Review and evaluation of Porosity Rate Model (PRM) for highly frost susceptible soils

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ABSTRACT: Frost heave is a frost action when the soil temperature is below freezing temperature. Construction in cold regions is difficult and might cause serious damage to structures. Therefore, it is important to estimate frost heave before construction. The purpose of this study is to introduce and modify a model that can predict frost heave behavior through the change in soil porosity. The Porosity Rate Model (PRM) is possibly applicable for engineering purposes in describing the frost heave process, but the previous studies only focus on clayey soils which may not be frost susceptible soils. This paper presents an assessment of PRM on frost susceptible soils prepared by sand-silt mixtures. Comparisons were made by comparing the predictions obtained with the same initial conditions on the PRM using frost heave data for frost-susceptible soils. Results show good agreement between them, PRM was found to be equally applicable to frost-susceptible soils.

Keywords: Frost Heave, Porosity Rate Model, Frost Susceptible, Silt.

1 BACKGROUND AND MOTIVATION

Permafrost, as well as seasonally frozen ground, refers to near-surface soil that remains at or below 0 ˚C (32 ˚F) for at least 15 days per year. It is found in high latitudes and high elevations, typically in areas with an annual average temperature of -2˚C (28.4 ˚F) or lower. Permafrost can be composed of any type of soil, including sand, clay, and organic matter. It is estimated that about 24% of the land in the Northern Hemisphere is covered by frozen ground. Within, especially the seasonally frozen soil (annual winter freezing of soil), frost action such as frost heave is observed in frost-susceptible soils. Frost-susceptible soils are distinguished by their vulnerability to freezing, which results in the upward movement of the ground surface induced by frost heave. Frost heave is a phenomenon that occurs when the freezing of soil causes ice lensing, pushing the ground surface upwards. Ice lens formation starts when the temperature of the soil drops below the freezing point of pore water with sufficient water supply. The frozen fringe refers to the partially frozen zone that exists between the growing ice lens and the warmest soil containing pore ice. This zone is characterized by a gradual transition between fully frozen and unfrozen soil (Miller, 1972). According to Rempel (2007), the process of ice lens formation commences with the immediate nucleation of ice behind the frozen fringe. Subsequently, water from both the surrounding voids and the unfrozen region of the soil is drawn toward the site of nucleation and contributes to the subsequent growth of the ice lenses. The volume expansion of soils resulting from frost heave can exert unexpected pressure on foundations and other structural elements, leading to cracks and other types of damage. These issues can necessitate costly repairs and, in extreme cases, even result in structural collapse. Additionally, frost heave can impact the stability and integrity of infrastructure, including roads and underground pipelines, potentially disrupting transportation and the delivery of essential services. While there were notable publications in the late 1920s (Taber, 1929) that contributed to understanding the phenomenon of frost heave in soils, modeling efforts did not begin until later. A reliable numerical simulation model is crucial in predicting the specific amount of frost heave and providing a reference for the design of building structures. It can also help maximize the avoidance of potential dangers caused by frost heave in the design stage. This study aims to generalize a porosity rate model that can predict the frost heave accurately for clayey soil.

2 POROSITY RATE MODEL (PRM)

Michalowski (1993) proposed the porosity function as a phenomenological model for describing frost heave in frost-susceptible soil. The porosity response model (PRM) describes the global response of soil to changes in porosity due to ice lens formation and has been shown to be effective in solving problems related to frost heave with complex geometries (Zhang, 2014). PRM can be applied as a material function that pertains specifically to the ability of soil to increase in volume. The model assumes that the soil is fully saturated and that only a relatively small number of parameters need to be determined to describe frost heave. A more comprehensive model was modified by Zhu & Michalowski (2006) and Zhang (2014):

$$\dot{n} = \dot{n}_m \cdot (\frac{T - T_0}{T_m})^2 \cdot e^{1-(\frac{T-T_0}{T_m})^2} \cdot \frac{\left|\frac{\partial T}{\partial l}\right|}{g_T} \cdot e^{-\frac{|\bar{\sigma}`kk|}{\zeta}} \cdot e^{-\frac{\theta_i}{\theta_w}} \tag{1}$$

where, $\dot{n}$ is the porosity rate($\partial n/\partial t$), $\dot{n}_m$ is the maximum porosity rate, T_m is the temperature of soil body when $\dot{n}_m$ occurs, and g_T is the temperature gradient at which $\dot{n}_m$ is determined. T is the soil temperature and T_0 is the freezing temperature of water. The term $\exp(-|\bar{\sigma}`kk|/\ \zeta\ )$ is a retardation function to describe the reduction porosity rate by the stress state. The term $\exp(-\theta_i\ /\ \theta_w)$ is to determine the retardation effect on the porosity growth rate with the ice fraction volume θ_i increasing and unfrozen water fraction θ_w decreasing simultaneously.

2.1 Parameters analysis

3 parameters such as $\dot{n}_m$, T_m, and ζ applied in this model are extremely sensitive to the final frost heave result. In the early porosity rate model proposed by Michalowski (1993), $\dot{n}_m$ and T_m are hypothesis soil parameters that are determined as a material constant. As shown in Fig. 1, silt exhibit a high frost heave rate at a temperature slightly below the freezing point followed by a quick diminishment with the decrease of unfrozen water content and hydraulic conductivity. Experiment results from Williams & Wood (1985) illustrate that, in a 1-D soil sample freezing test subjected to overburden pressure, the frost heave can be reduced by overburden pressure. This relationship is presented in PRM by the term exp $(-|\bar{\sigma}`kk|/\ \zeta)$, where is ζ a material parameter and this is a phenomenological that was found to fit the experiments well for a variety of stresses. But for material parameter ζ, it can only be interpolated from existing data because there is no direct experimental method to determine.

In addition, previous research introduced a maximum porosity threshold, $n_c$in order to represent the maximum ice lenses can be formed. Experimental results from step-freezing processes (Penner, 1986; McCabe & Kettle, 1985; Fukuda *et al.*, 1997) show that frost heave tends to stabilize or slow significantly after a period of intense growth. This phenomenon tried to be simulated by means of accommodating n_c beyond which further growth ceases. While n_c was not reached in the ramped freezing tests of which experimental results was used to find input parameters, it was estimated to be above 0.7 and was taken as 0.75 in step-freezing computations (Zhu, 2006). Zhang (2014) purposed the term exp(-θ_i / θ_w) to eliminate this threshold.

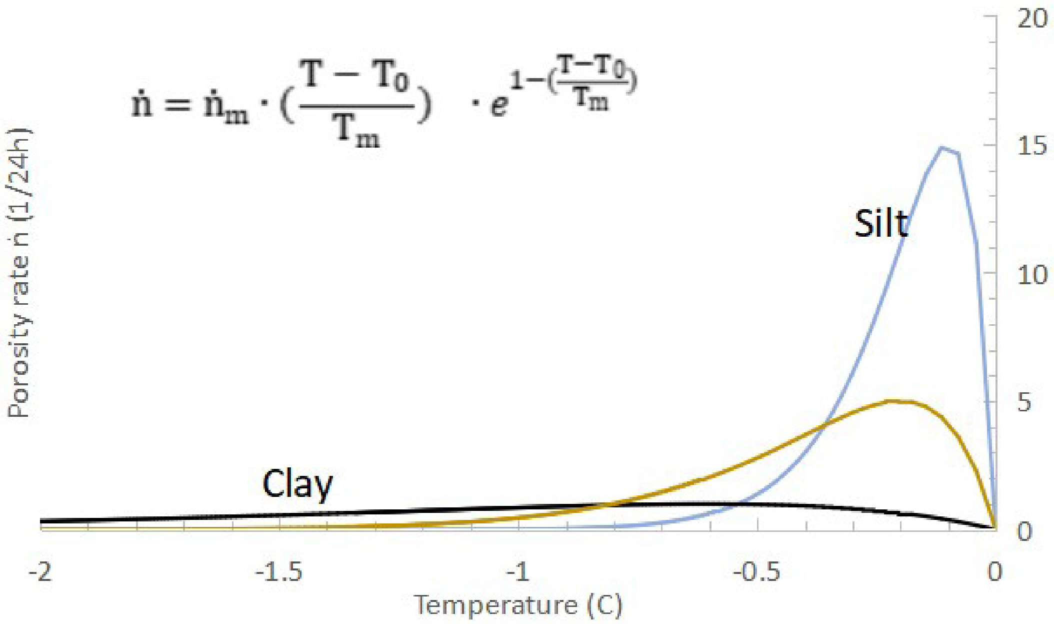

Figure 1. Porosity rate function Michalowski (1997).

3 MODEL VERIFICATION

3.1 Frost heave analysis

COMSOL, which is a commercial FEM program, was used to accommodate PRM, and the simulated results of frost heave were compared with those of step-freezing experiments on saturated clay by Fukuda *et al.* (1997). The thermal initial/boundary conditions in the step freezing process were as follows: a uniform initial temperature 5 °C was set. At t = 0, the temperature of the bottom plate was reduced to -5 °C and continues for 115 hours. The top plate temperature remains at 5 °C. The input parameters for PRM are $\dot{n}_m$ = 1.98E-5 /s, T_m = -0.82 °C, ζ = 0.75 MPa, and n_c = 0.75. The material properties of soil components are taken from William & Smith (1989) and summarized in Table 1. The simulated frost heave was found to be in close agreement with the experimental measurements as shown in Fig. 2. Even though Zhang (2014) purposed the term exp(-θ_i / θ_w) to eliminate n_c, but the frost heave amount was overestimated without n_c.

Table 1. Soil profiles of low frost susceptible soil.

	Mass heat capacity	Volumetric heat capacity	Latent heat	Thermal conductivity	Density
	(J/(kg·°C))	(J/(m^3·°C))	(J/kg)	(W/m·°C)	(kg/m^3)
Soil particles	900	2.36E6	-	1.95	2620
Water	4180	4.18E6	333000	0.56	1000
Ice	2000	1.93E6	333000	2.24	917

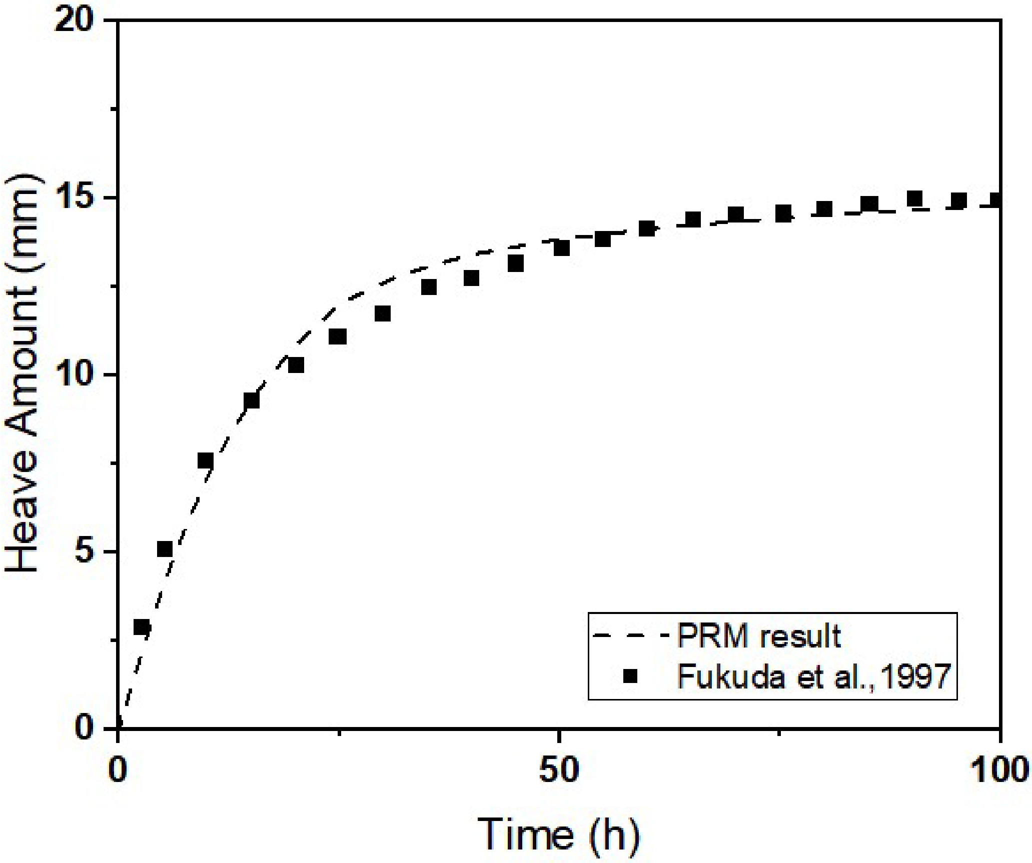

Figure 2. Comparison of Fukuda's test data and simulated result.

3.2 *Model generalization*

Clayey soils are generally classified as low frost-susceptible soils due to their low permeability. In order to evaluate the generalizability of PRM, it was applied to frost-susceptible soils. In this study, a frost-susceptible sample was prepared using a sand-silt mixture. The experimental data for this application were provided by Jin et al. (2022) and are summarized in Table 2.

Table 2. Soil profiles of high frost susceptible soil.

Specimen No.	Weight fraction(%)		Initial height(mm)	Initial Porosity	Dry density (g/cm^3)
	Joomunjin sand	Crushed basalt			
1	80	20	52.92	0.392	1.59
Thermal boundary condition	Top initial temperature(˚C)	Bottom initial temperature(˚C)			
	0.98	-3.65			
Hypothesis soil parameters	$\dot{n}_m$	T_m	ζ		
	9.02E-5/s	-0.82 °C	0.73MPa		

Fig. 3 shows that PRM provides a good match for heave behavior with highly frost-susceptible silty soil. The most accurate parameter was obtained through back analysis with an adjusted value of

$\dot{n}_m$ = 9.02E-5 /s. Except parameters such as as T_m, ζ, and n_c,which were used to provide the best match.

Compared with the frost heave ratio of relatively low to moderate frost-susceptible clayey soil presented by Fukuda *et al.* (1997) which is 21%, the frost heave ratio of silty soil presented by Jin *et al.* (2022) reaches 46% and $\dot{n}_m$ is more than 4 times higher than the former. Thus, it is proven that PRM can also be applicable to highly frost-susceptible soils.

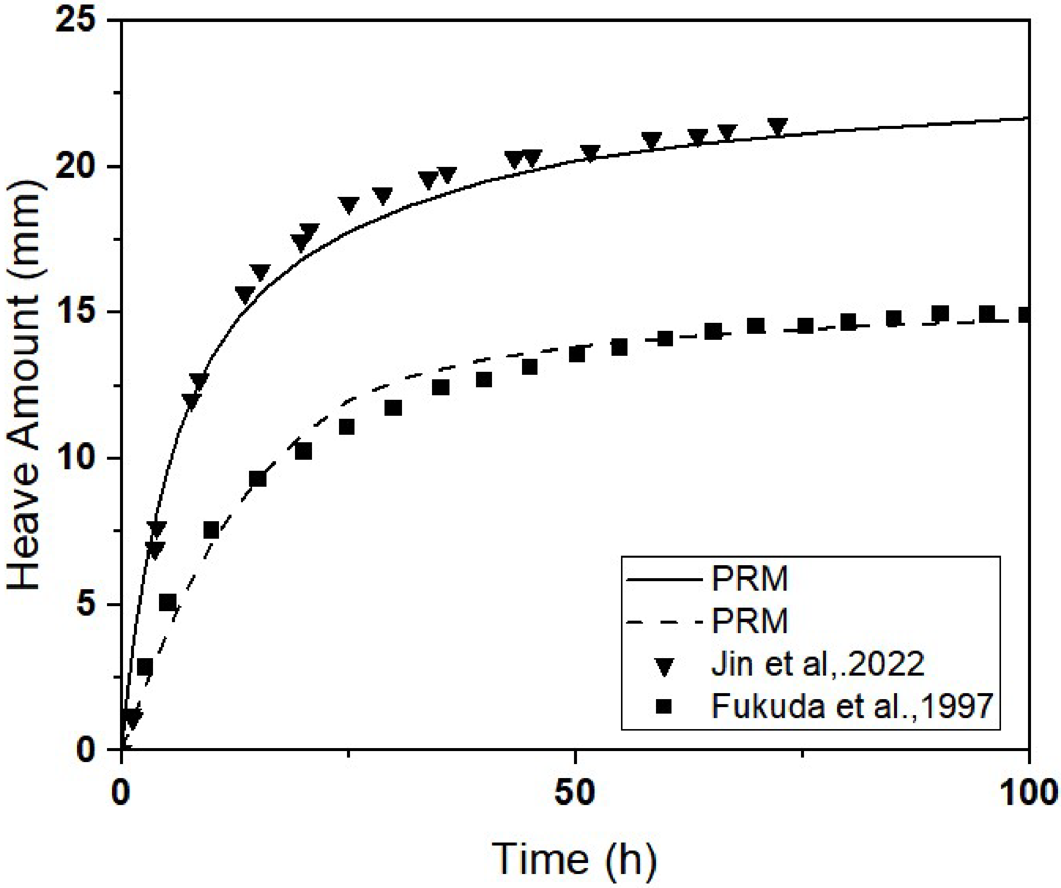

Figure 3. Porosity rate model application on different soils.

4 CONCLUSION

The numerical simulations of frost heave in low frost susceptible clayey soil were found to be in close agreement with the experimental measurements provided by Fukuda et al. (1997) using PRM reproduced with COMSOL. To verify the applicability of PRM for highly frost susceptible silty soils, numerical simulations were compared with experimental results provided by Jin et al. (2022). The numerical estimation showed close agreement with experimental data for the highly frost susceptible soil. Although the key parameter $\dot{n}_m$ still needs further investigation for various types of soils, PRM can possibly be applied for frost susceptible soils.

In this study, PRM still requires the maximum porosity n_c = 0.75 to suppress the porosity growth. However, the retardation coefficient given by Yao Zhang (2014) cannot completely effectively slow the porosity growth. In practice, this threshold is very difficult to measure and frost heave does not cease when this threshold is met as ice continues to grow in other regions. Furthermore, the model relies heavily on $\dot{n}_m$ and T_m, but these coefficients are only obtained after multiple fittings compared to laboratory frost heave data. This process is not only very cumbersome but also makes the application of the model very limited. Further study is needed to eliminate this limitation.

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