Development of excess pore-water pressure in thawing process of frozen subgrade soils: Based on analytical solutions and finite element method.

Dégel des sols et variation de la pression d'eau interstitielle: application de méthodes analytiques et des éléments finis.

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ABSTRACT: The spring thaw of a frozen soil is controlled by boundary conditions and soil thermal properties. Frozen soils have substantially reduced permeability and the melting water in the thaw front cannot drain through the still-frozen soil. Consequently, temporary excess pore-pressure is generated in the process which degrades the shear strength of the soil. This will ultimately reduce the bearing capacity in roads. In this paper, analytical solutions and a finite element method are used to estimate the thawing rate of frozen soils, in which a very good agreement is obtained for one-dimensional thawing. Axisymmertic geometry was used in Abaqus FEA to model the pavement layers with a sinusoidal surface temperature. From the numerical simulation, it was obtained that a constant rate of thawing can be assumed for frozen subgrade layers for one directional top-bottom thawing. The excess pore-water pressure largely depends on the initial ground temperature as well as on the magnitude of surface temperature.

RÉSUMÉ : Le mécanisme de dégel des sols est déterminé par les conditions limites et les propriétés thermiques des matériaux. Les sols gelés ont une perméabilité sensiblement réduite. De plus, lors du dégel, l'eau ne se draine pas toujours au même rythme que la fonte. Une fonte rapide entraine un excès de pression interstitielle, ce qui diminue la résistance au cisaillement et entraîne une diminution considérable de la portance des sols et des chaussées. Ce papier présente les résultats de l'estimation du taux de dégel des sols par des méthodes de résolution analytique et des éléments finis. Une très bonne corrélation est obtenue dans le cas de la simulation du dégel en une dimension. Les couches de chaussées ont été modélisées dans Abaqus FEA par géométrie asymétrique, en appliquant une courbe de température de surface sinusoïdale. Une simulation numérique a permis d'établir l'hypothèse d'un dégel unidirectionnel depuis la surface, à taux constant. L'excès de pression interstitielle dépend grandement de la température initiale du sol et de la température de surface.

KEYWORDS: FEM, pore-water pressure, temperature, thawing, thawing rate

1 INTRODUCTION

Climate condition is one of the factors that affect design and performance of pavements. Epecially in cold regions, seasonal freezing and thawing process may occur in subgrade soils. The extent of damage on the pavement surface due to freezing and subsequent thawing of subgrade soils depends on many factors such as the thermal gradient, availability of water in the sub-soil layers, frost susceptibility of the soil, consolidation coefficient, permeability and drainage conditions. If the rate of generation of water exceeds the discharge capacity of the soil, excess pore pressure will develop, which can lead to failure of foundations and slopes (Morgenstern and Nixon 1971). A pavement structure will be most susceptible to breakup during the period when excess water cannot drain downward through still-frozen soil. A major practical aspect of predicting the thawing mechanism can be for effective road management (especially for countries that imposed load restriction during spring thawing) and maintenance programs. When the bound layer of a road is thinner, the anticipated traffic load in the subgrade is high. Consequently, the excess pore water pressure(in the short term) during thawing increases, partly due to the phase change from the ice state, and partly due to the additional load from the traffic. The cumulative effect can be severe and this has been true in many cases especially for low-traffic volume roads since maintenance budgets are relatively low and appropriate drainage is missing. Full scale tests conducted at the Vormsund test road (Nordal and Hansen 1987) showed that the excess pore-water pressure developed during the spring thaw was the primary reason for the reduced bearing capacity. Pore water pressures of up to 0.90m above the drainage level was registered during thawing.

The problem of spring thawing has no exact solution. Analytical solutions for heat conduction are well known and are obtained from the Newmann's solution (Carslaw and Jaeger 1959). Nixon(1973) formulated an approximated analytical solution from the theory of consolidation and principle of heat conduction for the development of excess pore water pressure following the thawing process. This analytical solution is valid for thawing of soils over thick ice layers. The impact of seasonal frost penetration on pavement has been widely studied, with considerably less focus on thaw weakening from thawing (Simonsen and Isacsson 1999).This paper discusses on the rate of thawing (thaw advancement) in the frozen soil layers in pavements and the subsequent excess pore water pressure. The study is based on the existing analytical solutions and finite element method (FEM). The general FEM program, Abaqus has been used to model the thawing process. The thawing process is widely understood qualitatively. For example, the type of subgrade soils that are frost susceptible are well known (Johnson et al. 1986; NPRA 2011) and some empirical correlations exist relating the depth of frost penetration to the Freezing Index (Andersland and Ladanyi 2004). The study presented here focuses on the quantitative explanation of the thawing process based on the thermal properties of pavement materials and thermal boundary conditions. With a better understanding of the thawing process, optimization process can be carried out during the design phase, operation and maintenance of roads.

1.1 *Thermal properties of soils*

The principle of heat transfer in frozen soils is governed by conduction. The effect of radiation is negligible. The heat transfer process by convection is also minimal for fine-grained soils with very low permeability. During freezing, some of the water film is removed and ice crystals partially fill the voids between soil particles. This reduces the conductivity path for soil with low moisture content. In the contrary, experimental tests at high moisture content and densities showed increased conductivities in the frozen state, since ice fills the pores completely (Becker et al. 1992, Penner et al. 1975). The thermal conductivity of ice is more than four times greater than that of water (Penner 1970). In the thawing process of frozen soils, the amount of water in the frozen state plays a significant role in the development of pore water pressure. Some assumptions are made in the analyses in this paper such as the frozen soil is fully saturated, the heat transfer mechanism is only by conduction, and the thermal conductivity of the soil is isotropic.

2 ANALYTICAL AND NUMERICAL SOLUTIONS FOR THE THAWING PROCESS

Nixon and McRoberts (1973) studied on the thawing rate of homogeneous frozen soil subjected to a step increase in temperature from (Tg) in the ground to (Ts) at the surface. The analytical formulla relating the depth of thawing to the square root of time, based on Newmann's solution (Carslaw and Jaeger 1959) is shown in Eq. 1.

$$X = \mathrm{a}\sqrt{t} \qquad (1)$$

Where X is the depth of thaw, t is the time and $\propto$ is a constant determined from Newman's rigorous equation. When the ground temperature is close to zero, the equation from Newmann is simplified as (Nixon and McRoberts 1973);

$$\frac{e^{-\frac{\alpha^2}{4\kappa_u}}}{\operatorname{erf}\frac{\alpha}{2\sqrt{\kappa_u}}} = \frac{L\sqrt{\pi}\alpha}{2\sqrt{\kappa_u}c_u T_s} \qquad (2)$$

Where

α is the constant in Eq. 1.
κ_u is the diffusivity of the unfrozen soil (m^2/s).
K_u is the thermal conductivity of unfrozen $(J/°C.m.s)$.
c_u is the volumetric heat capacity of unfrozen $(J/°C.m^3)$.
L is the volumetric latent heat of the soil(J/m^3).
T_s is the applied constant surface temperature (°C).
erf is the error function.

2.1 *Finite element analysis*

In the thawing process, temperature has a direct effect on the water flow field in saturated and unsaturated soils which undergo drainage and consolidation upon thawing. As a result of this, the heat flow and fluid flow equations are coupled mathematically through the phase change component and an optimization procedure is incorporated into the computational scheme (Harlen 1973). In a saturated soil, the latent heat absorbed/released on the thaw-freeze front has a major impact on the rate of thawing. In the numerical scheme, the latent heat can be defined in two ways (Xu et al., 2009). It can be included in the heat conduction equations or it can be defined by using temperature dependent specific heat as shown in Figure (1). To ensure the accuracy of this method, the time increments or the maximum temperature change in each increment should be limited to assure the energy balance and a uniform temperature field is defined as initial condition. In this analysis, the latent heat is assumed to be released between -0.1°C and 0°C. Thermal properties of the soil, listed in Table (1) are used both for the analytical analysis and numerical simulation. For the numerical input, temperature dependent thermal properties are used for the frozen and thawed states. A frozen soil is almost impermeable and a very low permeability, $k = 1 \text{ x } 10^{-14}$ m/s, is used for the ground temperature less than zero degree Celsius.

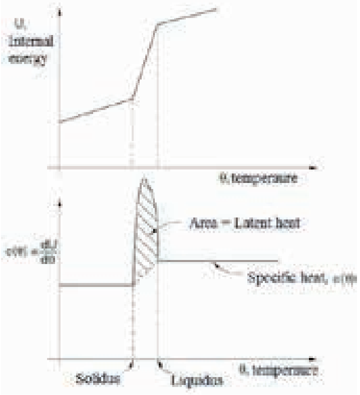

Figure 1. Specific heat, latent heat definition (Abaqus FEA, 2011)

Table 1: Input parameters

Parameters	Unit	Value
Thaw conductivity	J/m.s.^{0}C	1.05
Consolidation coefficient(c_v)	m^2/s	1.1 x 10^{-6}
Permeability(k)	m/s	2.5 x 10^{-7}
Unit weight(γ)	kg/m^3	1820
Latent heat of soil(volumetric)	J/m^3	1.73 x 10^8
Latent heat of water	J/kg	3.34 x 10^5
Surface temperature	^{0}C	12
Ground temperature	^{0}C	0

The conductivity of the frozen soil is assumed to be twice that of the thawed soil. Similarly, the stiffness of the frozen soil is assumed to be 100 times that of the stiffness in the thawed state. The amount of frozen water is directly related to the moisture content. For fully saturated soils, a reasonable assumption of void ratio can be made from the following relationship.

$$e = \frac{W * G_s}{S} \qquad (3)$$

Where e is the void ratio, ω is the water content, G_s is the specific gravity of the soil, and S is the degree of saturation ($S = 1$ for fully saturated condition). In reality, the void ratio of soils varies greatly upon freezing and thawing. The permeability of the soil can be defined as a function of void ratio in the numerical simulation.

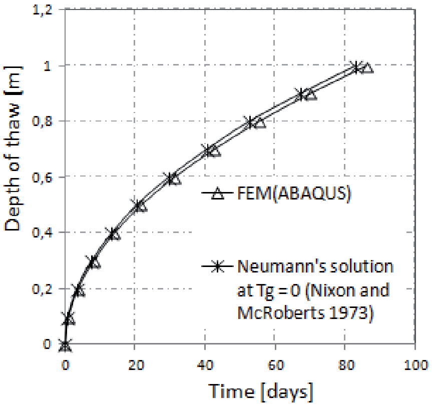

Figure 2. Comparison of analytical solution and numerical simulation

The stiffness of the thawed soil in the numerical analysis is determined from Poisson's ratio and the modulus which is related to the coefficient of consolidation (Janbu 1970, Berntsen 1993). Some variables for "predefined fields" in Abaqus are defined. The initial pore water pressure is set to zero. The initial temperature of the frozen soil(ground temperature) in assumed to be zero to compare the results with the simplified Neumann's solution in Eq. 2.The soil is also considered to be fully saturated prior to thawing. Detailed procedures for defining "predefined fields", "initial conditions", and thermal boundary conditions are available in the Abaqus FEA.The analytical solution from (Eq. 2) has been compared with the result obtained from a numerical analysis using axisymmetric geometry and coupled temperature-pore pressure elements in Abaqus. The thawing depth from the numerical simulation is obtained by plotting the time at which the temperature is changed from negative to positive(℃) at selected nodes in the frozen soil layer. A very good agreement is obtained from the analytical solution and numerical simulation (see Figure 2).

2.2 *Excess pore-water pressure*

One of the consequences of spring thawing is that the frozen water is melted upon thawing. Consequently, excess pore water is generated depending on the overburden stress from the pavement layers and external loading from the traffic. In the case where a thick ice layer exists, an excess pore water pressure can develop even from self-weight loading of the soil lying on the ice layer. This phenomenon was modeled analytically by Nixon(1973). The analysis is based on the principle of heat conduction and Terzaghi's one-dimensional consolidation theory. From the coupled numerical analysis (using Abaqus), it is possible to obtained excess-pore water pressure. The amount of excess pore water pressure is very sensitive the volumetric thermal expansion of pore water in the voids of the frozen soil and the stiffness of the frozen soil. So, a direct consideration of the output from the numerical analysis may be misleading. Since we can accurately predict the advancement of thawing by using the numerical analysis, we can relate the development of excess pore water to the thawing rate. A hydrostatic pore water pressure can be assumed for a thawed soil if no additional loading exists. For example, for a frozen subgrade soil under a pavement, the excess pore water pressure will be the total overburden pressure (asphalt, base and sub-base layers) including the loading from the traffic. This assumption is valid for undrained conditions. In many cases, subbase materials (aggregates) facilitate the dissipation of excess pore water pressure. Then, post-thaw consolidation follows. Detail analysis of one-dimensional thaw consolidation is presented in Morgenstern and Nixon(1971).

2.3 *Modelling of thawing subgrades in pavements*

Most of the analytical solutions available in the literature for the thawing process are based on a one step temperature increment on the surface. In reality, the change of surface temperature is neither a step change nor constant. It is closer to a sinusoidal curve. An advantage is gained by using numerical analysis for different boundary conditions and pavement layers. An axisymmetric geometry is modeled in Abaqus as shown in Figure 3. This modeling(geometrically) is a reasonable approximation for isotropic behavior of pavement materials and an efficient computation time is obtained for the numerical thermal analysis. The assumed thermal properties of the asphalt materials and base course are listed in Table 2. The frozen subgrade is modeled in the same way described in section 2.1. A sinusoidal surface temperature is considered based on a local weather data in Norway (Figure 4). The sinusoidal equation for the temperature data is established. A Fourier transformation is used to obtain the Fourier coefficients which are used as input in Abaqus to provide a smooth increment of temperature for each time increment.

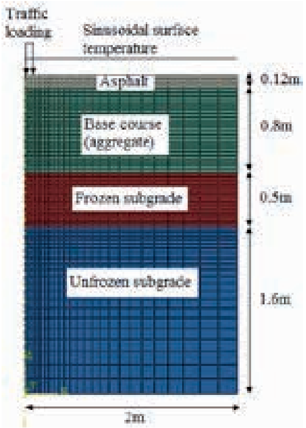

Figure 3: Numerical model

Table 2: Thermal properties of the asphalt and base layers

Parameters	Unit	Value	
		Asphalt	Base-course
Conductivity	J/m.s.^{0}C	0.75	0.5
Specific heat	J/kg.^{0}C	920	850
Coefficient of expansion	/^{0}C	2.2×10^{-5}	3×10^{-6}

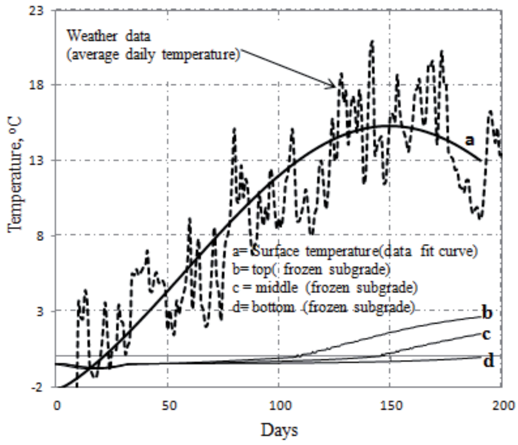

Figure 4 Temperature variation during spring thawing

Assuming a uniform initial ground temperature Tg=-2^{0}C the temperature distribution in the frozen subgrade due to the change of surface temperature on the pavement surface is shown in Figure 4. It is noted that it takes about 90 days for the frozen layer to start thawing from the time since the surface temperature has been greater than 0°C. Full scale field tests (Nordal and Hansen 1987) showed a time period of 70 days for the temperature measurement at 1.93m below the pavement surface for the subgrade soil temperature to be changed from negative to positive temperature(in degree celcius). Nordal and Hansen measured the temperature variations at at depth of 0.05m, 0.15m, 0.63m, 0.93m and 1.93m. The measurements showed that the surface temperature is higher than the data used in our numerical analysis. In accounting this fact, the approximation obtained from the numerical analysis can be accounted for practical case studies.

The analytical solutions for temperature distributions (for example Stephan's formula) relate the thawing depth to be proportional to the square root of time of thawing. Based on the results from the FEM analysis, when sinusoidal surface temperature and thermal properties of pavement layers such as asphalt and base layers are considered, the thawing depth can be directly proportional to the rate time (see Figure 5).

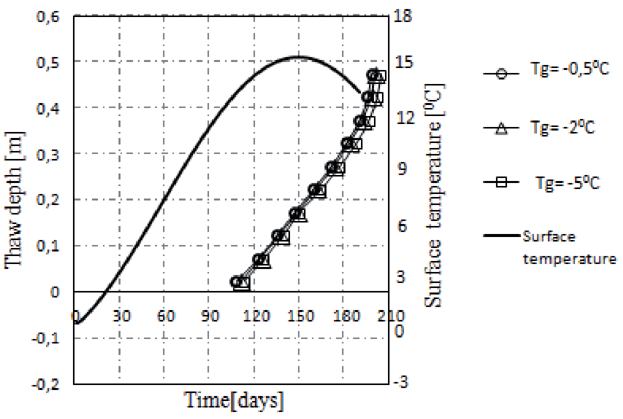

Figure 5: Thawing rate in frozen subgrade under a pavement.

An average of 110 days is required for the frozen layer to start thawing for the given thermal properties and boundary conditions assumed in this analysis. No significant difference is observed for the variation of the initial ground temperature on the thaw rate. Constant rate of thawing in subgrades(in terms of mm/day) has been observed in different field tests reported in Doré (2004).

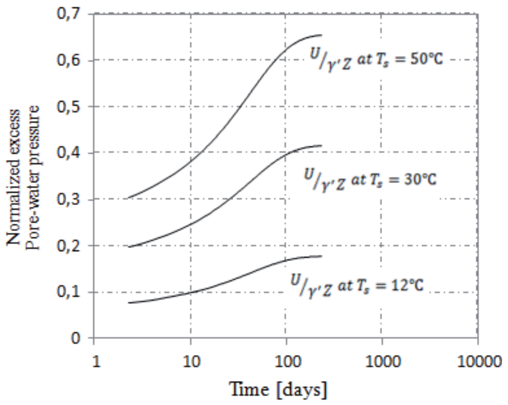

Figure 6: Excess pore pressure at soil-ice interface for a constant surface temperature. The curves are based on the analytical solution of Nixon(1973).

It can be observed (in Figure 6) from analytical solution of Nixon(1973) that the time required for the development of maximum excess pore water pressure at the soil-ice interface (thawing period) is the same regardless of the temperature gradient . In the contrary, the maximum excess pore water pressure generated when the surface temperature is 30°C, is twice the maximum excess pore pressure generated at a constant surface temperature of 10°C. This comparison is only for self-weight loading of the soil and the expected excess pore water pressure can be very high depending on the overburden pressure from the pavements and traffic loading.

3 CONCLUSION

In the previous analytical methods of thaw depth calculations, the Stephan's method is commonly used and the thaw depth is assumed to be proportional to the square root of the thawing time. This assumption is valid for constant surface temperature. The numerical simulation based on a sinusoidal surface temperature has shown that for the case of frozen layers in pavements, a constant rate of thawing is obtained. A higher thawing rate in less permeable frozen soils results in high excess pore water pressure. The late spring thawing can be predicted from the change in pavement temperature from available climatic data, and thermal and physical properties of the pavement materials. This has a significant importance in road design and maintenance planning in cold climate regions. The development of excess pore water pressure highly depends on the temperature distribution in the pavement layers and traffic load and initial states. The excess pore water pressure development is also largely dependent on the physical properties of the thawed soil such as the coefficient of consolidation and permeability.

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