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Application of the Frozen and Unfrozen Soil model to modelling effects of freeze-thaw on low-volume roads

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Abstract. Freezing and thawing of soils are of the utmost importance in the design of infrastructure in seasonally cold regions. Cycles of freezing-thawing can severely affect the performance of thinly paved low-volume roads, causing frost heave during the winter and thaw weakening in the spring. Thus, a designer must have an understanding of freezing effects on infrastructure and adequate design tools to deal with them. Freezing of soils entails several coupled processes, necessitating advanced analysis tools such as numerical modelling. This paper applies the Frozen and Unfrozen Soil material model for the finite element program Plaxis 2D into a case study of freezing and thawing induced deformation of a low-volume road on dry-crust clay subgrade in Vesilahti, Finland supported by a literature review and a laboratory study. The Vesilahti test site monitoring results of frost heave, temperature and groundwater level were used in this study to simulate the frost heave of a pavement with shallow structural layers. In addition, soil sampling and laboratory tests were performed to determine the Vesilahti dry-crust clay material properties at the Aalto University. These were combined to simulate the frost heave and thaw settlement measured on the site and to study the feasibility of the material model in replicating actual measured frost action. The road deformation at the measurement times was replicated qualitatively well and the model performed mostly according to expectations. However, the multitude of parameters, complexity of the coupled phenomena modelled and the black box nature of the model implementation in Plaxis make the evaluation of calculation errors tough and time-consuming. Further research on the model could include the implementation of various user-friendly improvements in Plaxis, development of cryogenic suction- and temperature-controlled laboratory testing for the model parameter determination and better utilization of the model's predictive capabilities by studying continuous frost heave measurements.

1. Introduction

Considering the effects of frost in infrastructure design is extremely important in seasonally frozen regions. With the onset of climate change, freezing-thawing cycles are likely to become even more common in Finland, presenting further challenge for low-volume roads that are susceptible to frost effects. Freezing and thawing soils present complex geotechnical problems requiring thermo-hydro-mechanical analysis, making numerical methods a necessity for an in-depth analysis of frozen soils.

Past decades have seen much research on the constitutive models for frozen soils. One prospect is the Frozen and Unfrozen Soil model, which is available as a user-defined soil model in the common geotechnical finite element program Plaxis 2D [1]. The model is based on the Barcelona Basic model



[2] and has been proven to be able to replicate many features of frozen soils such as frost heave and thaw settlement [3].

2. Freezing and thawing of roads

Major engineering concerns regarding pavements and frozen ground are the damaging effects of ice lens growth, frost heave of the pavement surface and thaw weakening of the subgrade [4].

Frost heave will occur, if the following factors are present: the soil is frost-susceptible, the ground is frozen and there is a source of water to initiate and keep up the growth of ice lenses. Freezing in the soil begins as heat from the soil is extracted into the air and ice crystals start coalescing into ice lenses. When there is water available from the unfrozen soil below, the ice lenses continue growing and the soil above is displaced [5].

The capillary flow of pore-water up toward the lower temperature ice-water interface results from the cryogenic suction induced by thermal and pressure gradients in the freezing soil. This induced force causing pore-water flow can be determined based on thermodynamics with the Clausius-Clapeyron equation. Ice segregation occurs if a threshold value of cryogenic suction is exceeded and a new ice lens forms in the direction of heat removal [6], [7].

Frost heave is usually uneven due to a variety of factors such as variability in soil permeability resulting in varying water flow [8]. Thus, road structures in the frost-heave zone will usually experience surface roughness and bumps and in some cases even frost heave cracking [4].

On soil thawing, the ice melts and the soil skeleton adapts to a new equilibrium void ratio, causing settlement and reduction of soil stiffness. If the thawing happens faster than the meltwater can drain, the soil can be transformed into a slurry incapable to support almost any load. This is called thaw weakening. Volume change will also result due to the phase change of water and the flow of the excess water out of the soil. This is referred to as thaw settlement [4], [9].

3. Frozen and Unfrozen Soil model

The Frozen and Unfrozen Soil model assumes fully saturated, isotropic and elasto-plastic soil behaviour, where the frozen soil is composed of solid soil grains, solid pore-ice and unfrozen liquid pore-water, which are all assumed to be incompressible. The Frozen and Unfrozen Soil model was published in its initial form in [3] by Ghoreishian Amiri et al. In his Master's thesis [7] Aukenthaler implemented the model within Plaxis 2D as a user-defined soil model.

The model considers frozen soil as analogous to unsaturated soil by assuming that the flow of water in pores is hindered by ice like air. Using this analogy, the model borrows ideas from the Barcelona Basic model for unsaturated soils [2] to model the behaviour of frozen saturated soil. In a fully unfrozen state, the model reduces to the Modified Cam-Clay model [10]. The theoretical framework and the parameters of the model and its Plaxis implementation are described at length in Ghoreishian Amiri's [3] and Aukenthaler's [7] publications.

4. Vesilahti case study

Valkkistentie, a low-volume road located in Vesilahti, Finland, was chosen as the case study subject. A section of the road was instrumented and monitored in the TIEIKA -project conducted by the Tampere University of Technology between the years 2006 and 2008 [11]. The pavement structure consists of a 40 mm layer of soft asphalt pavement, 100 mm layer of crushed rock, 150 mm layer of mixed old asphalt and crushed rock and 200 mm layer of crushed gravel. During sampling and laboratory tests, the subgrade was found to consist of frost-susceptible dry-crust clay extending up to a till layer at circa 2.5 m depth.

Three frost heave measurements were conducted by levelling during the winter 2006-2007, each time at three sections of the road: zero measurement in October 2006, the high frost heave measurement in March 2007 and after-thaw measurement in May 2007, when the road had settled. The continuous temperature and groundwater level monitoring began in November 2006 and continued until the year 2014 [11]. The frost depth was estimated from the temperature measurements,

which indicate that the road centre had fully thawed by end of April and the edge around a week earlier. The frost depth is shown in Figure 1.

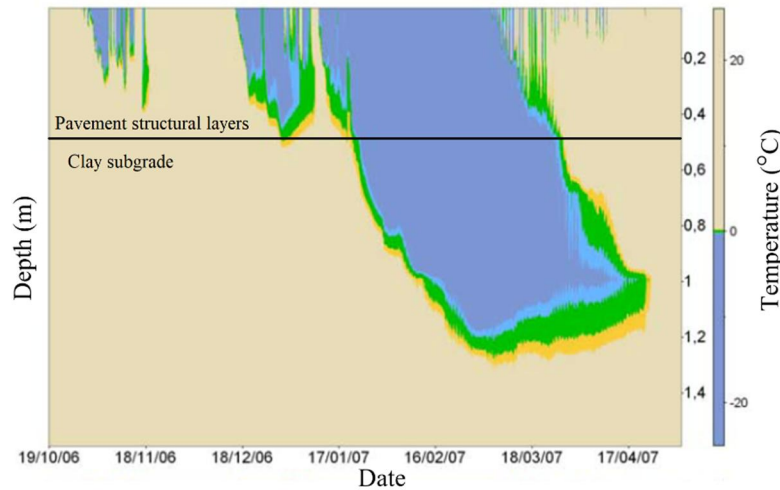


Figure 1 Frost depth in the middle of the road [11].

5. Simulation of frost action

5.1. Clay parameters used in modelling

Based on laboratory tests and, for the freezing specific model parameters, calibration for best fit to site measurements, the parameters in Table 1 and Table 2 were chosen for the clay. It was chosen to divide the clay into two layers at 1.3 m depth. The material was set as drained in Plaxis for calculation and dissipation of pore pressures.

Table 1 General parameters of clay used in the road modelling.

Parameter	Description	Clay layer 1	Clay layer 2	Unit
γ_{sat}	Soil saturated unit weight	18.3	16.7	kN/m ³
γ_{unsat}	Soil unsaturated unit weight	18.3	16.7	kN/m ³
e_0	Initial void ratio	1	1.4	-
S_{res}	Residual saturation	0.39	0.40	-
S_{sat}	Saturation in saturated conditions	1	1	-
g_n	Fitting parameter of rate of water extraction	1.27	1.23	-
g_a	Fitting parameter related to air entry value of soil	0.01	0.01	1/m
g_l	Fitting parameter for relative soil permeability	0.5	0.5	.
k_x	Horizontal permeability	$3.8 \cdot 10^{-9}$	$0.3 \cdot 10^{-9}$	m/s
k_y	Vertical permeability	$3.8 \cdot 10^{-9}$	$0.3 \cdot 10^{-9}$	m/s
c_s	Specific heat capacity	990	990	J/kg/K
ρ_s	Specific gravity	2820	2830	kg/m ³
λ_s	Thermal conductivity	1.1	1.4	W/m/K
$\alpha_{x,y,z}$	Thermal expansion coefficient	$1.8 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$	1/K
K_0	At rest earth pressure coefficient	0.5	0.5	-

Table 2 Frozen and Unfrozen Soil model parameters for clay used in the road modelling.

Model parameter	Description	Clay layer 1	Clay layer 2	Unit
$E_{f,ref}$	Frozen soil Young's modulus at a reference temperature	28.15	28.15	MPa
$E_{f,inc}$	Increase in Young's modulus with temperature	10	10	MPa/K
ν_f	Frozen soil Poisson's ratio	0.35	0.35	-
G_0	Unfrozen soil shear modulus	10.43	10.43	MPa
κ_0	Unfrozen soil elastic compressibility coefficient	0.026	0.057	-
κ_s	Elastic compressibility coefficient for suction variation	$0.1 \cdot 10^{-3}$	$0.1 \cdot 10^{-3}$	-
$(s_{c,seg})_{in}$	Initial segregation threshold	1.4	1	MPa
M	Slope of the critical state line	1.6	1.6	-
k_t	Rate of change in apparent cohesion with suction	0.15	0.07	-
m	Yield surface fitting parameter	1	1	-
γ	Plastic potential surface fitting parameter	1	1	-
λ_0	Unfrozen soil elasto-plastic compressibility coefficient	0.073	0.194	-
λ_s	Elasto-plastic compressibility coefficient for suction variation	0.9	0.6	-
$(p_{y0})_{in}^*$	Initial pre-consolidation stress for unfrozen condition	-120	-120	kPa
Δp_{y0}^*	Change of preconsolidation stress with depth	-110	-110	kPa/m
Y_{ref}	Reference depth	-0.3	-0.3	m
β	Rate of change in soil stiffness with suction variation	$0.8 \cdot 10^{-6}$	$0.8 \cdot 10^{-6}$	m^2/N
r	Coefficient related to the maximum soil stiffness	0.6	0.6	-
p_c^*	Reference stress	-50	-50	kPa
α	Constant parameter for freezing/thawing temperature	9	9	-
λ_r	Unfrozen water saturation fitting parameter	0.21	0.19	-
ρ_r	Unfrozen water saturation fitting parameter	$1 \cdot 10^6$	$800 \cdot 10^3$	-
T_{ref}	Reference temperature	273.16	273.16	K
p_{ref}	Reference pressure	-395	-395	MPa
e_0	Initial void ratio	1	1.4	-
K_w	Bulk modulus of water	1	1	GPa
p_{at}	Atmospheric pressure	-100	-100	kPa

5.2. Modelling the road frost action

Based on the available frost measurements, the goal of the study was chosen to be replicating the high frost heave measurements and the after-thaw measurements. The calculations were performed with the Plaxis 2D version 2018.01. The modelling was performed as a plane-strain problem and the used elements were 6-noded triangles. The depth of geometry was 2.5 m at the approximate boundary of the hard till layer. A 10 kPa line load was applied on the pavement surface to simulate the heavy vehicle traffic at the road during the measurement time [11].

The calculation phases were chosen to replicate the available temperature and groundwater level data. The initial phase was K0 procedure calculation type, all the other phases used the fully coupled

flow deformation type. The temperatures were implemented as temperature boundary conditions on the model top surface and on a line in 1.62 m depth as this was the deepest measurement available. The geometry's left-symmetry boundary was normally supported and closed for water and heat flow. The right boundary was normally supported, closed for heat flow and open for water flow. On the top surface boundary, the top temperature boundary condition was applied, and it was set to seepage for water flow. The bottom boundary was fully supported, and no other boundary conditions are imposed.

The temperature and groundwater level conditions imposed in each calculation phase are described in Table 3.

Table 3 Time interval, surface and bottom temperatures and groundwater depth variation in the calculation phases.

Phase	Time interval (d)	Surface temperature (°C)	Bottom temperature (°C)	Groundwater depth (m)
Initial phase	-	+3	+6	1.6
Constant temperature +3 °C (mid-November to mid-December)	30	+3	+6	Linear increase to 1.2
First freezing phase -2 °C (mid-December to mid-January)	30	-2	+2	Harmonic between 1.8 to 1.4
Primary freezing phase with varying temperature (mid-January to beginning of March)	45	Harmonic between -2.5 to -17.5	+2	Linear decrease to 2.5
Temperature increase to -2 °C (first week of March)	7	Linear increase to -2	+2	2.6
Thaw temperature increase 1 (early March to early April)	30	Linear increase to +10	+2	Linear increase to 1.4
Thaw temperature increase 2 (early April to early May)	30	Linear increase to +10	Linear increase to +3.8	Linear decrease to 2

A snow layer is added in the primary freezing phase and the temperature increase phase following it. The snow thickness is approximated as 30 cm in the primary phase and 40 cm in the temperature increase phase based on nearby measurements as no local data was available. As the snow melted very quickly after beginning of March, the layer was removed in the thaw phases.

5.3. Other parameters in the road modelling

The pavement materials and snow were modelled with the linear elastic material model for simplicity. These parameters were mostly estimated from literature values. The asphalt was set as non-porous and the other materials as drained. The water and ice thermal parameters shown in Table 4 and pavement materials and snow are compiled in Table 5.

Table 4 Water and ice thermal parameters in calculation.

Parameter		Value	Unit
T_{ref}	Reference temperature	274.16	K
γ_{water}	Water unit weight	10	kN/m ³
c_{water}	Water specific heat capacity	4181	J/kg/K
λ_{water}	Water thermal conductivity	0.6	W/m/K
L_{water}	Water latent heat of fusion	$334 \cdot 10^3$	J/kg
α_{water}	Water volumetric thermal expansion coefficient	$2.1 \cdot 10^{-4}$	1/K
T_{water}	Water temperature	274.16	K
c_{ice}	Ice specific heat capacity	2108	J/kg/K
λ_{ice}	Ice thermal conductivity	2.22	W/m/K
α_{ice}	Ice volumetric thermal expansion coefficient	$5 \cdot 10^{-5}$	1/K

Table 5 Pavement material and snow parameters.

Parameter	Asphalt	Crushed rock	Old mixture	Crushed gravel	Snow	Unit
γ_{sat}	24	22	21	21	3.9	kN/m ³
γ_{unsat}	24	22	21	21	3.9	kN/m ³
e_0	0.05	0.5	0.5	0.5	1.5	-
E	$14 \cdot 10^3$	150	150	150	300	MPa
ν	0.35	0.35	0.35	0.35	0.3	-
k_x	-	$5 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$8 \cdot 10^{-5}$	0.02	m/s
k_y	-	$5 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$8 \cdot 10^{-5}$	0.02	m/s
c_s	950	800	600	560	2100	J/kg/K
ρ_s	1900	2150	2200	2140	400	kg/m ³
λ_s	2	2.9	2.9	0.9	0.4	W/m/K
$\alpha_{x,y,z}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	1/K

5.4. Modelling results

The vertical deformations of the modelled geometry were inspected at six points corresponding to the frost heave levelling measurement points from the middle of the road to the edge of the road. The simulated vertical deformation with time is visible in Figure 2.

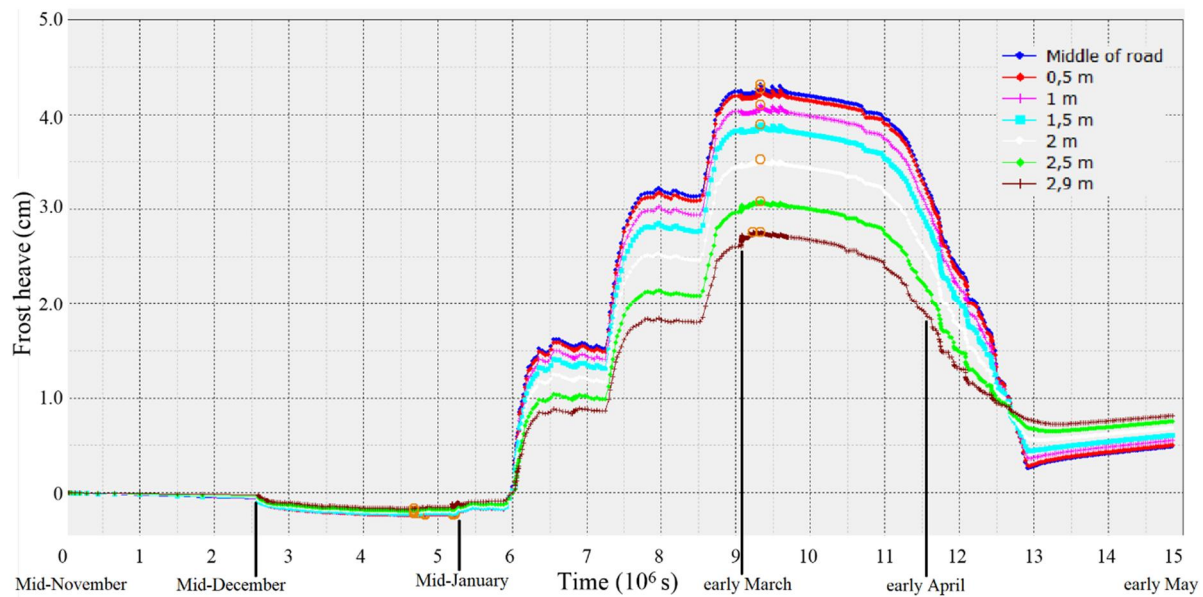


Figure 2 Calculated pavement surface deformation across the road cross section.

The road settles slightly under its own weight and the traffic load during the initial warm phase. The structure then settles more during the first mild freezing phase due to the effect of the elastic compressibility parameter κ_s that causes decrease of volume in the freezing soil when the cryogenic suction has not increased above the initial segregation threshold.

When the cyclic temperature variance is applied during the primary freezing phase, the effect of the varying temperature can be observed on the heave as it increases quickly when the temperature decreases, and conversely when the temperature rises the accumulation of heave stops. The cryogenic suction related parameters λ_s and $(s_{c,seg})_{in}$ both affect the frost heave significantly, and fitting these two parameters for the best match to measurements was one key issue in the simulations. The high frost heave measurement happens in the fourth phase when the temperature increases after the cyclic variation, the frost heave remains almost constant during that time.

During the first thaw phase the heave decreases initially slowly as the subgrade clay thaws only from below while the top remains still frozen. The heave decreases much more steeply as the clay starts to thaw from top down too when the pavement layers have thawed first. During the second thaw phase the road geometry thaws completely, and the after-thaw measurement corresponds to the end of the phase. After thawing fully, the simulated heave increases again, while the measurements show that the road settled back to its initial state. The reason behind this seems to be thermal expansion of the clay as running the calculation with unrealistically small values of clay thermal expansion coefficient yielded results with no surface heave after thawing. The thawing of the road with time agrees well with the measurement data as the calculation indicates the middle of the road is thawed at the end of April.

Comparing the simulation to the measurements of high frost heave in Figure 3, it can be seen that the simulation corresponds qualitatively well to the measured values. The measurement lines were located at c. 10 m intervals. The measurement at line 2 shows quite a bit higher frost heave, which could indicate local variation of road structure and subsoil conditions. Steel bars struck into the ground at the side of the road were used as reference points for the in-situ frost heave measurements and a possible source of error could be the movement of the bars along with the ground frost heave.

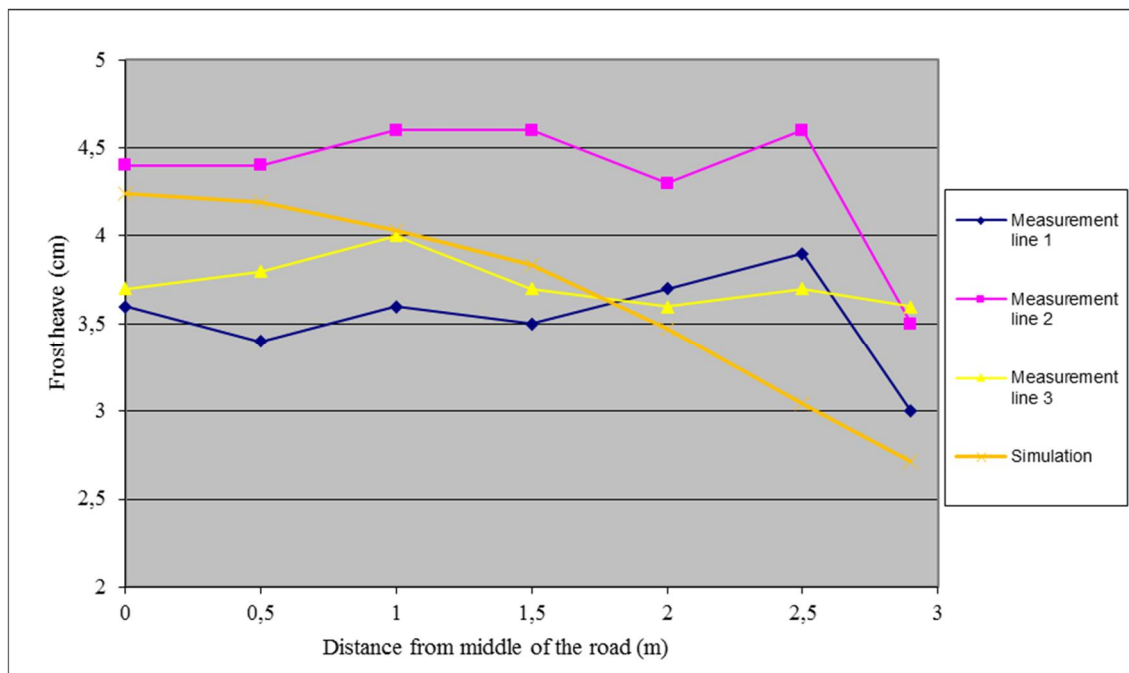


Figure 3 Calculated frost heave in comparison to the three measurements of the high frost heave.

The calculation results indicate that the heave decreases toward the road edge, while the measured heave is quite uniform across the surface except for the very edge. This seems to be due to the simulated snow layer hindering frost penetration at the edge. Decreasing the insulating effect of snow made the heave more uniform while increasing frost penetration, which was already higher than measured, so the current result was considered an acceptable compromise.

The simulated after-thaw surface compared to the three measurements is shown in Figure 4. As noted, the calculation indicates vertical deformation after thaw when using a realistic value of thermal expansion coefficient.

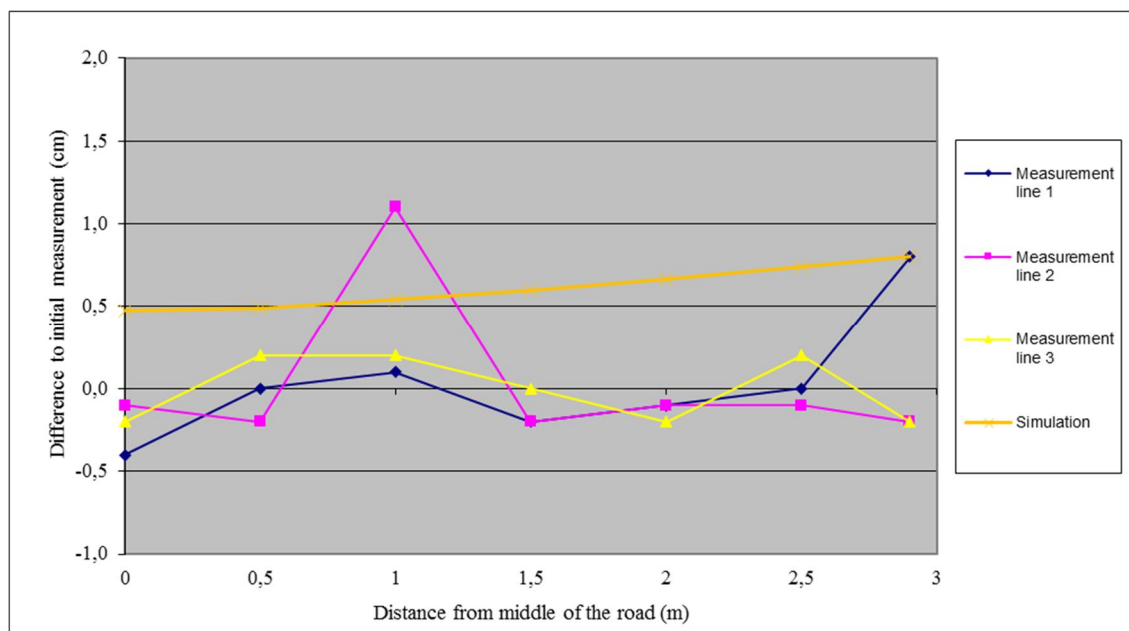


Figure 4 Calculated pavement surface after thaw compared to the three measurements after thaw.

The achieved frost heave results are in good qualitative accordance with the measurements as shown in Figure 3 and Figure 4 and the model yielded results in harmony with the expected behaviour for the most parts. The modelled frost depth was deeper than measured, 1.7 m at its deepest compared to 1.2 m, but in balancing the heave and frost penetration, the desired heave was the priority. Some issues with the decrease of preconsolidation stress and groundwater flow were encountered in the calculations, but the root cause of these remained unclear. The calculation process was time consuming as there were unelaborated calculation errors at many points which halted the simulation completely while no information was provided to the user to divine the nature of the error encountered. No complete step-by-step examples of simulations with the model are provided by the developers, limiting the ability of a user to study the model on their own. Including these in the model material would be a great help in using the model on a case study. One future prospect of improving the user-defined soil model would be to implement actual error messages so the user could have a deeper understanding of what went awry in a calculation and could improve their simulation more concisely instead of resorting to best estimates in face of unknown. In the current state of the model, no information was given on the nature of the problems encountered, limiting the insight a user could gain on the viability of the model constitutive framework implementation in Plaxis and making the calculation process uncertain at times as seemingly reasonable parameter combinations would yield no results at all.

6. Conclusions and suggestions for future research

In this paper the frost heave of a road in Southern Finland was studied using the Frozen and Unfrozen Soil model in Plaxis 2D finite element software.

The Frozen and Unfrozen Soil model has been proven to be able to model complex multiphysical phenomena in both freezing and thawing soil. The model is, however, rather complex, precisely due to the complexity of modelling those phenomena, and especially the choice of the many model parameters presents a challenge to bringing the model into design practice even though the model is available in the common geotechnical finite element software Plaxis 2D. The implementation of the model and its constitutive equations in Plaxis is non-transparent to the end user so the causes behind simulation results and especially calculation issues can be difficult to analyse. Sources of unexplained errors in the simulations often remained a mystery. Concluding, in its current state the model implementation in Plaxis is not deemed to be very user-friendly. Improvements could include, for example: (i) provision of full step-by-step examples of model simulations for the user to familiarize themselves with the model, and (ii) implementation of the actual user-defined soil model specific error messages in Plaxis in order to improve the information the user has on their calculation results and failures in calculation and enabling them to solve possible problems in a more effective manner.

In addition to the general soil parameters the model incorporates 28 model parameters, many of which are not standardly used in the engineering practice and deriving them can be quite challenging. In this paper these parameters were derived for Vesilahti clay based on previous works with the Frozen and Unfrozen Soil model and with a time-consuming trial and error process to fit the calculation results to measurements. Using the proposed temperature- and suction-controlled laboratory tests to obtain these parameters would reduce the degrees of freedom and sources of error in the calculation and calibration process and help to better validate the results beyond qualitative fitting of experimental measurements. However, suction-controlled frost heave tests are not performed in Finland at the moment of writing. Implementing these tests could provide interesting opportunities for testing model and its predicted behaviour, while comparing experimental parameters to the fitted ones. Additionally, utilizing continuous frost heave measurement for the simulations could be very beneficial as some of the predictive capabilities of the model are neglected by simply focusing on a few time intervals.

The model replicated the Vesilahti frost heave measurements qualitatively well. The freezing performance of the soil matched expected behaviour and the calculated heave at the high frost heave and the thaw time increments was very close to measured values. The heave in time corresponded with

expected behaviour due to variation of temperature conditions and cryogenic suction. The major effect on the development and magnitude of frost heave was by the temperature variation between extremes in the primary freezing phase, the clay initial value of ice segregation threshold and the elastoplastic compression coefficient of cryogenic suction variation, which affected the development of cryogenic suction in the clay and the deformation dependency on it.

Based on the simulations performed in this research it can be concluded that the Frozen and Unfrozen Soil model is a valid approach to assessing deformation of a road structure on frost-susceptible subgrade during freezing and thawing. As illustrated in the paper, the model can capture effects of freezing and thawing on pavement structure deformations caused by the subgrade soil. Work with the model can be very time consuming and demanding due to the complexity of the parameter determination and the multiple interlinked physical phenomena handled along with the black box model implementation nature for a user. Issues in the simulations might stem from many different combinations of parameters which makes special care in parameter definition and testing in calculations very much necessary. In its current state the model is not suitable for standard infrastructure design work in a state of practice context while simpler and easier to use methods for assessing frost effects in pavements exist. Further research into developing and performing suction-controlled frost heave tests and temperature-controlled oedometer and uniaxial compression tests in Finland would benefit the future work with the Frozen and Unfrozen Soil model and its utilization into practical problems by grounding the model parameter choice in experimental results and could provide opportunities in evaluating the model performance.

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