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Extended Abstract

# Comparative Analysis of Soil and Rock Behavior Under Freeze-Thaw Cycles: Applications in Structures and Petroleum Engineering in Cold Regions

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***Abstract***

The study of freeze-thaw cycles is significant due to their substantial impact on the stability of structures built in cold regions. Despite the existence of numerous models for predicting soil and rock behavior, no study has yet conducted a comparative analysis of these two media under identical thermal conditions. This research aims to bridge that gap using advanced numerical models. To this end, soil was simulated using the NTNU model in Plaxis software, while rock was modeled using the distinct element method in PFC2D software, both subjected to a shared thermal cycle (ranging from +1°C to -4°C over a two-hour period). The results demonstrated that, despite the irreversible behavior observed in both media, the mechanisms governing deformation differ significantly; in soil, the dominant phenomenon is ice segregation and the formation of ice lenses, leading to abrupt heave (approximately 2% volumetric strain) at -2°C, whereas in rock, the gradual growth of micro-cracks due to pore-water freezing results in a reduction of strength. The magnitude of change is far greater in soil than in rock, and critical temperature thresholds in rock occur at lower temperatures (-3°C). These findings indicate that soil behavior models, with appropriate calibration, can predict the behavior of highly porous rocks and have direct application in stability analysis for oil-related structures in cold regions.

## 1. Introduction

Freeze–thaw processes significantly influence the performance and long-term stability of porous geomaterials. Water expansion during freezing, generates internal stresses and can cause frost heave, progressive damage, and settlement during thawing [1],[2]. These effects are particularly important in cold regions such as Russia, Canada, northern China, and mountainous areas of Iran, where civil, mining, and petroleum-related infrastructure is frequently exposed to repeated temperature fluctuations [3].

The engineering significance of frozen ground and rock has been recognized since the early twentieth century, when frost heave and thaw settlement became major concerns in road construction and foundation design. More recently, the development of oil and gas projects in polar and cold regions has increased the need to understand the coupled thermo-hydro-mechanical response of frozen soils and rocks [4],[5]. Although several constitutive models have been developed for frozen soils, including the Alonso [6], Bishop [7],[8], and NTNU-based models [15,16], and numerous studies have examined the degradation of rock strength under freeze–thaw cycles [9],[10], direct comparisons between soil and rock under equivalent thermal conditions remain limited [11].

The objective of this study is therefore to

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compare the volumetric and mechanical responses of soil and rock subjected to freeze–thaw cycles. The analysis focuses on the differences between ice segregation and frost heave in soil and microcrack propagation in rock, with particular attention to their relevance to hydrocarbon reservoirs and cold region infrastructure.

## 2. Methodology

*2.1. Frozen soil model*

The NTNU model is a thermo-hydro-mechanical constitutive model for saturated frozen and unfrozen soils developed within the theoretical framework of Alonso's model. The formulation uses the solid-phase stress and cryogenic suction as principal state variables. Total strain is decomposed into elastic and plastic components associated with solid-phase stress and cryogenic suction. The model includes two principal yield surfaces: the loading-collapse surface and the grain-segregation surface. These surfaces enable the simulation of both mechanical loading and frost-induced particle separation [12],[13].

The soil specimen was represented by a cylindrical geometry with a diameter of 5 cm and a height of 20 cm. Owing to geometric symmetry, one quarter of the specimen was modeled in Plaxis. A confining pressure of 90 kPa was applied, and the temperature was varied sinusoidally. Simulations were performed for thermal cycle durations of 2h to evaluate the influence of cycle duration on volumetric response. For direct comparison with the rock model, the principal comparative case used a temperature range from +1 to -4°C and a duration of 2 h [9],[14].

*2.2. Frozen Rock model*

The rock response was simulated using the discrete element method in PFC2D. The specimen consisted of bonded rock-matrix particles and pore-water particles. The effect of freezing was represented through the temperature-dependent expansion of pore-water particles. Heat transfer was neglected, and a uniform temperature was assumed for the water particles at each stage of the thermal cycle [9],[15].

A parallel linear contact model was used to represent the mechanical interaction between particles. The model incorporates linear and bonded components acting in parallel. Key microscopic parameters included particle density and radius, porosity, stiffness ratio, tensile and shear bond strengths, friction coefficient, and internal friction angle. Acoustic emission and failure development were evaluated using the moment-tensor method, allowing tensile, shear, and mixed failure mechanisms to be identified. The modeled rock specimen had a diameter of 5 cm and a height of 10 cm [9],[16].

## 3. Results and Conclusions

*3.1. Soil response*

The soil response during cooling and heating can be divided into four stages. During cooling from $+1^{\circ}C$ to approximately $-2^{\circ}C$, the specimen undergoes elastic contraction caused by thermal shrinkage and the initial freezing of pore water. Between approximately $-2^{\circ}C$ and $-3^{\circ}C$, rapid frost heave develops as a result of ice segregation and ice-lens formation. This stage produces the largest volumetric change, with a volumetric strain of about 2%. From $-3^{\circ}C$ to $-4^{\circ}C$, the soil approaches a stable frozen state and the rate of volumetric deformation decreases.

During subsequent warming, melting causes thaw settlement and partial volume recovery. Nevertheless, the soil does not return to its initial state. A residual plastic strain of approximately $-0.003$ to $-0.004$ remains, indicating permanent structural rearrangement. The difference between the freezing and thawing paths confirms the existence of thermal hysteresis. Increasing the cycle duration from 2 to 12 h reduces the maximum frost-heave amplitude but increases the residual plastic strain. The surface region also experiences more pronounced strain fluctuations than the middle of the specimen, with differences of approximately 6.5%, indicating the role of thermal gradients and delayed heat penetration.

*3.2. Rock response*

Unlike soil, the rock does not exhibit a sudden frost-heave event. Its degradation occurs progressively through the initiation and propagation of microcracks caused by stresses generated by the freezing of water in pores. As the number of freeze-thaw cycles increases from 0 to 30, both uniaxial compressive strength and elastic modulus decrease approximately exponentially. This reduction reflects the progressive loosening of the mineral structure and the accumulation of internal damage.

The failure mode also changes with the number of cycles. Initially, the rock exhibits predominantly brittle failure. With continued cycling, the response changes to brittle–plastic and eventually becomes more plastic. The number of microcracks observed at the instant of failure decreases as the cycles increase, suggesting that a greater proportion of the damage develops before peak strength is reached. Joint inclination also affects the failure mechanism. A 30° joint angle promotes tensile failure and may lead to large-scale instability, whereas a 60° joint angle is associated mainly with shear failure and localized damage.

*3.3. Comparative Analysis*

Both materials show irreversible, history-dependent responses, but the mechanisms responsible for their behavior differ substantially. In soil, the dominant mechanism is the migration and segregation of water followed by ice-lens formation, which produces rapid frost heave and relatively large volumetric deformation. In rock, the dominant mechanism is the gradual accumulation of microcracks caused by pore-water expansion and mineral weakening. Accordingly, soil is more sensitive to temperature changes in terms of volumetric strain, while rock primarily exhibits progressive deterioration of strength and stiffness. The critical temperature points in rock occur at lower temperatures than the principal volumetric transition observed in soil.

*3.4. Conclusions*

The numerical comparison of frozen soil and saturated rock under a common freeze–thaw cycle leads to the following conclusions:

1. Both soil and rock exhibit irreversible and path-dependent behavior after freeze–thaw exposure.
2. Soil deformation is dominated by ice segregation and ice-lens formation, resulting in sudden frost heave and significant volumetric strain.
3. Rock degradation is controlled mainly by progressive microcrack growth and mineral-structure weakening, leading to reductions in compressive strength and elastic modulus.
4. Increasing the duration of the thermal cycle reduces the maximum frost heave but increases residual plastic deformation in soil.
5. Repeated freeze–thaw cycles change rock failure from brittle toward brittle–plastic and plastic behavior.
6. The volumetric response of soil is considerably larger than the mechanical variation observed in rock, whereas rock damage develops more gradually and becomes evident through strength and stiffness degradation.
7. These findings are relevant to the design and assessment of hydrocarbon reservoirs, foundations, pipelines, and other infrastructure in cold regions.

Future studies should investigate the effects of initial ice saturation and confining pressure, develop fully coupled thermo-hydro-mechanical models, and validate the numerical results through laboratory testing. Further research is also recommended for optimizing the design of petroleum-related foundations and facilities subjected to repeated freezing and thawing.

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