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Research Paper

Prediction models of the thermal field on ice-snow melting pavement with electric heating pipes

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HIGHLIGHTS

- Two thermal prediction models of ISMP with electric heating pipes are proposed.
- The theory model is developed by line heat resource theory and virtual image method.
- The influence of five key factors on models is introduced and discussed.
- The semi-empirical formula is a simplification of theory model by test discussion.
- Two models are systematically compared and correctly verified by experiments.

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ABSTRACT

The method of ice-snow melting pavement (ISMP) with electric heating pipes is presented to achieve the purpose of environmental protection, intelligence, and high efficiency. In order to determine the thermal field of the ISMP and prejudge the feasibility of heating schemes, two thermal field prediction models are proposed in this paper. The one is a theory model based on line heat source theory and virtual image method, the other is a semi-empirical formula based on theory model and experiment discussion. The effectiveness of the two models is verified by the heating experiment results of concrete slabs with electric heating pipes. Differences and advantages in the two models are compared. In summary, the theory model has the wider range of applications than the semi-empirical formula, but the semi-empirical formula is closer to the practice, and easier to conduct calculation than the theory model.

1. Introduction

Effective solutions to solve ice formation problems in cold climates are common objects in various transport networks [1]. It has been recognized that accumulated snow on the pavement surface sometimes causes traffic accidents, which not only hinders the traffic operation efficiency, but also threatens personal safety. For road snow melting, various deicing methods, such as chemical [2], mechanical or thermal can be applied. The thermal method is a clean and simple approach, which includes hydronic heating system [3–6], electric heating cables or pipes [7–9], and electrically conductive concrete [10,11]. Minsk [12] summarized the cost and operating characteristics of three different technologies (hydronic, heat pipe, and electric) used for heating bridge decks. Abraham [6] investigated the feasibility of pavement heat exchangers buried in the aggregate base layer to de-ice the pavement surface through the finite element models and proposed the recommended heating power considering the energy supply and demand. Zhao [8] validated the effectiveness of the deicing pavement with carbon fiber heating wires through finite element simulation and experiments. Lai [9] studied temperature and energy distribution along the pavement depth on airport pavement with carbon fiber grilles through snow-melting experiments. In these studies, heat transfer modeling was conducted by finite element simulation, and there was only one embedding scheme of a heating system. Therefore, it is necessary to study a concise heat transfer calculation model for different heating and embedded schemes.

For calculation models, some theory models are researched through analytical method [13–19]. The other simple models are applied in engineering practice [20–24]. Chapman [13] proposed equations for the heating requirements of a snow-melting system considering energy losses. Jain [14], Grine [15], Sadat [16] and Malinowski [17] studied the two-dimensional, transient heat

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transfer in different conditions and proposed analytical solutions respectively. Wang [18] and Bernier [19] analyzed the thermal response by function transformation. Carslaw and Jaeger [20] studied the heat conduction in solid based on the Kelvin's theory. Cui [21] established a transient three-dimensional heat conduction model by a single inclined line source. Gao [22] studied the temperature field around the heat pipe underground based on line heat source theory. Kupiec [23] analyzed the heat transfer in horizontal ground heat exchanger. Abdelaziz [24] established a multilayer finite line source model for vertical heat exchangers. Liu [25] studied the thermal field in mass concrete with a pipe water cooling system.

However, some analytical solutions for heat transfer are too complex to be applied in engineering practice. The heat transfer model based on line heat resource theory is a great coupling between theory and practicality, but there are few thermal field models by line heat resource theory for ISMP. Therefore, this paper validates the applicability of the proposed thermal field model by line heat resource theory and virtual image method. Meanwhile, a semi-empirical formula is developed to improve the theory model by experiment discussion. Two models are systematically compared and correctly verified by experiments. They can both predict the surface thermal field of the ISMP with electric heating pipes before the deicing system operation. The models are of significance for optimizing heating schemes and reducing energy consumption.

2. Simplified structure of ISMP with electric heating pipes

In ISMP, electric heating pipes are embedded in the surface course. The heat generated by electric heating pipes is transferred to the pavement surface directly through the surface course. The schematic diagram of ISMP is shown in Fig. 1.

Two-dimensional analysis was performed as demonstrated in Fig. 2(a), because the shapes are continuous lengthwise. The modeling is performed under the following assumptions:

(1) The bottom of the surface course has an adiabatic condition because it rests on a thermal insulation layer.

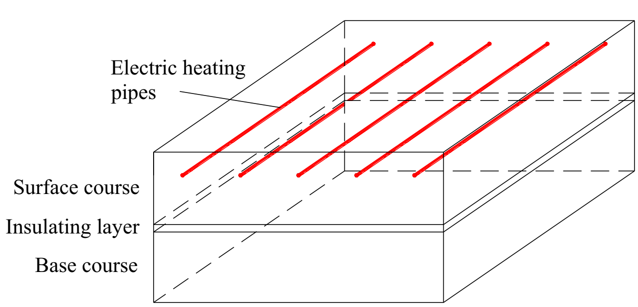

Fig. 1. Schematic of ISMP with electric heating pipes.

(2) The left and right boundaries are thermally insulated respectively. This assumption is proposed considering the practical application. The road can be seen as infinitely long, and there are ups and downs in its longitudinal slope, in order to facilitate the ISMP's construction, the heating pipes are embedded uniformly in the ISMP along the direction that is perpendicular to the driving direction (longitudinal slope). Based on the distribution, there are two conditions for the two-dimensional model: (1) The model comes from the middle of the ISMP (not including the heating pipe which is adjacent to the typical concrete pavement); (2) The model from the edge of the ISMP (including the heating pipe which is adjacent to the typical concrete pavement). For condition 1, due to the symmetrical distribution of the electric heating pipes which are embedded in the two sides of the boundaries, the left and right boundaries are thermally insulated [26]; For condition 2, in the ISMP, to improve the operation efficiency, the thermal conductivity of the concrete is enhanced by adjusting the proportion of concrete, so the thermal conductivity of the concrete in ISMP is higher than that of the typical concrete. In this condition, the heat conduction mainly occurs in the high thermal conductivity medium (the concrete in ISMP). Although there is somewhat heat transfer between the concrete in ISMP and the typical concrete, the heat transfer is weak and can be ignored [27]. Therefore, the boundaries are also assumed to be the adiabatic boundaries.

(3) The surface of the pavement has a convective boundary condition.

(4) The electric heating pipes are uniform. There is no energy loss in heat transfer from the electric heating pipes to concrete.

(5) The concrete in the pavement is uniform, isotropic, and homogeneous.

3. The prediction model based on line heat source theory and virtual image method

Heating pipe shown in Fig. 2(b) is considered as infinite length along depth direction and is regarded as the line heat source [20]. It is reliable to simplify the electric heating pipes to the line heat source.

3.1. The basic theory of line heat source

The heat conduction in the surface course is a two-dimensional and transient conduction process, where the coordinate system is $x-y$. The coordinate of heating pipe in the calculation is $x = x'$, $y = y'$. Surplus temperature physical parameter θ (°C) is defined,

$$\theta(x, y, \tau) = T - T_a \tag{1}$$

Here T (°C) is the temperature of the surface course, T_a (°C) is the ambient temperature, τ (s) is the heating time.

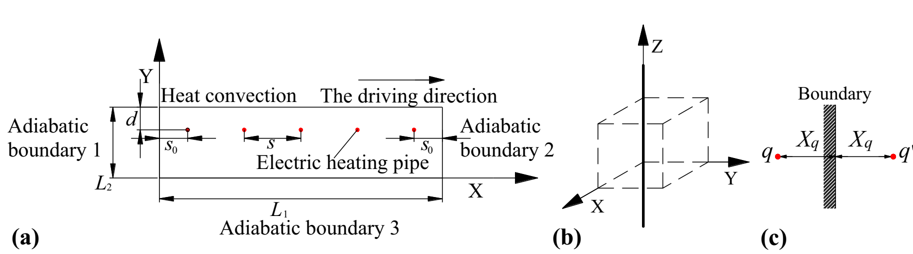

Fig. 2. Schematic of surface course: (a) schematic of surface course; (b) line heat source of infinite length; (c) virtual image heat source.