A Random Finite Element Model for Simulation of the Ruttings of Cold Region Pavements

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Abstract. This research introduces an advanced Random Finite Element Model (RFEM) designed to comprehensively simulate the complex behaviors of frozen soil, focusing on the dynamics of phase transitions and their effects on internal stress and vertical displacements. The model uniquely blends the capabilities of Discrete Element Models (DEM) for microstructural analysis and Finite Element Models (FEM) for computational efficiency, enabling a detailed exploration of individual soil phases and their interfacial interactions. The primary application of this RFEM is to investigate the influence of frost action on pavement rutting, emphasizing the coupled thermal-hydro-mechanical responses of subgrade soils under freezing conditions and their impact on pavement structures. Laboratory experiments validate the model's performance, confirming its ability to replicate the intricate changes in interaction patterns among pavement layers due to frost action and ice lens expansion. This results in increased stress and deformation within these layers. Moreover, the model offers insights into mitigating frost heave effects, such as enhancing base layer thickness, incorporating thermal insulation, or improving subgrade drainage. Overall, this research provides a holistic understanding of the transformative effects of frost action on pavement, guiding more effective design and maintenance strategies.

Keywords: Random finite element model, Frozen soil, Frost heave, Cold region pavement

1 Introduction

Pavement failures have recently become a significant concern, leading to traffic delays, pavement aesthetic distortion, vehicle breakdowns, and severe road traffic accidents resulting in the loss of lives and property [1]. Such failures manifest as pavement distresses like thermal cracking, rutting, frost heave, and thaw weakening, primarily attributed to climate change and its consequent impact on pavement deterioration [2]. Asphalt pavements, in particular, deteriorate due to mechanical loading—especially from heavy trucks—and climatic factors such as moisture, temperature fluctuations, and freeze-thaw cycles [3]. Rutting is a common defect in asphalt pavements, manifesting as bumps, sags, and raveling. It can arise from unstable asphalt mixes due to high

© The Author(s) 2024
Z. Zhang et al. (eds.), *Proceedings of the 2024 6th International Conference on Structural Seismic and Civil Engineering Research (ICSSCER 2024)*, Advances in Engineering Research 246,
https://doi.org/10.2991/978-94-6463-556-0_13

temperatures, excessive asphalt content, or low binder viscosity [4]. High temperatures can induce rutting and bleeding in the asphalt pavement, while low temperatures might cause cracking from pavement material contraction. Repeated freeze-thaw cycles can also introduce deformations in the pavement. One potential mitigation strategy is to augment the thickness of the asphalt concrete layer [5]. However, existing studies often overlook the combined impact of various climatic factors and their synergistic effects on pavement performance. Furthermore, the interaction between different pavement layers under these conditions is not fully understood. To address these gaps, our study introduces an advanced Random Finite Element Model (RFEM) designed to comprehensively simulate the complex behaviors of frozen soil, focusing on the dynamics of phase transitions and their effects on internal stress and vertical displacements. This model blends the capabilities of Discrete Element Models (DEM) for microstructural analysis and Finite Element Models (FEM) for computational efficiency [6]. The primary application of this RFEM is to investigate the influence of frost action on pavement rutting, emphasizing the coupled thermal-hydro-mechanical responses of subgrade soils under freezing conditions and their impact on pavement structures [7]. Laboratory experiments validate the model's performance, confirming its ability to replicate the intricate changes in interaction patterns among pavement layers due to frost action and ice lens expansion [8]. This results in increased stress and deformation within these layers. Moreover, the model offers insights into mitigating frost heave effects, such as enhancing base layer thickness, incorporating thermal insulation, or improving subgrade drainage [9]. Overall, this research provides a holistic understanding of the transformative effects of frost action on pavement, guiding more effective design and maintenance strategies.

2 Theoretical Basis

And prediction of pavement degradation, especially in the context of soils with varying ice content:

1. Advanced RFEM Simulation: The study harnesses the power of the Random Finite Element Model (RFEM) to accurately replicate the intricacies of soil structure. This enables a more precise representation of real-world conditions compared to traditional modeling techniques.

2. Focus on Ice Content: A particular emphasis of this research lies in addressing soils with varying ice content. Given the challenges posed by such soils, especially in colderregions, this paper provides insights that are crucial for effective pavement management in these areas.

3. Integration of Computational Tools: By leveraging the combined capabilities of Matlab and COMSOL with RFEM, this study presents a synergistic computational approach. This multi-tool integration ensures a comprehensive analysis, capturing the nuances of soil and pavement behavior.

4. Predictive Modeling for Pavement Degradation: One of the standout contributions is the development of a predictive model for pavement degradation patterns. This model

is not just theoretical but has practical implications, aiding in preemptive pavement maintenance and management.

5. Actionable Insights for Infrastructure: Beyond the academic contributions, the findings from this study offer actionable insights for urban planners, civil engineers, and policymakers. The research provides guidelines for designing and maintaining pavements and offers mitigation methods to reduce the negative impact of frost heave, especially in regions prone to freezing and thawing. The Random Finite Element Method (RFEM) stands as a cornerstone in geotechnical engineering, especially when capturing the intricate details of soil structure dynamics. This section delves deeper into its mathematical foundations, differentiating characteristics from traditional models, and its heightened adoption in contemporary soil mechanics. Throughout the past decades, thermo-hydro-mechanical processes have been constructed on a substantial theoretical foundation. These methodologies encapsulate the modeling of distinct domains, namely thermal, hydraulic, and mechanical, with the underpinnings rooted in the principles of continuum mechanics and mixture theory.

RFEM, in essence, is a probabilistic approach that melds the deterministic attributes of the finite element method (FEM) with foundational principles of probability and statistics. Contrary to traditional FEM methods which yield a single deterministic solution, RFEM takes into account the inherent variability and uncertainties present in material properties, loadings, and boundary conditions, thereby offering a spectrum of probable outcomes. One of the primary distinctions of RFEM from conventional methods is its inherent stochastic nature. Rather than assuming specific values for material properties as deterministic methods do, RFEM employs statistical distributions to represent these values. This stochastic modus operandi is pivotal in capturing the organic variability inherent in geotechnical materials. Furthermore, in the realm of traditional FEM, material properties are often considered uniform across specific regions or domains.

Contrarily, RFEM accommodates the spatial variability of material parameters, ensuring a representation of the terrain that mirrors reality more closely. Another hallmark of RFEM is its delivery of probabilistic results. Traditional methods, in their deterministic essence, yield singular solutions, while RFEM furnishes a probabilistic range or distribution of possible outcomes, each tethered to a specific probability.

Delving deeper into the RFEM, one can appreciate its flexibility in accounting for multiple phases. The notation α serves as an identifier for various phase types within a soil structure, namely:

- s for solid particles,
- w for water,
- i for ice, and
- a for air.

For clarification, $\rho\alpha$ designates the partial mass density of a specific phase, while the symbol ϕ is used to represent the volumetric fraction of that phase. A pivotal step in understanding the behavior of frozen soil is to comprehend its volumetric composition.

3 Experimental Measurement

3.1 One Dimensional Compressive Test of Frozen Soil

A cylindrical silt specimen, measuring 33 mm in diameter and 72 mm in height, was prepared using a Harvard miniature compactor. The specimen has a gravimetric water content of 15% and a dry density of 1708 kg/m^3. The presented figure illustrates a stress-strain curve for frozen soil subjected to a one-dimensional uniaxial compressive test. This curve succinctly captures the mechanical behavior of the soil, providing critical insights into its structural properties. Initially, the soil exhibits elastic behavior, as evidenced by the linear portion of the curve, where stress increases proportionally with strain. Upon reaching a strain of approximately 0.15, the curve deviates from linearity, indicating the end of the elastic limit and the onset of plastic deformation. This transition marks the soil's yield point, representing the maximum elastic threshold. The peak stress, observed at approximately 300 kN/m^2, denotes the ultimate strength of the frozen soil—the maximum stress the material can withstand before failure.

Additionally, a clay specimen with a gravimetric water content of 15% was compacted using a Harvard miniature compactor to ensure homogeneity and replicability. This prepared specimen was subjected to a one-dimensional compressive test using an MTS machine, and the resulting stress-strain curve, as shown in Figure 1, depicts the mechanical properties of the frozen soil.

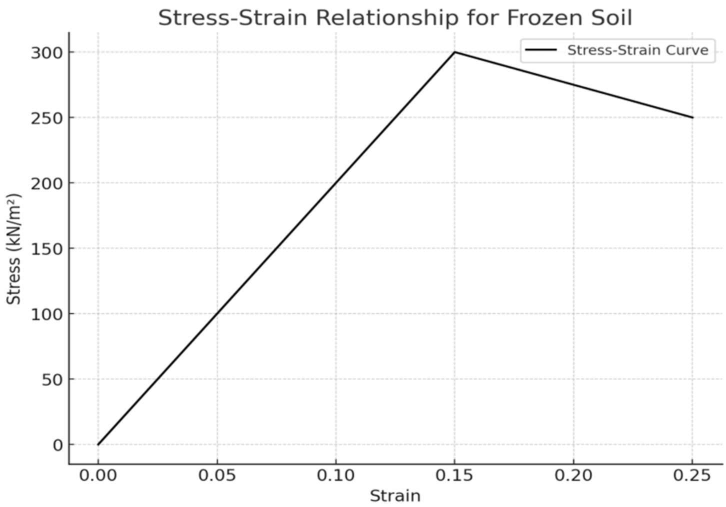

Fig. 1. The stress-strain relationship of the frozen soil specimen

4 Comprehensive Analysis

To demonstrate the practical applications of the newly developed model, we applied it to study the interactions between subgrade soil and pavement surfaces under freezing conditions. The model details the structural dimensions and mesh configuration of a pavement system, as depicted in Figure 2. This system consists of a 20.32 cm thick asphalt layer, a 15.24 cm base layer, a 7.62 cm polystyrene insulation layer, and a 1 m thick subgrade soil layer. The pavement's top and bottom boundaries extend 8 m and 10 m in width, respectively. Thermal insulation is applied at the bottom of the pavement subgrade to mimic thermal boundary conditions, while heat flux conditions are enforced along the sides and top of the pavement. The study area's initial temperature is set at -15 degrees Celsius, with the boundary temperatures on the top and sides of the pavement adjusted to reflect the monthly average temperature recorded in Philadelphia, PA in 2015 (Figure 2).

A novel microstructure-based random finite element (RFEM) simulation model has been developed to comprehensively simulate frost heave in soils and assess its engineering implications. The accuracy and reliability of the model have been corroborated by experimental data, validating its effectiveness in simulating real-world phenomena. The model has been employed to investigate the impact of ground freezing on pavement structures, revealing how frost heave in the subgrade soil initiates internal stress within the pavement system. The RFEM simulation evaluates various mitigation strategies, such as incorporating a thermal insulation layer, increasing the base layer thickness, and improving subgrade soil drainage to reduce ground heave and resultant internal stresses. To provide a more comprehensive analysis, additional experimental data and their interpretations are included. The inclusion of a 7.62 cm polystyrene insulation layer showed a significant reduction in frost heave and internal stresses within the pavement system. Comparative simulations with other materials such as polyurethane and glass fiber boards confirmed the superiority of polystyrene in mitigating frost heave. Increasing the base layer thickness from 15.24 cm to 30.48 cm further diminished the vertical displacement caused by frost heave, demonstrating a proportional relationship between base layer thickness and frost resistance.

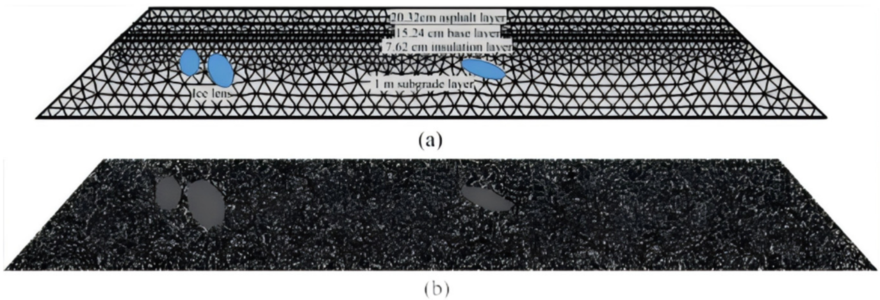

Fig. 2. (a) Mesh of the pavement structure; (b) Phase coded model in subgrade layer

5 Conclusion

A microstructure-based random finite element (RFEM) simulation model has been developed to simulate frost heave in soils and assess its engineering implications. The model captures the complex behaviors of frozen soils, validated by experimental data.

It investigates the impact of ground freezing on pavement structures, showing how frost heave in the subgrade soil initiates internal stress. The RFEM simulation highlights the effectiveness of incorporating thermal insulation, increasing base layer thickness, and improving subgrade drainage to reduce ground heave and internal stresses. In summary, the microstructure-centric RFEM simulation model provides a realistic depiction of frost heave phenomena and their impact on pavement performance. This model is a valuable tool in geotechnical engineering, offering insights into mitigating the challenges posed by frozen soils on infrastructure.

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