winter. Initial experimental data reveal important insights into subsurface energy storage.

2 BTES CONCEPT, SYSTEM FIELD CONSTRUCTION, AND INSTRUMENTATION

The BTES was constructed using 8 closely spaced GHEs installed 300 ft. (91.45 m) deep. The average distance between the GHEs is 11 ft. (3.35 m), compared to conventional spacing of 20 ft. (6.06 m) typically used in the region (Figure 2a). Figure 2b shows the construction of BTES based on the plan view. Three GHEs were instrumented with thermocouples installed at 50 ft. (15.24 m), 150 ft. (45.72 m), 250 ft. (76.20 m), and 275 ft. (83.82 m) depth below ground surface. The thermocouples are in contact with the pipe and the subsurface, recording averaged value between the subsurface and the u-pipe at the designated depth during system operation.

Figure 2c shows the geological cross section of the GHE, and the geometric shape of the u-pipe buried in the subsurface. The figure also shows the sensor locations with respect to the depth from existing ground.

A field test- thermal response test was performed to measure the thermal conductivity and diffusivity of the geological formation during system construction. An average thermal conductivity and diffusivity of 2 W/m.K. and 0.075m^2/day was obtained.

The site is also instrumented with a piezometer. Shallow groundwater is observed in the subsurface, ranging from 5-15 feet depth from the existing ground. Groundwater is typically observed to negatively impact energy storage, since the movement of water increases energy losses (Zhao et al., 2022).

The energy storage operation commenced during the summer of 2024, when fluid was circulated through the loops installed under the bridge. These loops are responsible for bridge deicing in winter, which keeps the bridge deck above freezing temperatures by circulating hot fluid.

For summer operation, the fluid was not heated; therefore, the fluid temperature before the beginning of the summer operation was approximately 20°C (equal to subsurface temperature). Since the temperature of the fluid is lower than the temperature of the bridge pavement (40-45°C), the fluid heats during summer operation and cools down the bridge deck. The energy captured by the fluid is transferred to the subsurface, where the temperature of soil and rock elevates due to the circulation of warm fluid. This operation was carried out for 15 days to assess the heat storage operation and was analyzed as part of this study.

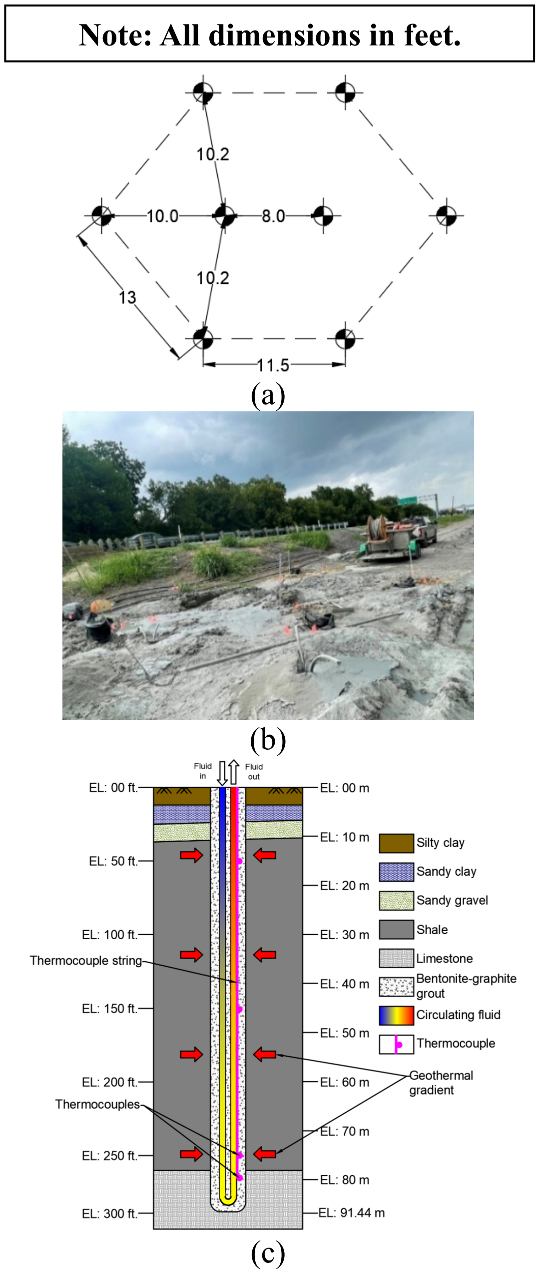

Figure 2. (a) Plan view of BTES (b) Field photograph of installed GHEs based on the plan view (c) GHE cross section and sensor locations (Deshmukh et al., 2025).

The energy stored in the subsurface during the summer can be utilized by the system for deicing operations. This process is known as inter-seasonal energy storage, where the energy is retained in the subsurface between seasons. The stored heat enhances the energy efficiency of the system in bridge deicing operation and reduces the carbon footprint of the system by utilizing solar energy and reducing the use of electricity to heat the bridge deck. The next section summarizes the observations of the field experiment based on the summer solar heat collection.

3 RESULTS

The BTES experiment started by commencing fluid circulation between the bridge and the GHE. As the bridge surface heated during the day, the fluid carried higher energy to the subsurface, and the energy flow diminished into the night every day.

The daily temperature fluctuations in the subsurface at various depths have been shown in Figure 3. Between 0-320 hours (heat injection period), the higher high of the 50 ft thermocouple depicts the daily peak temperature of the circulating, while the lower high represents the temperature during the night. The trend shows that switching off the energy storage operation may result in an effective energy injection, since the night operation reduces the temperature of the subsurface. The trend also shows that the temperature at shallower depths is relatively higher than at deeper depths. This observation shows that the BTES accumulates heat at shallow depths in the beginning, followed by downward movement of heat over time. Overall, the subsurface accumulates heat for the entire duration of the test.

After 15 days of energy injection, the fluid circulation was stopped to study the heat retention properties of the subsurface. The heat retention phase has been depicted in Figure 3. The heat injection stopped after 320 hours, followed by the heat retention phase. The data shows that the heat starts to dissipate as soon as the system shuts down. Moreover, the shallower thermocouples show a greater drop than deeper thermocouples, signifying that a considerable amount of heat is lost from the top surface. The next section summarizes the learnings and conclusions from the results observed during the experimentation.

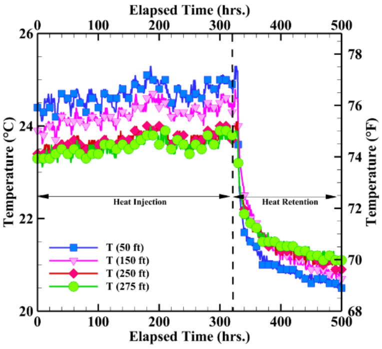

Figure 3. Subsurface temperature during heat storage and retention.

4 CONCLUSIONS AND SUMMARY

This study presents a field-scale evaluation inter-seasonal thermal energy storage system integrated with a shallow geothermal bridge deicing system on an in-service bridge in North Texas. The research demonstrates the feasibility of utilizing bridge deck surfaces as solar heat collectors during summer months to store thermal energy in the subsurface for subsequent winter deicing operations.

The 15-day field experiment conducted during summer 2024 provided valuable insights into the heat storage and retention characteristics of the Borehole Thermal Energy Storage (BTES) system. Key findings from this investigation include:

The bridge deck successfully functioned as a solar heat collector, with pavement temperatures reaching 40-45°C during summer operations. The temperature differential between the circulating fluid (initially at 20°C) and the heated bridge deck enabled significant heat transfer to the subsurface storage system.

Temperature monitoring at multiple depths (50 ft, 150 ft, 250 ft, and 275 ft) revealed that heat accumulation initially occurs at shallower depths, followed by gradual downward migration over time. This stratified heat storage pattern suggests that the BTES system can effectively store thermal energy at various subsurface levels. The observed daily temperature fluctuations in the shallow subsurface layers indicate that nighttime operations may reduce overall storage efficiency. These findings suggest that optimizing operational schedules to focus on peak solar radiation periods could enhance the system's energy storage capacity.

Post-injection monitoring revealed that heat dissipation begins immediately after system shutdown, and the rate of heat loss varies with depth. Shallower thermocouples exhibited greater temperature drops compared to deeper sensors, indicating that heat losses primarily occur through the upper surface. This observation underscores the importance of considering insulation strategies or operational protocols to minimize thermal losses during the retention phase.

The dual benefit of this system is particularly noteworthy: it not only stores energy for winter bridge deicing but also provides cooling to the bridge structure during summer months, potentially reducing thermal stresses and extending the infrastructure's service life. This synergistic approach represents a significant advancement in sustainable transportation infrastructure management.

5 ACKNOWLEDGEMENTS

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