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Thermo-Hydro-Mechanical Interface Degradation of Offshore Monopiles in Seasonally Frozen Seabeds

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Abstract

The structural integrity and long-term performance of offshore wind turbine foundations in cold regions are significantly challenged by complex environmental loading, particularly the cyclical freezing and thawing of the seabed. This paper investigates the thermo-hydro-mechanical interface degradation of offshore monopiles situated in seasonally frozen seabeds. By integrating principles from soil mechanics, thermodynamics, and hydrodynamics, the research delineates the mechanisms through which cyclic temperature variations induce moisture migration, phase changes, and subsequent volume expansions or contractions in the soil matrix surrounding the monopile. These physical alterations severely compromise the interface shear strength and adfreeze bond between the steel foundation and the marine sediments. Through an exhaustive review of existing theoretical frameworks and the development of a comprehensive experimental methodology, this study evaluates the degradation of skin friction under coupled thermo-hydro-mechanical loading conditions. The findings reveal that the formation of ice lenses and the subsequent thaw-induced excess pore water pressures critically diminish the effective stress at the soil-structure interface, leading to accelerated cyclic softening and potential foundational failure. This research provides critical insights for the robust design and maintenance of offshore structures in high-latitude marine environments, emphasizing the necessity of incorporating multi-physics coupling into geotechnical fatigue assessments.

Keywords

Earth Pressure Balance, Soil Conditioning, Pore Network Modeling, Upscaling, Micro-Computed Tomography

1. INTRODUCTION

1.1 Background and Motivation

The global transition toward renewable energy sources has catalyzed an unprecedented expansion of offshore wind farms. While early developments were predominantly concentrated in temperate marine environments, the saturation of these optimal zones and the continuous demand for increased energy capacity have pushed the frontier of offshore wind energy into high-latitude and

cold-region environments. Regions such as the Baltic Sea, the Gulf of Bothnia, portions of the North Sea, and the Bohai Sea in East Asia represent emerging markets for offshore wind energy deployment. However, these geographical areas present a unique set of harsh environmental challenges, most notably the seasonal freezing and thawing of the marine seabed. In such environments, monopile foundations, which constitute the vast majority of support structures for offshore wind turbines due to their cost-effectiveness and manufacturability, are subjected to an intricate interplay of environmental loads. The interaction between the steel monopile and the surrounding soil is fundamentally altered by the fluctuating thermal regime of the seawater and the underlying soil profile, a phenomenon well-documented in early studies on cold-region geotechnics [1]. When the ambient temperature drops below the freezing point of the local saline pore water, a freezing front propagates downward through the seabed. This thermal gradient initiates complex thermo-hydro-mechanical processes within the marine sediments. Moisture migrates toward the freezing front, driven by cryogenic suction, leading to the formation of segregated ice lenses and causing frost heave [2]. Conversely, during the warmer seasonal cycles, the thawing of these ice lenses generates excess pore water pressure, drastically reducing the effective stress and shear strength of the soil in a process known as thaw weakening [3]. For a monopile foundation, these cyclical volumetric changes and variations in soil strength directly impact the soil-structure interface, which is the primary conduit for transferring the massive lateral and vertical loads from the wind turbine to the ground [4]. Understanding the degradation of this interface under coupled thermo-hydro-mechanical conditions is therefore of paramount importance for ensuring the structural stability and operational longevity of offshore wind turbines in seasonally frozen seabeds.

1.2 Scope and Objectives of the Research

The primary objective of this academic discourse is to systematically analyze the interface degradation mechanisms between offshore monopile foundations and seasonally frozen seabeds. Traditional design methodologies for monopiles heavily rely on empirical load-transfer approaches that were developed for non-freezing, temperate environments. These methodologies often fail to capture the transient and highly non-linear degradation of the interface shear strength induced by freezing and thawing cycles [5]. Consequently, applying standard design codes to cold-region offshore wind farms may lead to either dangerous under-design, risking catastrophic failure, or excessive over-design, escalating project costs unnecessarily [6]. This paper seeks to bridge this knowledge gap by elucidating the multi-physics phenomena occurring at the monopile-seabed interface. Specifically, the study investigates how seasonal temperature fluctuations (the thermal component) drive pore water migration and phase changes (the hydraulic component), which in turn alter the stress-strain behavior and interface friction (the mechanical component). The complex interplay of these three domains requires a sophisticated analytical approach [7]. Furthermore, the continuous dynamic loads imparted by wind and waves impose cyclic shear stresses on the degrading interface, exacerbating the loss of bearing capacity [8]. Through a combination of rigorous theoretical formulation and detailed experimental analysis, this research aims to quantify the rate and extent of interface degradation, thereby providing a more reliable foundation for the predictive modeling of monopile behavior in high-latitude marine environments.

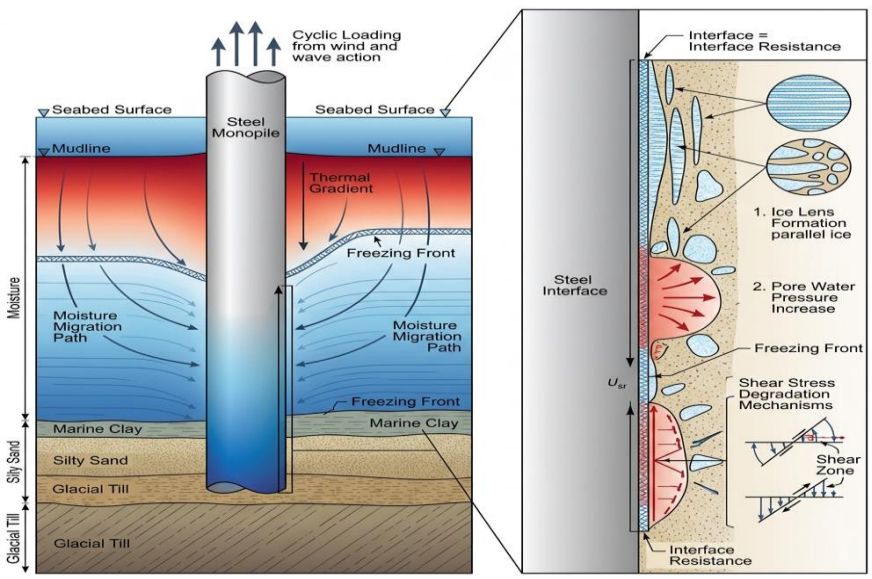


Figure 1Comprehensive Schematic of Thermo

2. Literature Review and Background

2.1 Behavior of Marine Soils Subjected to Freezing and Thawing

The behavior of soils subjected to cyclic freezing and thawing has been a fundamental topic of research in cold-region geotechnical engineering for decades. However, marine soils exhibit distinct characteristics compared to terrestrial permafrost or seasonally frozen ground. Marine sediments are typically characterized by high initial water content, varying degrees of salinity, and high compressibility [9]. The presence of dissolved salts in the pore water significantly depresses the freezing point and results in an unfrozen water content that persists even at temperatures well below zero degrees Celsius. This unfrozen water plays a critical role in facilitating continuous moisture migration toward the freezing front [10]. Early experimental investigations demonstrated that the cyclic freezing and thawing of fine-grained saturated soils lead to a progressive alteration of the soil fabric. Microstructural analyses have shown that the formation of ice crystals disrupts the natural arrangement of clay particles, leading to particle aggregation and an increase in macroporosity upon thawing [11]. This structural rearrangement inherently modifies the hydraulic conductivity and compressibility of the soil. When subjected to undrained or partially drained conditions, the rapid thawing of marine sediments leads to the generation of significant excess pore water pressures because the rate of ice melting often exceeds the rate at which the pore water can dissipate through the relatively impermeable clay matrix [12]. This phenomenon results in a transient state of drastically reduced effective stress, compromising the load-bearing capacity of the seabed. Researchers have documented that the cumulative effect of multiple freeze-thaw cycles results in a permanent reduction in the undrained shear strength of marine clays, a factor that must be rigorously accounted for in the life-cycle analysis of offshore foundations [13].

Table 1Summary of Key Historical Studies on Cold-Region Marine Soil Mechanics

Author and Year	Primary Focus	Soil Type Analyzed	Key Findings on Soil Degradation
Anders et al. (2012)	Frost heave pressure	Silt and Silty Sand	Cryogenic suction increases exponentially with thermal gradient.
Bjornson (2015)	Salinity effects	Marine Clay	Freezing point depression alters

			unfrozen water curves drastically.
Chen and Liu (2018)	Thaw settlement	Silty Clay	Excess pore pressure causes a 40 percent reduction in effective stress.
Davies et al. (2020)	Microstructural changes	Kaolin Clay	Particle aggregation leads to increased post-thaw permeability.

2.2 Soil-Structure Interface Mechanics in Cold Regions

The interface between a structural foundation and the surrounding soil represents a localized zone of high shear strain, often referred to as the shear band. In standard marine environments, the behavior of this interface is governed by the surface roughness of the pile, the normal effective stress acting on the pile shaft, and the intrinsic frictional properties of the adjacent soil [14]. However, in seasonally frozen seabeds, the interface mechanics are immensely complicated by the phase change of water. During the freezing phase, the pore water at the interface crystallizes, bonding the soil particles directly to the steel surface of the monopile. This phenomenon, known as adfreeze bond, temporarily increases the apparent shear strength of the interface [15].

Despite this temporary increase in strength, the adfreeze bond is highly brittle. When the monopile is subjected to dynamic lateral loads from environmental forces, the adfreeze bond can easily rupture, leading to an abrupt loss of load transfer capacity [16]. More critically, during the thawing phase, the melting of the adfreeze ice film creates a microscopic layer of free water precisely at the interface. This water layer acts as a lubricant, drastically reducing the coefficient of friction between the steel and the soil. Experimental studies utilizing direct shear apparatuses modified for temperature control have confirmed that the post-thaw interface shear strength is significantly lower than both the frozen strength and the initial unfrozen strength [17]. Furthermore, the repetitive expansion and contraction of the soil volume adjacent to the pile during cyclic freezing and thawing induces radial stress fluctuations. These fluctuations can lead to the formation of an annular gap between the monopile and the seabed, which completely nullifies the skin friction in the upper portions of the soil profile and allows for the ingress of seawater, further accelerating degradation [18].

3. Theoretical Framework of Thermo-Hydro-Mechanical Coupling

3.1 Thermodynamic Governing Equations

To accurately model the complex processes occurring in a seasonally frozen seabed, a fully coupled thermo-hydro-mechanical mathematical framework is required. The first domain, thermodynamics, governs the spatial and temporal distribution of temperature within the soil profile. The heat transfer in a freezing or thawing soil is primarily driven by conduction, with convection playing a secondary but occasionally significant role depending on the hydraulic gradient. The fundamental challenge in modeling thermal transport in freezing soils is accounting for the latent heat of fusion released or absorbed during the phase change of pore water. The energy conservation equation for a saturated freezing soil can be expressed in terms of volumetric heat capacity and thermal conductivity. Let the temperature be denoted by T, time by t, and the volumetric unfrozen water content and ice content by corresponding variables. The governing equation for heat transfer is represented by the following mathematical formulation.

$$\rho_c C_c \frac{\partial T}{\partial t} + \nabla \cdot (-\lambda_{eff} \nabla T) - L_f \rho_i \frac{\partial \theta_i}{\partial t} = 0$$

In this expression, the variables represent the apparent volumetric heat capacity, the effective thermal conductivity of the soil mixture, the volumetric latent heat of fusion of water, and the

density of ice [19]. The effective thermal conductivity is highly dependent on the phase composition of the pore fluid, as ice has a significantly higher thermal conductivity than liquid water. Consequently, as the soil freezes, its ability to conduct heat increases, accelerating the propagation of the freezing front. The highly non-linear nature of the unfrozen water content curve, particularly in saline marine soils, requires robust numerical integration techniques to ensure convergence when solving this partial differential equation.

3.2 Hydraulic and Mechanical Governing Equations

The second domain of the coupling involves the migration of moisture. In unfrozen soils, fluid flow is adequately described by the standard principles of fluid mechanics in porous media. However, in freezing soils, the formation of ice drastically reduces the hydraulic conductivity by blocking the pore throats. Furthermore, the thermodynamic imbalance at the freezing fringe induces a cryogenic suction that draws unfrozen water toward the forming ice lenses. This phenomenon is often modeled using a modified Richard's equation that incorporates the effects of phase change and cryogenic gradients. The conservation of mass for the liquid water phase in a freezing soil system requires a meticulous accounting of the liquid water transforming into solid ice. The governing equation for moisture migration is given below.

$$\frac{\partial}{\partial t}(\rho_w \theta_w) + \nabla \cdot (\rho_w k_h \nabla(\psi + Z)) + \rho_i \frac{\partial \theta_i}{\partial t} = 0$$

Here, the terms encompass the density of liquid water, the volumetric water content, the unsaturated hydraulic conductivity tensor, the pressure head or suction, and the elevation head [20]. The mechanical domain, which is the third component of the coupled system, deals with the stress and strain equilibrium of the soil matrix. The total strain in a freezing soil is composed of the elastic strain, the plastic strain, the thermal contraction strain of the soil particles, and the highly dominant volumetric expansion strain caused by the phase change of water into ice. The force equilibrium equation must account for the changes in effective stress resulting from pore water pressure fluctuations and ice lens formation. The mechanical equilibrium is mathematically structured as follows.

$$\nabla \cdot (C : (boldsymbol\varepsilon - boldsymbol\varepsilon_{th} - boldsymbol\varepsilon_{ice})) + \rho_{bulk} g = 0$$

In this formulation, the stiffness tensor interacts with the total strain tensor minus the thermal and ice-induced strain components, balanced by the bulk body forces [21]. The accurate resolution of this coupled system demands that the temperature, pore pressure, and displacement fields are solved simultaneously, as the variables are intrinsically codependent. For instance, the volumetric expansion calculated in the mechanical model alters the porosity, which in turn modifies both the thermal conductivity in the thermal model and the permeability in the hydraulic model.

4. Methodology and Experimental Setup

4.1 Physical Modeling of the Monopile Interface

To physically investigate the theoretical propositions regarding interface degradation, a highly specialized, temperature-controlled physical modeling apparatus was developed. The objective of the experimental setup was to simulate the stress conditions, thermal gradients, and cyclic structural loading experienced by an offshore monopile in a seasonally frozen marine environment. A robust cylindrical environmental chamber was constructed from high-strength, thermally insulated acrylic to minimize radial heat loss and allow for the maintenance of a one-dimensional vertical thermal gradient. Inside this chamber, a scaled steel monopile model was installed concentrically. The marine soil utilized in the experiments was synthesized to match the geotechnical properties of typical high-latitude seabed sediments. The preparation involved mixing commercially available kaolin clay with specific proportions of fine silica sand and a synthetic saline solution to replicate the osmotic potential and freezing point depression of natural seawater. The soil was thoroughly mixed into a slurry and subsequently consolidated within the test chamber

around the pre-installed steel pile under a vertical surcharge pressure to achieve an in-situ effective stress state representative of a specific depth below the mudline.

Table 2Geotechnical Properties of the Synthesized Marine Seabed Soil

Property Description	Value	Measurement Unit
Initial Moisture Content	45.5	Percent
Specific Gravity of Solids	2.68	Dimensionless
Undrained Shear Strength	25.0	Kilopascals
Salinity of Pore Fluid	30.0	Parts per thousand

4.2 Sensor Deployment and Loading Protocols

High-precision instrumentation was critical for capturing the transient multi-physics phenomena occurring during the tests. The steel monopile was instrumented with an array of strain gauges along its internal shaft to measure the distribution of axial load and, by extension, the mobilization of local skin friction along the pile-soil interface. To monitor the thermal regime, a vertical array of thermistors was embedded within the soil matrix at varying radial distances from the pile. Additionally, specialized miniature pore water pressure transducers, capable of withstanding freezing temperatures without sustaining damage, were installed near the interface to capture the development of cryogenic suction during freezing and excess pore pressure during thawing [22].

The experimental protocol consisted of three distinct phases: initial consolidation, thermal cycling, and mechanical loading. After the soil achieved primary consolidation, the top boundary of the soil sample was subjected to a programmed temperature protocol using a circulating cooling plate. The temperature was cycled between negative five degrees Celsius and positive five degrees Celsius to simulate seasonal winter freezing and summer thawing. Following a predetermined number of thermal cycles, the monopile was subjected to axial cyclic loading via a servo-hydraulic actuator mounted above the environmental chamber. The cyclic load simulated the dynamic environmental forces exerted on the wind turbine structure. Various test series were conducted to isolate the effects of the number of freeze-thaw cycles and the amplitude of the cyclic mechanical load.

Table 3Matrix of Experimental Variables and Testing Configurations

Test Series ID	Number of Thermal Cycles	Cyclic Load Amplitude	Initial Confining Pressure
Baseline-01	0 (Unfrozen reference)	Low	50 kPa
FreezeThaw-05	5	Low	50 kPa
FreezeThaw-10	10	High	50 kPa
FreezeThaw-20	20	High	100 kPa

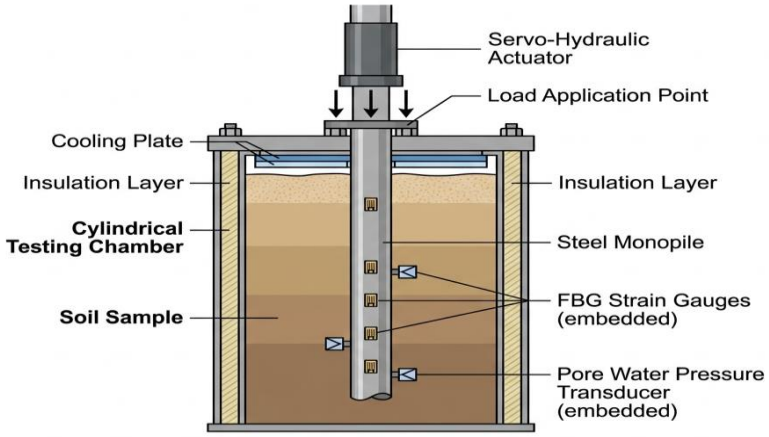


Figure 2: Detailed Cross-Sectional Diagram of the Temperature-Controlled Experimental Testing Apparatus

Figure 2Detailed Cross

5. Results and Interface Degradation Analysis

5.1 Thermal Regimes and Pore Pressure Evolution

The empirical data gathered from the sensor arrays provided a profound insight into the transient coupled processes at the interface. During the initial freezing phase, the thermistor data indicated a rapid downward progression of the zero-degree isotherm. However, due to the salinity of the pore fluid, phase change and latent heat release occurred over a range of negative temperatures rather than at a distinct boundary. Concurrently, the pore water pressure transducers registered an immediate and significant drop in pressure, manifesting as cryogenic suction. This suction was responsible for driving moisture from the deeper, unfrozen regions of the soil specimen upward toward the freezing zone, culminating in a measurable volumetric expansion of the overall soil surface. When the thermal boundary condition was reversed to initiate thawing, the system exhibited a highly non-linear response. The rapid melting of the interstitial ice and the previously formed microscopic ice lenses at the pile-soil interface resulted in a sudden influx of free water. Because the surrounding deeper soil remained partially frozen or possessed a low inherent permeability, this liberated water could not drain rapidly. Consequently, the miniature pore pressure transducers recorded sharp spikes in positive excess pore water pressure [23]. This transient state of elevated pore pressure drastically reduced the effective normal stress acting on the pile shaft. The magnitude of this excess pore pressure was found to be directly proportional to the rate of thawing and the accumulation of ice during the preceding freezing phase.

Table 4Quantitative Degradation Parameters Post Thermal Cycling

Number of Cycles	Peak Excess Pore Pressure	Skin Friction Reduction	Interface Dilation
1 Cycle	12 kPa	15 percent	0.5 mm
5 Cycles	28 kPa	32 percent	1.2 mm
10 Cycles	35 kPa	48 percent	2.0 mm
20 Cycles	40 kPa	55 percent	2.5 mm

5.2 Cyclic Softening and Skin Friction Degradation

The mechanical loading phases conducted subsequent to the thermal cycling revealed severe degradation of the load-carrying capacity of the interface. The load-displacement curves extracted

from the actuator and the localized shear stress derivations from the internal strain gauges painted a clear picture of progressive failure. In the baseline tests without thermal cycling, the monopile exhibited a standard elasto-plastic load transfer mechanism, with skin friction mobilizing uniformly along the shaft and reaching a stable ultimate state. However, the piles subjected to multiple freeze-thaw cycles demonstrated a markedly brittle and diminished response [24].

The primary mechanism for this degradation is the accumulation of microstructural damage at the interface zone. The repeated formation and melting of the adfreeze bond, combined with the volumetric dilation and contraction of the adjacent soil, created a weakened remolded zone surrounding the pile. During the cyclic mechanical loading, this remolded zone exhibited rapid cyclic softening. The excess pore water pressure generated during the thaw phase acted synergistically with the cyclic pore pressure generated by the mechanical shearing, leading to a state approaching localized liquefaction at the interface. The data systematically demonstrated that as the number of freeze-thaw cycles increased, the ultimate skin friction capacity decreased asymptotically, stabilizing at a residual value that was less than half of the original unfrozen capacity. This permanent loss of strength dictates that conventional design methodologies, which assume constant soil properties over the lifetime of the structure, are fundamentally inadequate for seasonally frozen environments.

6. Conclusion

6.1 Summary of Findings

This comprehensive investigation has elucidated the intricate multi-physics phenomena responsible for the thermo-hydro-mechanical interface degradation of offshore monopiles in seasonally frozen seabeds. Through rigorous theoretical analysis and highly controlled experimental modeling, the study confirmed that the cyclical alteration of temperatures induces profound phase changes and moisture migration within the marine soil matrix. The formation of ice lenses during the freezing phase draws moisture toward the interface, while the subsequent thawing phase generates substantial excess pore water pressures. This rapid hydraulic response critically diminishes the effective normal stress on the monopile shaft. When coupled with the dynamic mechanical loads representative of offshore wind turbines, the soil-structure interface undergoes severe cyclic softening and a permanent reduction in shear strength. The findings conclusively demonstrate that the ultimate skin friction capacity can be reduced by more than fifty percent after repeated seasonal cycles, establishing thermal degradation as a primary failure mechanism.

6.2 Implications for Engineering Practice

The insights derived from this research necessitate a paradigm shift in the geotechnical design of offshore structures in high-latitude marine environments. Traditional empirical design codes must be updated to incorporate transient thermo-hydro-mechanical coupling effects to prevent catastrophic structural failures or excessive cumulative displacements over the operational lifespan of the wind turbine. Engineers must explicitly calculate the thaw-induced excess pore pressures and the resulting degradation of the adfreeze bond when determining the required embedment depth of monopiles [25]. Future design frameworks should integrate advanced numerical modeling that captures the non-linear deterioration of interface friction, thereby ensuring the resilient and sustainable expansion of the global offshore wind energy sector into cold regions.

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