

Lab-to-Field Characterization of Sand-Silt Mixtures in Cold Regions

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ABSTRACT: Fines fraction impacts soil behavior, affecting load-bearing, volumetric response, and shear properties, especially in frozen soils. Freeze-thaw cycles and ice bonding further alter strength and stiffness in extreme regions. This study investigates the mechanical behavior and strength characteristics of frozen sand-silt mixtures, emphasizing the effects of silt fraction. Ice bonding and silt fraction influence the fracture mode, transitioning from brittle splitting to ductile shear as silt content increases. Void ratio and frozen water content are also affected by silt fraction, underscoring its importance in evaluating the strength and stiffness of frozen soils. To facilitate field applications, an instrumented dynamic cone penetrometer (IDCP) was developed, providing a reliable correlation between the strength index and shear strength of frozen sand-silt mixtures. The energy-corrected dynamic cone penetration index (EDCPI) is introduced as an effective tool for assessing shear strength. The IDCP was tested in extreme environments and compared with traditional laboratory methods, including the California bearing ratio (CBR) and stiffness tests. Results highlight the critical role of particle size distribution in Arctic soils, where small particles can disrupt the load-bearing skeleton formed by larger particles. This research provides insights for evaluating and designing infrastructure in cold regions.

KEYWORDS: dynamic cone penetrometer, fines fraction, freeze-thaw, strength, volumetric response.

1 INTRODUCTION

Estimation of mechanical behavior of soils under extreme environmental conditions is important in geotechnical engineering, particularly for infrastructure built in cold regions (Korshunov et al., 2016; Kim et al., 2024). Seasonal freeze-thaw cycles and repetitive mechanical loads significantly alter the fabric and performance of soils, leading to challenges in the design and maintenance of embankments, pavements, and foundations (Wang, 2017; Lee et al., 2020). The formation of ice within the pore spaces changes the volume and impacts the bonding between particles, thereby influencing strength and stiffness when the soils undergo freezing (Huang et al., 2022). During thawing, the bonds dissipate, resulting in potential settlement or loss of structural integrity (Zhang and Michalowski, 2015; Xu et al., 2025). As climate change accelerates, the cycles are expected to become more frequent and severe, emphasizing the need for a deeper understanding of the cumulative effects.

A critical aspect of soil response in the environments is the role of fines (i.e., particles that pass the 0.075 mm sieve) and fill the voids among larger grains. Fines content can fundamentally shift the dominant load-carrying mechanisms within a granular matrix, from coarse-controlled to fine-controlled behavior (Park and Santamarina, 2017). At lower fines fractions, fines primarily fill intergranular spaces and contribute to denser packing (Yeo et al., 2023). Conversely, at higher fractions, they create a continuous matrix that reduces drainage and alters stiffness (Park et al., 2023). This dual role complicates predictions of strength and deformation, especially when freeze-thaw cycles further modify the distribution and state of pore water.

Repetitive mechanical loading, such as that induced by traffic or cyclic environmental forces, also plays a critical role in soil evolution over time. The loads can drive soils towards a terminal void ratio, compacting or loosening the soils depending on the initial density and composition (Cha et al.,

2023). The combination of cyclic loading and freeze-thaw processes introduces complex interactions that standard laboratory methods often fail to capture comprehensively. Thus, integrating advanced instrumentation and field validation is essential for bridging the gap between controlled experiments and real-world performance.

The objective of this study is to investigate the effects of freeze-thaw cycles, repetitive loading, fines content, and particle size distribution interaction in cold regions. Laboratory experiments included uniaxial compression, direct shear, and triaxial tests with instrumentation of sensors. Field tests were conducted to evaluate the applicability of laboratory-derived correlations. By developing characterization methods and integrating multiple datasets, the research aimed to improve predictive models for soil performance in challenging environments.

2 LAB STUDY

2.1 Freeze-Thaw Effects Under Deviatoric Load

The experimental setup focused on the exploration of soils during repeated freezing and thawing while subjected to constant deviatoric stress. Sand and clay specimens were consolidated isotropically and loaded with a deviatoric component before undergoing 10 freeze-thaw cycles. The temperature, vertical deformation, and pore water pressure were monitored to investigate the volumetric and shear responses.

In sands, ice formed by infiltrating the pore spaces between grains, a mechanism referred to as pore-invasive ice formation (Liu and Santamarina, 2022). This led to modest expansion during freezing and contraction during thawing. The overall void ratio evolved toward a stable asymptote over repetitive cycles. In contrast, clay specimens displayed grain-displacive ice formation, where ice lenses developed by displacing soil particles (Liu et al., 2022). This resulted in substantial fabric changes and higher susceptibility to pore

pressure buildup during thawing. In particular, thawing cycles induced pronounced deviatoric strain accumulation in clays, associated with the thawing of segregated ice lenses, which created localized zones of weakness. Regardless of drainage condition, both soils exhibited “ratcheting,” a pattern of continuous shear deformation accumulation over cycles (Kim et al., 2021).

Drainage conditions played a critical role. Under undrained conditions, pore water pressures increased significantly, especially in clays, threatening mechanical stability. Drained condition moderated pressure increases; however, it cannot eliminate volumetric contraction or deviatoric strain. The observations confirmed that the interplay between ice formation habit and boundary drainage conditions determines the degree of fabric disruption and the evolution of soil strength during freeze-thaw processes.

Pore-habits – Conceptual Figures

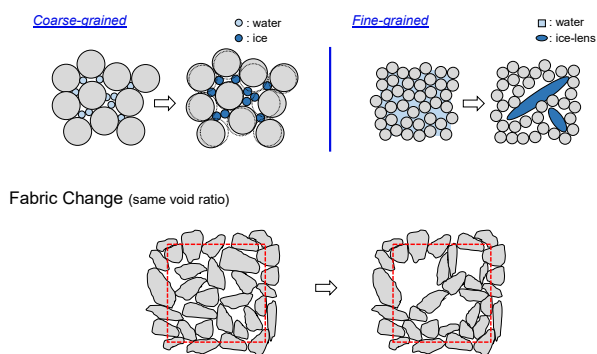


Figure 1. Conceptual drawings of pore habits and fabric change before and after freezing.

2.2 Repetitive Mechanical Loading of Sand-Silt Mixtures

To explore the effect of repeated loading on coarse-fine mixtures, sand-silt specimens with varying fines fractions were subjected to Ko-loading cycles. Each mixture evolved toward a characteristic terminal void ratio regardless of the initial packing state. The terminal void ratio represented a state beyond which additional loading produced minimal volume change.

Shear wave velocity, measured after each loading phase, served as an indicator of small-strain stiffness (Lee and Santamarina, 2005). Results showed that stiffness increased progressively in mixtures with higher fractions of rounded fine particles, which effectively participated in the load-bearing skeleton. Conversely, mixtures dominated by angular coarse particles retained more open structures and exhibited lower stiffness gains under repeated loading. This transition from coarse-dominant to fine-dominant behavior suggested that the traditional classification systems based on grain-size distribution are insufficient to capture the evolving mechanical response under cyclic loading (Kim et al., 2021). Instead, both fines fraction and particle shape should be considered to predict the long-term performance of granular soils subjected to repeated stresses.

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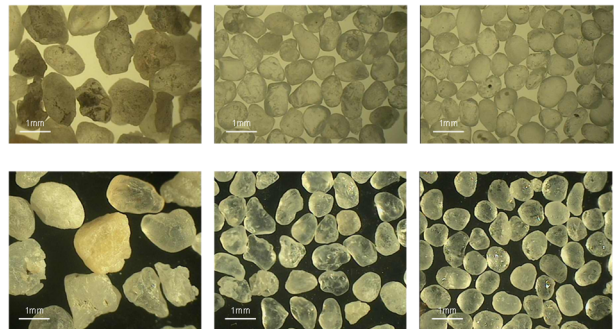


Figure 2. Images of used coarse particles with different particle size and angularity.

2.3 Strength of Frozen Sand-Silt Mixtures

Uniaxial compression tests were conducted on sand-silt mixtures frozen under controlled temperature to estimate the effects of fines content and frozen water. The specimens were prepared to fixed degrees of saturation and frozen, after which uniaxial loading was applied until failure. The results revealed a relationship between silt fraction, frozen water content, and mechanical strength.

Mixtures containing approximately 30% silt achieved the lowest void ratios and the highest unconfined compressive strength. As the silt fraction increased beyond 30%, strength declined, reflecting the transition from a coarse-dominant structure to a more ductile, fines-dominant matrix (Jiang et al., 2015). Ice bonding within pore spaces contributed substantially to strength increases with the critical role of frozen water in stabilizing particle contacts. Moreover, the fracture mode evolved with composition: clean sands failed in a brittle splitting mode, while silt-rich mixtures transitioned to more ductile shear failures (Kim et al., 2021). The observation emphasized that the degree of brittleness or ductility in frozen soils is not merely a function of temperature but is significantly governed by the interplay between ice and fines.

2.4 Direct Shear and Shear Wave Correlation

Specimens were prepared in the direct shear box instrumented with time domain reflectometry (TDR) probes and bender element (BE) to track volumetric water content and shear wave velocity before and after freezing and shearing. The frozen specimens were sheared under controlled normal stresses while deformation and wave propagation were recorded.

Results demonstrated that peak shear strength correlated linearly with volumetric frozen water content. This relationship confirmed that the ice bonding significantly determines the strength (Chai et al., 2017). Similarly, shear wave velocity after freezing exhibited a strong positive correlation with frozen water content, suggesting that non-destructive wave-based techniques can effectively predict stiffness due to freezing (Kim et al., 2018). Residual strength and pre-freezing wave velocities were also influenced by silt fraction, indicating that particle packing and the initial moisture condition both contribute to the load-carrying capacity.

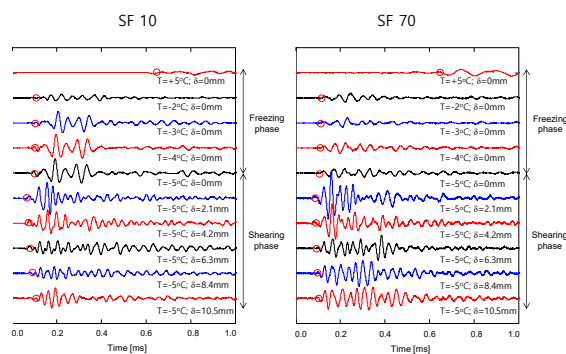


Figure 3. Typical shear wave signals of sand-silt mixtures during freezing and shearing phases.

3 FIELD STUDY

3.1 Instrumented Dynamic Cone Penetrometer (IDCP)

To extend laboratory characterization with field applications, a instrumented dynamic cone penetrometer (IDCP) was developed. The IDCP incorporated strain gauges and accelerometer to measure the force and energy transmitted to the cone tip during penetration (Park et al., 2023). This allowed calculation of the energy-corrected dynamic cone penetration index (EDCPI) to correlate strongly with laboratory-determined shear strength.

Calibration tests were conducted in a freezing chamber under different vertical confining stresses. The results indicated that while both freezing phase and testing phase confinement affected penetration resistance, the stress applied during testing had a more pronounced impact. The EDCPI was inversely proportional to measured shear strength, validating the utility for field strength estimation. The result provides a rapid, reliable alternative to traditional sampling and laboratory testing in cold regions where expedient assessment is essential (Kim and Lee, 2020).

3.2 Field Application and Soil Characterization in Active Layers

Field trials were performed on natural sands collected from Arctic active layers exhibiting a wide range of gradation and organic content. California bearing ratio (CBR) tests, mini-cone penetration, and shear wave velocity measurements were carried out. Results confirmed that soils with higher coefficients of uniformity (C_u) generally showed lower strength and stiffness due to less interlocking and greater void spaces.

CBR values decreased with increasing C_u , while dynamic penetration indices decrease, reflecting reduced resistance to penetration (Kim et al., 2019). The strong inverse correlation between CBR and DCPI, and the direct relationships with dynamic cone resistance and maximum shear modulus, indicated that particle size distribution remains a primary control on in-situ strength. The integration of IDCP and wave-based methods enabled a comprehensive, non-destructive evaluation of the properties, demonstrating the potential for routine characterization of cold-region soils.

4 CONCLUSIONS

This research provided a comprehensive exploration of the effects of freeze-thaw cycles, repetitive loading, and fines content on the mechanical behavior of granular soils.

Laboratory experiments demonstrated that the pattern of ice formation, whether pore-invasive or grain-displacive, fundamentally alters volumetric and shear response. Repetitive mechanical loading drives soils toward stable void ratios, and fines proportion critically governs both strength and deformation. Unconfined compression and direct shear testing confirmed that frozen water content substantially increases stiffness and strength through ice bonding. The development and field validation of the instrumented dynamic cone penetrometer established a rapid, reliable means for estimating in-situ strength. The remarkable observations are follow.

- Ice formation habits determine whether soils exhibit expansion or contraction and whether pore pressures build up during thawing, potentially compromising stability.
- Fines fraction plays a dual role in both strengthening soils through matrix formation and reducing brittleness through ductile failure modes.
- Repeated loading under constant stress conditions leads to predictable evolution toward terminal void ratios, emphasizing the need to account for long-term performance in design.
- Shear wave velocity and energy-corrected dynamic cone penetration indices provide robust proxies for estimating strength and stiffness, allowing for more efficient field assessments.
- Particle gradation remains a critical determinant of mechanical behavior and should be explicitly incorporated into predictive models for infrastructure design in cold regions.

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