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Feasibility of geothermal heat exchanger pile-based bridge deck snow melting system: A simulation based analysis

Chanjuan Han [a], Xiong (Bill) Yu [b, c, *]

[a] Department of Civil Engineering, Case Western Reserve University, 10900 Euclid Avenue, Bingham Building-Room 203B, Cleveland, OH 44106, USA
[b] School of Civil Engineering, Hubei University of Technology, China
[c] Department of Civil Engineering, Case Western Reserve University, 10900 Euclid Avenue, Bingham Building-Room 206, Cleveland, OH 44106, USA

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ABSTRACT

Snow melting system based on geothermal heat exchanger pile is an innovative technology that combines geothermal energy with structural foundation. It overcomes the problems of conventional chemical based snow melting in mitigating infrastructure corrosion and negative environmental effects. By integrating the underground heat exchanger into pile foundation that support the bridge structure, it effectively reduces the installation cost of geothermal system. This paper analyses the applicability and performance of such snow melting system for different regions. Energy demand for snow removal is firstly determined with ASHRAE criteria. A holistic 3D simulation model is developed to predict the energy extraction rate under different operation conditions. A hypothetical bridge deck (200 m length by 14.8 m (4 lanes) width) is analyzed to assess the feasibility of geothermal heat exchanger pile based snow melting system for 10 cities representing a variety of climatic regions of the United States. The number of pile foundation required for snow melting is used as indication of the technical feasibility. The results show that its feasibility and performance in bridge deck snow removal is dependent upon the geological and snow conditions of a particular region, as well as the design snow removal criteria.

1. Introduction

Over 70% of United State territory is located in areas with snow fall [1]. Snow can cause serious issues affecting the safety, mobility, and productivity of the transportation system [1]. According to the Federal Highway Administration (FHWA), during 2002–2012, around 5,878,000 annual vehicle crashes occurred on the road, 23% of which are weather-related [1]. Each year, more than 1300 people are killed and over 116,800 people get injured in vehicle crashes on snowy, slushy or icy pavement [1]. In addition, snow incurs significant road winter maintenance cost [1]. Over 2.3 billion dollars are spent on the snow and ice removal annually, which account for 20% of state Department of Transportation (DOT) winter road maintenance budgets [2].

The prevalent method for snow and ice removal is mechanical plowing together with spraying deicing salt. This method, however, is associated with extensive transportation infrastructure corrosion, huge amount of material consumption, and negative environmental impacts. To resolve these issues, alternative methods for deicing have been proposed, such as different pavement heating techniques that use hydronic system, electric heater system or infrared radiant heating system to melt the snow and prevent pavement from freezing [3]. In 1999, FHWA reported the implementation and performance of 10 pilots projects in the United States involving the application of different heating techniques for bridge deck snow melting; these projects demonstrated positive performance for the control of snow accumulation on bridge decks [4]. Other similar projects have also been reported in Switzerland [5,6], Japan [7–10], Germany [11], Portland [12], China [13] and Korea [14]. The hydronic system, which employs fluid to extract the natural heat from the ground, is among the most popular types of heat based snow and ice removal methods as it utilizes heat source that is widely available. It is also advantageous over the fossil fuels based heating system in terms of low environment footprint during operation. The hydronic system typically involves installing

* Corresponding author. Department of Civil Engineering, Case Western Reserve University, 10900 Euclid Avenue, Bingham Building-Room 206, Cleveland, OH 44106, USA

E-mail addresses: cxh432@case.edu (C. Han), xxy21@case.edu (X. Yu).

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hydronic heat exchangers in the pavement. It integrates sustainable geothermal energy as the heat source. The geothermal snow melting system in Switzerland, which is part of the Solar Energy Recovery from Road Surfaces (SERSO) pilot plants, is among the most well-known geothermal snow melting systems. The system started working since 1994 and is still in service currently [5,11]. Yoshitake et al. [7], developed an innovative geothermal snow melting system that directly used the heat from water stored in an underground water tank as the heat source. Spitler and Ramamoorthy [15] presented a comprehensive design procedure for a geothermal bridge deck de-icing system using TRNSYS and HVACSim + based system simulation model. Various numerical models have been developed to simulate the heat transfer of pavement snow melting process aiming at optimizing the pavement surface heating system design [15–21].

The application of geothermal heating technique is primarily for hotspot locations (i.e., bridge, airports, and hospital emergency entrances, etc.) due to its high initial installation cost, a major portion is for ground drilling and installation. The development of geothermal energy foundation, which incorporates the heat exchanger pipe into deep foundation, provides an appealing solution to save the expensive investment associated with borehole drilling. Geothermal energy pile is estimated to save up to 33% of installation cost for geothermal heat exchanger (GHE) [22]. The concept of geothermal energy pile based snow-melting system was proposed in 1990s [23]. It has received significant attention ever since, mostly concentrated on the system performance evaluation. Nagai et al. [10] reported a successful application of geothermal heat exchanger pile based snow melting system in Japan for parking lots and bridge with deck area of 1820 m^2. The study also proposed the optimal design through a verified numerical model. Brower and Olgun [24] described an experimental study on energy pile based passive bridge-deck deicing system. The testbed includes a 2.4 m × 3.0 m bridge deck with half of it heated by geothermal heating system (consisting of four piles each of around 30.5 m length). The results demonstrated the effectiveness of energy pile based geothermal snow melting system. An important issue identified is summer heat recharge. Dupary et al. [25] numerically analyzed the mechanical response of geothermal heat exchanger pile based on the prototypes of SERSO and Shin-Kiyonage bridge projects.

In this paper, computational model assisted analyses are carried out to investigate the feasibility of geothermal heat exchanger pile based snow melting system for bridge decks. Ten cities located in different climatic regions across the United States are selected for the analyses (Fig. 1(a)). These selected cities spread across 10 different states with the undisturbed ground temperature ranging from 8 °C (46.4 °F) to 18 °C (64.4 °F) (Fig. 1(b)) and snowfall ranging from 13 to 224 h/year. The computational model is used to evaluate the influence of types of heat exchanger pipe and ground heat exchanger (GHE) operational conditions (i.e., fluid circulation velocity) on the performance of GHE installed in pile foundation. The number of piles required to achieve desired snow and ice melting performance is used as criteria to evaluate the feasibility of geothermal heat exchanger pipe based snow melting system in the selected cities.

2. Geothermal heat exchanger piles based snow melting system

Geothermal heat exchanger pile based snow melting system generally includes four main components, i.e., 1) Pavement surface heating system; 2) Heat pump; 3) Geothermal heat-exchanger piles; and 4) System controllers and sensors. The analyses in this paper are primarily based on heat exchange aspect.

2.1. Pavement surface heating system

The pavement surface heating system consists of the hydraulic heat exchanger pipe installed beneath the pavement surface (Fig. 2). The determination of heating requirement for snow/ice removal, which is normally described by surface heat flux, provides important design capacity of the whole system. According to ASHRAE Handbook 2007, the heating requirement for snow melting are determined by five atmospheric parameters: air dry-bulb temperature, rate of snow fall, relative humidity, wind velocity and apparent sky temperature [3]. The required heat flux for snow melting on the basis of steady-state energy balance is given by Ref. [26]:

$$q_0 = q_s + q_m + A_r(q_h + q_e) \tag{1}$$

where, q_0 denotes to heat flux required at snow melting surface, W/m^2. q_s is sensible heat flux, W/m^2. q_m represents latent heat flux, W/m^2. q_h is convective and radiative heat flux from snow-free surface, W/m^2. q_e denotes to heat flux of evaporation, W/m^2. A_r is snow-free ratio, which is defined as the ratio of equivalent snow-free area to total area. A_r values of 0, 0.5 and 1 are normally used as the design conditions. $A_r = 1$ represents the condition that the heat flux is sufficient to melt snow immediately so that there is no snow accumulation. $A_r = 0.5$ represents the condition that all or a part of pavement is covered by a thin layer snow, which is equivalent to half of the pavement area is insulated by snow layer. $A_r = 0$ represents the condition that all the pavement surface is covered by snow layer. The thickness of the snow layer is just adequate to prevent heat and evaporation losses, but the snow at the bottom of the layer melts at the same rate of snow accumulate. For most traffic conditions, snow melting rate that achieves $A_r = 0.5$ is regarded as acceptable [27].

Based on the criteria described, the ASHRAE handbook (ASHRAE 2007) estimates the required heat fluxes for snow melting at 46 selected cities in U.S.. These include the heat fluxes satisfying different percentages of snow-melting loads at three different snow-free area ratios for each city [3].

This study assumes that the geothermal snow melting system is installed to heat a hypothetical bridge deck 200 m in length and 14.8 m in width (four lanes: 3.7 m × 4). Situations at 10 different selected cities are analyzed. The corresponding heat flux demands are calculated based on ASHRAE criteria and are listed in Table 1. The undisturbed ground temperature shown in this table is evaluated from Fig. 1(b). In principle, the most accurate undisturbed ground temperature can be derived from the results of geological survey; this however is impractical for every project due to high cost. An alternative way of applying groundwater temperature contour map is used, and this temperature yields the undisturbed ground temperature within 2 °C [3]. The snowfall is assumed to be the average annual snowfall hours from 1982 to 1993 for each city [3]. The heat fluxes that achieve different reliabilities (90%, 95%, 99% and 100%) of snow melting area ratio are listed in Table 1. For example, Amarillo, TX (location 1), achieving snow melting area ratio Ar = 1 for 90% of times requires heat demand of 1397 kW.

2.2. Heat pump

Heat pump plays the role of energy carrier that transfers the harvested energy from the ground to the pavement. The refrigerant circulation in the heat pump is accomplished via four core components of Carnot cycle (Fig. 2), i.e., heat exchangers (evaporator and condenser), compressor, and expansion valve. During cold winter days, the thermal energy collected from energy piles (source load: Q_{source}) is transferred to the evaporator and then disperses to