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Preliminary Design of Frozen Soil Simulation System Based on Finite Element Simulation

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***Abstract*—**Full - Scale Accelerated Loading System, one part of "the Eleventh - Five - Year National Grand Technology Infrastructure Program" is a facility to evaluate the performance and service life of different kinds of pavements subjected to traffic loading under full - controlled environment. While simulating the environments of frigid zone and permafrost zone, the accurate control of air temperature, road temperature and roadbed temperature are the key points and also aporias for the designment. In this paper, numerical simulations are used to determine the design parameters of the frozen soil simulation system. At first, a brief introduction of the Full - Scale Accelerate Loading System was given. Then, the temperature control method of frozen soil simulation system was proposed. Finally, by using finite element simulations, the optimal design of frozen soil simulation system was obtained. This proposed design, which was obtained by finite element simulations, provided significant referents to the ultimate design of the environment simulation system.

***Keywords*—**China, finite element simulation, frozen soil simulation system, preliminary design.

I. Introduction

CHINA is now constructing the world's largest high - speed rail network in which a train runs at a speed of over 400 kilometers an hour. At such speed, the stability and performance of roadbed are of critical importance. In the northern part of China, the temperature varies greatly between summer and winter. The roadbed freezes in winter and the ice inside the roadbed melts in summer. This thawing process often leads to damage of roadbed. Full - scale Accelerated Loading Test (ALT) is the most important and direct way to obtain structural behavior of pavements subjected to traffic loading, as it avoids many assumption compared to that in the laboratory.[1] Traditional Accelerated Loading System can test different roadbed materials under varies loading conditions. AASHTO [2], WesTrack, TxMLS in the US, ALF in Australia, LCPC in France and CEDEX in Spain are all well-known Accelerated Loading Systems. However, such systems are unable to precisely simulate different kinds of climate. As one part of "the Eleventh - Five - Year National Grand Technology Infrastructure Program", The Ministry of Communications of the PRC designed a full - scale Accelerated Loading System with full - controlled environment conditions. In the facility, the temperature of air and the temperature field of roadbed can be precisely controlled; the freezing and thawing process of roadbed can be accelerated as well. By using this new style of accelerated loading system, roadbed materials can be tested under simulated environment which is closest to the real environment. And What's more, the tests will not be affected by weather or seasons. While designing the system, experiences for reference are quite few, therefore, numerical simulations are used to determine the design parameters.

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II. Structure of Frozen Soil Simulation System

Full-Scale Accelerated Loading System is a closed circular track on which runs a test car (Fig. 1). The axle load of test car is adjustable, varies from a sedan car to a Boeing 747. The temperature of road surface is adjusted by the temperature and speed of air; the temperature of roadbed is adjusted by the temperature of underground heat exchangers.

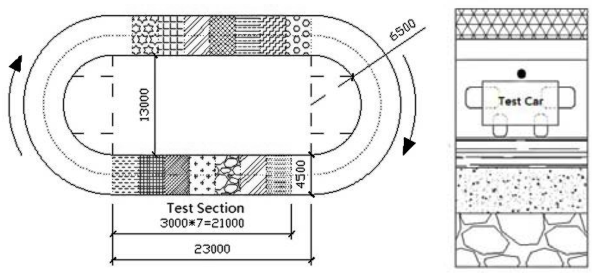

Fig. 1 Structure of Full-Scale Accelerated Loading System

The freezing process of everfrost in natural environment is a double direction freezing process [3]. Therefore, several underground heat exchangers are buried under the roadbed. The section drawing of frozen soil simulation system is shown in Fig. 2. Based on the typical road structure, H1 = 20cm, H2 = 40cm, H3 = 140cm, H4 = 30cm, H5 = 15cm, while the values of D1, L1 and H6 are determined by numerical simulations.

TABLE I
PROPERTIES OF ROADBED MATERIALS

Material	ρ/Kg·m^{-3}	C_f/J·kg^{-1}·K^{-1}	C_u/J·kg^{-1}·K^{-1}	λ_f/W·m^{-1}·K^{-1}	λ_u/W·m^{-1}·K^{-1}	L/J·kg^{-1}
Sand	2000	957	1114	1.98	1.919	10200
Clay	1750	1074	1347	1.351	1.125	34457
Asphalt	2100	1880		1.75		
Dirt	1700	840		1.3		
Perlite	153	760		0.12		
Stainless steel	7850	510		24.5		

TABLE II
PROPERTY OF SECONDARY REFRIGERANT

ρ/Kg·m^{-3}	ωB/%	T_f/℃	T/℃	C/kJ·kg^{-1}·K^{-1}	λ/W·m^{-1}·K^{-1}	μ/10^{-4}N·s·m^{-2}	Pr
			0	2.738	0.528	56.9	29.5
			-10	2.7	0.515	90.4	47.5
			-20	2.68	0.502	144.2	77
1286	30（42.7）	-55	-30	2.659	0.488	225.6	123
			-35	2.638	0.483	284.4	156.5
			-40	2.638	0.476	353	196
			-45	2.617	0.47	431.5	240

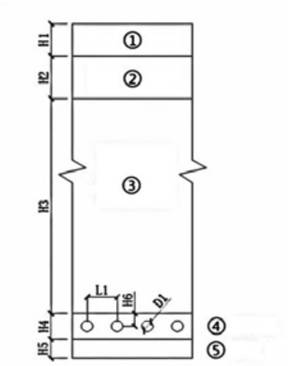

Fig. 2 Section drawing of frozen soil simulation system
① Asphalt Layer ② Ash Layer ③ Roadbed
④ Heat Exchanger ⑤ Insulating Layer

The temperature control methods of Frozen soil simulation system are as follows: 1. Cold air blows over the road surface, by adjusting the speed and the temperature of cold wind, the temperature of road surface is cooled down to -20℃; 2. Heat exchangers, made of Thick wall stainless steel pipe, buried under the roadbed. Secondary refrigerant in the heat exchangers is calcium chloride solution, by adjusting the flow rate and the temperature of secondary refrigerant, the highest temperature inside the roadbed is -5℃. The property of roadbed materials and secondary refrigerant are given in table 1 [4][5] and table 2 [6].

III. Physical And Mathematical Model

To obtain the analytical solution, some assumptions are made:

1. The thermal and physical properties of road bed materials are isotropic.
2. The thermal and physical properties of the soil are kept constant but they differ between frozen and unfrozen.
3. Heat diffusion caused by water diffusion is ignored.
4. The freezing point of soil is -1℃.

The temperature outside the frozen soil simulation system holds constant.

The heat conducting differential equation of roadbed is:

$$\frac{\partial T}{\partial \tau} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{1}$$

When phase change occurs inside the roadbed, energy equation turns into:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \boldsymbol{v} H) = \nabla \cdot (k \nabla T) + S \tag{2}$$

in which

$$H = h + \Delta H \tag{3}$$

The boundary conditions used in numerical simulation are given in table III.

TABLE III
BOUNDARY CONDITIONS

Position	Type of boundary	Value
Top	Wall (convection)	T=233K, h=32.82W·m^{2}·K^{-1}
Left & Right	Symmetry	
Front & Back	Wall	
Bottom	Wall (temperature)	288K
Entrance	Velocity-inlet	V=1m·s^{-1}, T=233K
Exit	Outflow	
Pipe	Wall	coupled

IV. Result And Discussion

According to physical and mathematical model mentioned above, freezing process inside the roadbed is simulated by using Fluent 12.1 and UDF.

A. Distance between flat isothermal surface and tube bundle

In natural environment, the heat conduction process inside the roadbed is a flat heat conduction process. Therefore, isothermal surface at the lower boundary of roadbed of frozen soil simulation system should be a flat isothermal surface as well. The temperature field is the mutual superposition of several temperature fields, each of which is generated by single pipe. While the difference between the highest and the lowest temperature at the lower boundary of roadbed is less than 1℃ , the heat conduction process inside the roadbed is considered as a flat heat conduction process. The relationship between the tube pitch and the position of flat isothermal surface is given in Fig. 3. The roadbed material is sand, the velocity of secondary refrigerant is 0.5m•s-1 with the temperature of -40℃, the diameter of pipe is 22mm. When the roadbed material is replaced by clay, similar result is obtained. When the diameter of the pipe is increased from 22mm to 32mm, similar result is obtained. Consequently, the relationship between the pitch and the position of flat isothermal surface is irrelevant to roadbed material.

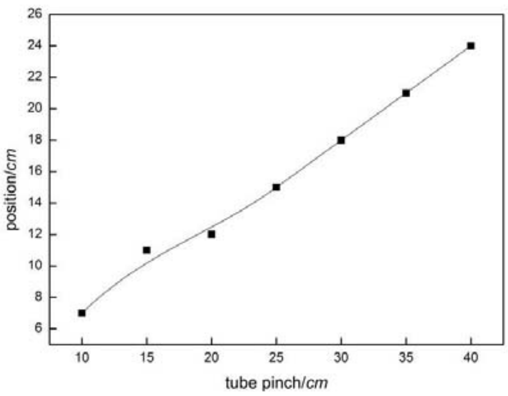

Fig. 3 Effect of tube pitch on flat position

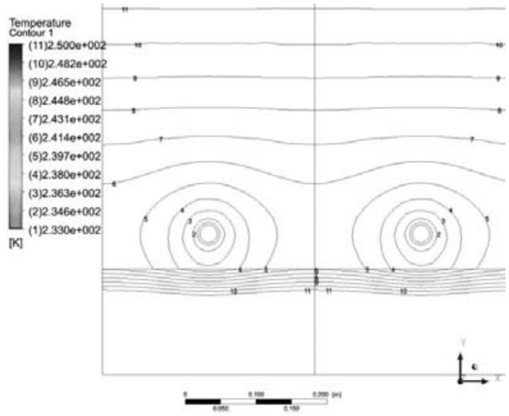

Fig. 4 Contour of temperature field around the tubes

B. Effect of tube pitch on cooling time

The cooling process finishes when the highest temperature inside the roadbed reaches -5℃. For sand and clay, the duration of cooling process under different tube pitches is given in Fig. 5.

The velocity of cold wind is 10m• s-1 with the temperature of -40℃; the velocity of secondary refrigerant is 0.5m• s-1 with the temperature of -40℃, the diameter of pipe is 22mm. For different roadbed materials, the tendencies of duration of cooling process are same when the tube pitch is greater than 25cm. In other words, the duration of cooling process is irrelevant to roadbed material while the tube pitch is greater than 25cm. As a result, the most reasonable tube pitch of underground heat exchanger is 30cm.

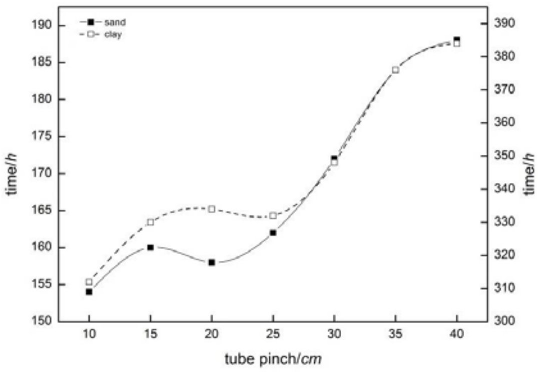

Fig. 5 Cooling time under different tube pitches

C. The highest temperature inside the roadbed

With the same boundary conditions in C and roadbed material of sand, the highest temperature inside roadbed is shown in Fig. 6. The highest temperature point locates at 1.2m under the road surface. During the freezing process, phase change process of roadbed material takes 1/4 time of total cooling time. The freezing front moves at a very low speed. According to Bronfenbrener's research, moisture transfer in soil mainly happens at the freezing front. [7] Therefore, for further investigation, moisture transfer phenomenon could not be ignored.

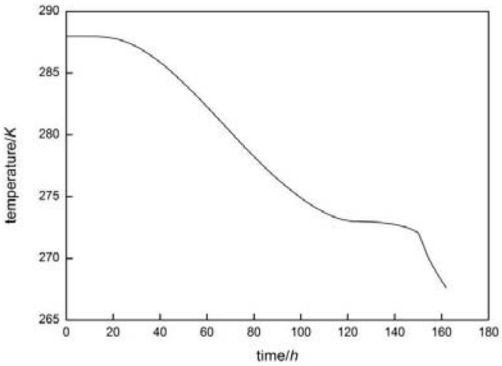

Fig. 6 Highest temperature inside roadbed

D. Temperature difference of secondary refrigerant between inlet and outlet surfaces

With the same boundary conditions and roadbed material in C, temperature difference of secondary refrigerant between inlet and outlet surfaces of heat exchanger is obtained. According to Fig. 7, heat transfer intensity reduces rapidly during the first 20 hours and remains stable after 60 hours, which provides significant evidence for the selection of circulation system.

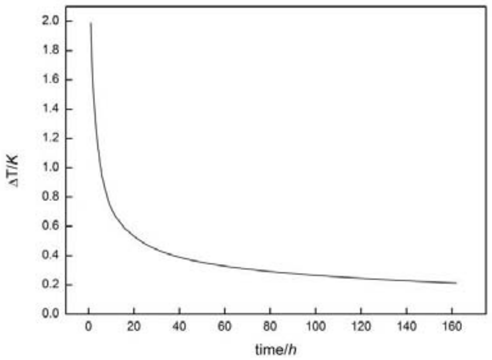

Fig. 7 Temperature difference between inlet and outlet of heat exchanger

V. CONCULSION

1. The position of flat isothermal surface is only affected by the tube pitch of underground heat exchanger, irrelevant to the diameter of tube and the type of roadbed materials. With the thickness of heat exchanger layer (H¬4) of 30cm, the maximum allowable tube pitch (L1) is 40cm.

2. Based on the numerical simulation on two different types of roadbed material, the tendencies of duration of cooling process are overlapping curves when the tube pitch is greater than 25cm. Therefore, the duration of cooling process is irrelevant to roadbed material while the tube pitch is greater than 25cm. As a result, the most reasonable tube pitch of underground heat exchanger is 30cm.

3. During the phase change stage, moisture transfer phenomenon occurs at the freezing front. Therefore, Moisture transfer phenomenon could not be ignored in further investigation.

4. Heat transfer intensity reduces rapidly during the first 20 hours and remains stable after 60 hours, which provides significant evidence for the selection of circulation system.

APPENDIX

C	volumetric specific heat [$kJ \cdot m^{-3} \cdot K^{-1}$]
h	sensible enthalpy in Eq. (3) [$kJ \cdot kg^{-1}$]
H	total enthalpy in Eq. (3) [$kJ \cdot kg^{-1}$]
L	latent heat [$J \cdot kg^{-1}$]
Pr	Prandtl number
T	temperature [℃]

Greek symbols

ΔH	latent heat in Eq. (3) [$kJ \cdot kg^{-1}$]
ρ	density [$Kg \cdot m^{-3}$]
ωB	water content
λ	thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]
μ	kinetic viscosity [$10^{-4} N \cdot s \cdot m^{-2}$]

Subcripts

f	frozen
u	unfrozen

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