Feasibility analysis of low thermal conductivity asphalt concrete bridge deck deicing by using geothermal energy

REN Lian-wei, HAN Zhi-pan, HUO Ji-wei, GAO Yu-jia

1 School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454000, China;
2 The Fourth Construction Co., Ltd. Of CSCEC 7th Division, Xi’an 710000, China

Abstract. Deicing of bridge deck is studied based on ground source heat. In this paper, a COMSOL finite element numerical model is established, it considers the generalized heat flux, convective radiation heat flux and snow melting heat rate as the cold source. The designed pipe spacing of the model is 20cm, 25cm and 30cm respectively. The influence of low thermal conductivity of asphalt bridge deck on deicing effect is considered in the model, and the temperature and stress of bridge deck are simulated, and the relevant data results are obtained. The actual heat flux required for deicing is calculated, and it is concluded that the deicing effect increases gradually with the increase of pipe spacing, but the increase of 20cm spacing is smaller than that of 25cm spacing. 25cm spacing has good effect and is the most economical.

1 Introduction

Bridge icing is a very important problem in winter, which not only causes travel inconvenience, but also traffic obstruction, and even causes a series of traffic accidents. At the same time, the current traditional salt deicing method not only pollutes the environment, causes land salinization, but also easily corrodes the bridge structure, causing greater economic losses1-3. Therefore, it is necessary to carry out green, safe and effective deicing.

Using geothermal energy to deice bridge deck has a good application prospect. Shallow geothermal energy is a clean, sustainable development of new energy, with large reserves, no pollution, no carbon emissions and other characteristics4, has great potential and broad application prospects5-6. There is a high temperature in the shallow layer of the earth's surface (within 400m underground). It is a natural Solar Geothermal collector, which collects 47% of the solar energy and preserves the gradient temperature increase of the earth. This kind of renewable and pollution-free shallow low-temperature energy is called geothermal energy. Geothermal energy is subject to seasonal changes, and its temperature is very suitable to be used as new energy: compared with cold winter, the temperature of geothermal energy is higher, and in hot summer, the temperature of geothermal energy is lower. Geothermal energy is used as energy supply, which can be directly utilized without heat conversion, and it is a renewable, green, clean and environment-friendly energy7-9.

At present, there are mainly chemical and mechanical methods for snow removal on bridge deck. The existing literature10-11 described that chloride ion erosion in deicing salt can cause corrosion of bridge facilities. In reinforced concrete bridge deck, the corrosion of reinforcement will threaten the integrity of bridge deck structure. Under the influence of chemical substances, the oxidation of steel bars will reduce the cross-sectional area of steel bars and increase the stress of steel bars. The collapse of some overpasses and bridges is caused by the corrosion of steel bars on the bridge deck and bridges12. In
addition, the molten salt not only pollutes the environment, but also shortens the life of buildings, roads and bridges.

In addition to chemical substances, other methods are often used for deck deicing. Mechanical deicing method is a method to remove the harm of ice and snow through the direct effect of mechanical devices on road icing and compaction of snow. At present, the main mechanical deicing methods are impact deicing, multi whip deicing, roller rotary deicing and shovel cutting deicing. When the power system is applied in the bridge deck deicing, the insulated cables are laid in the bridge deck first, and when deicing is needed, the system is turned on to transmit the current to the wires on the bridge deck for resistance heat generation. Conductive concrete can also be used in the deicing of bridge deck in power system, which can be realized by adding conductive steel fiber and carbon into concrete; When the current is supplied, the resistance generates heat throughout the concrete slab.

The related deicing methods have their limitations: (1) The mechanical method damages the structure, makes it difficult to clean and deice quickly, and hinders the normal traffic; (2) The chemical method corrodes the structure and pollutes the environment;

In recent years, a series of finite element models of snow removal for energy pile bridge decking have been established: (1) Rees (2002) developed a two-dimensional numerical model considering the transient effect of snow melt process and then improved the model; (2) Xu (2015) established a thermo-mass coupling model of road surface snow melting using low temperature heat flow, this has been used in HVAC systems to simulate the performance of hydrodynamic road heating; (3) Ho (2017) studied the heat generation model and simulation of a collector pipe in an underground temperature stable zone; (4) Liu (2019) established the energy balance equation of solar radiation, snowfall and convective heat flow on the bridge surface, and studied the minimum energy required for snow melting by Nelder-Mead algorithm.

In view of the field test, relevant scholars have done the following studies: (1) Liu, Rees (2007) carried out a scale test on de-icing and snow melting, calculated from the similarity ratio, and then carried out an experimental study. The experimental results were good, and the snow melting was obvious in the distribution area; (2) Asim Balbay (2010) conducted outdoor snow thawing tests on the bridge deck and road surface containing energy tubes, and analyzed the strain variation of the bridge deck thermometer, and the snow removal effect was good; (3) Japanese scholars (2011) used an underground heat storage tank to provide heat for the bridge deck road to conduct a snow thawing test on the bridge deck. The temperature of the heat storage tank was higher than that of the non-heat pump energy pile system, and there was an obvious phenomenon in the test; (4) Kong (2018) conducted a melting snow test on the bridge deck with asphalt layer. The heat exchange pipe was located on the concrete slab, and the asphalt layer was still on the upper part. After 48h of the test, the snow in the pipe distribution area had obvious snow thawing. The relative field tests have achieved relatively ideal snowmelt effect.

For this paper, a parametric study was conducted to determine the heat that is required for a snow-melting system in Lingbao City, Sanmenxia, Henan Province. COMSOL finite element analysis is used to simulate the heat generated through the collector tube. The simulation considers the influence of different pipe spacing on the deicing effect and the influence of asphalt concrete with low thermal conductivity on the deicing effect.

2 Parameter study and model establishment

2.1 Establishment of numerical model

According to the three kinds of pipe spacing in the field bridge deck pavement, 1:1 full-size simulation analysis was carried out for the snowmelt area of the bridge deck with different flow rates and different pipe spacing. The model size of the three snowmelt areas is 10m×3m×0.2m (length × width × height). The numerical model consists of three concrete layers, with 10cm C50 concrete at the bottom and 5cm asphalt concrete at the middle and upper parts. Among them, a heat exchange tube is set in the C50 concrete layer, and the heat conduction liquid in the heat exchange tube is simulated by multi-segment
The model is coupled with three physical fields: non-isothermal pipeline flow, porous medium heat transfer, and solid mechanics. The non-isothermal pipeline flow module is used to simulate the heat transfer between the heat conducting fluid and the bridge deck. The material of the heat conducting fluid is water. The variable relationship of its thermal physical property parameters with time can be directly imported into the model library:

\[ \rho \frac{\partial \mu}{\partial t} = -\nabla p + e_t \left( \frac{1}{2} f D \right) |\mu| + F \cdot e_t \]  
\[ \frac{\partial A \rho}{\partial t} + \nabla \cdot (A \rho \mu e_t) = 0 \]  
\[ \rho A C_p \frac{\partial T}{\partial t} + \rho A C_p \mu e_t \cdot \nabla T = \nabla \cdot (A k \nabla T) + \frac{1}{2} f D \left( \frac{\partial A}{\partial \rho} \right) |\mu|^2 + Q + Q_{\text{wall}} \]  

The simulation and experimental research on the basis of further research in winter, the winter test, low temperature heat in the water after energy pile temperature increases, the winter test is short cycle, the outlet temperature energy pile up to 14 to 15 °C, energy pile deicing system running, the water tank temperature rising, stable after 2 h in 12 °C, the outlet temperature of pile around 14 ℃. At the initial stage of the model, \( T_{in} \) was set as a small 10°C, and after field test, the pile outlet temperature was found to be 14°C, so it was set as 14°C later.

C50 concrete slab and asphalt concrete slab are simulated by porous media heat transfer module, and the heat transfer equation is imported from COMSOL model library as follows:

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p \mu e_t \cdot \nabla T = \nabla \cdot (A k \nabla T) + \frac{1}{2} f D \left( \frac{\partial A}{\partial \rho} \right) |\mu|^2 + Q + Q_{\text{ced}} \]  
\[ Q = k \nabla T \]  

Where: \( \rho \) is the density of concrete; \( T \) is the concrete temperature; \( C_p \) is the constant pressure heat capacity of concrete; \( q, Q \) is the source term; \( k \) is the thermal conductivity of concrete, in which the material is set according to the actual site construction.

Solid mechanics module is used to simulate the stress and strain caused by low temperature heating of bridge deck, and three field coupling is used to simulate the thermal response of bridge deck. The heat exchange fluid in the pile body is water, and the model base material is directly imported and the parameters are set. The corresponding parameters of bridge deck and heat exchange are as follows (Table.1, Table.2).

| Table.1 Properties of soil layer |
|-----------------------------|
| Layer  | Soil Type  | Level, m | Thermal Conductivity, (W/m·k) |
|-------|-------|---------|-----------------------------|
| 1     | Loess silt | 0-1.8   | 0.2-0.3                     |
| 2     | Gravel sand | 1.8-6   | 0.3-0.4                     |
| 3     | Gravel sand | 6-10.1  | 1.7-1.9                     |
| 3     | silt       | 10.1-14.8 | 1.5-1.6                |
| 4     | Fine sand  | 14.8-25  | 1.7-1.9                     |
Table 2 Material characteristics of bridge deck

| Bridge deck layer | Thickness (mm) | Oil-stone ratio | Thermal Conductivity, (W/m·k) | Density, (kg/m³) |
|-------------------|----------------|-----------------|-------------------------------|-----------------|
| AC-16C            | 50             | 4.5             | 1                             | 2430            |
| AC-25C            | 50             | 3.7             | 1.2                           | 2450            |
| C50               | 100            | -               | 1.6                           | 2500            |

During the mesh generation of the numerical model, each part of the bridge deck is divided by free tetrahedral mesh. In order to improve the calculation accuracy of the model, the whole model is refined. The mesh generation is shown in Figure 1.

Fig. 1 Construction of bridge deck model and meshing with different pipe spacing

In order to make the calculation results more accurate, the pile outlet temperature obtained from the energy pile test in winter is taken as the reference data for numerical simulation. The C50 concrete floor is set to have no heat transfer with the outside, and the surrounding and bottom surfaces of the model are defined as thermal insulation surfaces in the porous medium heat transfer module. In the solid mechanics module, roller support is set around the model and fixed constraint is set at the bottom.

2.2 Heat flux calculation

Most of the similar snow-melting designs that have been proposed are based on steady-state conditions. Variables such as the snowfall rate, ambient air temperature, and wind speed are often considered based on weather data compiled over several years. These data that are used for heat requirement calculations
usually are based either on the average or upper value during a snowfall event. The ASHRAE Handbook 2012 provides guidelines to calculate the required heat flux for snow melting according to five factors: (1) hourly rate of snowfall, (2) air temperature, (3) relative humidity, (4) wind velocity, and (5) geometry of the heated slab. The heat flux is required for efficient snow melting can be determined by the following equations:

\[ q_0 = q_s + q_m + A_r (q_h + q_e) \]  

\[ q_s = \rho_{water} s (C_{p, ice} (T_s - T_a) + C_{p, water} (T_f - T_s)) / C_1 \]  

\[ q_m = \rho_{water} s \cdot h_{if} / C_1 \]  

Where \( q_s \) is the sensible heat flux in W/m\(^2\); \( q_m \) is the latent heat flux in W/m\(^2\); \( q_h \) is the convective and radiative heat flux from the snow free surface in W/m\(^2\); \( q_e \) is the heat required for the water evaporation in W/m\(^2\); \( A_r \) is the snow free area ratio; \( \rho_{water} \) is the density of water in kg/m\(^3\); \( s \) is the snowfall rate water equivalent in mm/h; \( C_{p, ice} \) is the specific heat of ice in J/(kg·K); \( T_s \) is the melting temperature in °C; \( T_a \) is the ambient temperature in °C; \( T_f \) is the liquid film temperature and is usually taken as 0.56°C; \( C_{p, water} \) is the specific heat of water in J/(kg·K); \( C_1 \) is equal to 3.6\times10^6; and \( h_{if} \) is the heat of fusion of snow in J/kg. Heat flux calculation parameters as Table.3.

| Parameters                  | Value                  |
|-----------------------------|------------------------|
| Specific heat of ice, \( C_{p, ice} \) | 2100 J/(kg·K)         |
| Specific heat of water, \( C_{p, water} \) | 4200 J/(kg·K)         |
| Density of water, \( \rho_{water} \) | 1000 kg/m\(^3\)      |
| Snowfall rate and icing rate | (No snow, estimated icing value) |
| Melting temperature, \( T_s \) | 0°C                   |
| Ambient temperature, \( T_a \) | -3°C                  |
| Liquid film temperature, \( T_f \) | 0.56°C                |
| Heat of fusion of snow, \( h_{if} \) | 334 000 J/kg          |

According to the weather conditions of the field test, the calculated \( q_m \) is 92.7W/m\(^2\); \( q_s \) is 2.4W/m\(^2\). Convection heat and evaporation heat (\( q_h \), \( q_e \)) are treated according to COMSOL import formula:

\[ q_h, e = h(T_{ext} - T_2) \]  

Where \( h \) is the heat transfer coefficient, it is determined by the input parameters (Characteristic length, and convection model selection); \( T_{ext} \) is the external ambient temperature and \( T_2 \) is the internal temperature of the structure. Convection heat and evaporation heat (\( q_h \), \( q_e \)) chooses the external natural convection, the upper side of the horizontal plate model. The characteristic length of Convection heat and evaporation heat (\( q_h \), \( q_e \)) is 1.1538, absolute pressure is 1Pa, \( T_{ext} \) is -5°C, external relative humidity is 0.3, and surface relative humidity is 0.5.

However, when I input \( q_m = 92.7W/m^2 \) into the model, the temperature distribution of the deck pipe obtained from the field test is quite different. It can be seen from the Fig.2 that \( T_{out} \) is stable at 9.5 °C.
when tin is at 14 ℃, it is different from $T_{in}$ is 14 ℃ and $T_{out}$ is in the range of 11~12 ℃ when it is tested on site.

It is found that the calculated $q_m$ cannot be directly imported as one of the heat flux parameters of COMSOL model. It is the heat flux $q_m$ required by the deicing system in order to achieve the deicing effect, not the heat flux generated by ice on the deck roof. After several times of $q_m$ import calculation, it is concluded that $q_m = -50 \text{ W/m}^2$ is close to the field pipeline temperature distribution.

![Fig. 2 Temperature distribution in bridge deck pipeline](image)

(a) $q_m = -92.7 \text{ W/m}^2$  
(b) $q_m = -50 \text{ W/m}^2$

**3 Temperature distribution each layer and heat flux calculation**

![Fig. 3 Temperature distribution of bridge deck C50 concrete and asphalt concrete (AC)](image)

**Fig. 3** is the temperature distribution pattern of the bridge deck at different time points intercepted from the d=20cm model. The temperature pattern of C50 concrete is on the left, and the temperature distribution pattern of the top asphalt concrete is on the right. It can be seen from the figure that the
temperature of C50 concrete rises rapidly. After one hour, the temperature of C50 concrete pipe laying area has risen to about 1 ℃, and the temperature of non-pipe laying area is still -1 to -2 ℃. After 3 hours, the overall temperature in the pipe laying area has reached 2 to 3 ℃, but the temperature of the top asphalt concrete is still 3 to 4 ℃. With the increase of time, the temperature of C50 concrete continues to rise above 4 ℃. After 5h, the temperature of top asphalt changes, and the temperature of some areas increases by 1 ℃. From 6h to 9h, the overall temperature of top asphalt concrete increases, but the temperature is still about -1 ℃. After 11h, the temperature of the top asphalt is higher than 0 ℃. In 13h top layer asphalt, the overall temperature of pipe laying area is higher than 0 ℃, and the temperature of some areas is higher than 1 ℃. With the increase of time, the top asphalt temperature needs to be increased. Under the influence of three different heat fluxes, the temperature of the bridge deck reaches 0 ℃, indicating that the ice in the area has melted. The de-icing time of 13h may seem long, because the simulation is 24h continuous snow or ice, the simulation environment is the most extreme environment, generally the snowfall time will not last very long, around 2-10h; At the same time, the system does not carry out the pre-heating stage before snowfall. If the system is turned on in advance for pre-heating when the weather forecast has snowfall or freezing phenomenon, then the speed of de-icing and snow melting will be faster.

![Fig. 4](https://example.com/fig4.png)

As shown in Fig.4, during the simulation period, the asphalt concrete on the top floor of the bridge deck has partial stress, and the stress change is small before 8h. Then, the tin area changed obviously at 10h, and the stress changed by 0.2MPa. After 13h, the strain change area becomes larger and larger, and the maximum stress has reached 0.3MPa. At 15h, the stress changes in almost general bridge deck asphalt layer, and the maximum stress reaches 0.4MPa. With the increase of time, the area of stress change and the size of stress are increasing. Finally, at 24h, the bridge deck has a larger stress change, and the stress in most areas reaches 0.3 ~ 0.4 MPa.

The actual heat flux of the deicing system was calculated according to the simulated inlet and outlet temperatures. Fig. 5-(a) shows the outlet temperature $T_{out}$ and temperature difference ($\Delta T$) of the bridge deck with 20 cm pipe spacing during the simulated 24 h period. The outlet water temperature $T_{out}$ tends to be stable after 8 hours, and $T_{out}$ can reach 11.7 ℃. The temperature difference $\Delta T$ is about 3.3 ℃.
Then, the actual heat flux of the bridge deck is calculated, as shown in Fig.5-(b). It can be seen from the figure that the heat flux is larger in the initial stage, and tends to be stable with time, and finally stabilized at 40W/m². Therefore, the deicing effect can be achieved when the designed heat flux of the model is kept at 50-60W/m². The model is mainly used in the field test of Didong bridge in Lingbao City, Sanmenxia City, it has great limitations. However, considering the influence of asphalt layer with low thermal conductivity on deicing effect, the heat flux expanded to 80W on this basis should be enough to meet the deicing requirements for small and medium-sized deicing systems.

![Fig. 5 Heat flux and temperature curve](image)

4 Analysis of the results of different pipe spacing

The temperature of C50 concrete, middle layer asphalt concrete and top layer asphalt concrete are analyzed by the model of 20cm pipe spacing. Three representative points are selected in each layer of concrete of d=20cm model, and the three points are listed according to the heating sequence of concrete. As shown in Figure.6, the coordinates of midpoint, B1 and B2 in C50 concrete layer are (0, 0, 50), (0, 1000, 50) and (0, -1000, 50) respectively. The same is in the top asphalt concrete is (0, 0, 150), (0, 1000, 150) and (0, -1000, 150).

![Fig. 6 Three representative observation points of bridge deck](image)

Firstly, the temperature distribution of the midpoint in the three layers is studied, as shown in Fig.7. It can be seen from the figure that the temperature of C50 concrete is the highest, up to 8℃. This is different from the maximum temperature of C50 concrete up to 9.5℃ in the field test, but the temperature up to 9 ℃ in the field test is the pre heating period without deicing period. During the field de-icing test, the field temperature showed a downward trend. Followed by the middle asphalt concrete, and finally the top asphalt concrete. And it can also be seen in Fig.7 that there is a period of temperature decrease during 1-2h, and the overall trend of temperature is decreasing first and then increasing. That is because the temperature drop of ice layer is still dominant in the early stage, and the temperature of thermal system is lower in the early stage. With the increase of time, the temperature of thermal system increases, and the curve shows an increasing trend.
**Fig. 8** is the stress distribution diagram of the asphalt layer on the bridge deck. It can be seen from the diagram that part of the stress occurs during the test, and the stress of the top asphalt concrete is larger, but with the increase of heating time, the stress gradually decreases. This is because the ice heat flux directly applied to the top layer of asphalt concrete at the initial stage of the model causes a large change of stress. With the heating of the system, the stress gradually decreases and recovers.

**Fig. 7** Temperature distribution in each layer

**Fig. 8** Stress distribution in each layer

**Fig. 9, 10** show the comparison of temperature distribution in C50 concrete and top asphalt concrete respectively. It can be seen from the figure that the temperature increase of point C50-B1 is the largest, and the maximum temperature can reach 8.2 ℃. Then there is the C50-M, and the maximum temperature can reach 7.6 ℃. The minimum temperature rise is C50-B2, and the maximum temperature is only 6 ℃. The same result occurs in the top layer of asphalt concrete, AC-TB1 temperature is the largest, at 2.2 ℃, the midpoint temperature of AC-T is the second, at about 2 ℃. Finally, AC-TB2, the temperature is 1.1 ℃. Because point B1 is close to the water inlet temperature, the corresponding bridge deck gets more heat first, while point B2, which is farthest from the water inlet, gets the least heat at the same time, so the heat transfer effect and the temperature distribution are different.

**Fig. 9** Temperature distribution at different observation points (C50)

**Fig. 10** Temperature distribution at different observation points (AC-T)

**Fig. 11, 12** are the temperature distribution maps of bridge deck with pipe spacing of 25cm and 30cm respectively. They have the same rule as the deck with 20cm pipe spacing (**Fig. 7**). This indicates that the temperature is gradually transferred from C50 concrete to the top, which results in the maximum temperature of C50 concrete, while the temperature of top asphalt concrete is the lowest. And with the
increase of pipe spacing, the temperature of C50 concrete has an increasing trend, but the change of 25cm pipe and 20cm pipe is small. This phenomenon is more obvious in asphalt concrete. In the top layer of asphalt concrete, the maximum temperature of 30 spacing pipe is above 0 ℃, while the maximum temperature of 25 cm pipe is above 1 ℃, and the maximum temperature of 20 cm pipe is above 2 ℃, with obvious increase.

With the decrease of pipe spacing from 30cm to 25cm and 20cm, the temperature of C50 concrete increases from 5.9 ℃ to 7.2 ℃ and 7.8 ℃, increasing by 22% and 32.2% respectively. However, the increase of temperature is only 8.3% when the spacing is reduced from 25 cm to 20 cm. The temperature increase from 25cm to 20cm (8.3%) is much lower than that from 30cm to 25cm (22%). Similarly, the temperature of middle asphalt concrete from 30cm ~ 25cm ~ 20cm is 3.97 ℃, 5.1 ℃ and 5.5 ℃ respectively, and the increase rate is 28.4% and 38.5% respectively; Only 7.8% increase in 25cm ~ 20cm. The temperature of top asphalt concrete from 30cm ~ 25cm ~ 20cm is 1.26 ℃, 2.35 ℃ and 2.8 ℃ respectively, and the increase rate is 86.5% and 122% respectively; Only 19.1% increase in 25cm ~ 20cm. The reason why the temperature rise is greatly reduced (25cm ~ 20cm) is that the temperature of the concrete slab with the two kinds of pipe spacing is close to the maximum value that can be increased. The temperature of the heat transfer fluid is 14 ℃, it has a certain main heat radiation radius for the concrete slab, and the temperature has a gradient change outside the main heat radiation radius (30cm pipe spacing); However, within the main heat radiation radius (25cm pipe spacing, 20cm pipe spacing), the gradient change is very small. If the gradient change is obvious in this area, the temperature of heat transfer fluid must be increased. From the top asphalt temperature, from 25cm pipe spacing to 20cm pipe spacing, the temperature increase is 19.1%. Although there is a large increase, it is smaller than that from 30cm to 25cm. Therefore, when designing the deicing system, it is considered that the effect of 25cm pipe laying is excellent, it can maximize the benefits.

![Fig. 11 Temperature distribution (25cm spacing)](image1)
![Fig. 12 Temperature distribution (30cm spacing)](image2)

5 Conclusion

Based on the field test of Didong bridge, the finite element model was verified. The generalized heat flux, convective radiation heat flux and melting heat power of ice and snow were added to the model to apply cold source. According to the field deicing effect and model simulation results, it is considered that the system has good deicing effect. The heat flux required for deicing and the stress distribution of bridge deck thermometer are simulated and analyzed, and the influence of different pipe spacing on deicing effect is summarized. The conclusions are as follows:

1. The results show that it takes 13 hours for asphalt concrete with low thermal conductivity to reach above 0 ℃ under the condition of 20 cm pipe laying; At the same time, the asphalt concrete layer has obvious stress change, and the maximum stress change can reach 0.5MPa.
(2) Under the condition of this model, the actual heat flux required for deicing is 50 ~ 60W, which is close to the heat flux obtained from field test.

(3) With the decrease of the pipe distribution distance, the temperature rise of the bridge deck is obvious. However, the effect of pipe layout design from 25cm to 20cm is very small, when designing the deicing system, it is considered that the effect of 25cm pipe laying is excellent, which can maximize the benefits.

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