Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1341

Experimental and Numerical Analysis of Frost Heave Characteristics in Organic-rich Backfill Soils

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ABSTRACT: In regions where subzero temperatures persist for extended periods, pore water within the soil freezes, forming ice lenses that lead to the phenomenon known as frost heave. This process results in an upward expansion of the soil layers, causing considerable mechanical stress and structural deformation. Alberta, Canada, is home to vast oil sand reserves and is characterized by soil layers with high-organic-matter content. Although organic-rich soils provide certain ecological and environmental benefits, they present major challenges for construction and infrastructure because of their high-water retention, compressibility, and susceptibility to freeze–thaw cycles. This study focused on evaluating the frost heave characteristics of backfill soils containing organic matter. To achieve this, a series of controlled experiments was conducted by constructing a test bed with varying levels of organic matter. The testbed was designed to monitor key geotechnical parameters, including soil pressure, vertical settlement, and heave across different soil layers. A numerical analysis model was developed to simulate the freeze–thaw processes observed in the test bed. The model incorporates key factors such as soil thermal conductivity, phase change of pore water, and the mechanical response of the soil matrix to the formation of ice. The primary objective of the model was to replicate the observed experimental conditions and predict the frost heave response of soils with varying organic matter contents. To validate the accuracy and reliability of the numerical model, the simulation results were compared with field data obtained from the testbed experiments. This comparison involved assessing the alignment between the predicted and observed values for parameters such as the frost heave magnitude, soil pressure distribution, and settlement patterns. The results indicated that the numerical model effectively captured the essential behaviors of the backfill soil during freeze–thaw cycles, providing a reliable tool for predicting frost heave in cold-region construction projects.

KEYWORDS: Oil sand, Organic, Frost heave, Field experiment, Numerical analysis.

1 INTRODUCTION

Frost heave refers to the upward swelling of the soil caused by the formation of ice lenses during freezing. When the ground freezes, water migrates toward the freezing front, accumulates as ice, and forces the soil matrix to expand. This phenomenon was recognized in early geotechnical studies and has been the subject of extensive research for decades. Frost heave is of particular concern in cold-region engineering because it can damage pavements, foundations, pipelines, and other infrastructures by inducing differential heave and subsequent settlement upon thawing. The severity of frost heave depends on factors such as the soil type, moisture availability, freezing rate, and soil thermal properties. Fine-grained and moisture-retentive soils are particularly susceptible to frost because they support the development of substantial ice lenses.

Organic-rich soils present unique challenges regarding frost heave. These soils, which contain a high percentage of organic matter, often have a high porosity and water-holding capacity. The presence of organic matter can influence the freezing behavior in two ways. Organic particles may reduce the thermal conductivity of soil, potentially slowing frost penetration. In contrast, organic soils usually have a higher unfrozen water content at subfreezing temperatures owing to adsorption and freezing-point depression effects, which can sustain water migration during freezing and promote ice lens growth (He, et al., 2023). Consequently, organic-rich backfill soils tend to be highly frosted, and extensive heave can occur if they are used without proper mitigation in cold climates (Wu, et al., 2021). Understanding the frost heave characteristics of such soils is essential for the safe and reliable design of embankments, retaining structures, and backfilled excavations on seasonally frozen ground.

In recent years, advanced numerical techniques have been developed to analyze the coupled thermal, hydraulic, and mechanical processes governing freeze–thaw behavior in soils (Cai, et al., 2019). These approaches allow the simulation of transient heat transfer, phase change, and the associated deformation under freezing and thawing conditions. Finite element and finite difference models such as those implemented in PLAXIS, ABAQUS, and FLAC3D have been successfully applied to predict frost heave across various soil types. Despite these advances, experimental data specific to organic-rich soils remain limited, and further research is required to validate and refine numerical models for these materials. Furthermore, field-scale monitoring under natural freezing conditions is scarce, which makes it difficult to capture the combined effects of seasonal climate, soil composition, and construction practices.

This study addresses this gap by conducting controlled field experiments on an organic-rich backfill soil and developing a numerical model to analyze the frost heave mechanism. The objectives of this research are the following: (1) characterization of the frost heave behavior of an organic-rich backfill soil through field tests and (2) calibration and validation of a numerical frost heave model against experimental results, thereby assessing its applicability for predicting field performance.

2 FIELD EXPERIMENTS

2.1 *Experimental method*

A full-scale field experiment was conducted in Yeoncheon, Korea, which has seasonally frozen climate. Two organic content levels were used for the backfill material: 3% and 9% organic content by dry weight. The base soil consisted of manufactured silica sand with a particle size range of 1.5–2.4

mm and a specific gravity of 2.65, to which Canadian peat moss with an organic content greater than 99% was added in the prescribed proportions by weight. The particle size analysis and laboratory compaction tests results for each backfill material are summarized in Table 1.

Table 1. Laboratory test results for backfill materials.

Category		Organic content, 3%	Organic content, 9%
Particle size analysis	Maximum particle size (mm)	2.0	2.0
	5 mm sieve passing percentage (%)	100	100
	0.075 mm sieve passing percentage (%)	0.9	2.6
Laboratory compaction tests	Maximum dry density (g/cm^3)	1.64	1.25
	Optimum moisture content (%)	20.34	19.05

The test section had a total length of 8 m and was divided equally into two long segments (4 m each) for the 3% and 9% organic content cases within a shared, continuous cross-section. Excavation was conducted at a depth of 3.0 m with a base width of 2.0 m. Side slopes were cut at a 1:1 (45°) incline, resulting in a trapezoidal cross-sectional profile. All backfills in the field experiments were compacted to achieve a maximum dry density of at least 95%. The backfill construction and instrumentation are shown in Figure 1.

(1) Excavation: The pit was excavated to the specified dimensions (3.0 m deep, 2.0 m base width, 1:1 side slopes, 8 m length).

(2) Waterproof lining: A durable waterproof membrane was placed on the exposed soil surfaces of the pit to prevent lateral water flow between the surrounding ground and the backfill, ensuring a closed-system condition for moisture.

(3) Layered backfilling with sensors: The pit was backfilled in three lifts (each having an approximate thickness of 1.0 m). During the placement of each lift, sensors were installed at predetermined depths. The 3% organic mixture was placed in one half of the pit, and the 9% mixture in the other half, each occupying 4 m in length. The sensors embedded in the fill were as follows:

- Earth pressure cells: Installed at the base (approximately 3.0 m depth) of each section to measure vertical stress in the backfill at the original ground level.
- Settlement gauges: Placed at depths of approximately 1.0 m, 2.0 m, and 3.0 m within each backfill section to track vertical displacement (heave or settlement) of the soil at these levels. The data obtained from each gauge enabled quantification of the vertical displacement of the soil layer over time.
- The thermocouples were co-located with settlement gauges at the depths of 1.0 m, 2.0 m, and 3.0 m to monitor the temperature profile inside the backfill. This provided data on the development of the freezing front and thermal gradients during the experiment.

(4) Data acquisition: After backfilling and sensor installation, all the instruments were connected to a centralized data logger. The data logger was programmed to automatically record readings at regular intervals throughout the winter freeze–thaw and spring thaw periods.

Monitoring was conducted at 6 h intervals, capturing the diurnal and seasonal changes in temperature, earth pressure, and deformation. The field experiment spanned the entire freezing season and continued into the subsequent thawing season. This allowed the observation of both frost heave development and behavior during thaw settlement under natural climatic conditions.

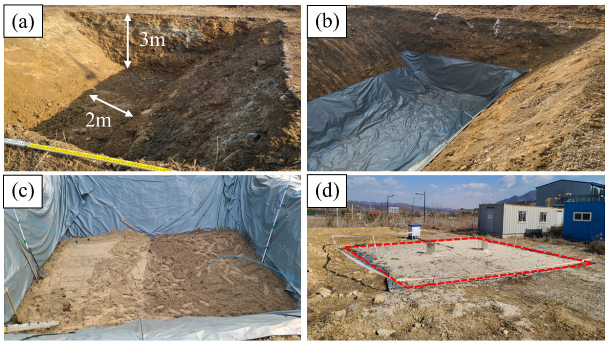

Figure 1. Field experiment construction process: (a) excavation; (b) waterproof lining; (c) layered backfilling with sensors, and (d) data acquisition.

2.2 *Field experiment results*

The field measurements provided clear evidence of frost penetration and the resulting ground deformations in both backfill sections. As winter progressed, the near-surface temperature dropped below 0°C and a freezing front advanced downward from the exposed surface. The thermocouple data indicated that the soil froze to a maximum depth of approximately 0.6 m below the surface at the coldest period of the season. This frost depth was similar in both the 3% and 9% organic sections, reflecting comparable thermal conditions and soil thermal properties in the two adjacent test areas. Frost heave was observed once the soil pore water began to freeze in the upper layers. The timing of the heave corresponded to the period of sustained subfreezing temperatures and ice lens formation within the soil.

Despite experiencing the same freezing conditions, the magnitude of frost heave differed considerably between the two backfill compositions. In the section with an organic content of 3%, the accumulated surface heave reached approximately 0.88 mm at its peak. In contrast, the section with an organic content of 9% exhibited a substantially greater heave approximately equal to 1.85 mm (Figure 2). This observation indicates that high-organic-matter content markedly increases the magnitude of frost heave. A higher organic content intensified frost heave; this was attributed to increased water retention, which in turn enhanced frost susceptibility.

Subsurface displacement measurements revealed a complementary behavior to that of surface heave. When the ground surface was swollen, the deeper settlement recorded a slight settlement during the freezing period. This implies that as the upper soil expanded owing to ice formation, the underlying unfrozen soil was compressed or consolidated. Settlement was more pronounced in the 9% organic section, suggesting that larger ice lens growth induced greater stress and slight compaction in the soil below. During the subsequent spring thaw, the trends were reversed; the frozen soil layer gradually thawed from the surface downward, and the surface heave diminished as the ice melted and the ground settled. Much of the heave was recovered, although a minor net uplift may have remained in the highly organic section, indicating irreversible soil fabric changes.

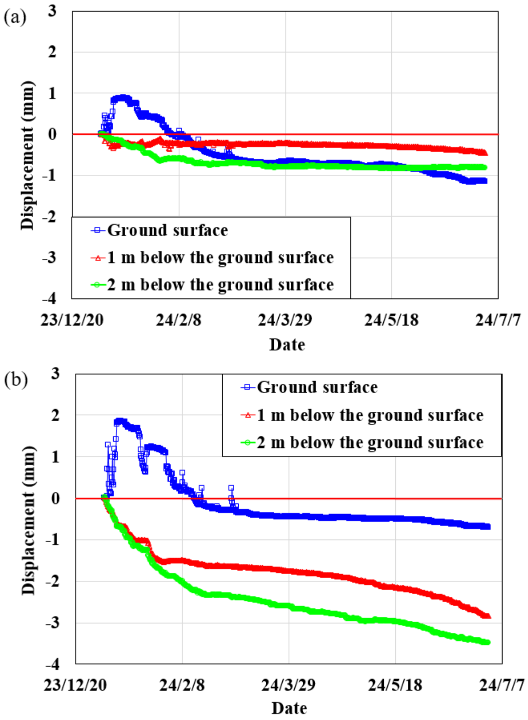

Figure 2. Measured displacement at each depth levels over time for backfill soils with organic contents of (a) 3% and (b) 9%.

The earth pressure cells installed at the base of the backfill recorded the stress variations associated with the freeze–thaw cycle. During freezing, the vertical earth pressures remained stable or slightly decreased, likely due to the reduced overburden unit weight from ice expansion, with part of the load supported by ice bonding or redistributed laterally. Both organic content sections showed an 8–11% rise in vertical earth pressure during thawing, coinciding with meltwater release from ice lenses. This meltwater likely percolated downward, temporarily increasing the pore water pressure or unit weight in the lower layers, thereby elevating the total stress; settlement from frost heave loss may also have imposed a transient load. The temporal variation in earth pressure is shown in Figure 3.

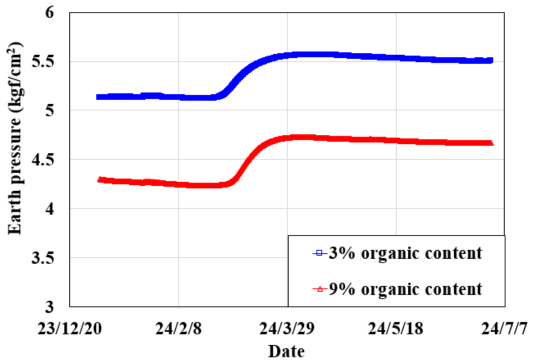

Figure 3. Variation in earth pressure at a depth of 3 m during the freeze–thaw cycle.

3 NUMERICAL ANALYSIS

3.1 *Constitutive equation*

A coupled thermomechanical numerical analysis was conducted using FLAC3D to reproduce analytically and explain the field observations. The model employed an elastoplastic Mohr–Coulomb constitutive framework augmented with strain components for thermal expansion/contraction and frost-induced volumetric expansion. The fundamental constitutive relationship for the stress–strain response with these effects can be expressed by Equation (1).

$$\sigma_{ij} = D_{ijkl}\left[\varepsilon_{kl} - \alpha(T - T_0)\delta_{kl} - \varepsilon_{kl}^{ft}\right] \qquad (1)$$

where σ_{ij} is the stress tensor, D_{ijkl} is the elastic stiffness tensor of the soil, and ε_{kl} is the total strain tensor. The term $\alpha(T - T_0)\delta_{kl}$ represents the thermal strain, while ε_{kl}^{ft} denotes frost-induced volumetric strain from ice lens formation and the volumetric expansion of water upon freezing.

The Mohr–Coulomb parameters (elastic modulus, cohesion, friction angle, etc.) for the soil were specified separately for the unfrozen and frozen states to reflect the change in material behavior with temperature. In particular, upon freezing, the soil gains apparent cohesion and stiffness due to ice bonding between particles, which is incorporated by increasing the cohesion and elastic modulus when $T < 0$°C in the model. Conversely, thermal softening was not considerable above freezing temperatures in this soil. The transition of material properties and the activation of the frost strain term were programmed as functions of temperature within the simulation, thus capturing the nonlinear response of the soil as it freezes and thaws.

3.2 *Modeling*

A three-dimensional finite difference model was constructed in FLAC3D to simulate a field experiment scenario. As shown in Figure 4, the model domain spanned 20 m in the horizontal direction (length and width) and extended to a depth of 10 m. This domain size was chosen to be considerably larger than the 8 m test section and 3 m excavation so that the boundaries would have minimal influence on the results. The mesh was refined in and around the backfill region to capture the steep thermal gradients and localized deformations expected near the freezing front accurately.

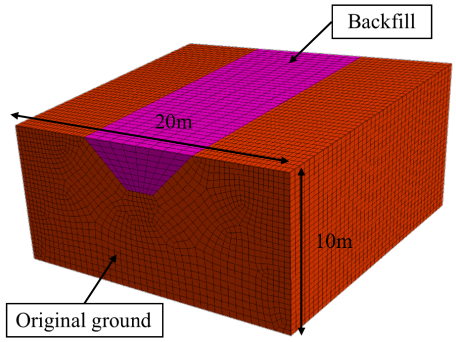

Figure 4. Geometry of three-dimensional numerical model.

The bottom part of the domain was fixed in the vertical direction with no settlement or heave at a depth of 10 m to simulate a rigid underlying stratum, whereas the lateral boundaries were fixed in the horizontal direction but were allowed to move vertically. The top surface of the model was subjected to time-dependent temperature boundary conditions derived from the air temperatures measured during the field experiments (Figure 5). The surface temperature of the model was constrained to replicate the actual atmospheric temperature fluctuations recorded at Yeoncheon, which drove the freezing and thawing of the ground downward from the surface. All lateral side boundaries were treated as adiabatic, which assumes that the horizontal heat flow is negligible compared with the vertical heat flow. This is reasonable given the large extent and symmetry of the model. The bottom boundary, at a depth of 10 m, was set to a constant temperature representing the deep-ground temperature, which remained relatively constant.

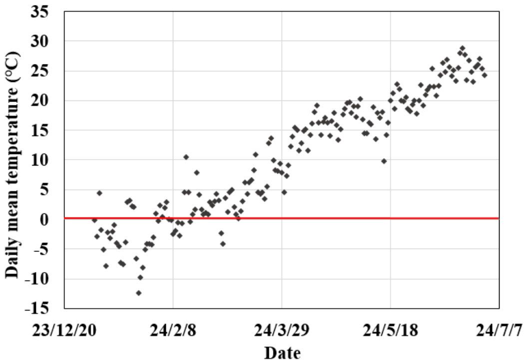

Figure 5. Time-dependent air temperature applied as the upper thermal boundary condition.

The backfill soil was modeled using the aforementioned thermomechanical constitutive behavior. Two sets of material properties were used, corresponding to organic contents of 3% and 9% (Table 2). The material properties of the backfill were specified based on laboratory experiments and the literature values for organic soils.

Table 2. Material properties used in the conducted numerical analysis.

Category	Backfill Unfrozen	 Frozen	Original ground
Unit weight (kg/m^3)	1835		2040
Cohesion (kPa)	5	867	10
Elastic modulus (MPa)	25	260	100
Thermal conductivity (W/m·K)	1.61	3.36	2.20
Thermal expansion coefficient (1/°C)	8.3×10^{-5}		2.0×10^{-5}

3.3 *Simulation results*

The numerical model produced results that closely corresponded to the measured field experimental data, demonstrating the validity of the modeling approach. The evolution of the freezing front in the simulation matched the field observations: as the surface temperatures dropped, the computed 0°C isotherm gradually penetrated the soil, reaching a depth of ~0.6 m at the height of winter. This simulated frost depth was essentially identical to the approximate 0.6 m frost penetration recorded by the thermocouples in the field, indicating that the applied thermal boundary conditions and material properties were appropriately defined. The model's time-dependent temperature profile agreed with the field data at the instrumented depths, confirming the capability of the model to reproduce both seasonal freezing and subsequent thawing cycles.

The model accurately reproduced the frost heave response, predicting approximately 1.65 mm of heave for the backfill with an organic content of 9%. This is consistent with the field measurement of approximately 1.85 mm for that section, with the model underestimating the heave by less than 15% relative to the observed value (Figure 6). In the case in which the organic content was 3%, the predicted heave was much smaller, reflecting a lower frost susceptibility, which is consistent with the maximum heave field outcome of 0.88 mm. Thus, the numerical analysis correctly reproduced the trend in which a higher organic content leads to greater frost heave. The minor heave underestimation in the high-organic case may be owing to minor model simplifications; however, the overall magnitude and timing of the heave were well captured.

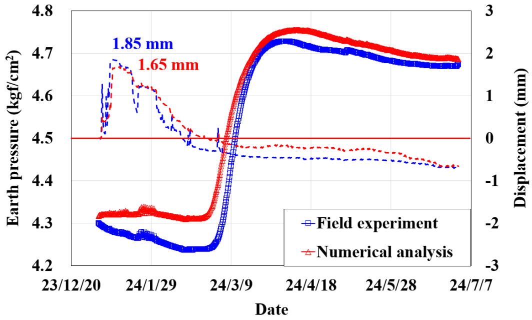

Figure 6. Comparison of numerical analysis results with field experiment monitoring data.

4 CONCLUSION

This study investigated the frost heave behavior of organic-rich backfill soils based on full-scale field experiments and validated the three-dimensional coupled thermomechanical numerical simulations. Two backfill mixtures containing organic matter at the proportions of 3% and 9% by weight were tested under identical environmental conditions in Yeoncheon, Korea, during a natural seasonal freeze–thaw cycle. The key findings are the following:

- The measured frost penetration depth in both backfill sections was approximately 0.6 m. However, the 9% organic content section exhibited a maximum surface heave (~1.85 mm), which was almost double that of the 3% organic section (~0.88 mm), indicating that higher organic matter content increases frost susceptibility owing to enhanced water retention and ice lens formation.
- The vertical earth pressure at a depth of 3 m remained relatively stable during the freezing period. However, an increase of approximately 10% was observed in both cases during the thawing phase. This rise is attributed to thaw-induced consolidation and a transient pore water pressure increase caused by the downward infiltration of meltwater released from ice lenses.
- The numerical analysis, which incorporated thermal expansion and frost-induced volumetric strain into a Mohr–Coulomb soil model, successfully reproduced the frost penetration depth, magnitude, and timing of surface heave, and the increase in earth pressure during thawing observed in the field. The predicted maximum heave was within approximately 15% of the measured field value, confirming the validity of the modeling approach.

5 ACKNOWLEDGEMENTS

This research was supported by a Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure, and Transport (RS-2022-00143644, Development of packaging design and integrated demonstration technology for oil production plant).

6 REFERENCES

Cai, H., Li, S., Liang, Y., Yao, Z., and Cheng, H. 2019. Model test and numerical simulation of frost heave during twin-tunnel construction using artificial ground-freezing technique. *Computers and Geotechnics* 115, 103155.

He, Y., Xu, Y., Lv, Y., Nie, L., Kong, F., Yang, S., Wang, H., and Li T. 2023. Characterization of unfrozen water in highly organic turfy soil during freeze–thaw by nuclear magnetic resonance. *Engineering Geology* 312, 106937.

Wu, Y., Zhai, E., Zhang, X., Wang, G., and Lu, Y. 2021. A study on frost heave and thaw settlement of soil subjected to cyclic freeze–thaw conditions based on hydro–thermal–mechanical coupling analysis. *Cold Regions Science and Technology* 188, 103296.