

Cryosuction and Its Role in Infrastructure Distress from Freeze-Thaw Cycles

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Research Needs

Pavement systems in cold regions are subjected to repeated freeze-thaw cycles, leading to moisture migration, frost heave, and significant structural damage (Simonsen and Isacsson 1999; Yan et al. 2024; Yang et al. 2020). In the United States, 70% of pavement infrastructure involve low-volume roads, and half of these are located in seasonal frost areas (Kestler et al. 2011; Mahedi et al. 2019). Cryosuction, a phenomenon where moisture is drawn toward freezing fronts in soil due to negative pore water pressure, plays a crucial role in this phenomenon. The distribution of water caused by cryosuction amplifies frost heave, accelerates deterioration, and compromises the long-term performance of pavements (Rosa et al. 2017). Despite its critical impact, the specific role of cryosuction in moisture migration and subsequent pavement damage remains poorly understood, particularly when interacting with varying soil types, thermal gradients, and pavement materials. The coexistence of ice and unfrozen water in the soil pores is the most fundamental property of frozen soils whose study requires consideration of phase change and freezing points (Dall'Amico et al. 2011; Hu et al. 2020; Huang and Rudolph 2023; Thomas et al. 2009). It is known that frost heave is caused not only by freezing in-situ pore water, but also by water flowing to the freezing front (Kim et al. 2008). This water flow is induced by cryosuction that develops in the frozen soil in response to the temperature gradient in the soil mass and water migrates into the frozen zone where it freezes to form an ice lens (Zheng

et al. 2023). Cryosuction contributes to moisture migration by drawing water towards freezing zones, leading to: (a) frost heave and (b) post-thaw weakening (Zhang et al. 2025). Frost heave is the accumulation and subsequent freezing of water cause the pavement to lift, leading to surface deformations. Whereas, post-thaw weakening upon thawing, the previously frozen water can lead to increased moisture content in the pavement structure, potentially weakening the material and reducing its load-bearing capacity.

The effect of freeze-thaw (F-T) cycles on soil freezing characteristic curve (SFCC) is an essential topic. SFCC depends on a variety of factors such as pore size distribution, initial water content of soil, capillarity, surface tension, curvature of ice-water interface, rate of cooling, super cooling effect, contact angle, presence or absence of bubbles nucleation site in soil mass, and others (Bai et al. 2018; Koopmans and Miller 1966; Li et al. 2023, 2024; Li and Vanapalli 2023; Meng et al. 2024; Teng et al. 2020; Wang et al. 2017; Wu et al. 2015, 2023). However, effect of F-T cycles on SFCC has not been extensively examined (Ren and Vanapalli 2020). Limited research exists, such as studies by Kozlowski & Nartowska (2013) on bentonite and He & Dyck (2013) on silty loam and loamy sand. However, these studies either lacked comparison of freezing branches across cycles or were constrained by experimental limitations (Ren and Vanapalli 2020). The recent concerns of extreme weather condition and the increased occurrence of F-T cycles, it is necessary to investigate their effect on the SFCC of different natural soils and the role of cryosuction in moisture distribution. It is important to understand the ground freezing correlating with cryosuction and its potential changes in soil characteristics to avoid future damage to geotechnical structures like foundation, pavement and pipelines due to frost heave or other volume change phenomena especially in the region with significant freeze-thaw cycle. Some of the damage to pavement systems in the region due to freeze-thaw cycles are shown in Figure 1.



Figure 1. Pavement distress due to frost heave during freeze-thaw cycles

The current understanding of moisture migration in pavement systems during freeze-thaw cycles does not adequately consider the effects of cryosuction. Laboratory studies, field observations, and numerical models rarely isolate or quantify the contribution of cryosuction, limiting their utility for real-world applications. As a result, engineers lack reliable tools to predict the extent of damage caused by cryosuction or implement effective mitigation techniques. This gap in knowledge hinders efforts to improve pavement performance and resilience in cold climates.

Research Objectives

The primary objectives of this research are to:

- 1. Quantify the influence of cryosuction on moisture migration during freeze-thaw cycles in pavement systems.
- 2. Investigate the interactions between cryosuction, soil properties, soil salinity, and climatic condition.
- 3. Develop a method to determine the soil freezing characteristic curve and compare it with soil water characteristic curve for different salinity levels.

Research Methods

The proposed project involves the measurement of soil suction and determination of SFCC and SWCC for different soil salinity levels. The fabrication of the setup needed for the study is detailed in a later section. The measurement of suction in frozen soils will be conducted using suction probes. The volumetric moisture content and electrical conductivity of the soil at different levels of salinity will be measured from appropriate sensors. These sensors have been calibrated for application and testing. The SWCC will be obtained by using the dew point potentiometer (W4PC) and HYPROP 2 from the METER GROUP, INC. The SFCC will be obtained by using the experimental setup that will be fabricated in the laboratory. The changes in volume due to frost heave will be measured by using the linear variable displacement transducer (LVDT) with data logger. The standard geotechnical tests will be conducted as per the ASTM standards. All insulation materials will be selected and used for testing after rigorous verification of its insulation.

Relevance to Strategic Goals

The expected outcomes of the proposed project are directly related to the strategic goals, such as Transformation where the project informs the design of infrastructure for the future. The aim would be to modernize a transportation infrastructure system that will serve everyone in the decades to come. From the proposed project, enhanced material behavior prediction when subjected to freeze-thaw cycles will aid in the design of resilient pavements. This increased quality of the pavements that will cater to the conditions of Region 8 will result in better rehabilitated pavements that will have better ride quality for the users and increase the life of the pavement between repairs. Addressing the issues of distresses from freeze-thaw cycles will result in fewer maintenance activities during the life of the pavement. This will lead to higher savings and decreased user cost in the form of loss of time due to slower traffic during construction and less vehicle maintenance cost due to better ride quality. This would also lead to Economic Strength and Global Competitiveness.

Educational Benefits

The project will provide valuable learning experience for the graduate student working on the project. Undergraduate students will be hired and will be working along with the graduate student, where he/she will learn the fundamentals of how experimental research is conducted. The PI (Banerjee) will be guiding the undergraduate researcher and ensure that he/she learns not only about soil mechanics and geotechnical testing but also about teamwork, planning, and work ethics. The findings from the study will be incorporated in a graduate course on Soil Behavior.

Overall, one undergraduate student and one graduate student will be working on the project and gain direct experience.

Outputs through Technology Transfer

The primary form of technology transfer would be through the final report and dissemination through journal publications and presentations at conferences. The target conferences include the ASCE annual Geo-Congress and Transportation Research Board (TRB) Annual Meetings in Washington, DC. The latter has a broader participation and includes personnel from various universities, FHWA, various state DOTs, and private agencies. These presentations and classroom teaching will aid in building a stronger transportation workforce which is a major portion of CTIPS mission and vision. The findings will be summarized and shared with the local DOT engineers to disseminate the findings.

Expected Outcomes and Impacts

The essential outcome of this proposed study is to develop a quantitative understanding of the role of cryosuction in moisture migration and frost heave and to compare the SFCCs and SWCCs for one soil type at different salinity levels. The impact of the study would be to enhance the design of pavement systems for regions experiencing pavement distresses from freeze-thaw cycles. Due to the current concern regarding the impact of extreme weather conditions and more frequent freeze-thaw cycles, this study will highlight the need to consider cryosuction and soil salinity levels in the life-cycle cost analysis. It is expected that properly designed systems reduce the risk of premature failure and thereby reduce the cost and frequency of pavement maintenance.

Work Plan

Various tasks have been planned to reach the research objectives to understand the role of cryosuction in moisture distribution in frozen soils.

Task 1: Conduct literature review of the role of cryosuction in soils and related distresses in pavement due to freeze thaw cycles

A detailed review of literature will be conducted will conducted to inform the research team regarding the influence of cryosuction in understanding the moisture distribution in soils and resulting distresses in infrastructure systems such as pavements and bridge approach slabs. The effect of soil salinity and saltwater intrusion on cryosuction will also be investigated through a literature review.

Task 2: Fabricate an experimental setup to determine cryosuction in soils

A setup will be fabricated that will involve soil sensors such as moisture and suction probes being imbedded in compacted soil and will be insulated from the sides to control the thermodynamic conditions. The setup may be placed in a large-scale low temperature chamber to maintain cold conditions when needed. Different setups will be fabricated to allow multiple samples to be tested and to accelerate testing times. The setup will be frozen from the surface, while thawing is also initiated from the surface to replicate practical conditions in the field. The humidity, air temperature, soil temperature, and frost penetration depth will be recorded. The frost heaves and thawing-induced subsidence will be measured by using linear variable differential transformers (LVDTs).

Task 3: Soil selection, characterization, and determination of soil salinity levels

Frost-susceptible soils from the region will be selected for the study. Typically frost-susceptible soils are silty soils. A series of basic geotechnical tests for determining the soil properties, such as standard Proctor tests, grain-size distribution, Atterberg limits, specific gravity will be conducted, and the soil will be classified. Different soil salinity levels will be considered for the study such as 0 (control), 5,000 ppm, and 35,000 ppm, which would simulate low to very high soil salinity levels. Soil salinity will be induced by managing the concentration of salts such as sodium chloride, calcium carbonate, potassium chloride, and magnesium sulfate in native soil. The specific surface area and pore size distribution of the compacted soil will be determined by using the mercury intrusion porosimetry. The thermal properties such as thermal conductivity and heat capacity of the soil will be measured by using appropriate equipment such as thermal properties analyzer.

Task 4: Effect of soil salinity on cryosuction

A series of tests will be conducted where the compacted soil at different levels of soil salinity will be frozen, and water will be infiltrated from the surface at a predefined rate. The setup will be maintained at a predefined temperature just above freezing conditions. The distribution of water in the chamber will be studied by using the embedded sensors and compared against that for control sample where the soil will be in unfrozen condition but at similar temperature above freezing conditions to avoid the issues of change of soil permeability and viscosity of water with temperature. For all tests, the initial moisture in the chamber will be monitored to mitigate the effect of changes of soil permeability due to change in matric suction. Parametric studies will be conducted by changing the variables such as temperature used to freeze the soil sample, temperature used to induce thawing, varying number of freeze-thaw cycles, and changes in initial degree of saturation of the soil sample. These will recreate different conditions to simulate different climatic conditions.

Task 5: Develop and compare the Soil Freezing Characteristic Curve (SFCC) and Soil Water Characteristic Curve (SWCC) for different soil salinity levels

A series of tests will be conducted on the test at different salinity levels to determine the soil water characteristics curve (SWCC). The dew point potentiometer like WP4C, tensiometers like HYPROP2, and filter paper technique will be used to determine the SWCC. The SFCC will be determined by using soil sensors such as those for measuring volumetric water content, electrical conductivity, and suction. The variation of volumetric water content in the presence of ice will be studied using a procedure as mentioned by other researchers (Zhou et al. 2014). The variation of cryosuction with soil salinity, compaction, and initial degree of saturation will be studied.

The SFCC and SWCC will be compared for frozen and unfrozen conditions for different salinity levels. A model for SFCC will be developed or modified based on the previous studies (Azmatch et al. 2012; Bai et al. 2018; Li et al. 2023, 2024; Noh et al. 2012; Teng et al. 2020; Wang et al. 2017; Wu et al. 2023). The changes to the freezing temperature due to soil salinity will be explored as it dictates the generation of cryosuction in soil.

Task 6: Identify the parameters that affect the SFCC

The variables used in the study in Task 5 along with the detailed literature review conducted in Task 1 will be used to identify the factors affecting SFCC. The major parameters governing SFCC will be estimated as not well established in the literature, and it will be determined how

these parameters may vary with soil salinity and other environmental and thermodynamic factors. This will aid in developing advanced models for SFCC for a variety of soil and climatic conditions.

Task 7: Project deliverables including final report and dissemination of findings.

At the completion of the project the research findings will be compiled in the final report and disseminated through journal publications and conference papers.

TASK	YEAR/MONTH		YEAR 1				YEAR 2																		
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1. Literature review																									
2. Fabricate an experimental cryosuction in soils	setup to determine																								
3. Soil selection, characteriza of soil salinity levels	tion, and determination																								
4. Effect of soil salinity on cryosuction																									
Develop and compare SFCC and SWCC for different soil salinity levels																									
6. Identify the parameters that affect the SFCC																									
7. Submit final report and disseminate research findings																									

Project Cost

Total Project Costs:	\$147,000
CTIPS Funds Requested:	\$ 70,000
Matching Funds:	\$ 77,000
Source of Matching Funds:	SDSU Foundation – \$20,000
-	South Dakota State University – \$57,000

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