파이프라인이 매설된 폐쇄형 동결토의 동결심도 결정

Determination of the Frozen Penetration Depth of a Freezing Soil Medium including a Pipeline in a Closed System

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(논문접수일 : 2004년 8월 10일 ; 심사종료일 : 2004년 12월 8일)

요 지

본 연구는 동결토의 동결심도 및 매설된 파이프라인의 온도분포를 예측하기 위하여 유효열용량 개념을 반영한 수치해석 모델의 개발에 초점이 맞추어져 있다. 이를 위하여 저자는 상용코드인 ABAQUS를 활용하여 파이프라인이 매설된 폐쇄형 시스템의 화강 동결토에 대하여 비정상 열전달 수치해석을 수행하였다. 제안된 수치해석 모델은 Frozen Fringe에서 간극수의 상변화 효과가 반영되었다. 제안된 수치해석 모델과 실내 실험으로부터 얻어진 결과들을 비교함으로써 유효열용량 모델의 적용성을 검증하였다.

핵심용어 : 화강동결토, 폐쇄형 시스템, 유효열용량 모델, 동결심도, 상변화 효과

Abstract

The study was focused on the development of computational scheme in three dimensional configurations by applying effective heat capacity model to the numerical procedure in order to predict the temperature profiles of a buried pipeline and the frozen penetration depth(FPD) of a freezing soil medium. To realize this, the investigator conducted the unsteady state heat transfer analysis, using the commercial code ABAQUS, for the freezing granite soil medium including a pipeline in a closed system. The proposed model took into consideration the phase change effect of in situ pore water in the frozen fringe. The comparison of results obtained by the proposed model and the actual performances was valuable in establishing a level of confidence in the application of introduced theory.

keywords : *freezing granite soil medium, closed system, effective heat capacity model, frozen penetration depth (FPD), phase change effect*

1. INTRODUCTION

Cold regions may be subdivided into three temperature-defined climatic zones such as seasonally frozen zone, discontinuous permafrost and continuous permafrost zones. It is possible that most regions of the South Korea can be defined by the freezing index(FI :℃ · days) classification as the seasonally frozen zone. The investigation of an interaction between a surrounding soil medium and underground structures in seasonally frost as well as permafrost zones necessitates the thermal transfer studies in the closed or the open systems. The numerical study in this paper, examined using the commercial code ABAQUS, presented the analysis schemes that are used to obtained the temperature profiles of ground and pipeline. To realize this, the effort of previous study by Song *et al.*[1] was focused on determining the thermal

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• 이 논문에 대한 토론을 2005년 3월 31일까지 본 학회에 보내주시면 2005년 6월호에 그 결과를 게재하겠습니다.

properties of granite soils that are distributed more than 70(%) in the South Korea.

Characteristics of a freezing multiphase body such as soils are given considerable attention in the literature. Anderson and Morgenstern[2], and Tsytovich[3] have reviewed the characteristics of unfrozen water in frozen soils. Clear evidence of mass transport through an unfrozen zone underneath an ice lens was given by Dirksen and Miller[4], and Hoekstra.[5] This led Miller[6] to propose that an ice lens grows somewhere in the freezing soil, slightly behind the frost front, i.e., the warmest isotherm at which an ice can exist in the soil pores. The frozen soil between the frost front and the freezing front is called the frozen fringe(see Fig. 1). Direct evidence for the existence of the frozen fringe has been published by Loch and Kay.[7] In addition to these considerations, Hoekstra[8], and Mageau and Morgenstern[9] published experimental data indicating that an ice lens acts like a cutoff with regard to water flow.

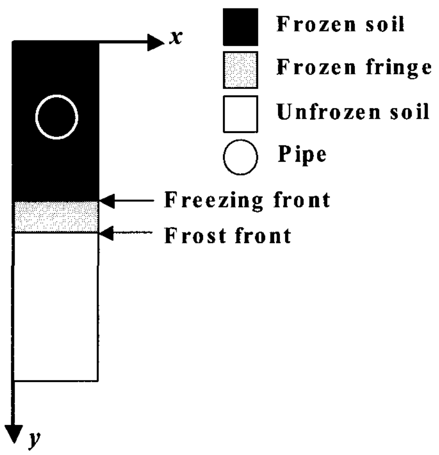

Fig 1 Characteristics of a freezing soil medium

To conduct the thermal transfer analysis, three mathematical models have been proposed. These include: (1) effective heat capacity model; (2) coupled heat and mass transfer model; (3) segregation potential(*SP*) model. Zhang and Osterkamp[10] determined the apparent thermal diffusivity of an active layer and the permafrost by the effective heat capacity model using the finite difference method. It was established on the assumption that providedheat flow is conductive and phase-change does not occur in the volume of interest. The finite difference method has been also used by Nelson *et al.*[11], and Outcult and Hinkel.[12),13] The phase-change effect of in-situ pore water was proposed by Allen and Maxwell.[14]

The transfer of heat and water during the freezing of a soil medium is interrelated, and a comprehensive analysis is necessary to deal with the coupled heat and water movement. The coupled heat and mass transfer model has been developed by Nakano and Brown[15], Harlan[16], Guyman and Luthin[17], Kinosita[18] and Outcalt.[19] Outcalt incorporated heaving in this model by expanding the soil matrix when ice contents exceeded a critical value.

Konrad and Morgenstern[20] have developed the *SP* model. It calls for the needs to define the coupled equations of the heat transfer, the mass transfer and the frost heave.

The water flow effect by the suction on the heat movement within a granite soil medium is not strong in the closed system. This is the reason why the effective heat capacity model was considered in order to simplify the soil-pipeline interaction problem that incorporates the thermal transfer analysis. The thermal transfer FE analysis of this work within a freezing soil medium, including a buried pipeline, was achieved by appealing the thermo-mechanical findings in previous studies mentioned above to the effective heat capacity concept. The physical phenomenon of the proposed model is to assume that the thermal transfer can be considered as successive "thermal transfer" and "phase transformation" processes.

The pipeline designer requires two values for the soil thermal conductivity and the ground or ambient temperature surrounding a buried pipeline. The results obtained by the thermal transfer analyses will be of use for the determination of stress field on the pipe walls. This study will contribute to better understanding of the soil-pipeline interaction problem considering domestic frozen soil properties.

2. BASIC ASSUMPTIONS

Before discussing the FE procedure in the numerical analyses for the thermal transfer, it is necessary to outline assumptions in order to apply the thermal characteristics of a freezing soil medium to the proposed model. The thermal transfer in porous multiphase material can be induced by a variety of factors including the heat convection, the heat radiation, the heat conduction, the water movement by the suction and the phase-change of in-situ pore water, *etc.* Among them, only the effect of heat conduction and the phase-change effect in the frozen fringe wasere taken into account in the numerical studies. The single ice lens with constant thickness, advancing in the depth-direction of a freezing soil medium, was considered. A great part of the phase-change effect of in-situ pore water took place in the ice lens to which the temperature domain of -0.1~0(℃) was applied. It could be also assumed that the ground in the dry season like the winter of the South Korea is of characteristic to the closed system because of the low ground water level. Finally, the materials of soil and metallic pipe are isotropic and homogeneous.

3. FINTE ELEMENT METHODS

The present work developed the three-dimensional continuum approach that possesses complex temperature nonlinear phenomena. If we consider a system in the domain of the element to be in the equilibrium, then the equilibrium equation for the unsteady state thermal transfer may be expressed as

$$\int_{V(e)}[k\{(\frac{\partial\delta T}{\partial x})(\frac{\partial T}{\partial x})+(\frac{\partial\delta T}{\partial y})(\frac{\partial T}{\partial y})+(\frac{\partial\delta T}{\partial z})(\frac{\partial T}{\partial z})\}$$

$$+\delta T^T C\frac{\partial T}{\partial t}]dV(e)=\int_{V(e)}\delta T^T q dV(e) \qquad (1)$$

where:

$$T = N_{th}T_e \qquad (2)$$

N_{th} is the shape function; T_e(℃) is the nodal temperature; $k(W/m℃)$ is the thermal conductivity; $C(J/m^3℃)$ is the heat capacity; q is the heat generation per unit volume; x, y and z are the Cartesian coordinates.

Substituting Eq. (2) into Eq. (1), we arrived at the following set of equation to be solved for T_e

$$C_{th}\frac{\partial T_e}{\partial t}+K_{th}T_e = R_q \qquad (3)$$

in which

$$C_{th}=\sum\int_{V(e)}N_{th}^T C N_{th}dV(e) \qquad (4)$$

$$K_{th}=\sum\int_{V(e)}B_{th}^T\chi B_{th}dV(e) \qquad (5)$$

B_{th} is the spatial derivative of the field variables and x is the matrix of thermal conductivity;

$$R_q=\sum\int_{V(e)}N_{th}^T q dV(e) \qquad (6)$$

A soil medium was divided into three parts (see Fig. 1) as the unfrozen zone(7a), the frozen zone(7b) and the frozen fringe(7c) for reflecting the characteristics of the freezing soil on the proposed mathematical model. The heat capacities of soil in Eq.(1), corresponding to the three zones mentioned above, are presented in consideration of the phase change effect in the frozen fringe as follows:

$$C_{s,un}=\frac{\gamma_{s,d}}{\gamma_w}(0.16+1.0\frac{w}{100})C_w \qquad (7a)$$

$$C_{s,f}=\frac{\gamma_{s,d}}{\gamma_w}(0.16+0.5\frac{w}{100})C_w \qquad (7b)$$

$$C_{s,ff} = C_{s,f} + L_u \frac{\rho_{ice}}{\rho_w} \frac{\partial W_u}{\partial T} \tag{7c}$$

where: $C_{s,un}(J/m^{3o}C)$, $C_{s,f}(J/m^{3o}C)$, $C_{s,ff}(J/m^{3o}C)$ and $C_w(J/m^{3o}C)$ are the heat capacities of unfrozen zone, frozen zone, frozen fringe of soil and water, respectively; $r_{s,d}(kg/m^3)$ and $r_w(kg/m^3)$ are the maximum dry unit weight of soil and the unit weight of water, respectively; $w(\%)$ is the in situ pore water content; $L_u(J/m^3)$ is the volumetric latent heat of water; $\rho_{ice}(kg/m^3)$ and $\rho_w(kg/m^3)$ are the densities of an ice and water, respectively; W_u is the unfrozen water content and $T(°C)$ is temperature.

4. LABORATORY TESTS OF SOILS

4.1 Determination of Thermal Properties

A reasonable prediction for the temperature change in the ground can be made for a given location if climatic data are available, and the thermal properties of a soil medium are known. Unfortunately, the lack of experimental data of frozen granite soils of the South Korea has limited the numerical studies. The soil samples were obtained in the late May 2000 in Pasoo City. The basic thermomechanical properties for the granite soil were determined in the previous studies by Song *et al.*(2004). The studies included the change of the unfrozen water content and the thermal conductivities observed in the cylindrical soil specimen test at various subzero temperatures. The basic soil propertiesl obtained by the laboratory tests are given in Table 1. Fig. 2 shows the particle size analyses.

Table 1 Characteristics of the granite soil

PI	$C_{s,u}$	$C_{s,c}$	G_s	$r_{s,d}$	$w_{s,o}$	$USCS$
N.P	34.55	3.44	2.67	1920	13.2	SM

where: PI is the plasticity index of soil; $C_{s,u}$ is the uniformity coefficient of soil; $C_{s,c}$ is the coefficient of gradation of soil; G_s is the specific gravity of soil; $w_{s,o}(\%)$ is the optimum water content of soil.

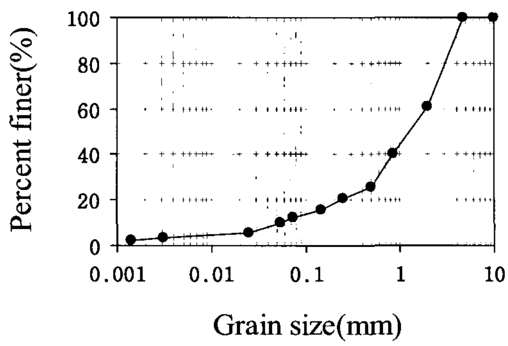

Fig. 2 Particle size distribution curve

4.2 Temperature Measurements

The temperature measurements of freezing granite soil were achieved under the controlled condition of the freezing chamber in the laboratory(Song *et al.*, 2004). The curves with the initial in-situ pore water contents at the percentage level of 10, 15 and 20, respectively, compare the temperatures measured in the laboratory test with the numerical ones for the freezing soil medium in the closed system. The results of the previous study showed that the thermal properties of a freezing soil medium are valid and the findings are effectively supported by the experimental data. In present study, the thermal properties of the granite soil were used to obtain the temperature profiles of a soil medium including a buried pipeline on the field.

5. UNDERGROUND TEMPERATURE DISTRIBUTION

A thermal transfer FE analysis for the freezing ground, subjected to the ground surface temperature, was conducted in order to determined the temperature profiles along a buried pipeline and the frozen penetration depth(FPD:m).

5.1 FE Mesh for Modeling

The symmetry of geometry for the structure and boundary condition permitted the quarter model(see Fig. 3) with 13,158 node numbers for a surrounding soil medium and a buried pipeline in the analyses. We used 8-node 11,126 solid elements for the soil medium, the metallic pipeline and the concrete box. The far field of a soil medium consisted of the infinite elements. The ground temperature profile should be reflected by heat flow from the interior of the Earth. In this work, we applied the isothermal surface of 10(℃) that is the annual average atmospheric temperature below the center regions of the Korean Peninsula to the thermal boundary of a soil medium at 10 (m) from the ground surface according to the knowledge of geology.

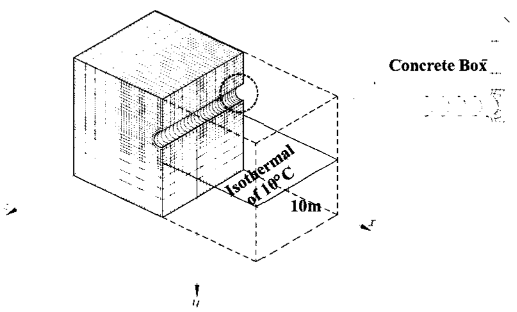

Fig 3 FE mesh

5.2 Underground Temperature Profiles

Pipelines can be broadly classified into two categories, namely, high energy and low energy input cases. For high energy input pipelines, the thermal regimes in a soil medium around the pipeline are strongly dominated by the temperatures imposed by the pipeline itself. Gas pipelines will result in the flowing gas equilibrating at some temperature lower than one of a surrounding soil medium. Low energy input pipelines, on the other hand, adapt relatively quickly to the surrounding soil temperatures. The latter are known as "ambient temperature" pipeline. The buried pipelines in this study, being constructed as geotechnical facilities that are used to transport and water, belong to the latter cases. All underground high energy input as well as low energy input pipelines will eventually approach equilibrium with a surrounding soil medium at some temperature.

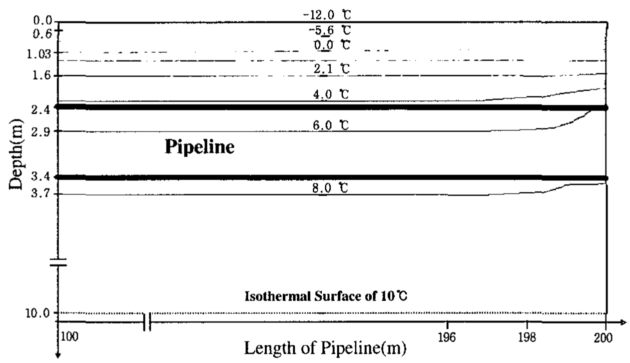

Fig. 4 Temperature line diagram for the underground temperature field

Fig. 4 illustrates the temperature profile of thermal equilibrium state for the freezing soil medium including a pipeline and a concrete box. As shown in this figure, the *FPD* of a granite soil medium was determined at about 1.03(*m*). The temperature profile on inner surface for a half of the buried pipeline length is also shown in Fig. 5. The maximum temperature difference between the top and the bottom of the pipeline was about 3.6(℃).

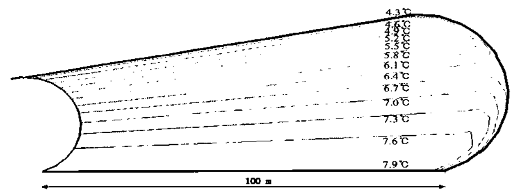

Fig. 5 Temperature profile on the pipe wall

The temperatures profiles in Figs. 4~5 were obtained under the pipe diameter of 2.0(*m*), the pipe thickness of 0.015(*m*), the pipeline length of 200(*m*), the backfill height of 2.4 (*m*), the initial in situ pore water content of 10(%) and the ground surface temperature of -12(℃) maintained for 24hours.

Hong and Kim[21] proposed the equation to predict the maximum *FPD* on the field. The functional relation, considering the maximum dry unit weight and the in situ pore water content of soil, between the maximum *FPD* of ground and the *FI* was recommended as follows:

$$FPD_{max} = 0.5\log_{10}\left(\frac{FI}{10\gamma_{s,d}\times10^{-3}\cdot w}\right) \quad (8)$$

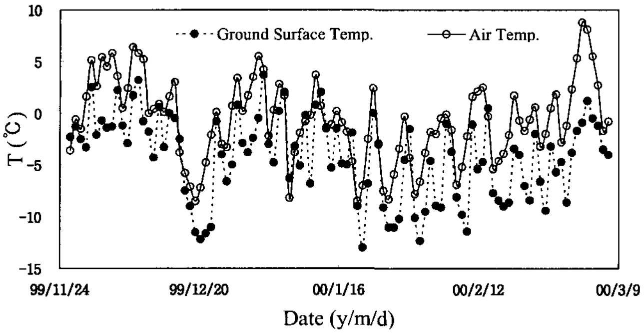

Fig. 6 Temperatures of Seoul City

Fig. 6 presents the changes of average ambient air temperatures a day and ground surface temperatures, observed from Korea Meteorological Administration, at AM 3:00 hours for the 1999~2000 season. Fig. 7 shows the variation of *FPD* obtained by the propose model in Seoul City for this period.

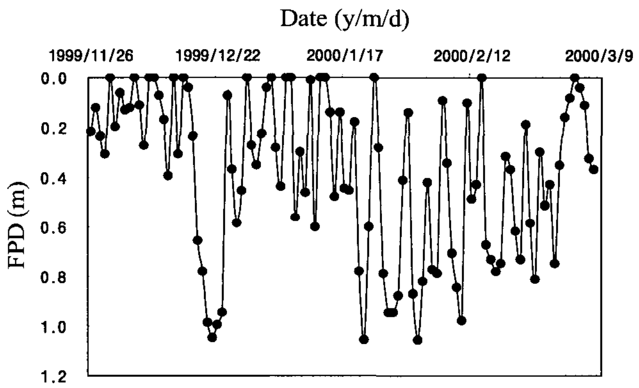

Fig. 7 Variation of the FPD in Seoul City

By varying the input in-situ pore water content, the maximum values of *FPD* shown in table 2 could be calculated for the 1999~2000 season. In these cases, we used the *FI* which was calculated by the average ambient air temperature curve for the Hong & Kim's formula. formula. The maximum relative error between the depths by proposed model and estimated by Hong & Kim's formula. formula. was within 12.3(%) for Seoul City.

6. CONCLUSIONS

This investigation was restricted within narrow selection of soil samples. But, in view of the primary objectives, this study was sufficient to illustrate the methodologies for predicting the temperature profiles of ground and the FPD. The results may give consequence to this work as the preceding investigation for an interaction problem between a soil medium that experienced frost heave and a buried pipeline. The comparison between the experimental and the numerical results indicated that the FE calculation with the idealized assumptions was able to provide an acceptable estimation of the thermal properties, from an engineering stand point, on the freezing granite soil. The prediction for the development of underground temperature fields was made within the range of the practicability by this investigation.

(1) The effective heat capacity model for a

Table 2 Comparison between the maximum values of $FPD_{proposed}$ and the $FPD_{Hong\ \&\ kim's}$

No	City	Measuring locations		FI (℃·days)	Max. FPD (*m*)								
		East longitude	North latitude		*w* = 10 (%)			*w* = 15 (%)			*w* = 20 (%)		
					Hong & Kim's formula	Proposed model	Relative Error (%)	Hong & Kim's formula	Proposed model	Relative Error (%)	Hong & Kim's formula	Proposed model	Relative Error (%)
1	Chuncheon	37°54'	127° 44'	274.4	1.080	0.979	10.3	0.992	0.903	9.8	0.929	0.840	10.6
2	Seoul	37° 34'	126° 58'	148.3	0.944	1.060	10.9	0.856	0.976	12.3	0.793	0.905	12.3
3	Sokcho	38° 15'	128° 34'	126.8	0.910	0.834	9.1	0.822	0.771	6.6	0.759	0.721	5.3
4	Chungju	36° 38'	127° 27'	125.0	0.907	0.858	5.7	0.819	0.794	3.1	0.756	0.741	2.1
5	Inchon	37° 28'	126° 38'	113.3	0.885	0.858	3.2	0.797	0.794	0.4	0.735	0.741	0.8
6	Taegu	35° 53'	128° 37'	72.5	0.789	0.744	6.0	0.700	0.689	1.7	0.638	0.646	1.2
7	Gangneung	35° 10'	126° 54'	67.5	0.773	0.755	2.4	0.685	0.697	1.7	0.622	0.653	4.7

※ $Relative\ error = \frac{FPD_{proposed} - FPD_{Hong\ \&\ Kim's}}{FPD_{proposed}} \times 100$

freezing granite soil medium in the closed system was introduced into the study in consideration of the phase-change effect in the frozen fringe. The findings showed that a great part of the phase-change of in situ pore water within the freezing granite soil medium medium was made over the temperature range, -0.1~0 (°C), of frozen fringe.

(2) The maximum values of *FPD* in ground, obtained by the proposed model and the Hong's formula, were compared. The comparative results between them illustrated the potential applications of proposed model on the field.

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