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Numerical Simulation of Geothermal Heated Bridge Deck

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ABSTRACT: Use of geothermal energy for deicing bridge deck is an alternative to the use of salts and therefore can reduce corrosion and extend the service life of deck slabs. In this study, a series of three dimensional numerical simulation of a single geothermal heated bridged deck was performed. The effects of system parameters including pipe spacing, concrete cover, fluid flow rate, inlet fluid temperature, ambient temperature and wind speed were investigated. The results reveal that flow rate has small effect on heating performance of the system. The other factors should be considered comprehensively in the design of geothermal heating system for the bridge deck.

INTRODUCTION

A bridge is an integral part of highway infrastructure, and it is also critical to economy and security for a nation (Bowers and Olgun, 2014). Deterioration of the aging bridge infrastructure due to the use of salts or other chemicals for deicing bridge decks causes significant economic and engineering challenges. For example, there are about 600,000 bridges in the United States, of which about 60% were built either with traditional reinforced concrete or prestressed concrete, and 25% are structurally deficient or functionally obsolete.

Geothermal energy is a clean, sustainable, and renewable energy source, which has various engineering applications such as ground source heat pumps (GSHPs), borehole thermal energy storage (BTES), geothermal energy piles (GEPs). Because earth has a relatively constant temperature under certain depth (typically about 40-50 ft.), its thermal storage capacity can be exploited for heating bridge decks and pavement slabs in winter, which results in a considerable reduction in the use of salts and chemicals. Heat carrier fluid is circulated in pipes that are embedded in bridge decks and ground to transfer heat. Geothermal energy is extracted from ground, and then injected into the bridge decks for deicing purpose. Additionally, it can also be used to decrease the temperature of bridge decks during concrete curing, and help minimize early age cracking. Similarly, temperature of bridge deck can be regulated to reduce the severity of heating/cooling cycles between day and night in summer (Bowers and Olgun, 2014).

Liu et al. (2003) conducted simulation on hydronic heating of bridge deck over a lifetime as opposed to singular storm events incorporating a ground-source heat pump. The entire model consisted of four sub-models: a hydronically heated bridge deck model, a ground loop heat exchanger model, a water to water heat pump model, and a system control model. Liu and Spitler (2004) performed a parametric study to investigate the effects of idling time, pipe spacing, slab insulation, and control strategies on system performance.

They also found that preemptive heating is required to achieve the expected snow-melting performance when using the tabulated ASHRAE surface heat flux. Moreover, system performance will be significantly improved by preheating the slab with full heating capacity before snowfall event occurs. Their model was further and validated (2007a, 2007b).

This study presents the results of numerical simulations of geothermal heated bridge deck to investigate the effect of design parameters of geothermal heating system on deicing performance. The simulation was conducted using finite element software, i.e. COMSOL Multiphysics. The design parameters include pipe spacing, concrete cover thickness, fluid flow rate, as well as some environmental factors such as inlet fluid temperature, ambient temperature and wind speed. The results are presented and discussed to serve as a benchmark to guide the design of geothermal heated bridge deck system.

NUMERICAL SIMULATION PROGRAM

A series of three-dimensional numerical analyses were performed to simulate geothermal heated bridge deck using the finite element software COMSOL Multiphysics.

Finite Element Method (FEM) Model

A 3D FEM model of a geothermal heated bridge deck was created as shown in Fig. 1. The dimensions of the deck are 3.5 m x 2s m x 0.25 m. "s" denotes as the pipe spacing. The two long sides of the model are considered as adiabatic due to symmetric pipe loop arrangement. The top, bottom, front and end surfaces are convective interface between concrete and air. The pipe selected has an outer diameter of 2.0 cm and an inner diameter of 1.4 cm. Water with 25% propylene was used as heat carrier fluid, and circulated through the circulation pipe at a constant flow rate. The temperature distribution and progression within the deck was investigated during heating process. Inlet fluid temperature was assumed to be constant in the simulation even though it is likely to vary slightly as a result of colder fluid being injected into the ground.

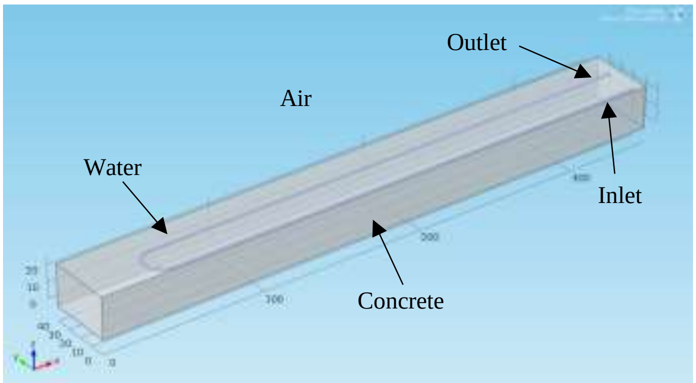


Figure 1. Configuration of geothermal heated bridge deck.

Mesh of Bridge Deck

Figure 2 shows the mesh of bridge deck and circulation fluid in 3D. The specification of interaction between the concrete and the fluid is important to the heat transfer process, so the extra finer free triangular element was utilized to mesh the interface. Moreover, finer free tetrahedral element was adopted to mesh the both the concrete and the fluid. The total number of element generated in this model was 408,772 for the base case. In addition, the number of element was changed slightly for different thickness of concrete cover and pipe spacing because of the change in configuration of the bridge deck and the fluid.

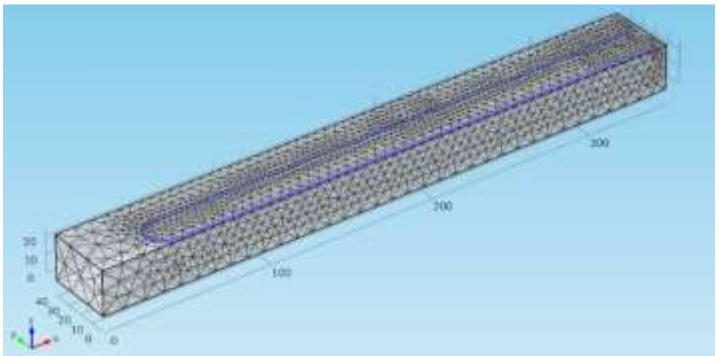


Figure 2. Mesh of bridge deck and circulation fluid in 3D.

Six influence factors including pipe spacing, inlet fluid temperature, flow rate, wind speed, ambient temperature and thickness of concrete cover over the circulation pipes were considered in the modeling. The ambient temperature remained constant throughout the analyses. Parametric study was conducted to evaluate the effects of different factors on the heating process of bridge deck. It is noted the rebar was not modeled in this study because its volumetric mass and heat capacity is small, and its thermal conductivity is much higher compared to the concrete, heat carrier fluid and pipe. In addition, the volume of rebar is relatively small and would require an extremely fine mesh, leading to a significant increase of computation time. Bowers and Olgun (2014) indicated that the effect of rebar was negligible based on their preliminary numerical analyses in COMSOL.

This numerical study was limited to the heating process of bridge deck. Melting of the snow/ice was not included in order to simply the simulation to develop a guideline for the design of this geothermal heating system. This condition is considered as the case when the bridge deck is preemptively heated to above 0^{o}C before snowfall occurs. Hence, the bridge deck is kept snow-free after precipitation if the heat injection can compensate the latent and evaporative heat demands from snow/ice melting after precipitation.

Properties of materials used in the analyses are summarized in Table 1. A total of 27 models were analyzed where different model parameters were systematically varied as presented in Table 2 in order to investigate the effects of six influence factors on the performance of geothermal heated bridge deck. The center-to-center spacing of the circulation pipes was 20 cm, and the centerline of the pipes was 6.0 cm below the deck surface for the base case. Heat carrier fluid with 12 °C inlet temperature was circulated at a flow rate of 0.6 m/s. The initial temperatures of the bridge deck and the air are -2 °C, and wind speed is 0 m/s for the base case.

Table 1. Property of Materials in Numerical Simulation.

Property	Material	Value	Unit
Density	Concrete	2300	kg/m^3
	Fluid	1000	kg/m^3
	Air	1.23	kg/m^3
Heat capacity	Concrete	880	J/kg⋆K
	Fluid	3691	J/kg⋆K
	Air	1006	J/kg⋆K
Thermal conductivity	Concrete	1.88	W/m⋆K
	Fluid	0.61	W/m⋆K
	Air	0.0239	W/m⋆K
Surface emissivity	Concrete	0.91	
Dynamic viscosity	Fluid	0.00273	kg/m⋆s
Kinematic viscosity	Air	1.315×10^{-5}	m^2/s

Table 2. Parameters for Numerical Simulations.

Pipe spacing (cm)	Wind speed (m/s)	Concrete cover (cm)	Inlet fluid temperature (^{o}C)	Ambient temperature (^{o}C)	Flow rate (m/s)	Number of runs
20	0	6	12	-2.0	0.6	1 (Base)
20	0	6	12	-2.0	0.3, 0.9, 1.2, 1.5	4
20	0	6	12	-10, -8, -6, -4	0.6	4
20	0	6	6, 8, 10, 14, 16, 18, 20	-2.0	0.6	7
20	1, 2, 4, 6	6	12	-2.0	0.6	4
15, 25, 30, 35	0	6	12	-2.0	0.6	4
20	0	4, 8, 10, 12	12	-2.0	0.6	4

RESULTS

Average temperature at top surface of bridge deck

Figure 3 (a)-(f) present the average temperature at the top surface of the bridge deck for various: (a) Pipe spacing; (b) Wind speed; (c) Concrete cover; (d) Inlet fluid temperature; (e) Ambient temperature; (f) Flow rate. It is found that the average temperature at top surface of bridge deck was increasing rapidly at the beginning of the simulation, and then it became gradual after 3 hours. Moreover, the increase of temperature was reduced as pipe spacing increased as shown in Figure 3 (a). The effect of wind speed on the surface temperature of bridge deck can be divided into two regimes as shown in Figure 3 (b). When the wind speed was less than 4 m/s, it has no obvious affect surface temperature; however, the temperature of top surface decreases quickly when the speed exceeds 4 m/s.

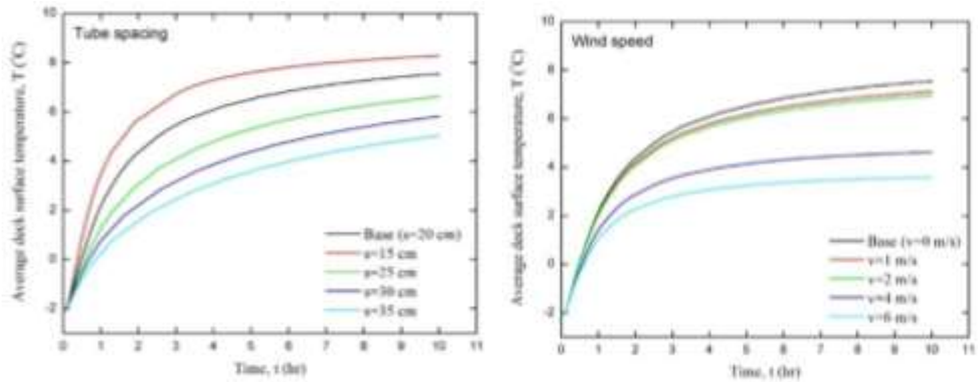
In Figure 3 (c), it is indicated that the concrete cover effect on surface temperature was almost proportional to the thickness of concrete over the circulation pipe, since it directly affects the heat transfer distance from the heat source (i.e., heat carrier fluid to the surface of bridge deck). In Figure 3 (d), the effect of inlet temperature followed the same pattern of the effect of pipe spacing. The increase in inlet fluid temperature resulted in an increase in surface temperature. Figure 3 (e) shows the effect of ambient temperature on the heated bridge deck. Ambient temperature did not affect the evolution of surface temperature of bridge deck. In addition, the effect of flow rate was found to be negligible compared with other factors as shown in Figure 4 (f).

Time required to reach 0^{o}C at deck surface

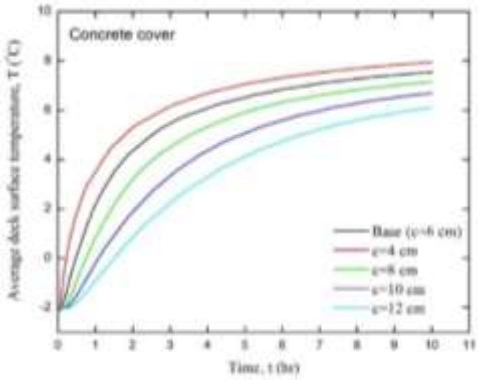
Figure 4 (a)-(e) show the time required to reach 0^{o}C at top surface of bridge deck: (a) Pipe spacing; (b) Wind speed; (c) Concrete cover; (d) Inlet fluid temperature; (e) Ambient temperature; (f) Flow rate. The time required to reach 0^{o}C at top surface is around 0.5 hr for the base case in the analyses. It is evident that the time required was increasing with pipe spacing, wind speed and concrete cover; while it was decreasing with inlet fluid temperature, ambient temperature and flow rate. It is also found that the effects of wind speed and flow rate on the required time were not prominent compared to other factors. As a result, they are not critical parameters in the design of geothermal heated bridge deck system. Moreover, the increase in concrete cover increased the required time by 200% from c=6 cm to c=12 cm; the increase in ambient temperature decreased the required time by 300% from T=-10^{o}C to T=-2^{o}C. Hence, concrete cover and ambient temperature are the main concern in the design.

Temperature distribution along vertical section

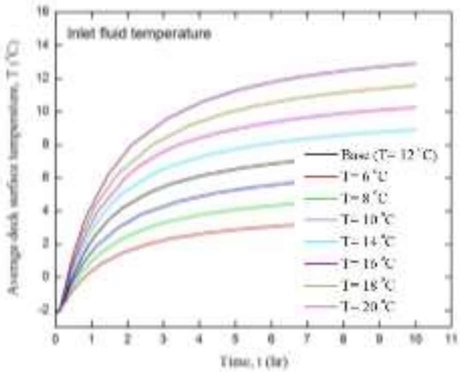
Figure 5 shows the temperature distribution along the vertical section in the middle between circulation pipes for different thickness of concrete cover: (a) c=4 cm; (b) c=6 cm (Base case); (c) c=8 cm; (d) c=10 cm; (e) c=12 cm. The centerline section represents the most distant point from each pipe in the horizontal direction. It is found that the temperature rise was the fastest at the pipe elevation within the deck. The bridge deck was progressively warmer with higher temperatures expectedly at the surface in comparison to the deck base. In this analysis, the top 7.5 cm of the deck slab was greater than 0°C at the end of 1 hr of heating with 12°C circulation fluid for the base case. In addition, the observed temperature contour was shown in different patterns for different thickness of concrete cover. The maximum temperature was always located at the same depth of the circulation fluid. As the thickness of concrete cover increased, the temperature at top surface was decreasing, whereas the temperature at base was increasing, which is because of the change of heat transfer distance between the heat source and the two surfaces.



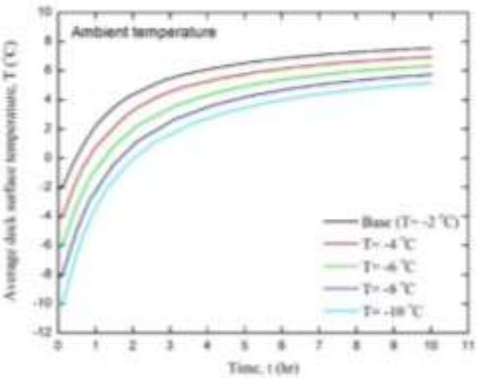
(a) (b)



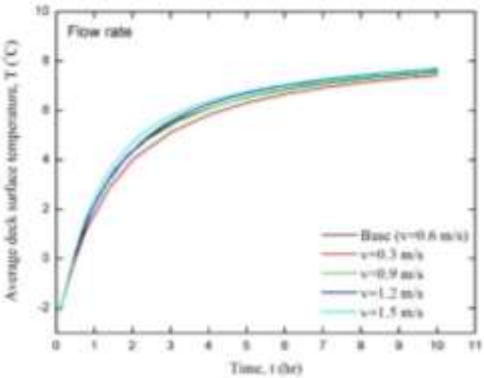
(c)



(d)

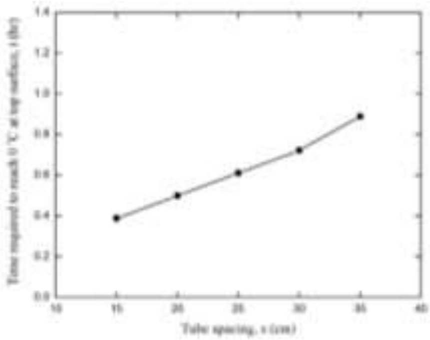


(e)

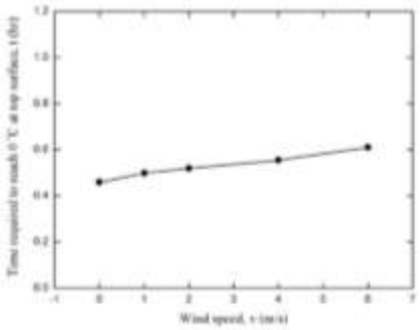


(f)

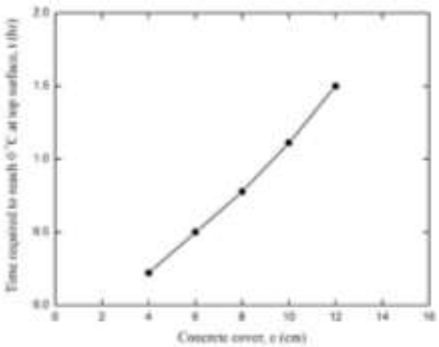
Figure 3. Average temperature at top surface of bridge deck: (a) Pipe spacing; (b) Wind speed; (c) Concrete cover; (d) Inlet fluid temperature; (e) Ambient temperature; (f) Flow rate.



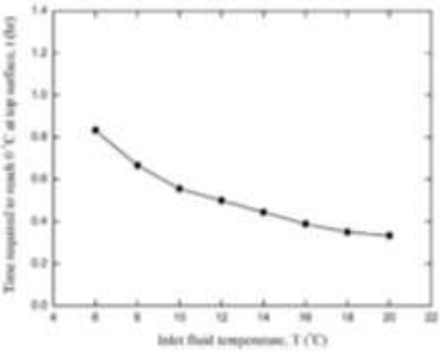
(a)



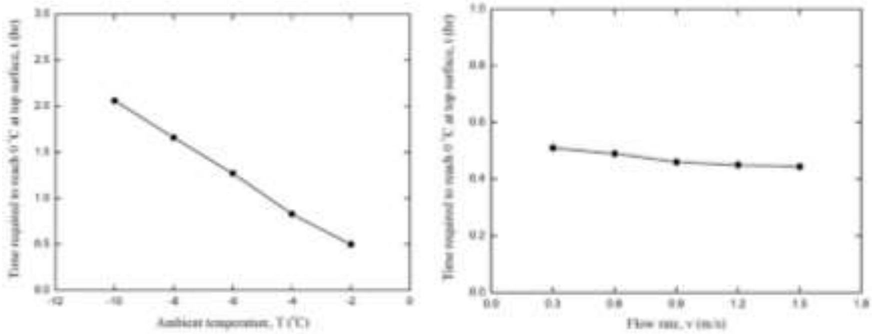
(b)



(c)

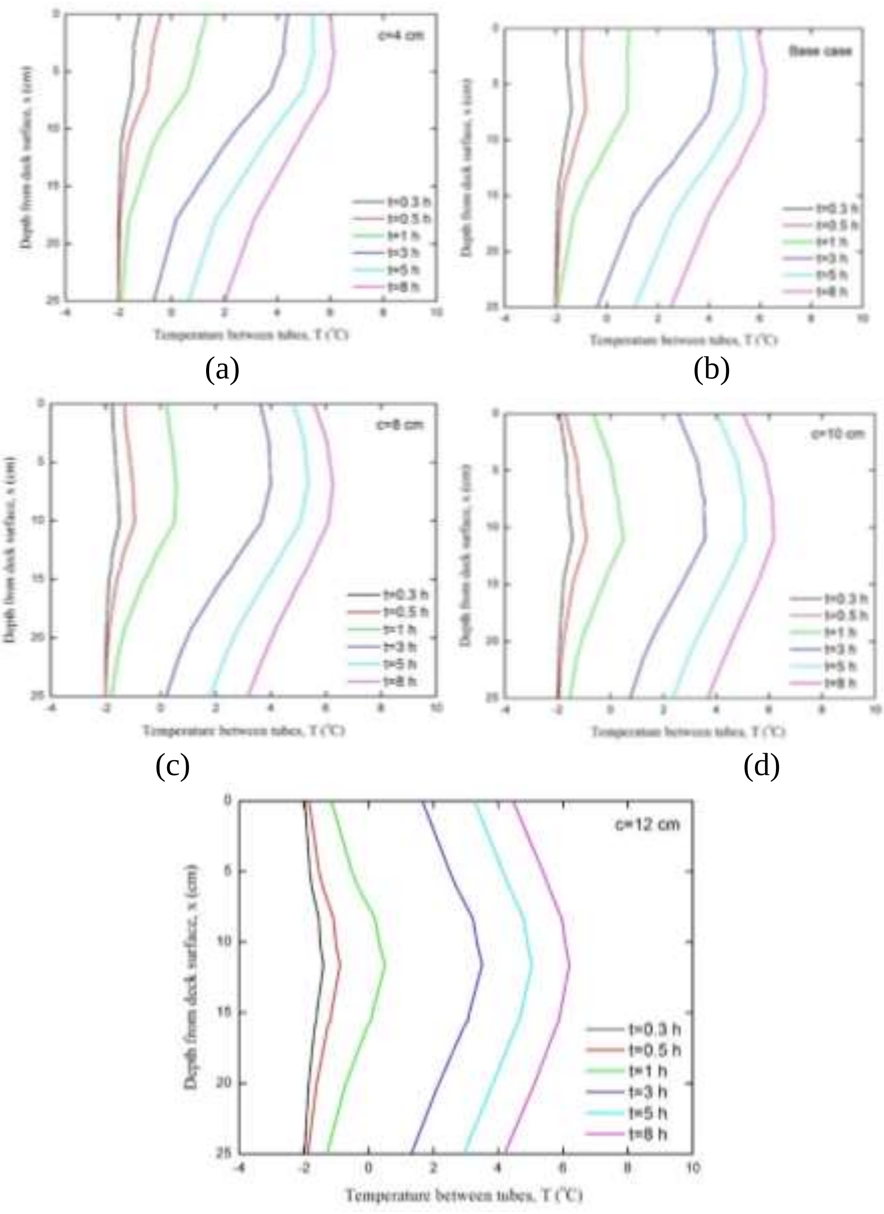


(d)



(e) (f)

Figure 4. Time required to reach 0°C at top surface of bridge deck: (a) Pipe spacing; (b) Wind speed; (c) Concrete cover; (d) Inlet fluid temperature; (e) Ambient temperature; (f) Flow rate.



(a) (b)

(c) (d)

(e)

Figure 5. Temperature along the vertical section in between circulation pipes: (a) c=4 cm; (b) c=6 cm (Base case); (c) c=8 cm; (d) c=10 cm; (e) c=12 cm.

CONCLUDING REMARKS

Three dimensional numerical simulation of a single geothermal heated bridged deck is carried out in this paper. The effects of system parameters including pipe spacing, concrete cover, fluid flow rate, inlet fluid temperature, ambient temperature and wind speed were investigated. It is demonstrated that the wind speed and flow rate have quite small effect on heating efficiency of the system. The other factors should be considered comprehensively in the design of hydronically geothermal heating system for the bridge deck. The new findings in this study can serve as a benchmark to gauge the operational conditions and the energy requirements for designing ground-source bridge deck deicing system.

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