

THERMALLY INDUCED TENSILE HOOP STRESSES IN ENERGY PILES:
INFLUENCE ON CRACK FORMATION AND IMPLICATIONS FOR DESIGN

by

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To my family

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ABSTRACT

THERMALLY INDUCED TENSILE HOOP STRESSES IN ENERGY PILES: INFLUENCE ON CRACK FORMATION AND IMPLICATIONS FOR DESIGN

Energy piles, also known as thermoactive piles, serve dual purposes: providing structural stability and harvesting shallow geothermal energy. As such, their design must account for both structural and thermal loads. However, current practice typically only considers the axial components of thermal loads. This study aims to investigate thermal loads in three-dimensions, as well as their implications for structural integrity and durability, with a particular focus on tensile hoop stresses in the clear concrete cover. Through numerical modelling, this study examines the positional and temporal variations of hoop stresses and elucidates the underlying mechanisms. The findings demonstrate that significant tensile hoop stresses can develop within the clear concrete cover during the operation of energy piles, and these stresses shift positions with seasonal operation changes, extending the affected region. Therefore, it is crucial to consider hoop stresses in the design of energy piles to ensure structural integrity and durability. A sensitivity analysis was conducted, varying material properties, geometric aspects, operational preferences, and climatic conditions to identify the relationship between influential parameters and hoop stresses. The study concludes with design recommendations based on these findings.

ÖZET

ENERJİ KAZIKLARINDA TERMAL OLARAK İNDÜKLENEN TEĞETSEL (HOOP) GERİLMELERİ: ÇATLAK OLUŞUMUNA ETKİSİ VE TASARIM ÜZERİNDEKİ SONUÇLARI

Termoaktif kazıklar olarak da bilinen enerji kazıkları, iki ana amaçlı olarak kullanılır: üst yapı yüklerini zemine aktararak yapısal stabilite sağlamak ve sığ derinliklerdeki mevcut geotermal enerjiyi toplamak. Bu nedenle, enerji kazıklarının tasarımlarında hem yapısal hem de termal yükler dikkate alınması gerekmektedir. Ancak, mevcut uygulamalar genellikle sadece termal yüklerin eksenel bileşenlerini göz önünde bulundurmaktadır. Bu çalışma, termal yükleri üç boyutlu olarak incelemeyi ve bunların yapısal bütünlük ile durabilite üzerindeki etkilerini, özellikle beton paspayı kaplamasındaki hoop çekme gerilmelerine odaklanarak araştırmayı amaçlamaktadır. Sayısal modelleme yoluyla, bu çalışma çember gerilmelerinin konumsal ve zamana bağlı değişimlerini incelemekte ve buna sebep olan mekanizmaları açıklamaktadır. Bulgular, enerji kazıklarının işletimi sırasında beton paspayı kaplamasında önemli teğetsel çekme gerilmelerinin oluşabileceğini ve bu gerilmelerin mevsimsel işletim değişiklikleriyle konum değiştirdiğini, etkilenen bölgenin genişlediğini göstermektedir. Bu nedenle, enerji kazıklarının tasarımında teğetsel gerilmelerinin dikkate alınması, yapısal bütünlük ve durabilite sağlanması için kritik öneme sahiptir. Çalışmada; malzeme özellikleri, geometrik unsurlar, işletim tercihleri ve iklim koşulları gibi parametrelerin değiştirildiği bir hassasiyet analizi gerçekleştirilmiş ve bu parametreler ile teğetsel gerilmeler arasındaki ilişkiyi belirlemiştir. Bahsi geçen bulgulara dayalı tasarım önerileri sunulmuştur.

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LIST OF SYMBOLS

A	Cross-sectional area
$A_{concrete}$	Concrete cross-sectional area
A_p	Cross-sectional area of the pipe
$A_{s,min}$	Minimum longitudinal reinforcement ratio
B_{slab}	Width or dimension for the foundation
C	Specific heat capacity
C_1	Integration constant 1
C_2	Integration constant 2
D	Diameter
D_{ijkl}	Elastic stiffness tensor
E	Elastic modulus
E_d	Resultant design actions
E_s	Soil elastic modulus
F_v	Volume force factor
f_{ck}	Characteristic compressive strength of concrete
f_{ct}	Tensile strength of concrete
f_{ctm}	Design tensile strength of concrete
f_d	Coefficient of friction
f_y	Yield strength of steel
f_{yk}	Characteristic yield strength of steel
G_k	Permanent mechanical load
h	Heat transfer coefficient
h_{eff}	Effective heat transfer coefficient
h_{int}	Internal convective heat transfer coefficient
I_{cr}	Thermal crack index
K_h	Horizontal stiffness of soil
L	Length
L_{slab}	Length for the foundation
M	Moment

M_{Ed}	Design moment
M_{Rd}	Design moment resistance
N	Axial force
N_{Ed}	Design axial force
N_{Rd}	Design axial force resistance
Nu	Nusselt number
$Nu_{turbulent}$	Nusselt number for turbulent flow in pipes
P_k	Characteristic mechanical load
Q_k	Variable mechanical load
Q_s	Pile shaft capacity
Q_b	Pile base capacity
Q_{wall}	Heat flux per unit pipe length
r	Radial distance
r_{int}	Internal pipe radius
r_{ext}	External pipe radius
$S_{r,max}$	Maximum crack spacing
$s_{u,soil}$	Soil undrained strength
T	Temperature
T_{ext}	Temperature of the outer surface of the pipe
T_k	Thermal load
T_l	Temperature
u	Displacement
u_l	Velocity of fluid in pipes
V	Volume
w_k	Crack width
α	Coefficient of thermal expansion
$\alpha_{concrete}$	Coefficient of thermal expansion for concrete
α_{steel}	Coefficient of thermal expansion for steel
β	Thermal strain vector
β_{kl}	a vector that includes the linear thermal expansion coefficient of the material

γ	Unit weight
δ_{ij}	Kronecker delta
ΔT	Temperature difference
ΔT_k	Characteristic thermal load difference
ε	Strain
ε_{cm}	Mean concrete strain
ε_{ij}^m	Strain based on mechanical loading
ε_{ij}^{th}	Strain based on thermal loading
ε_{ij}^T	Total strain
ε_{kl}	Total strain tensor
ε_{rr}	Radial strain
$\varepsilon_{r\theta}$	Shear strain on the $r\theta$ plane
ε_{rz}	Shear strain on the rz plane
ε_{sm}	Mean steel strain
$\varepsilon_{\theta\theta}$	Hoop (circumferential) strain
$\varepsilon_{z\theta}$	Shear strain on the $z\theta$ plane
ε_{zz}	Axial strain
λ	Thermal conductivity
∇	Divergence
μ	Dynamic viscosity
ν	Poisson's ratio
ν_{soil}	Soil poisson's ratio
ρ	Density
σ	Characteristic concrete strength
σ_{ck}	Stress
σ_{kk}	Resultant stress
σ_r	Radial stress
σ_{θ}	Hoop (circumferential) stress
σ_z	Axial stress
τ	Shear stress
φ'	Effective friction angle
ψ_2	Combination factor for quasi-permanent loads

LIST OF ACRONYMS/ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
A1	Action Partial Factors 1
A2	Action Partial Factors 2
ACI	American Concrete Institute
API	American Petroleum Institute
ASD	Allowable Strength Design
ASHRAE	American Society of Heating Refrigerating and Air- Conditioning Engineers
BS	British Standards
CDP	Concrete Damage Plasticity
CFA	Continuous Flight Auger
CIRIA	Construction Industry Research and Information Association
COP	Coefficient of Performance
DA1-C1	Design approach 1 and combination 1
DA1-C2	Design approach 1 and combination 2
DA2	Design approach 2
DA3	Design approach 3
DA4	Design approach 4
DOF	Degree of Freedom
EIA	U.S. Energy Information Administration
EP-1	Energy Pile-1
EP-2	Energy Pile-2
FEA	Finite Element Analysis
FHWA	Federal Highway Administration
FRP	Fiber Reinforced Polymer
GSHPs	Ground Source Heat Pump Systems
HDPE	High Density Polyethylene
HVAC	Heating, Ventilation and Air Conditioning

IEA	International Energy Agency
JSCE	Japanese Standard Specifications for Concrete Structures
LNG	Liquefied Natural Gas
M1	Material Partial Factors 1
M2	Material Partial Factors 2
NGI	Norwegian Geotechnical Institute
UN	United Nations
PCM	Phase Change Materials
PEX	Crosslinked Polyethylene
R1	Resistance Partial Factors 1
R2	Resistance Partial Factors 2
R3	Resistance Partial Factors 3
R4	Resistance Partial Factors 4
TIP	Thermal Integrity Profiling
TP-1	Test Pile-1
TP-2	Test Pile-2
TP-3	Test Pile-3
UCS	Unconfined Compressive Strength
ULS	Ultimate Limit State
USA	United States of America
UTES	Underground Thermal Energy Storage Systems
VWSG	Vibrating Wire Strain Gauge

1. INTRODUCTION

Over the past two decades, energy piles have gained significant popularity. This technology captures renewable energy by employing foundation systems that are already critical for stability and functionality, utilizing the constant geothermal energy present at the location. As a result, in addition to other energy foundation systems, researchers are examining all facets of energy pile design and behavior. Because energy piles serve as structural components that interact both mechanically and thermally with the surrounding soil, investigators and engineers are exploring a variety of subjects, including heat exchange processes (Kong et al., 2019; Li et al., 2021), performance under different conditions and climates (Loveridge et al., 2020; Sutman et al., 2020), properties of the materials involved (Cecinato and Salciarini, 2022; Mousa et al., 2020), long-term behavior (Adinolfi et al., 2018; Sutman et al., 2020), environmental impact (Peng et al., 2021; Zhang et al., 2024), design and optimization (Carotenuto et al., 2017; Fadejev et al., 2017; Park et al., 2015), integration with other systems (Ma et al., 2023), group behavior (Mimouni and Laloui, 2015; Ravera et al., 2024; Rotta Loria and Laloui, 2017, 2018), and thermally induced stresses (Abdelaziz and Ozudogru, 2016; Faizal et al., 2016; Moradshahi et al., 2021a, 2022; Sutman et al., 2019). Among these factors, thermally generated stresses must be considered in structural design. Changes in heat transfer rates and temperatures within and around piles, combined with project-specific system constraints, result in time-varying non-uniform temperature patterns, displacements, and internal stresses (Abdelaziz and Ozudogru, 2016; Faizal et al., 2019; Fang et al., 2020; Li et al., 2022).

Thermal stresses and deformations are crucial for energy pile structural design. Investigators have performed instrumented energy pile experiments to monitor stress magnitudes and fluctuations under varying conditions. During testing, sensors recording strain and temperature data are installed on the reinforcement cage or within the pile's central section (Bourne-Webb et al., 2009; Brandl, 2006; Faizal et al., 2019, 2022; Jensen-Page et al., 2019; Kong et al., 2019, 2021; Laloui et al., 2006; Loveridge and Powrie, 2013; Lv et al., 2020; Moradshahi et al., 2021a, 2021b, 2022; Murphy et al., 2015; Rotta Loria and Laloui, 2017; Sutman et al., 2019; Wang et al., 2015). These experiments provided direct

strain and temperature measurements, along with indirect stress evaluations at various locations along energy piles.

However, in all such tests, sensors were installed to measure parameters needed for pile design according to standard procedures. Current energy pile design approaches model piles as one-dimensional elements with bending stiffness determined by material properties, cross-section dimensions, and shape. This method assumes uniform behavior across pile cross-sections. While valid for conventional piles, this assumption becomes problematic for energy piles. Energy piles contain pipes circulating heat transfer fluids at temperatures differing from the pile itself. These temperature differences create thermal gradients that lead to uneven volume changes and corresponding stresses. However, existing energy pile test data fails to capture these effects because the instrumentation types and their locations were not designed to study cross-sectional behavior.

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The only exceptions were tests in which radial stresses were also measured (Lv et al., 2020; Moradshahi et al. 2021a, 2022). Studies have pointed to the nonuniform temperature evolution in pile cross-sections under thermal loading (Abdelaziz and Ozudogru, 2016; McCartney et al., 2015; Moradshahi et al., 2021b; Murphy et al., 2015; Zhou et al., 2023a, b). These investigations enhanced comprehension of energy pile structural performance by including radial stress analysis alongside axial stresses. Nevertheless, they still fail to fully characterize the three-dimensional stress distribution.

Using a cylindrical coordinate system (suitable for piles), stresses can be described in three directions: axial, radial, and circumferential. Standard energy pile design primarily considers axial stress values. Research examining radial stresses demonstrates they remain within safe limits and are not structurally significant. However, circumferential stresses - representing tangential normal stresses - have not been studied in energy piles. Therefore, this research concentrates on circumferential stresses. Throughout this paper, we will use the term 'hoop stresses' instead of circumferential stresses, as it more accurately describes the mechanical behavior discussed in subsequent sections.

For reinforced concrete structures, thermally induced hoop stresses are particularly detrimental to the clear concrete cover made of plain concrete. This issue affects not just energy piles but also other applications. For instance, in mass concrete dam construction, hydration heat during curing generates substantial stresses that can crack concrete covers without proper precautions (Ha et al., 2014). Similarly, power plant structures and thermosiphons may develop tensile failures from thermal hoop stresses (Bravo et al., 2023). The concrete cover plays a vital protective role, safeguarding reinforcement against corrosion and ensuring long-term structural durability.

This study investigates three-dimensional stress distributions in energy piles, with particular emphasis on hoop stresses. The optimal measurement location would be the concrete cover's outer surface, where temperatures best represent circumferential stress conditions. However, installing strain sensors in this position proves impractical for cast-in-place piles due to construction limitations. Lacking direct field measurements of hoop stresses, the research adopts an elastic analytical and numerical approach, consistent with previous studies examining axial stress variations across pile cross-sections. (Abdelaziz and Ozudogru, 2016; Erginag et al., 2025; Faizal et al., 2019; Moradshahi et al., 2021b). This approach examines only elastic behavior to identify the key mechanisms generating thermal hoop stresses and evaluate their potential structural impact. The analysis first investigates how reinforcement and surcharge loads influence thermally induced hoop stresses in energy piles. Three variations of the base model are developed for comparison: a simple unreinforced model without surcharge, a reinforced model, and a model that includes surcharge loading. These variations help establish the optimal modeling approach that maintains precision while minimizing computational demands. Following this, a series of

sensitivity studies are performed using a verified numerical model to pinpoint key factors affecting hoop stress development. The investigation quantifies typical hoop stress ranges across diverse material properties, operational parameters, and geometric configurations. The research culminates in practical recommendations for both the design methodology and operational protocols of energy pile systems, providing engineers with actionable insights for improved performance and reliability. The results are presented, and their implications for structural integrity and durability are discussed in terms of cracking occurrence probability. Finally, suggestions for the design and operation of energy piles are provided.

1.1. Aims and Objectives

The primary aim of this thesis is to investigate the development and implications of thermally induced tensile hoop stresses in energy piles, with a focus on their structural impact on the clear concrete cover. By integrating numerical modeling, sensitivity analysis, and analytical validation, this research seeks to enhance the understanding of three-dimensional thermal stress distributions in energy piles and provide actionable recommendations for their design and operation.

The first objective is to develop a thorough mechanical understanding of the spatial and temporal evolution of hoop stresses in energy piles subjected to thermal loading. This involves identifying the fundamental physical processes that lead to tensile hoop stress formation in the clear concrete cover during both heating and cooling operational phases.

The second objective focuses on the development and validation of a robust three-dimensional finite element model capable of accurately simulating the thermo-mechanical behavior of energy piles. This model will be used to assess the relative importance of factors such as reinforcement presence and surcharge loads on hoop stress distribution, enabling optimization of computational efficiency without sacrificing accuracy.

A third key objective is to conduct an extensive sensitivity analysis to quantify the influence of various parameters on hoop stress development. This includes evaluating material properties such as thermal conductivity and expansion coefficients, geometric factors including pile diameter and pipe configuration, and operational variables like heat-

carrier fluid flow rates and climatic conditions. The analysis aims to identify critical combinations where hoop stresses may approach or exceed concrete's tensile capacity.

The fourth objective centers on deriving practical design and operational recommendations based on the research findings. This involves proposing mitigation strategies such as material modifications, geometric optimizations, and operational adjustments to control excessive hoop stresses. Special attention will be given to the implications of multiaxial stress states and their effect on concrete's reduced tensile capacity under combined loading conditions.

Finally, the thesis aims to contribute to the advancement of energy pile design methodologies by highlighting the significance of hoop stress considerations. The research seeks to inform the development of more comprehensive design standards that account for three-dimensional thermal stress effects, thereby promoting safer and more reliable implementation of energy pile technology in sustainable infrastructure projects.

Through these objectives, the thesis will address a critical gap in current energy pile design practices while providing actionable insights for engineers and researchers working in the field of thermoactive geostructures.

1.2. Dissertation Structure

This dissertation is organized into eight chapters that systematically investigate thermally induced tensile hoop stresses in energy piles and their implications for structural design. The structure is designed to present theoretical foundations, numerical modeling approaches, sensitivity analyses, and practical design recommendations in a logical progression.

Chapter 1 (Introduction) provides the research background, objectives, and significance of studying hoop stresses in energy piles. It outlines the motivation for addressing this gap in current design practices and summarizes the key contributions of this work.

Chapter 2 (Fundamental Concepts) introduces essential principles of geothermal energy systems, energy geostructures, and ground-source heat pump operation. It establishes the technical foundation for understanding the dual structural and thermal functions of energy piles.

Chapter 3 (Literature Review) critically examines prior research on thermally induced stresses in energy piles, emphasizing the predominance of axial stress studies and the lack of attention to hoop stresses. It also discusses analogous cases of hoop stress in other concrete structures, such as mass concrete and pressurized pipes.

Chapter 4 (Thermally Induced Stress State) presents the theoretical framework for analyzing three-dimensional thermal stresses in energy piles, including governing equations and coordinate system considerations.

Chapter 5 (Verification of Numerical Modeling) validates the finite element approach using field test data from existing energy pile studies. Two case studies are analyzed to confirm accuracy of the numerical models in predicting temperature distributions and stress responses.

Chapter 6 (Definition of the Problem) specifies the details for numerical modeling methodology, including boundary conditions, material properties, and sensitivity parameters. It compares different modeling approaches (with/without reinforcement and surcharge) to optimize computational efficiency.

Chapter 7 (Results and Discussion) investigates the thermo-mechanical behavior of energy piles under operational conditions, with a focus on thermally induced hoop stresses in the concrete cover region. The analysis begins by establishing baseline performance through a reference case study of unreinforced piles under seasonal temperature variations, revealing distinct stress patterns between heating and cooling modes. The study then examines how structural reinforcement and mechanical loading influence stress distributions, demonstrating that conventional reinforcement provides limited mitigation of thermal stresses. Analytical methods complement numerical simulations to validate stress prediction approaches. A detailed sensitivity analysis evaluates how material properties,

geometric parameters, and operational conditions affect stress development, identifying key governing factors. The chapter emphasizes critical design implications, particularly the vulnerability of unreinforced concrete covers to thermally induced cracking under cyclic loading. Practical mitigation strategies are explored, including operational controls and material enhancements, providing a foundation for durable energy pile design.

Chapter 8 (Conclusion) summarizes the research outcomes, highlights practical recommendations for energy pile design, and suggests future work to expand on the findings.

This structured approach ensures a comprehensive investigation of thermally induced hoop stresses, bridging the gap between theoretical analysis and practical engineering applications

2. FUNDAMENTAL CONCEPTS

The continuously rising energy consumption largely depending on the increasing population forces nations to seek alternatives to current energy sources (IEA, 2023). Accordingly, regarding current projections about the future population, the expected world population will be up to 9.8 milliard by 2050 while it is 8.2 milliard in 2025 based on UN (2023). Depending on these projections, both IEA (2023) and EIA (2025) estimates doubling energy consumption. The significant portion of energy production -the current value is on the order of 60%- is coming from fossil fuels yielding greenhouse effect (EIA, 2025). While stepping, there exists climate change problem and therefore, it enforces countries to diminish the percentage of fossil fuel consumption being dependent on those fuels. To do this, carbon emissions should be reduced, and concrete steps should be taken. Many countries including Iceland, USA, Kenya, Indonesia, United Kingdom, Switzerland, Canada and several European Union countries initiated lowering carbon emission approach by implementing regulations or offering inducement in usage of renewable energy sources including solar, wind, hydropower, geothermal, biomass, tidal-wave energy to replace fossil fuels. In this work, the geothermal part of the mentioned sources will be considered. In this section, fundamental concepts related with geothermal energy and its usage will be given.

2.1. Geothermal Energy

Geothermal energy is one of the sustainably renewable energy types within the Earth due to the fact that radioactive reactions can cause the breakdown of certain types of elements such as thorium, uranium, and potassium (Lee et al., 2007). This natural energy is presented Earth all segments, namely; core, mantle and crust. Also, solar surface radiation provides additional energy limited only to shallow depths. The mentioned mechanism produces a direct release of energy within the Earth, including groundwater. The ground temperature is nearly hundred percent greater than 1000°C while only 0.1% of the earth has temperature less than 100°C (Barbier, 2002).

The thermal regime of near-surface geological strata exhibits pronounced sensitivity to meteorological influences within the upper 4-10 meter zone (Figure 2.1), demonstrating greatest responsiveness to thermal fluctuations while showing more attenuated response to seasonal thermal variations. Below this critical depth threshold which depends the geographical location, subsurface temperatures stabilize to an approximately isothermal condition, typically maintaining values between 10-25°C that correlate strongly with local mean annual atmospheric temperatures. This thermal inertia creates a thermodynamic phenomenon whereby subsurface temperatures remain elevated relative to ambient winter conditions while providing cooling potential during summer periods - a characteristic that persists across most geographic regions irrespective of lithological composition.

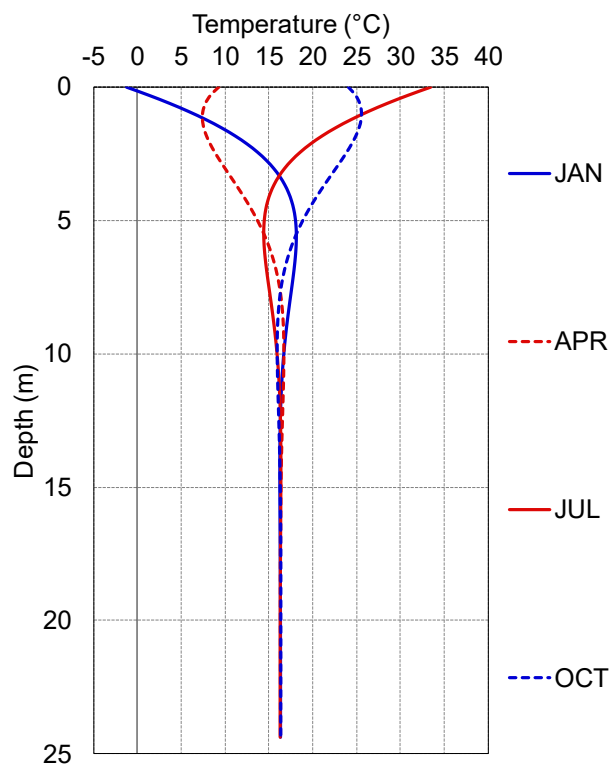


Figure 2.1. The temperature distribution throughout the depth for Istanbul corresponding to each mid-month of the season.

The geothermal gradient manifests as a progressive temperature increase with depth through the crustal column, exhibiting a mean value of 3°C/100m within conventional exploitation depths (Barbier, 2002). Significant spatial variability exists in this gradient, ranging from 1°C/100 m in stable cratonic regions to 10°C/100m in active tectonic zones.

At greater depths approaching the upper mantle boundary, this gradient attenuates substantially to approximately $0.1^{\circ}\text{C}/100\text{ m}$. These predictable thermal characteristics present exploitable thermodynamic potential for anthropogenic utilization in built environment applications through appropriate geothermal energy conversion technologies.

As a geothermal source, engineered or natural wells covering a wide range of depths make this energy attainable hot water is found at different temperatures and depths below the ground surface. The important thing is that thermal energy is independent with respect to the season and it is available all over the world. Furthermore, by special deep drilling techniques, it is possible to harvest this energy, too (Laloui and Rotta Loria, 2020). Also, geothermal energy does not offer limited usage and it is possible to utilize this energy for direct usage in household, industrial needs providing electricity heating-cooling and direct usage

2.2. Geothermal Systems

Geothermal systems are useful tools to obtain geothermal energy that is always present in the ground. Heat source, heat sink and heat exchanger are fundamental components, and they form geothermal systems.

The ground itself acts as the heat source, supplying thermal energy. Meanwhile, the heat sink is typically the structure of the built environment. Interestingly, the roles of the heat source and heat sink can be intentionally reversed. The heat exchanger facilitates heat transfer between the heat source and the heat sink. Additionally, the heat exchanger consists of several components, including a heat exchanger fluid enclosed within it.

Geothermal systems can be categorized into two groups. A shallow geothermal system as depicted in Figure 2.2 refers to a system used for heat exchange at depths of up to 400 meters, whereas a deep geothermal system shown in Figure 2.3 is employed when heat exchange is required at greater depths. Shallow geothermal systems rely on low-temperature enthalpy, while deep geothermal systems operate at high temperatures and enthalpy. There exist differences between both systems with respect to properties and the way thermal energy is used.

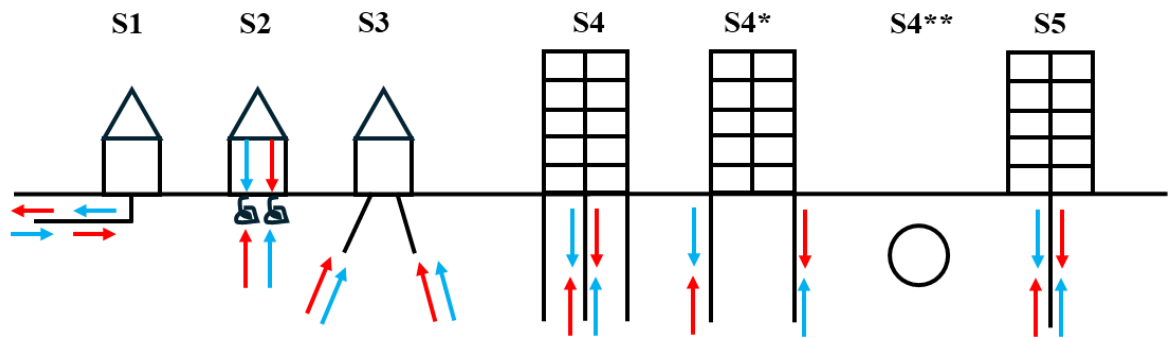


Figure 2.2. The shallow geothermal systems.

For shallow geothermal systems, geothermal energy is obtained via mentioned fundamental components, but its usage is indirect. That is, once geothermal energy (input energy) is obtained from the ground, it is generally adjusted by certain machines like heat pump to increase or lower output energy to intended energy. However, there is no need for adjustment of the output energy for the deep geothermal systems.

For domestical needs such as heating, cooling and hot water, shallow geothermal systems are used. The reason for that, in such case, the underground temperature is not higher than 25°C and this temperature range is enough for geothermal energy to fulfill domestical needs. For deep geothermal systems, heating and cooling can be for the temperature in between 25°C - 200°C . However, deep geothermal systems can also be used to produce electrical power if the underground temperature is higher than 175°C . The general properties and typical applications of the geothermal systems are presented in Table 2.1 (Laloui and Rotta Loria, 2020).

For the heat exchanger usage, there are two types, namely; closed-loop and open-loop. In open loop, groundwater present in the man-made wells is directly utilized by either extracting or injecting. On the other hand, liquid composed of water and some additions like anti-freezing circulates in a closed pipe system conveyed to the structure from the ground.

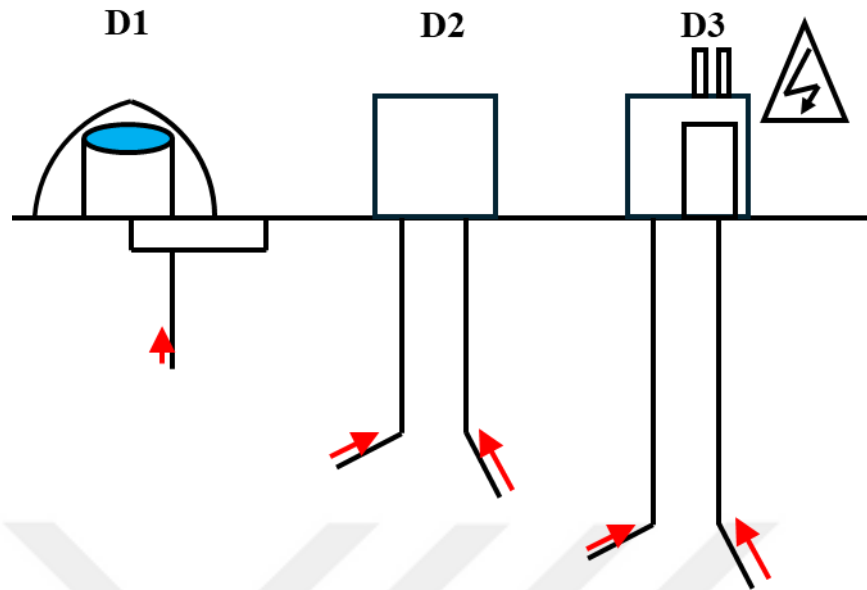


Figure 2.3. The deep geothermal systems.

Horizontal geothermal boreholes are the most basic and shallow type of geothermal system. These boreholes consist of polyethylene pipes that are laid out horizontally in the ground, close to the surface between 1 to 5 m deep. A special fluid flows through these pipes, picking up or releasing heat from the ground. The mechanism is such that soil absorbs heat from the sun, so even at shallow depths, there exist a stable temperature to work with. These systems are often used to heat homes, farms, or fish farms, and if installed under buildings, they can also be used to store heat for later use.

As compared to horizontal geothermal boreholes, geothermal baskets are densely placed, and it is more compacted. The mentioned system is buried at very shallow depths, especially less than 10 m. In the baskets, closely spaced spirally formed polyethylene pipes take place and inside it, heat exchanger fluid circulates. Spiral coils can also be installed in surface water conditions adjacent to buildings, given that the reservoirs are sufficiently deep to avoid operational issues such as freezing for the heat transfer fluid in the pipes.

Groundwater heating systems use wells dug into shallow underground water (5-20 meters deep). For system workability, problematic conditions should not exist in terms of geological, hydrogeological and environmental issues. These systems extract geothermal energy from groundwater. Small buildings might use one well, while larger ones need a pair. One well is used to take heat out of the ground, and the other puts it back in. This helps keep

the underground temperature stable, which is important for making the system work well and, in some cases, to avoid harming the environment.

Table 2.1. Geothermal systems and corresponding properties.

	ID	Name	Heat Exchanger Type	Application Depth (m)	Ground Temperature (°C)
Shallow geothermal systems	S1	Horizontal geothermal boreholes	Closed loop	2-5	8-12
	S2	Geothermal baskets	Closed loop	2-10	8-12
	S3	Groundwater capture systems	Open loop	5-20	8-12
	S4	Energy piles	Closed loop	10-50	10-12
	S4*	Energy walls			
	S4**	Energy tunnels			
	S5	Vertical geothermal borehole(s)	Closed loop	50-300	10-20
Deep geothermal systems	D1	Thermal springs	Open loop	500-1000	25-80
	D2	Hydrothermal systems	Open loop	1000-4000	25-130
	D3	Petrothermal systems	Open loop	40000-6000	130-200

Vertical geothermal boreholes use closed polyethylene pipes. These pipes are installed deep underground near buildings between 50 or 300 m deep. The boreholes are typically filled with special material like bentonite. This improves heat transfer between the ground and pipes. Heat exchanger fluid circulates through the pipes to exchange heat. The system can provide heating, cooling, hot water, and energy storage for various buildings. Small

buildings may need just one borehole. Larger buildings require multiple boreholes working together. These systems access higher ground temperatures at depth. This allows more energy transfer than shallow geothermal systems.

Thermal springs are known for deep geothermal systems. Open wells are required for this system deep underground for hot water sources. The wells typically reach 500-1000 m deep. The main purpose is in the usage of thermal springs for bathing and medical treatments. The heat comes from the warm groundwater below.

Hydrothermal systems use open wells to extract groundwater from great depths between 1000 or 4000 m. At these depths, the temperature and thermal energy are high enough for large-scale heating. These systems are commonly employed for district heating. They can also effectively heat large industrial or agricultural facilities.

Groundwater is extracted through open wells in petrothermal systems, reaching greater depths (4000-6000 m) than hydrothermal systems. Electrical power production on a large scale becomes possible through utilization of the intense thermal energy present at these depths.

2.3. Energy Geostructures

Energy geostructures are multifunctional systems that have been recently developed especially after 2000. They serve a structural support role like ordinary geostructures, while also functioning as heat exchangers in shallow geothermal systems. These structures benefit low enthalpy and almost constant underground temperature with respect to the role for heat exchangers.

Both driven and bored piles including barrettes, large piers, shallow foundations, earth retaining structures, anchors and tunnel linings enable to obtain shallow geothermal energy (Batini et al., 2015). With the help of this energy, heating and cooling buildings to maintain intended comfort in the built environment, supplying hot water for domestic, agricultural, or aquaculture needs, preventing ice formation on pavements and structural surfaces such as

roads, bridges, station platforms, and airport runways, and storing thermal energy in the ground for later use.

Energy geostructures can be created by installing heat exchanger pipes into or onto the reinforcement cage within conventional geostructures. This assembly can be carried out either on-site or in a manufacturing facility. After concrete is poured, a water leakage test is performed by applying pressure to the pipes one day later to check the integrity of the pipes embedded in the concrete (Batini et al., 2015; Brandl, 2006; Guo et al., 2018). The typical nominal diameter of the pipes ranges from 10 to 50 mm, with wall thicknesses varying between 2 and 5 mm. The heat exchanger fluid inside the pipes can be either saline water or water mixed with antifreeze.

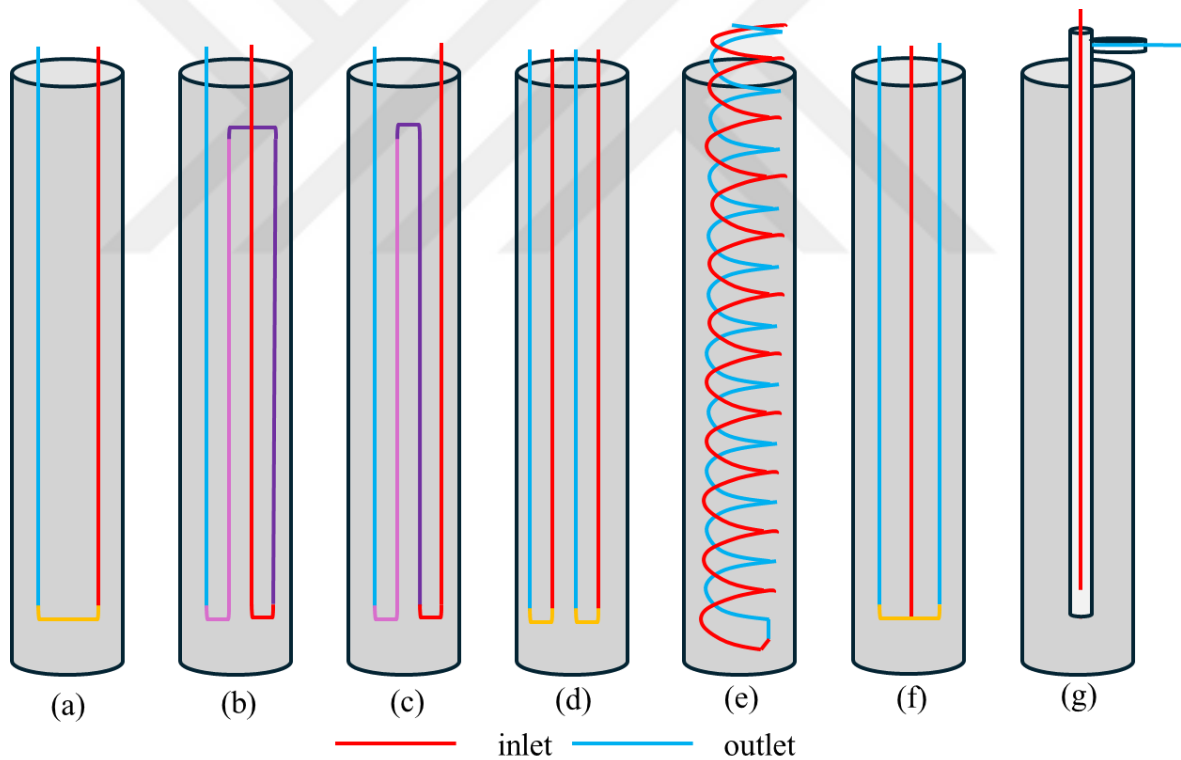


Figure 2.4. Pipe configurations for an energy pile: (a) single U, (b) bent U, (c) W, (d) double U, (e) spiral, (f) indirect double, and (g) coaxial.

According to the energy demand, different pipe configurations can be adopted, including single U-shaped, double U-shaped, multi U-shaped, W-shaped, spiral, and coaxial configurations. Some of the corresponding pipe arrangements within the reinforcement cage of an energy pile are shown in Figure 2.4. When selecting a pipe configuration, the main

objective is to maximize the surface area to achieve the desired heat exchange and energy output at a reasonable cost.

2.3.1. Operational Modes for Energy Geostructures

Energy geostructures can operate under two distinct modes. These modes have different service purposes, namely; heat exchange and heat storage. When utilized for heat exchange, these structures are integrated with GSHPS, which transfer thermal energy between the ground and buildings. Conversely, when employed for heat storage, they function as part of UTES, which store excess thermal energy for later use. The choice between these modes depends on whether the primary objective is energy transfer or thermal energy retention.

In terms of heat exchange, energy geostructures function by utilizing the ground as a thermal reservoir, exchanging heat with the surrounding soil depending on seasonal or climatic conditions. In other words, it is heat extracting from the ground in colder periods and injecting excess heat into it during warmer times. The operation mode of these systems depends largely on the ability of the ground to naturally recharge thermally during inactive periods. In permeable soils with active groundwater flow, the natural recharge is typically sufficient to maintain stable subsurface temperatures, allowing systems to operate solely for heating or cooling. However, in soils of low permeability where groundwater flow is limited, natural thermal recovery is often inadequate, necessitating the incorporation of heat storage strategies to ensure long-term efficiency and temperature stability.

In heat storage operations, the main goal of energy geostructures is to transform the ground into a reliable thermal storage system. This involves injecting excess heat that is solar sources or waste heat into the subsurface. Solar heat is often stored during the hot months in warm climates, with the intention of retrieving it later during colder periods to meet heating demands. On the contrary, waste heat, can originate from various industrial or building systems and may involve both high and low temperatures. It can be stored underground for future use in both heating and cooling applications, depending on whether the system is operating in a cold or warm climate. The need for heat storage becomes particularly important when there is a temporal mismatch between energy demand and energy

availability. In other words, when the periods of required heating or cooling do not align with when heat or coolness can be produced or captured efficiently, storing thermal energy in the ground ensures that the system can still operate effectively and sustainably.

2.4. Ground Source Heat Pump Systems

Ground source heat pump systems operate through two interconnected circuits that facilitate thermal energy transfer between the subsurface and buildings via energy geostructures. The primary circuit consists of the ground heat exchanger system, which circulates a heat transfer fluid through pipes embedded in the ground or energy geostructures to absorb or reject heat. The secondary circuit connects to HVAC system of the building, distributing the exchanged heat to warm or cool the indoor environment as needed. This dual-circuit design enables efficient heat exchange between the earth and built structures.

The primary circuit facilitates thermal exchange between the ground and the geostructure, gathering thermal energy for distribution to buildings. The secondary circuit then delivers this energy to the built environment for space conditioning. Between these circuits, electrically powered devices like heat pumps or reversible heat pumps may be installed to enhance energy transfer, though their inclusion depends on system requirements. When heating or cooling is achieved without these mechanical devices, the process is termed as free heating or free cooling. The necessity for heat pumps hinges on the temperature gradient between the ground (primary circuit) and the building (secondary circuit). A substantial temperature difference between these circuits determines how efficiently heat can be exchanged. That is, larger differences may require mechanical assistance, while smaller ones may allow for passive thermal transfer.

GSHP systems can provide both heating and cooling for buildings, but the ground temperatures may not always be at optimal levels for direct use. When the underground temperature is suitable for direct heating or cooling, the system can operate in free mode without needing heat pumps. However, when the ground temperature is insufficient for the desired heating or cooling effect, heat pumps (or reversible heat pumps) become necessary. These devices adjust the temperature by either increasing it for heating or decreasing it for

cooling, compensating for cases where the ground's natural thermal energy alone would be inadequate.

This capability is crucial because it overcomes a fundamental thermodynamic limitation: naturally, heat flows only from warmer to cooler areas. Heat pumps essentially reverse this natural flow, allowing us to extract heat from cooler ground for building heating or reject heat to warmer ground for cooling.

In practical applications, heat pumps typically elevate temperatures from 10-15°C (ground temperature) to 40-45°C for effective space heating in buildings. This temperature boost ensures comfortable indoor conditions even when the ground's thermal energy alone would be insufficient (Laloui and Rotta Loria, 2020).

While the term free is used to describe heating or cooling operations that don't require heat pumps, it's important to clarify that these systems still need electrically powered circulation pumps to move heat transfer fluid between the ground and the building. These pumps facilitate thermal energy exchange without performing temperature amplification. Figure 2.5 illustrates a standard ground-source heat pump system configuration used for building heating, showing how these components interact in the heating process.

2.4.1. Energy Efficiency

The energy efficiency of the ground source heat pumps can be computed in terms of external energy required for the heat pump and total energy in the system as shown in Figure 2.5. Therefore, to represent the efficiency of the mentioned system, COP is needed to determine that can be written as (Brandl, 2006)

$$COP = \frac{\text{Total energy after heat pump operation}}{\text{Energy required for the heat pump}}. \quad (2.1)$$

The coefficient of performance, a key parameter indicating how much heat energy is produced per unit of electricity consumed. A higher COP means less external energy is needed relative to the useful heat output. For instance, a COP of 4.5 implies that one unit of electrical energy, combined with 3.5 units of geothermal energy, yields 4.5 units of usable

energy. Typically, geothermal heat pumps achieve COPs between 3.5 and 4, with a COP of at least 4 being economically desirable.

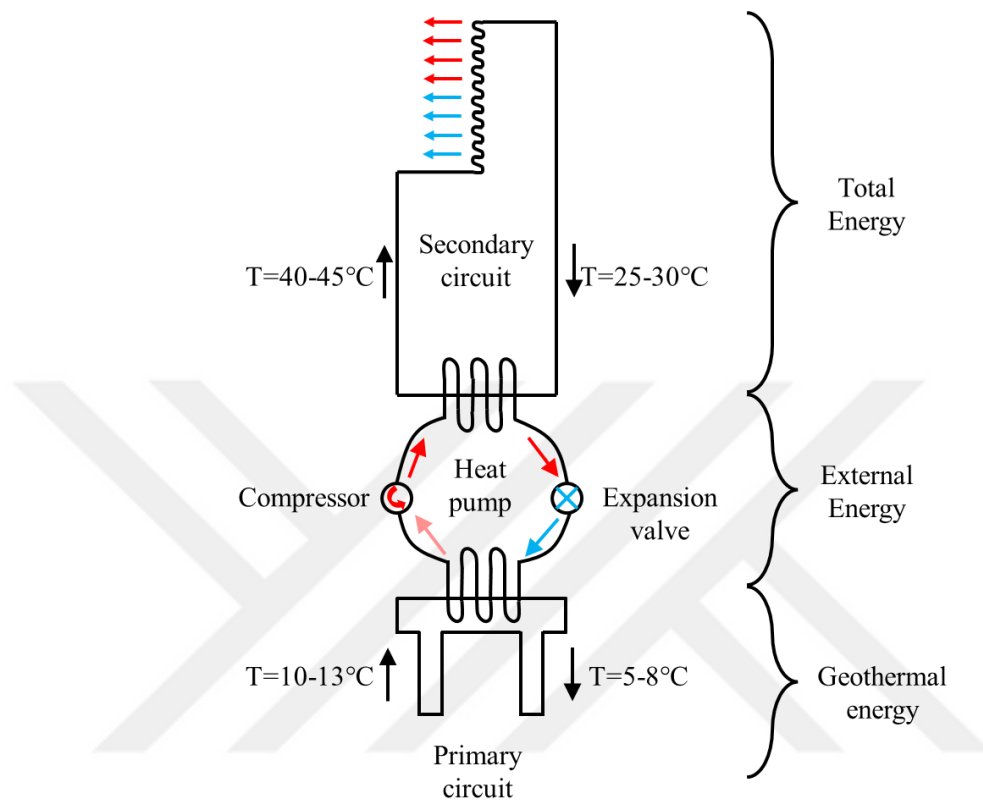


Figure 2.5. Ground source heat pump system and corresponding components.

A heat pump's efficiency depends on internal design factors, such as heat exchanger performance and thermal losses, as well as the temperature difference between the heat source and the heating system. Higher user-side temperatures (e.g., in the secondary heating circuit) and lower extraction temperatures (e.g., due to insufficient return flow in the primary circuit) reduce efficiency. For optimal performance, the building's heating temperature should stay below 45°C , while the ground heat extraction temperature should not drop below 0°C (Brandl, 2006).

3. LITERATURE REVIEW

This chapter provides a comprehensive review of thermally induced stresses in energy piles, focusing on axial and radial stresses as investigated in prior studies. The literature highlights that energy piles experience complex thermo-mechanical behavior due to non-uniform temperature distributions caused by heat exchange processes. Key findings from field tests and numerical simulations reveal that axial stresses dominate the structural response, often reaching significant magnitudes during heating and cooling cycles. In contrast, radial stresses, while measurable, remain negligible compared to axial stresses and concrete capacity. The chapter also identifies gaps in current research, particularly the lack of attention to circumferential (hoop) stresses, which are critical for understanding the full three-dimensional stress state in energy piles. By synthesizing existing knowledge, this chapter sets the stage for addressing these gaps and underscores the need for a more holistic approach to energy pile design that accounts for all stress components.

3.1. Thermally Induced Stresses

In literature, various researchers have investigated thermally induced stress for energy piles. The featured works cover only axial and radial stresses and they are shown below.

A full-scale geothermal energy pile test to explore the thermo-mechanical behavior of a geothermal energy pile subjected to varying operational modes was conducted (Faizal et al., 2016). The test pile measured 0.6 m in diameter and extended 16.1 m into the ground, which comprised a layered soil profile including silty clay fill (0–1.5 m), sandy clay (1.5–2.5 m), dense sandy strata with clay inclusions (2.5–10 m), and highly compact quartz-rich sand (10–16.1 m). Thermal conductivity increased with depth, ranging from 1.5 to 2.4 W/m·K. The pile incorporated three U-loop heat exchangers with 25 mm external and 20 mm internal diameters. These loops reached down to 14.2 m and were spaced 175 mm apart. Axial strain monitoring was conducted using vibrating wire strain gauges placed at depths of 5.4, 8.2, 11.6, and 13.3 m, while ground temperature was measured via thermocouples positioned 0.5 m and 2.0 m from the pile perimeter. The study compared thermal responses under two distinct operating strategies one of which is continuous 24-hour

cooling and cyclic modes involving alternating cooling and rest periods. During uninterrupted operation, the pile developed peak axial compressive stresses of -1.63 MPa at 5.4 m depth, averaging -1.21 MPa over the measured region. Under an intermittent regime (16 hours of cooling at 7 – 16°C followed by 8 hours of heating at 30 – 55°C), maximum stress was reduced to -0.94 MPa at 5.4 m, equating to a 42.3% decrease, with an average reduction of 38.1% along the pile. Analysis of radial stresses revealed -0.85 MPa at the pile-soil interface, falling to -0.12 MPa at a 0.5 m radial distance (an 86% reduction), diminishing further to -0.04 MPa at 1.0 m, and becoming negligible beyond 2 m. Intermittent loading also led to a 35–40% drop in radial stress magnitudes compared to continuous operation. Thermal performance assessment indicated that continuous operation achieved an energy extraction rate of 12.4 kWh/m. This was surpassed under intermittent scenarios, reaching 14.2 kWh/m (a 14.8% increase) for the 16-hour cooling schedule and 17.5 kWh/m (a 40.9% improvement) for the 8-hour cooling setup. Ground temperature variation at a 0.5 m radius was 8.2°C during continuous cooling, dropping to 7.7°C (-5.9%) and 7.0°C (-14.5%) for the respective intermittent cycles. The results conclusively show that intermittent thermal operation not only decreases axial stress levels by up to 42.3% and reduces radial loading, but also enhances energy harvesting efficiency and mitigates thermal disturbance in the surrounding soil. Notably, the complete recovery of axial stresses during rest phases supports the interpretation of the system's behavior as predominantly thermo-elastic under cyclical loading conditions.

The development of non-uniform thermal strains and stresses in energy piles subjected to transient thermal loads during operation was studied numerically (Abdelaziz and Ozudogru, 2016). The investigation employs a finite element framework in COMSOL Multiphysics (2025) to simulate the thermomechanical behavior of energy piles, with model validation achieved through comparison with analytical methods and previously published full-scale field results. No laboratory or field testing is directly included in this work. The simulation approach comprises two sequential stages. The first stage uses a three-dimensional finite element model to estimate temperature distributions within the pile and adjacent soil. Simulations are based on circular concrete piles with lengths of 10 meters and diameters of 250 mm (single loop) and 500 mm (double loop). The surrounding soil is idealized as a homogeneous, saturated clay layer at 15°C . Thermal and mechanical parameters used in the model include a Young's modulus of 40 GPa, a Poisson's ratio of

0.15, and a thermal expansion coefficient of $10^{-5} \text{ }^{\circ}\text{C}^{-1}$ for the pile, while the soil's undrained shear strength ranges from 50 to 100 kPa for sensitivity testing. Soil-pile interactions are modeled using elastic-perfectly plastic interface elements, with stiffness values derived from typical load-displacement behavior. In the second modeling stage, a hybrid 1D–3D finite element method calculates thermally induced strains and stresses, with the pile meshed using hexahedral elements and soil resistance represented by interface layers. The imposed thermal load is defined as a sinusoidal annual variation with a peak amplitude of $\pm 80 \text{ W/m}$, simulating realistic building energy demands over a heating and cooling cycle. Model validation is achieved by comparing temperature fields to the finite-line source solution and stress-strain predictions to results from both previous 3D simulations and field observations. The comparisons demonstrate a high degree of agreement, supporting the reliability of the modeling approach. Simulation results indicate that non-uniform radial temperature distributions result in complex strain behavior across the pile cross-section. Maximum localized temperature changes near heat exchanger loops reach $\pm 28^{\circ}\text{C}$, while the pile-soil boundary exhibits lower changes around $\pm 18^{\circ}\text{C}$, yielding an average of $\pm 22.2^{\circ}\text{C}$. These variations generate spatially varying free thermal strains, which are constrained by internal strain compatibility, producing uniform observed strains of $210 \text{ }\mu\epsilon$ during heating and $-194 \text{ }\mu\epsilon$ during cooling. The difference between free and observed strain gives rise to constrained thermal strains, with compressive components reaching $-75 \text{ }\mu\epsilon$ and tensile components up to $+23 \text{ }\mu\epsilon$. The resulting thermal stresses are comprised of internal stresses arising from strain compatibility and external stresses from soil restraint. For the 250 mm pile embedded in 50 kPa clay, internal compatibility leads to maximum compressive stresses of -2520 kPa and tensile stresses of 1400 kPa . The external stress imposed by the soil reaches -488 kPa . When combined, these can create zones of tensile stress during heating, challenging the conventional assumption that heating produces only compression. Likewise, cooling may induce compressive stresses in specific regions of the pile. Neglecting non-uniform temperature profiles during analysis can significantly distort the estimation of thermal stresses. The simulations further highlight that pile geometry, the thermal conductivity of surrounding soil, and material stiffness influence temperature and stress distribution. Larger-diameter piles show more uniform temperature fields and reduced stress magnitudes, while low-conductivity soils intensify non-uniform behavior.

The results for a full-scale field investigation into the thermo-mechanical behavior of energy piles under different end-restraining conditions, conducted on three instrumented piles in Houston, Texas were shown (Sutman et al., 2019). The research focused on understanding how head and base restraints influence thermally induced stresses and shaft resistance mobilization. The experimental setup involved three cast-in-place concrete piles of two 15.24 m long and 45.7 cm diameter piles (TP-1 and TP-3) bearing on very dense sand, and one 9.14 m long pile (TP-2) of the same diameter embedded entirely in stiff to very stiff clay. Each pile was instrumented with vibrating wire strain gauges at multiple depths (six for TP-1/TP-3, four for TP-2), thermal integrity profiler wires, and thermistors to monitor strain and temperature changes. A single-loop polyethylene pipe system facilitated geothermal heat exchange. The testing protocol included pure thermal loading on TP-1 (five heating-cooling cycles between 8°C and 43°C without mechanical load) and thermo-mechanical loading on TP-2 and TP-3 (single heating-cooling cycle between 8°C and 45°C under maintained mechanical load). Key findings revealed significant variations in thermally induced stresses based on restraint conditions. TP-1, with a free head, developed maximum compressive stress of 1600 kPa at 8.7 m depth during heating and 1040 kPa tensile stress at the same depth during cooling. TP-3, with mechanical head restraint, showed 1850 kPa compressive stress at 5.8 m depth during heating and a 490 kPa stress reduction during cooling. TP-2, with clay base support, exhibited 1020 kPa compressive stress at 2.7-5.8 m depth during heating. Shaft resistance mobilization varied considerably, with TP-1 showing 21 kPa upward resistance in upper sections during heating, while TP-3 developed 14.5 kPa downward resistance below 5.8 m due to head restraint. The study demonstrated that head restraints increased compressive stresses near the pile head (up to 80% of fully restrained conditions) and shifted the neutral point upward, while base restraints in dense sand induced higher stresses between 740 and 850 kPa compared to 510 kPa for clay. During cooling, restraint effects diminished, causing stress reductions and neutral point migration toward the pile base. These findings emphasize the critical influence of end-restraint conditions on energy pile behavior and highlight the need for their careful consideration in design to ensure structural integrity and performance.

A full scale field experiment to examine the axial and radial thermal responses of friction-type energy piles embedded in clay under monotonic thermal loading conditions was performed (Lv et al., 2020). The experimental work was conducted on a full-scale bored

concrete pile with a diameter of 0.6 m and a length of 24 m, constructed using C30 commercial concrete with a specified compressive strength of 30 MPa and a thermal expansion coefficient of $10 \mu\epsilon/^\circ\text{C}$. The pile was instrumented with vibrating wire sensors positioned at 2 m intervals along the reinforcement cage to monitor axial strains and temperature variations, while horizontal circular vibrating string sensors at 16 m depth measured radial thermal strains. The heat exchange system employed W-shaped high-density polyethylene pipes with an outer diameter of 25 mm, installed 0.05 m from the pile periphery and extending to 22 m depth. The surrounding soil profile consisted of layered clay with low and high plasticity, characterized by shear strengths ranging from 84 to 180 kPa and an elastic modulus of 6.9 MPa. The experimental program implemented two heating power modes (2.5 kW and 5.0 kW), resulting in stabilized inlet water temperatures of 40°C and 68.4°C respectively, with monitoring conducted over 15-day periods. Key findings revealed significant differences in thermal stress development between axial and radial directions. Axial thermal stresses in clay reached substantial magnitudes of 3.2 MPa and 5.9 MPa under 2.5 kW and 5.0 kW loading respectively, demonstrating a clear relationship between heating power and axial stress generation. In contrast, radial thermal stresses remained minimal at 0.36 kPa and 0.83 kPa for the respective loading conditions, representing just 0.01% of the concurrent axial stresses. The study observed that axial thermal strain responses in clay ($2.5\text{--}4.1 \mu\epsilon/^\circ\text{C}$) were markedly constrained compared to free thermal expansion potential ($10 \mu\epsilon/^\circ\text{C}$), while radial strains ($5.6\text{--}6.0 \mu\epsilon/^\circ\text{C}$) showed less restraint. Comparative data from dense sand conditions revealed higher radial stress development (11.6 kPa), though still negligible relative to axial stresses (2.2 MPa) and concrete capacity. These results demonstrate that soil type significantly influences thermal stress distribution, with clay providing greater axial constraint than dense sand, as evidenced by the higher axial stress to temperature change ratio in clay ($0.2 \text{ MPa}/^\circ\text{C}$) versus sand ($0.1 \text{ MPa}/^\circ\text{C}$). The research concludes that radial thermal stresses remain insignificant for structural considerations in both soil types, while axial thermal stresses constitute the dominant mechanical response. The findings emphasize that pile-soil interaction characteristics vary substantially between directions, with radial constraints being orders of magnitude lower than axial constraints, and that soil shear strength alone cannot predict constraint behavior. The maximum observed radial stress of 0.83 kPa in clay and 11.6 kPa in sand represents only 0.003% and 0.04% respectively of the concrete's compressive strength, confirming their negligible structural impact.

A combined study covering field tests and numerical modeling to investigate the cross-sectional thermo-mechanical responses of energy piles was performed (Moradshahi et al., 2021a). The field experiments were conducted on two energy piles EP-1 and EP-2 installed under a six-storey residential building, each with a diameter of 0.6 m and a length of 10 m, spaced at a center-to-center distance of 3.5 m. The piles were equipped VWSGs and thermocouples to measure axial strains and temperatures at multiple depths and radial positions. The soil profile consisted of dense to very dense clayey sands, and the piles were subjected to heating and cooling experiments under both single and dual pile operations. The numerical model, developed using COMSOL Multiphysics, was validated against the field data and used to explore the effects of varying inlet fluid temperatures, soil thermal conductivity, elastic modulus, and thermal expansion coefficient on the thermal responses of the piles. The findings revealed significant non-uniform temperature and stress distributions across the pile cross-section. Temperatures and thermal stresses were highest at the center of the pile and decreased toward the edge, with differences of up to 4 °C and 2.2 MPa, respectively, between the center and edge. The study highlighted that conventional design methods, which assume uniform temperature or rely on single-point measurements, overestimate thermal stresses by up to 2 MPa, leading to potential overdesign. Sensitivity studies showed that soil elastic modulus had the most pronounced effect on thermal stresses, while soil thermal conductivity primarily influenced ground temperatures. The presence of a nearby EP-2 had negligible impact on the thermal responses of EP-1 for the given spacing, though ground temperatures between the piles were affected during dual pile operations. The results emphasize the importance of accounting for cross-sectional variations in temperature and stress for accurate energy pile design.

Field tests for two instrumented energy piles including one unrestrained pile with a diameter of 0.6 m and length of 16.1 m, and one restrained pile of the same diameter but 10 m long, installed beneath a six-story structure were performed (Faizal et al., 2019). Both piles were equipped with U-loop heat exchangers made from pipes with a nominal diameter of 25 mm and an inner diameter of 20 mm. The unrestrained pile contained three U-loops extending to 14.2 m depth, spaced 175 mm apart, while the restrained pile included four full-depth loops spaced at 200 mm, resulting in a 25% increase in heat exchange surface area. Stress monitoring revealed that the unrestrained pile experienced maximum axial compressive stresses of -2.1 MPa at a depth of 5.4 m under continuous heating. When

subjected to cyclic thermal loading, these peak stresses were significantly reduced to -1.3 MPa, marking a 38% decrease at the same depth. In contrast, the restrained pile showed lower peak stresses of -1.8 MPa at 5.4 m, highlighting the stress-reducing benefit of structural integration. Measurements of radial stress showed a steep decline from -0.9 MPa at the pile-soil interface to -0.09 MPa at 0.5 m away, indicating a 90% reduction within the first half-meter. Stress profiles recorded at several depths revealed a clear trend: at 5.4 m, stresses dropped from -2.1 MPa (continuous) to -1.3 MPa (cyclic); at 8.2 m, from -1.4 MPa to -0.9 MPa; at 11.6 m, from -0.7 MPa to -0.4 MPa; and at 13.3 m, the lowest values of -0.3 MPa (continuous) and -0.2 MPa (cyclic) were observed. The extra loop in the restrained pile configuration led to notable performance enhancements, improving heat transfer by 25% and increasing energy extraction efficiency by 18–22%. Furthermore, it reduced the surrounding soil temperature change by 35–40% and narrowed the thermal influence radius from 2.2 m to 0.4 m. Overall, while continuous operation can induce substantial stresses near the top of the pile, integrating optimized heat exchanger design and cyclic loading can effectively maintain stress levels below 1.5 MPa and enhance overall system efficiency.

3.2. Hoop Stress Examples in other Concrete Structures

Hoop stress is a problematic kind of stress for reinforced concrete structures, as it can lead to tensile force development and potential cracking. The encountered situations include hydration heat-induced hoop stresses in mass concrete, internal pressure-induced hoop stresses in cylindrical pipes, and thermal gradients in structures such as nuclear containment vessels, chimneys, and LNG storage tanks. Studies have shown that thermally induced hoop stresses can exceed concrete's tensile capacity, leading to crack initiation and durability concerns. For example, in mass concrete, excessive temperature differentials between the core and surface generate tensile hoop stresses, while in pressurized pipes, internal loading creates circumferential tension. Understanding these mechanisms is crucial for assessing similar risks in energy piles, where cyclic thermal loading may induce comparable stress patterns in the clear concrete cover. This section explores these cases to highlight the structural implications of hoop stresses and their relevance to energy pile design.

3.2.1. Operational Modes for Energy Geostructures

It was numerically studied to show thermal stress redistribution in cylindrical reinforced concrete shells, such as nuclear containments, chimneys, and silos, focusing on the transition boundary between regions with different hoop reinforcement configurations (Wang, 2015). The main output was that thermal gradients induce significant hoop stresses, which are redistributed due to reinforcement discontinuities, leading to localized stress concentrations and potential cracking.

The effectiveness of an automated curing system in mitigating thermal cracks in mass concrete structures was investigated (Ha et al., 2014). The research addresses the challenge of tensile thermal cracking especially hoop caused by heat of hydration, which induces tensile stresses when the temperature difference between the internal and external parts of the concrete exceeds critical thresholds. The automated curing system developed in this study maintains the temperature difference between the core and surface of the concrete below 20°C, a criterion derived from standards like CIRIA C660 (2007). The critical temperature gradient with respect to tensile strength for early-age concrete was calculated using the equation

$$\Delta T_{max} = \frac{3.7 \cdot \varepsilon_{cu}}{\alpha_c}, \quad (3.1)$$

where ε_{cu} is the tensile strain capacity ($\sim 70 \times 10^{-6}$) and α_c is the concrete thermal expansion coefficient ($\sim 10 \times 10^{-5}$). This yielded a maximum allowable ΔT is 19.9°C. In the tests, two mass concrete specimens (3 m $\times$ 2 m $\times$ 5 m) were compared: one cured with the automated system (Mass-1) and the other with conventional methods (Mass-2). Mass-1 was maintained ΔT less than 20°C while it was 29°C for Mass-2 leading to tensile stresses exceeding the concrete's tensile strength and causing cracks widths up to 0.4 mm.

Thermal stress and cracking in the concrete outer wall of LNG tank during construction, with a focus on hoop stress and its consequences were investigated (Zhai et al., 2016). It was shown that hoop stress at the outer surface of the concrete wall exceeded the ultimate tensile stress after casting, leading to the initiation of microcracks. Visual cracks manifested as vertical cracks on the concrete wall surface and circumferential cracks on the buttress column surface. At the buttress column inner surface, vertical tensile stress exceeded

the ultimate tensile stress within just 10 hours of casting, causing early circumferential cracks. Concrete shrinkage was identified as a major contributor, adding up to 4.1 MPa of additional tensile hoop stress in early casting stages. A 40% reduction in shrinkage—achievable through improved curing or mix design—proportionally reduced stress. The construction season also played a critical role; building during February–July, when ambient temperatures rise, helped counteract shrinkage strain and minimized hoop stress, preventing cracks without requiring shrinkage reduction. While steel formwork slightly reduced thermal stress compared to plywood due to relatively higher thermal conductivity, its impact was insufficient to prevent cracking.

A comprehensive simulation methodology for assessing the structural safety of concrete tunnel linings exposed to fire was performed (Bernardi et al., 2020). During a fire, the lining's inner surface heats up rapidly, causing thermal expansion. It was shown that non-uniform temperature distributions across the lining thickness and perimeter occurred very quickly less than 900 seconds in case of firing.

The thermo-mechanical behavior of refractory concrete linings in industrial applications, focusing on hoop stress and its implications for lining performance was investigated (Bareiro et al., 2021). It was stated that hoop stresses were significantly higher than radial stresses, with maximum compressive stresses occurring at the innermost surface of the lining. The onset of visual cracks was observed in the outer layer of the lining, where tensile stresses exceeded the material's tensile strength. This occurred during the heating process, particularly after 36–40 hours for some combinations, indicating a critical risk of cracking under prolonged thermal exposure. It was highlighted that steep thermal gradients rose up these stresses, accelerating damage in the lining system.

An analytical model to predict the axial stress-strain behavior of heat-damaged unreinforced concrete columns wrapped with FRP jackets was studied (Shayanfar et al., 2023). FRP confinement significantly improved the axial strength, ductility, and stiffness of heat-damaged concrete columns, though the effectiveness diminishes with increasing exposure temperature. The hoop stress in FRP-confined concrete columns had a critical role in restraining transverse expansion and volumetric response. However, as exposure temperature rises, the likelihood of FRP hoop rupture increased, particularly at low axial

deformation levels, reducing axial strain ductility by 14–71%. Microcracks began to form at temperatures around 200°C, evolving into macro-cracks at higher temperatures (400°C and above).

3.2.2. Internal Pressure Induced Hoop Stress

The stress distribution in buried concrete pipes under various environmental conditions, focusing on the critical role of hoop stress and its implications for pipeline integrity was studied (Lee et al., 2016). Besides, it was shown that how different loading conditions (uniform, longitudinal, and transverse), backfill materials (gravelly sand, silty sand, and silty clay), and the presence of voids influence hoop stress and circumferential thrust in the pipe. Key findings revealed that uniform loading induces the highest hoop stress, approaching the concrete's tensile strength. Longitudinal loading also generated significant tensile stress, while transverse loading produced the lowest stress concentrations. Among backfill materials, gravelly sand increased stress due to its stiffness, whereas silty clay minimizes stress, making it a preferable choice for high-load zones. The study highlights the risk of crack initiation when hoop stress exceeds 80% of the characteristic strength of the concrete, with visible cracks likely forming at the concrete's tensile limit.

A full scale experiment to show that hoop stress is a critical factor in the performance and failure of prestressed concrete cylinder pipes for water conveyance projects was conducted (Hu et al., 2019). In such pipes, prestressing wires are designed to withstand hoop stress caused by internal hydrostatic pressure. When these wires break due to corrosion, manufacturing defects, or other factors, the hoop stress is no longer adequately resisted, leading to pipe deformation and potential rupture. Broken prestressing wires disrupt the equilibrium of hoop stress, leading to deformation and rupture. Therefore, cracking of both inner, outer and mortar can be triggered. It was noted that visual tensile cracking started at 11 times of the concrete strain corresponding to peak strength.

The mechanical behavior of prestressed concrete cylinder pipes under internal water pressure, with a focus on hoop stress distribution and its consequences was experimentally investigated (Cheng et al., 2020). Hoop stress, primarily resisted by prestressing wires and the steel cylinder as a coating, initially causes linear elastic deformation until microcracks

form in the mortar coating at 1.5 times of the concrete strain corresponding to peak tensile strength. When visible cracks appear in the concrete cores, marking the serviceability limit-state, where hoop stress overcomes the prestress in the concrete. It was also noted that after onset of visible cracking of the mortar corrosion risks start to take place.

3.3. Current Standards and Regulations over Structural Aspects of Energy Piles

An energy pile design can be performed according to Eurocode 2 (2023) and Eurocode 7 (2024) as shown below.

- *Determination of the input parameters*

The determination of input parameters for the design of an ordinary energy pile requires a comprehensive characterization of the geotechnical, structural, and environmental conditions. This begins with defining the soil properties, including the soil modulus (E_{soil}), Poisson's ratio (ν_{soil}), undrained shear strength ($S_{u,\text{soil}}$), effective angle of shearing resistance (ϕ'), and unconfined compressive strength (UCS), alongside its thermal properties. Concurrently, the pile properties must be specified, such as its slenderness ratio, diameter, length, and the material grades—namely the characteristic compressive strength of concrete (f_{ck}) and the yield strength of steel (f_{yk})—in addition to the pile's own thermal characteristics. The applied loads are categorized into mechanical actions, including characteristic permanent (P_k) and variable (Q_k) loads, and thermal actions (ΔT_k) resulting from temperature changes. Finally, the environmental conditions, particularly the exposure class, are critical for assessing durability requirements and potential degradation mechanisms.

- *Ultimate limit state (ULS) design*

For the geotechnical ultimate limit state (ULS) verification of the energy piles, the following design approaches are defined as

$$\text{DA1} - \text{C1: } A1 + M1 + R1A1 + M1 + R1, \quad (3.2)$$

$$\text{DA1} - \text{C2: } A2 + M1 + R4A2 + M1 + R1, \quad (3.3)$$

$$\text{DA2: } A1 + M1 + R2A1 + M1 + R2, \quad (3.4)$$

$$\text{DA3: } A1 + M2 + R3A1 + M2 + R3. \quad (3.5)$$

A single set of partial factors, as shown below, is adopted for computing the shaft capacity (Q_s) and base capacity (Q_b) in coarse-grained, fine-grained, and rocky soils

$$A1 + M1 + R1 A1 + M1 + R1. \quad (3.6)$$

The required longitudinal reinforcement area (A_s) must be the greater of the calculated values

$$A_{s,min}: A_{concrete} \leq 0.5 m^2 \quad A_{s,min} \geq 0.5\% A_{concrete}, \quad (3.7)$$

$$A_{s,min}: A_{concrete} > 0.5 m^2 \quad A_{s,min} \geq 0.25\% A_{concrete}. \quad (3.8)$$

The required longitudinal reinforcement (A_s) shall be the greater of the values calculated for structural capacity or for ductility

$$A_{s,min}: A_{s,min} = \frac{f_{ctm} A_{concrete}}{f_{yd}} \text{ where } f_{ctm} = 0.3 f_{ck}^{2/3}. \quad (3.9)$$

To adequately confine the core concrete, tie spacing under transverse loads is limited to a maximum of 200 mm. Furthermore, N-M interaction controls for the concrete capacity should be made

$$N_{Ed} \leq N_{Rd} \text{ and } M_{Ed} \leq M_{Rd}. \quad (3.10)$$

- *Serviceability limit state (SLS) design*

For the serviceability limit state (SLS) verification of the energy piles, the following load combinations are utilized regarding the characteristic situation and the quasi-permanent action, respectively

$$E_{d,k} = G_k + Q_k + \Delta T_k, \quad (3.11)$$

$$E_{d,qp} = G_k + \psi_2 Q_k + \psi_2 \Delta T_k. \quad (3.12)$$

From the tensile strength of the concrete point of view in the axial direction, the limiting tension limit state can be controlled as

$$\sigma_c \leq 0.6 f_{ck} \text{ and } \sigma_c \leq 0.45 f_{ck} \text{ (quasi – permanent)}. \quad (3.13)$$

Similar stress check should be made for the steel reinforcement

$$\sigma_s \leq 0.8 f_{yk} \text{ and } \sigma_s \leq f_{yk} \text{ (under thermal loading)}. \quad (3.14)$$

The cracking limit state ensures that cracks in the concrete remain acceptably small for the durability of the energy piles. This is verified by calculating the design crack width (w_k) using Equation 3.15, which should not exceed a specified limit, typically between 0.2 and 0.3 mm depending on the exposure class. The crack width is a product of the maximum crack spacing ($S_{r,max}$) from Equation 3.16 and the difference in mean strain ($\epsilon_{sm} - \epsilon_{cm}$) between the reinforcing steel and the surrounding concrete from Equation 3.17. The mentioned equations are

$$w_k = S_{r,max} (\epsilon_{sm} - \epsilon_{cm}) \leq 0.2 \sim 0.3 \text{ mm}, \quad (3.15)$$

$$S_{r,max} = 3.4c + 0.425\phi / \rho_{eff}, \quad (3.16)$$

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \frac{f_{ct,eff}}{\rho_{p,eff}} (1 + n\rho_{p,eff})}{E_s} \geq 0.6 \frac{\sigma_s}{E_s}. \quad (3.17)$$

The settlement limit state is a serviceability requirement that ensures the total settlement of a pile foundation, arising from both mechanical loads and thermally-induced loads, does not cause excessive deformation or damage to the structure or connected services. The total calculated settlement should be less than or equal to the pile spacing divided by 500. This criterion, effectively limiting settlement to 0.2% of the pile spacing, is primarily intended to mitigate the risk of negative skin friction or downdrag on the piles. The beforementioned settlement criterion is

$$w^{mechanical+thermal} \leq \text{pile spacing}/500. \quad (3.18)$$

- *Thermo-mechanical analysis*

Thermo-mechanical analysis for energy pile foundations requires specific modeling strategies to accurately capture the complex interaction between the pile, the surrounding soil, and thermally induced stresses. For a single pile, simplified material properties are often adopted to account for cracking under combined mechanical and thermal loads; a common approach is to reduce the concrete's modulus of elasticity as

$$E_{cracked} = E_{cm}/3. \quad (3.19)$$

The interaction with the soil might be defined through boundary conditions, typically modeled as winkler springs. However, to analyze the complex interactions within a pile group, where the response of one pile affects its neighbors, a full 3D Finite Element Analysis (3D-FEA) method is necessary. This advanced numerical technique is the most robust way to model the fully coupled thermo-mechanical-geotechnical system, capturing group effects, load redistribution, and differential settlements that simplified methods cannot.

- *Cyclically applied thermal loading checks*

The long-term design of energy pile foundations requires specific checks beyond those for conventional piles, primarily due to the effects of cyclically applied thermal loading. These checks involve rigorous stress and displacement controls to prevent accumulated fatigue damage, excessive settlement, or ratcheting (the progressive build-up of strain or stress over cycles) in both the concrete pile and the surrounding soil. Simultaneously, durability is a paramount concern, as the pile is a structural element intended to last for the building's lifespan. A key durability provision, often

specified as a minimum clear cover of 40 mm, is compulsory to protect the reinforcing steel from corrosion. This increased cover is crucial for energy piles because the constant thermal cycles can potentially accelerate degradation processes, making robust protection against environmental chlorides, carbonation, and other aggressive agents even more critical.



4. THERMALLY INDUCED STRESSES STATE

When materials are heated, they tend to expand, and when cooled, they contract. However, if this thermal movement is restrained, the resulting deformation cannot occur freely—this condition is referred to as constrained or blocked thermal strain. Therefore, the thermoelastic constitutive relations consist of temperature-dependent strains and their effect on stress distributions. Like energy piles having circular cross section, it is beneficial to adopt polar coordinates (r, θ, z) rather than cartesian coordinates (x, y, z) shown in Figure 4.1.

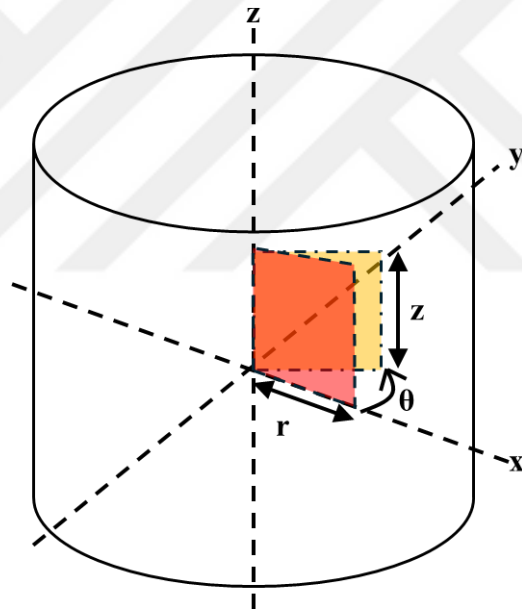


Figure 4.1. Coordinate systems.

In general, the total strain (ε_{ij}^T) for a body is the sum of the mechanical (ε_{ij}^m) and thermal (ε_{ij}^{th}) types of strains

$$\varepsilon_{ij}^T = \varepsilon_{ij}^m + \varepsilon_{ij}^{th}. \quad (4.1)$$

The corresponding thermal strain can be written as

$$\varepsilon_{ij}^{th} = \delta_{ij} \cdot \alpha \cdot \Delta T, \quad (4.2)$$

where α is the coefficient of thermal expansion, δ_{ij} is the kronecker delta and ΔT is the temperature difference.

Also, the mechanical strain caused by external load can be computed via Hook's law as

$$\varepsilon_{ij}^m = \frac{1+\nu}{E} \cdot \sigma_{ij} - \frac{\nu}{E} \cdot \sigma_{kk} \cdot \delta_{ij}. \quad (4.3)$$

By reorganizing Equation 4.3, the general representation of the stress-strain relation with thermal effects are

$$\sigma_{ij} = 2 \cdot \mu \cdot \varepsilon_{ij} + \lambda \cdot \varepsilon_{kk} \cdot \delta_{ij} - (3\lambda + 2\mu) \cdot \alpha \cdot \Delta T \cdot \delta_{ij}, \quad (4.4)$$

where

$$\lambda = \frac{E \cdot \nu}{(1+\nu) \cdot (1-2\nu)}, \quad (4.5)$$

$$\mu = \frac{E}{2 \cdot (1+\nu)}, \quad (4.6)$$

$$\varepsilon_{kk} = \varepsilon_{rr} + \varepsilon_{\theta\theta} + \varepsilon_{zz}. \quad (4.7)$$

The strain-displacement relation can be computed as

$$\varepsilon_{rr} = \frac{\partial u_r}{\partial r}, \quad \varepsilon_{\theta\theta} = \frac{u_r}{r}, \quad \varepsilon_{zz} = \frac{\partial u_z}{\partial z}, \quad (4.8)$$

$$\varepsilon_{rz} = \frac{1}{2} \cdot \left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \right), \quad \varepsilon_{r\theta} = \varepsilon_{z\theta} = 0, \quad (4.9)$$

where u_r and u_z are radial and axial displacement, respectively. The necessary displacement and stress directions are shown in Figure 4.2.

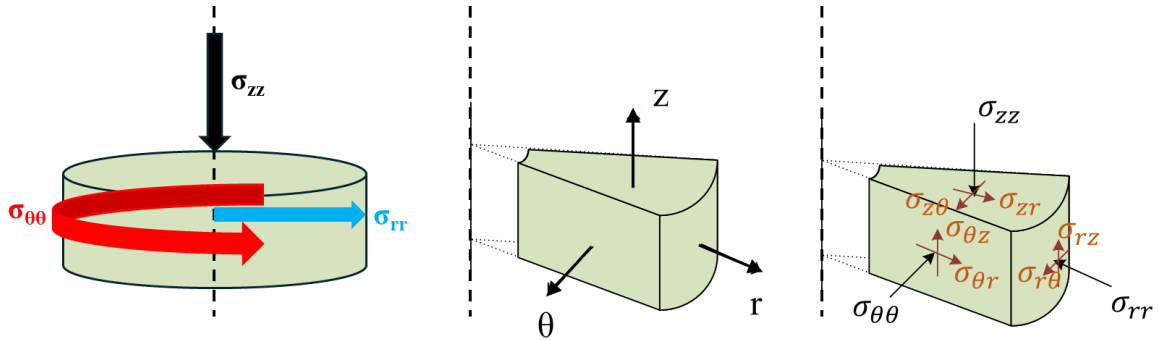


Figure 4.2. Stress and displacement directions.

Besides, the stress equilibrium equations can be expressed as

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{\partial \sigma_{rz}}{\partial z} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} = 0, \quad (4.10)$$

$$\frac{\partial \sigma_{rz}}{\partial r} + \frac{\partial \sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r} = 0. \quad (4.11)$$

By combining strain-displacement relation with the thermoelastic stress-strain law yields as

$$\sigma_{rr} = 2\mu \frac{\partial u_r}{\partial r} + \lambda \left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} \right) - (3\lambda + 2\mu)\alpha\Delta T, \quad (4.12)$$

$$\sigma_{\theta\theta} = 2\mu \frac{u_r}{r} + \lambda \left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} \right) - (3\lambda + 2\mu)\alpha\Delta T, \quad (4.13)$$

$$\sigma_{zz} = 2\mu \frac{\partial u_z}{\partial z} + \lambda \left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} \right) - (3\lambda + 2\mu)\alpha\Delta T, \quad (4.14)$$

$$\sigma_{rz} = \mu \left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \right). \quad (4.15)$$

Like energy piles representing long cylinder, the axisymmetric plane strain solutions for thermal loading are

$$\frac{d}{dr} \left(\frac{1}{r} \frac{d}{dr} (ru_r) \right) = \frac{1+\nu}{1-\nu} \alpha \frac{dT}{dr}, \quad (4.16)$$

$$u_r = C_1 r + \frac{C_2}{r} + \frac{1+\nu}{1-\nu} \alpha \int_a^r T(\rho) \rho d\rho, \quad (4.17)$$

where $u_r(r)$, C_1 , C_2 , $T(\rho)$, a and r represent radial displacement at radius, integration constants depending on boundary conditions, temperature function as a function of radial position, inner boundary and point of interest.

4.1. Utilized Equations

Radial stress (σ_r) and hoop stress (σ_θ) are depicted in Figure 4.3. Radial stress represents normal stress acting perpendicular to the pile axis within the same plane. Hoop stress (also called tangential or circumferential stress) is an established design factor in multiple engineering fields. For example, in liquid storage tanks, hoop stresses are crucial as they represent the tensile stress in tank walls caused by internal fluid pressure. Non-uniform thermal loading across a section can also produce thermal shear stresses ($\tau_{r\theta}$). These thermally generated stresses vary with both the intensity and speed of temperature changes (Praveen et al., 1999). Figure 4.3 illustrates a standard energy pile cross-section and the resulting thermal stresses at point A.

The thermal stresses can be mathematically represented using Cartesian coordinates

$$\sigma_r = \sigma_x \cos^2 \theta + \sigma_y \sin^2 \theta + 2\tau_{xy} \sin\theta \cos\theta, \quad (4.18)$$

$$\sigma_\theta = \sigma_x \sin^2 \theta + \sigma_y \cos^2 \theta - 2\tau_{xy} \sin\theta \cos\theta, \quad (4.19)$$

$$\tau_{r\theta} = (\sigma_y - \sigma_x) \sin\theta \cos\theta + \tau_{xy} (\cos^2 \theta - \sin^2 \theta), \quad (4.20)$$

where σ_x , σ_y , and τ_{xy} are normal and shear stresses within the cross-section associated with the cartesian coordinate system whose z-axis coincides with the pile axis. In the following sections, hoop stresses will be investigated as the primary focus of this study.

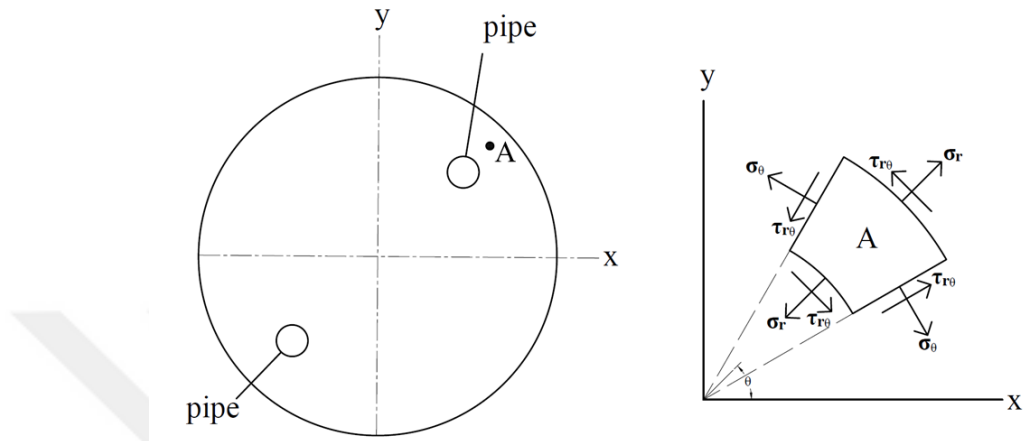


Figure 4.3. Stress state at an element A.

5. VERIFICATIONS FOR NUMERICAL MODELLING

This chapter presents the modeling of two field tests using COMSOL Multiphysics v6.3 (2025), a widely recognized structural FEA software. The reason for that is to show the capabilities of the software for thermo-mechanical calculations.

5.1. Case Studies for Verification

5.1.1. Analyses of Thermoactive Piles Considering Surface Radiation and Wind Convection Effects (Polat et al., 2024)

The field test data for the thermal loading of an energy pile test utilized in this study was obtained from Sutman's study (Sutman, 2016). The experimental site, located in Houston, Texas, features a comprehensive setup that includes three test piles, three heat sink piles, eight reaction piles, and several boreholes, as depicted in Figure 5.1. The test piles were constructed using the CFA cast-in-place method, each with a uniform diameter of 45.7 cm. Test Piles 1 (TP-1) and 3 (TP-3) are 15.2 m long, while Test Pile 2 (TP-2) measures 9.1 m in length.

The reinforcement detailing for the test piles includes a rebar cage comprising four full-length vertical Ø22 rebars, evenly spaced, and encircled by Ø10 stirrup steel bar rings positioned at 0.3-meter intervals throughout the 0.3-meter diameter cage (Figure 5.2a). Additionally, a Ø25 center bar extends along the entire pile length to enhance structural integrity. The in-situ experimental setup incorporated two water-to-water ground source heat pumps having a nominal capacity of 7 kW for each. TP-1 was directly connected to one of these heat pumps. For the purpose of validation as a numerical study, TP-1 was numerically modelled and corresponding performance of it was evaluated. The soil profile along the pile length, illustrated in Figure 5.2b, reveals a stratified composition of sand and clay layers, with the groundwater table located approximately 3.7 meters below the surface. The heating and cooling system embedded within the test pile features a single U-shaped PEX pipe with a nominal diameter of 25.4 mm and a wall thickness of 3.2 mm. Due to construction

constraints, the spacing between the pipes varies slightly in some sections, averaging around 6.4 cm, as illustrated in Figure 5.2a.

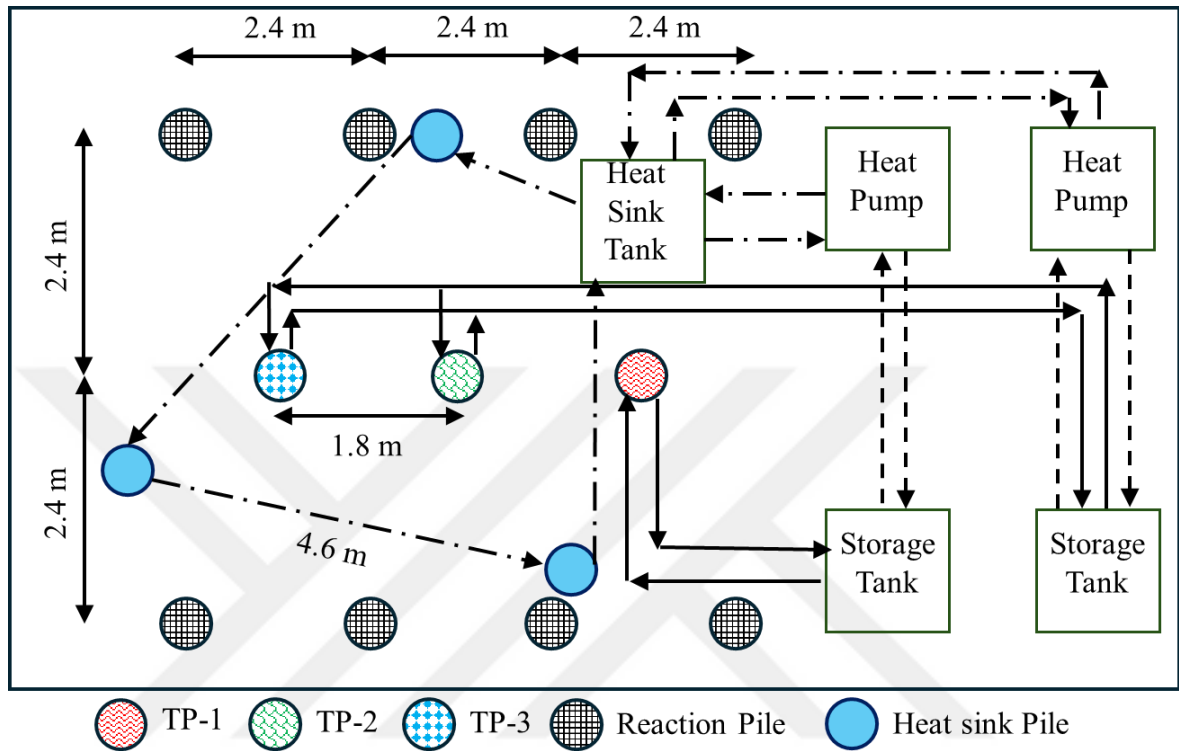


Figure 5.1. Field test layout (modified after Sutman, 2016).

The instrumentation layout for the energy pile is detailed in Figure 5.2 which was predetermined arrangement of monitoring devices. VWSGs were strategically positioned at five different depths as pairs along the pile length, as indicated in Figure 5.2b. These gauges were specifically designed to capture both strain and temperature data, providing essential insights into the pile's thermal and mechanical behavior during operation.

A combination of field tests and empirical correlations was employed to determine the thermal and mechanical properties of the soil and pile materials. In-situ measurements were conducted at depths corresponding to three primary soil units: clay above the groundwater table, clay below the groundwater table, and sand below the groundwater table. Thermal parameters for these soil units were derived as bulk values based on field test results reported in previous studies (Brettmann and Amis, 2011; Sutman, 2016; Sutman et al. 2019). Table 5.1 provides a comprehensive summary of the parameters associated with the soil layers and the energy pile.

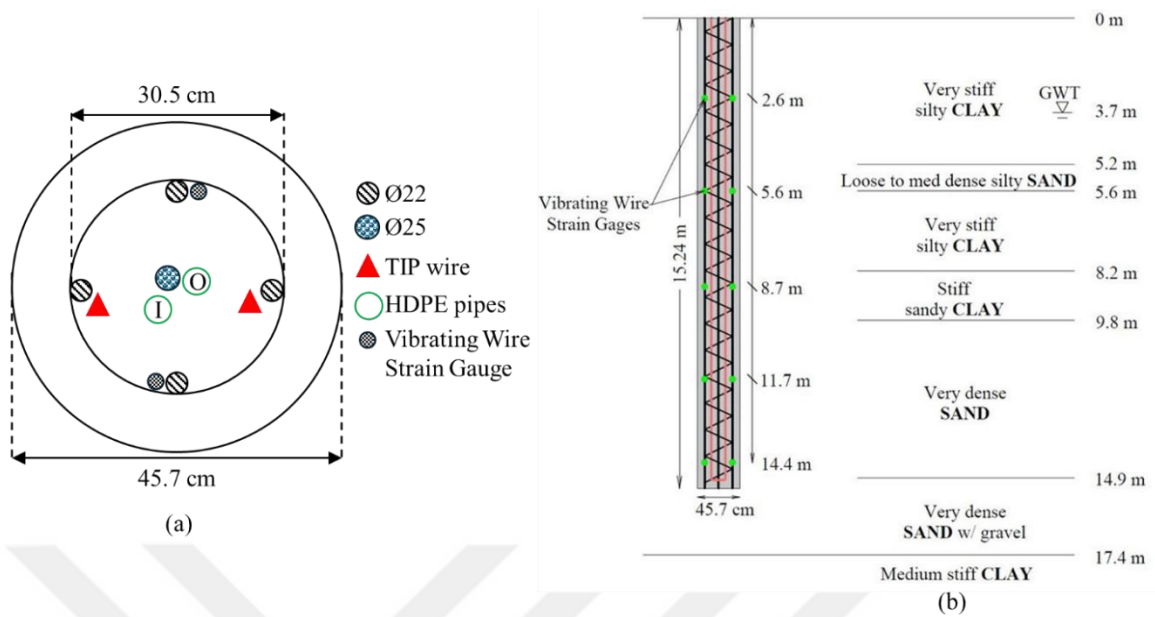


Figure 5.2. (a) Reinforcement detailing, and (b) soil profile.

Table 5.1. Summary of the parameters.

Properties	Clay	Sand	Pile
Elastic modulus, E (MPa)	45	75	36000
Poisson's ratio, ν (-)	0.495	0.3	0.18
Unit weight, γ (kN/m ³)	2005	1986	2044
Volumetric heat capacity, C (MJ/m ³ °C)	2.61	2.61	1.8
Thermal conductivity, λ (W/m°C)	2.1	1	2
Thermal expansion coefficient, α ($\mu\epsilon/^\circ\text{C}$)	1.5	1	12.9
Friction angle ($^\circ$)	0	43	-
Apparent cohesion (kPa)	114	5	-

In this field test, five cyclic thermal loading was applied to TP-1 without any mechanical load being applied. The thermal loading lasted over a six-week period, as illustrated in Figure 5.3. The heat exchanger fluid, a mixture of 80% water and 20% antifreeze (ethylene glycol), was carefully adjusted daily, with its temperature either increased or decreased by 10°C. The temperature was controlled within a range, reaching a maximum of 43°C and a minimum of 8°C.

According to field measurements based on boreholes prior to thermal loading of the pile, there existed temperature fluctuation at very shallow depths up to 6 m depth. Beyond the mentioned depth, it became uniform throughout the further depths. These fluctuations near the surface were attributed to the effects of air temperature changes and surface

radiation. To realistically capture the initial temperature conditions, ambient environmental data including ground surface temperature and wind effects from the two months preceding and during the field test were incorporated into the model. Meteorological data for 2013 were obtained from the Houston William P. Hobby weather station by ASHRAE Data Viewer 5.0 (ASHRAE, 2016), located approximately 45 km from the site. The used data also consists of air pressure, dew point and solar radiation apart from the weather temperature and wind action. In the numerical model, surface-to-surface radiation effect option was utilized to simulate ground surface solar radiation. That is, in exposed environments, surface temperatures are influenced not only by solar radiation but also by wind, which induces free and forced heat convection from all exposed surfaces to the ambient air. To account for that, a convective heat flux was additionally applied to the ground surface. Moreover, the heat transfer coefficient which is a function of air properties and wind speed was obtained based on (Rao, 2004). The external temperature used in the simulation was sourced from weather station data, while—dependent on wind speed and air properties—was calculated using a specific relation developed by (Rao, 2004). The proposed approach is valid for the low wind speeds less than 4 m/s that predominated at the field site. Therefore, the corresponding heat transfer coefficient can be computed as

$$h = 0.025\rho_a C_{p,air} v_a^{0.3}, \quad (5.1)$$

where ρ_a and $C_{p,air}$ are density and specific heat capacity of air, respectively and v_a represent wind velocity.

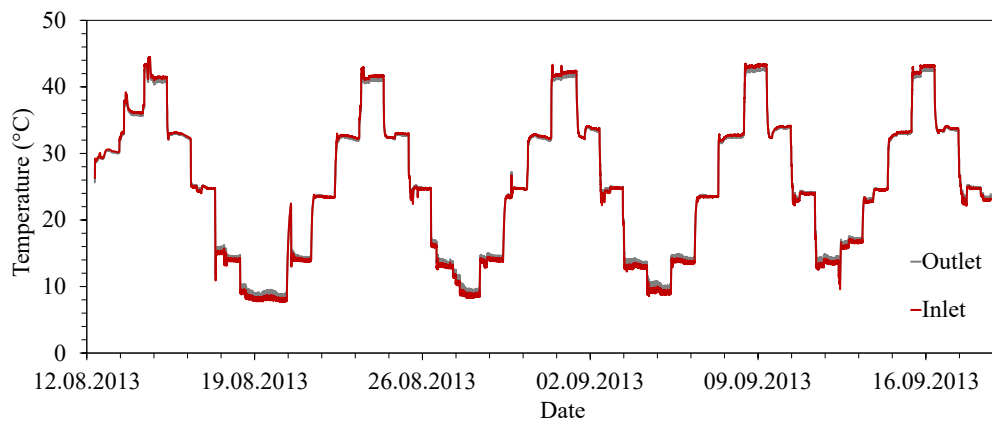


Figure 5.3. Thermal loading protocol.

COMSOL Multiphysics software was used for numerical modelling (Figure 5.4). Thermal boundaries are thermally insulating for the sides and the base. Linear elastic model

was adopted for the pile while it is Mohr Coulomb for soils. Only one week of cyclic thermal loading was applied. There is no mechanical load except self-weight of the pile. Rigid interface between pile and soil was defined.

Knowing the exact positions of sensors is a key factor to obtain compatible results between the temperature and stress outputs from the model and the field test data. However, due to the nature of the pile drilling technique, there exists a potential of changing of the sensor positions during concrete pouring. To address this, the analysis defines a reasonable distance range from the pile center for output locations. According to Sutman et al. (Sutman et al., 2019), the sensors were mounted on the vertical rebars, as shown in Figure 5.2. Considering the dimensions of the vertical rebars along pile, the possible sensor positions might be in between 11.7 cm to 12.9 cm from the pile center. In the finite element analysis, temperature and stress data were collected from this region ($D = 11.7$ cm to $D = 12.9$ cm). For simplicity, this distance range is denoted as "D".

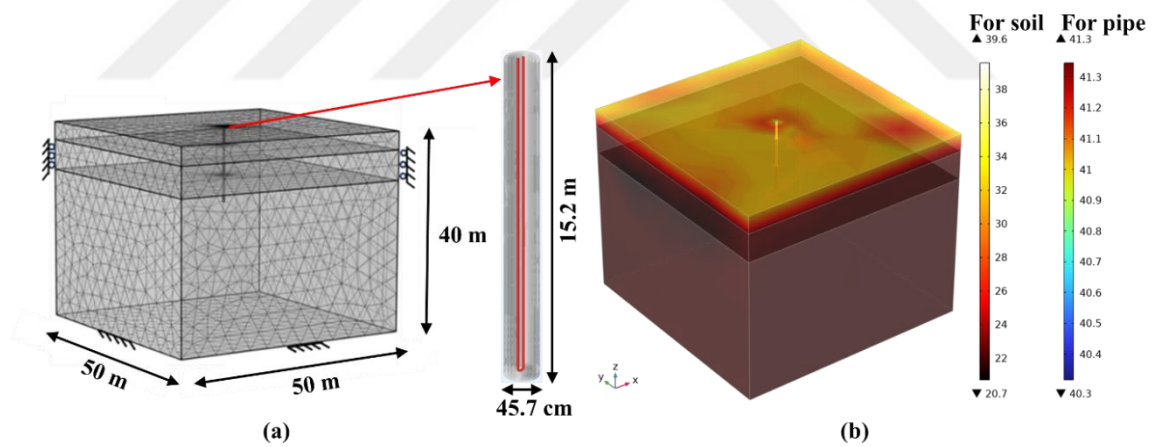


Figure 5.4. 3D numerical model: (a) general view, and (b) initial temperatures prior to thermal loading (modified after Polat et al., 2025).

Figure 5.5-Figure 5.8 depicts temperatures and thermally induced axial stresses along the pile during the first heating and cooling cycle. Prior to the thermal loading and during the entire test duration, wind convection and surface solar radiation were applied in the numerical model. By doing this, the actual site conditions in terms of temperature distribution were obtained. Especially at the first 6 m depth where atmospheric effects are effective, temperature distribution along depth was totally captured.

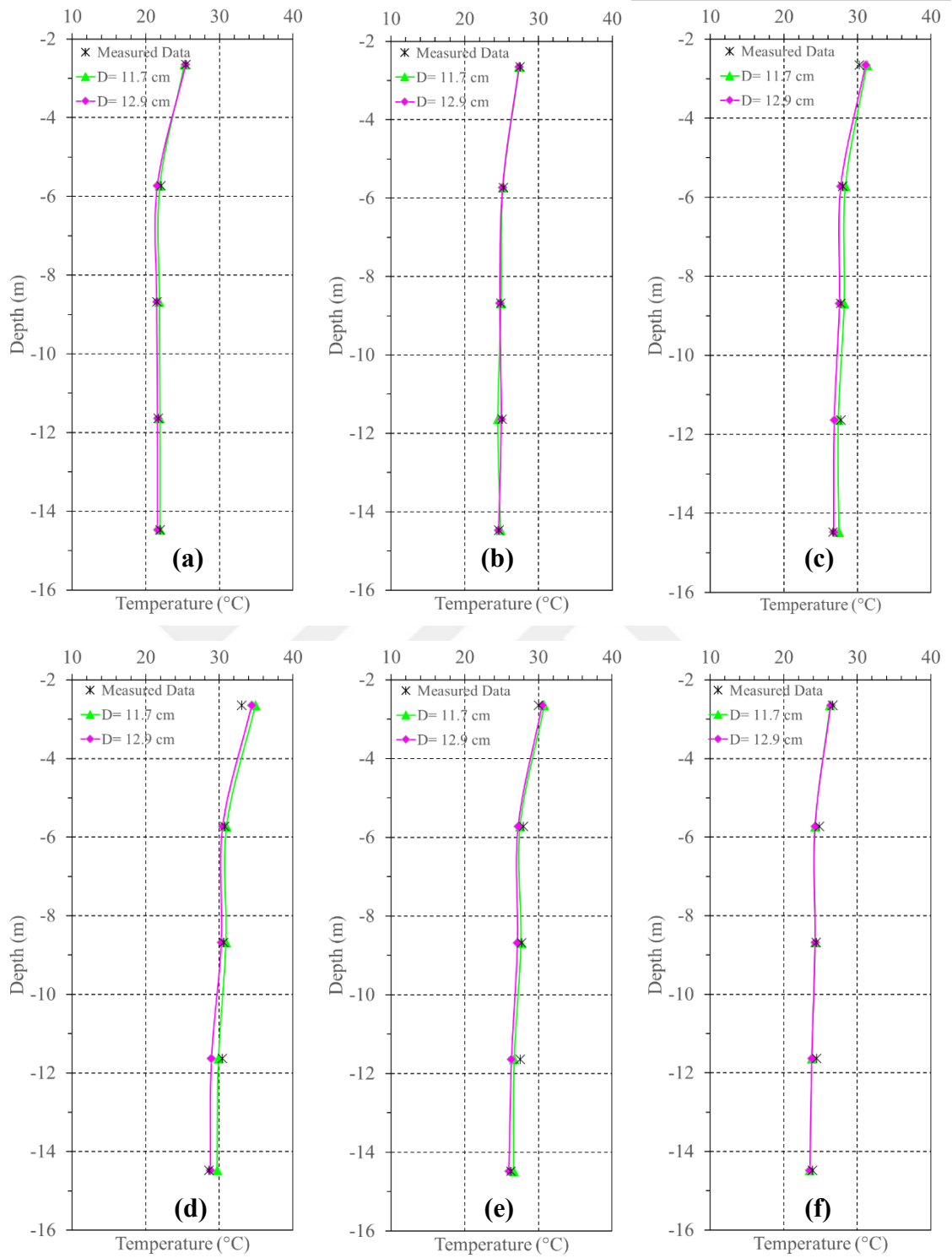


Figure 5.5. Field and numerical temperature values for (a) prior to the thermal loading, (b) Day 1, (c) Day 2, (d) Day 3, (e) Day 4, and (f) Day 5 (modified after Polat et al., 2025).

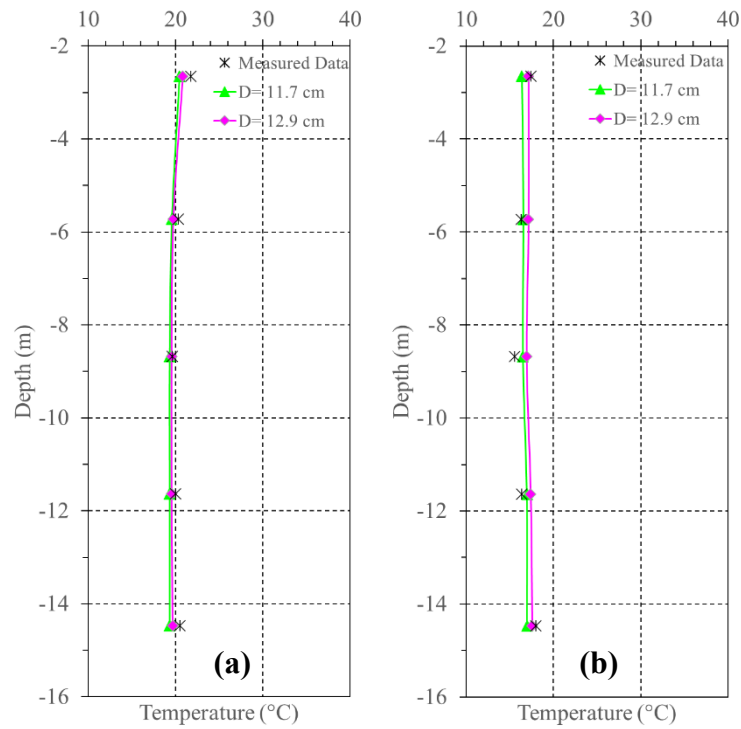


Figure 5.6. Field and numerical temperature values for (a) Day 6, and (b) Day 7 (modified after Polat et al., 2025).

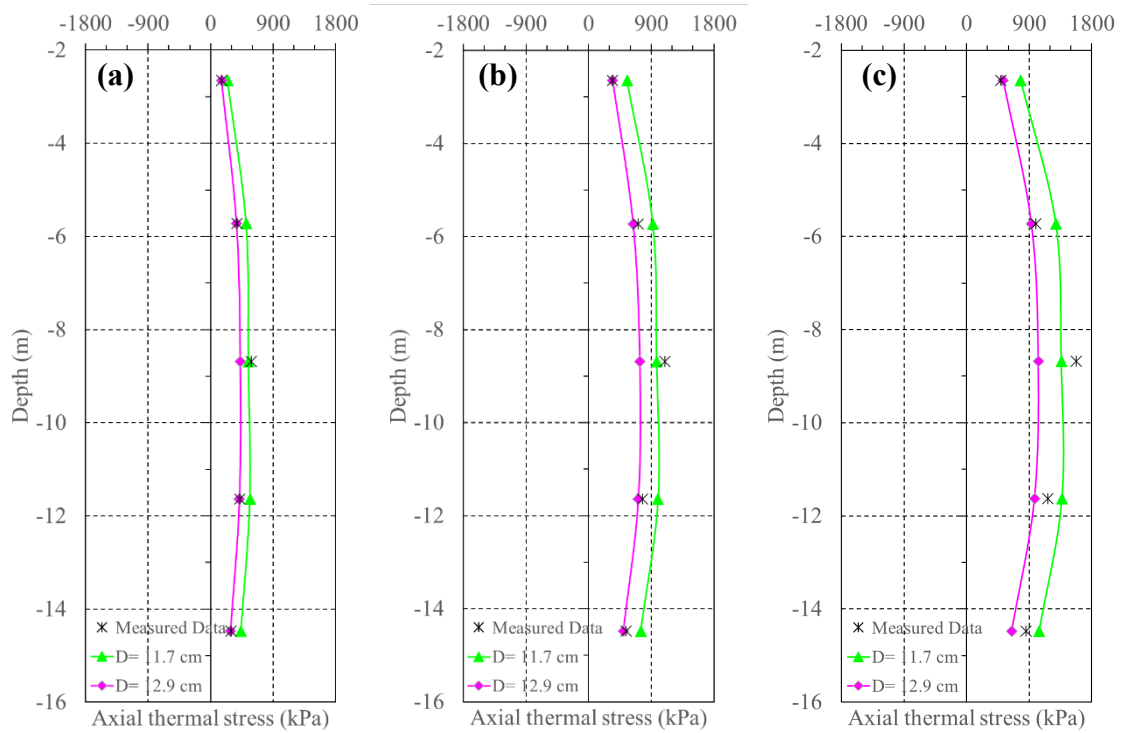


Figure 5.7. Field and numerical thermally induced axial stress values for (a) Day 1, (b) Day 2, and (c) Day 3 (modified after Polat et al., 2025).

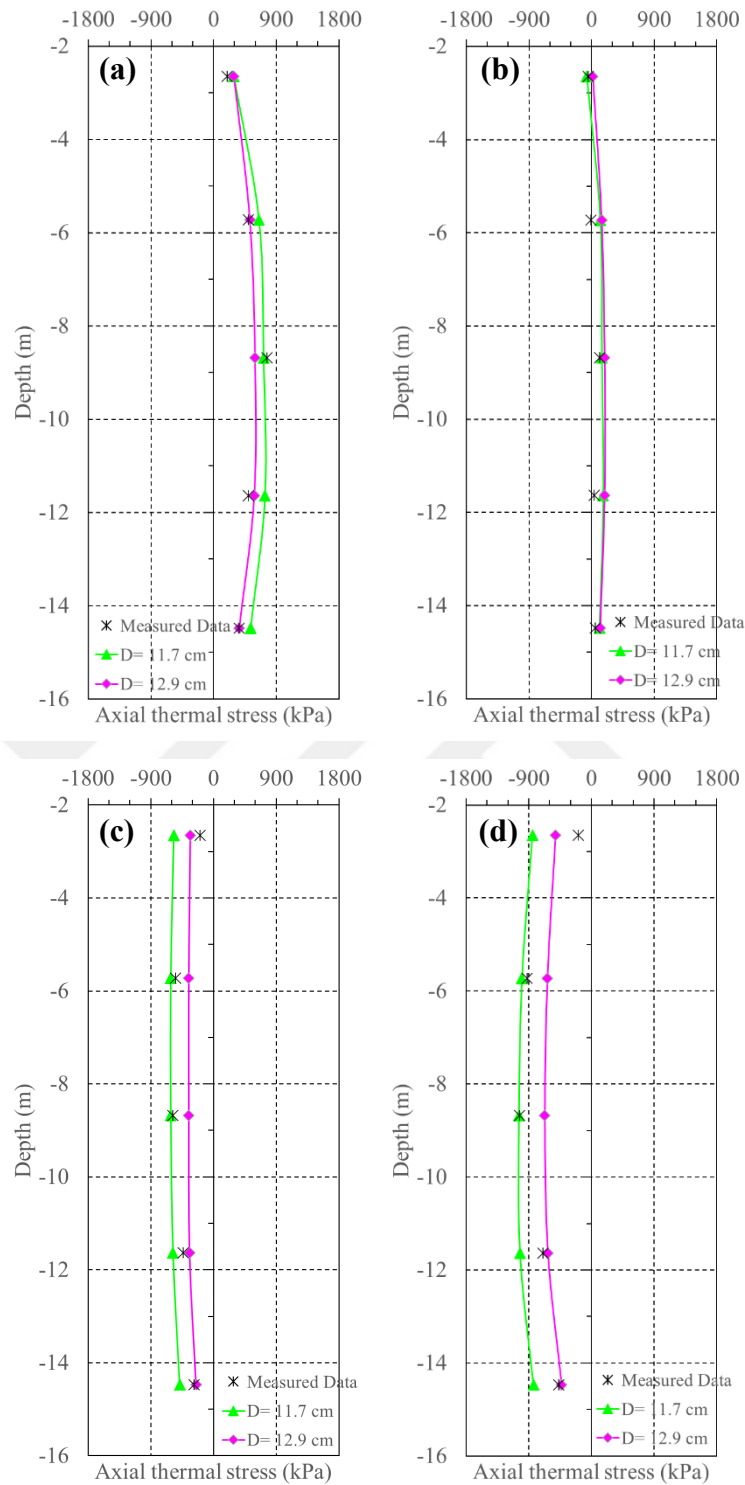


Figure 5.8. Field and numerical thermally induced axial stress values for (a) Day 4, (b) Day 5, (c) Day 6, and (d) Day 7 (modified after Polat et al., 2025).

Also, the thermally induced axial stress values are in good relation with respect to observed temperature changes. The mentioned stresses were calculated by subtracting the

in-situ stresses recorded prior to thermal activation from those measured after activation, following a sign convention where compressive stresses are considered positive. During the heating phase, compressive stresses increased, with the most pronounced change occurring at approximately 8.7 meters depth. Once cooling cycle started, axial compressive stresses decreased, as expectedly. According to the analysis performed, field measurements and computed results are in compatible.

5.1.2. Axial and Radial Thermal Responses of Energy Pile under Six Storey Residential Building (Faizal et al., 2019b)

As mentioned in the third chapter, thermally induced stresses are three dimensional and many researchers have tried to identify and measure them. In this section, another field study about energy pile was selected and it was tried to model numerically. Thermally induced axial stresses and temperature distribution along and around the pile form interest.

To construct the numerical model, information about the field test of the energy pile subjected to both thermal and mechanical loading was gathered from the literature (Faizal et al., 2019; Moradshahi et al., 2021b). The test was conducted at Monash University, Melbourne in Australia. The test setup involved a 0.6 m diameter, 10 m long cast-in-place bored pile (aspect ratio 16.7) constructed within a six-story residential building foundation. The pile disposition is shown in Figure 5.9.

The soil profile consists of three distinct soil strata: The fill material was damp and moderately dense, consisting of crushed rock and/or silty sands extending to a depth of 0.4 meters. Below the fill, down to about 3.5 meters, the natural soil was moist silty and sandy clay with a stiff to very stiff texture, interspersed with thin sandy layers. From approximately 3.5 to 12.5 meters deep, the soil transitioned to dense, moist sand containing alternating layers of clayey sand and silty sand, along with some cemented lenses. No groundwater was found within the pile's depth, and the soil across the site remained drained.

The energy pile was instrumented with an array of 30 VWSGs distributed at five depth levels (1.0, 3.05, 5.0, 7.28, and 9.5 m) to measure both axial and radial strains (Figure 5.10). Each level contained four peripheral axial gauges (160 mm concrete cover) and one central

axial-radial gauge pair mounted on foam blocks to isolate concrete strains. The heat exchange system consisted of four 25 mm HDPE U-loops spaced at 200 mm intervals within the reinforcement cage, with thermocouples monitoring inlet/outlet temperatures.

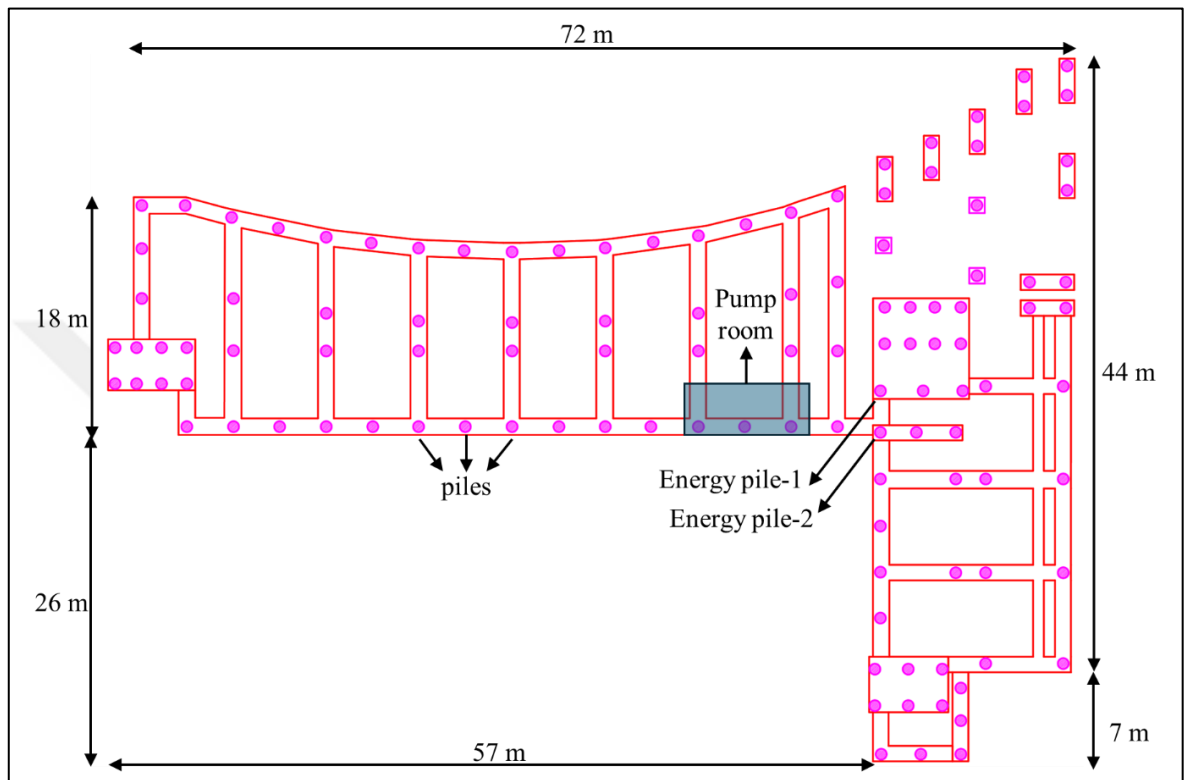


Figure 5.9. Pile disposition (modified after Faizal et al., 2019).

The thermal loading protocol involved 18 days of continuous heating (11 L/min flow rate, 48°C inlet temperature) followed by 50 days of passive cooling. This experimental design enabled detailed analysis of axial/radial strain distributions, temperature profiles across pile cross-sections, and the evolution of pile-soil interaction stresses under realistic boundary conditions, providing crucial validation data for energy pile design methodologies in unsaturated granular soils.

Numerical modeling was performed using COMSOL Multiphysics software (Figure 5.11). The side and bottom boundaries were set as thermally insulated. The pile was modeled as a linear elastic material, while the soil was represented using the Mohr-Coulomb model. The two separate raft foundations and two pile beneath it were modelled (Moradshahi et al.,

2021a). Also, a compressive mechanical load of 1400 kN was applied to the pile head to simulate real life situation.

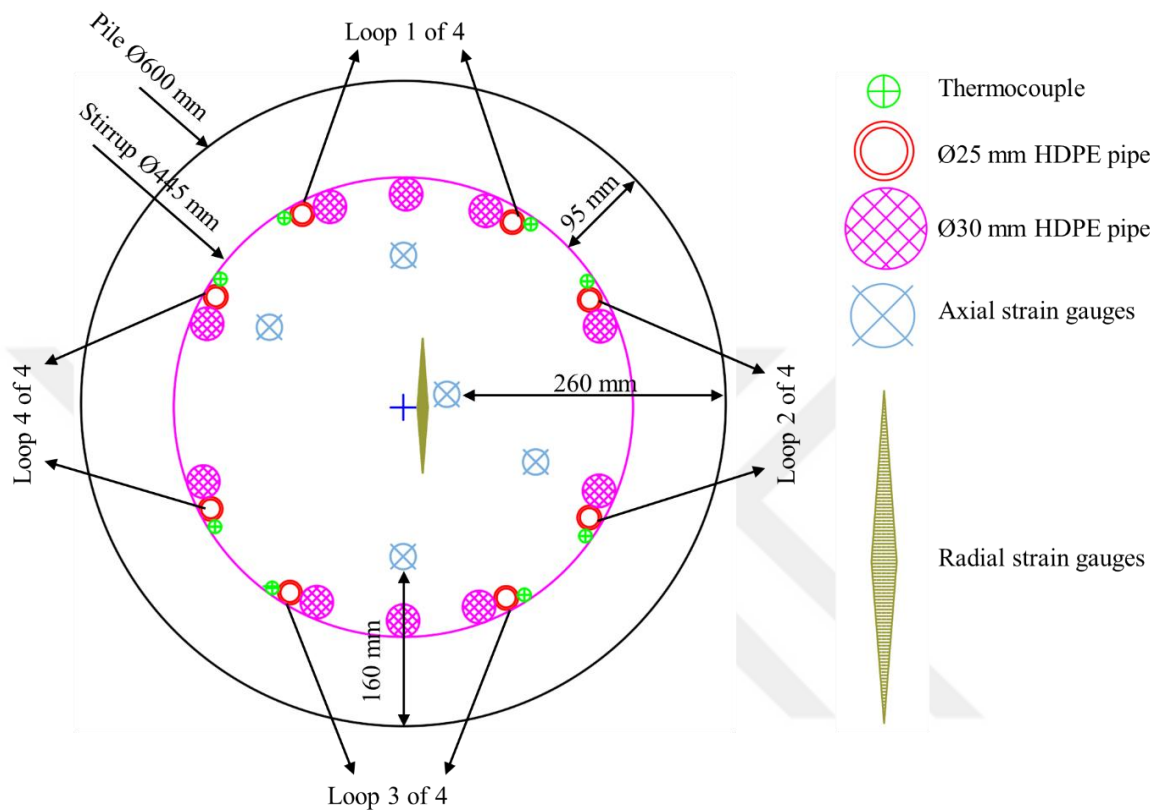


Figure 5.10. Pile cross section and sensor locations (modified after Faizal et al., 2019).

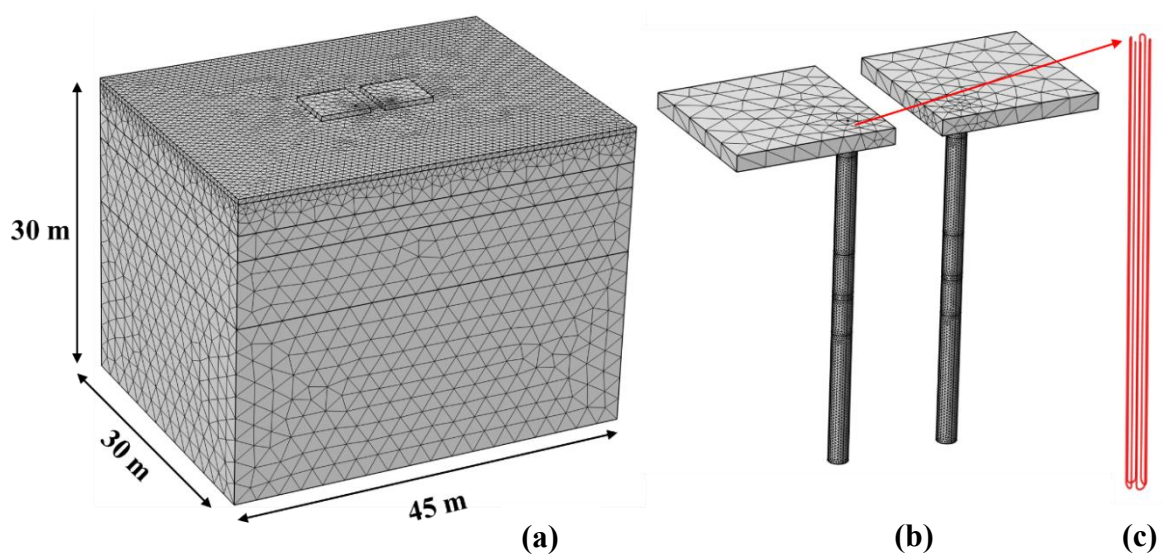


Figure 5.11. 3D numerical model: (a) general view, (b) raft and piles, and (c) HDPE pipes.

Figures 5.12 present the evolution of axial stresses, respectively, along the pile length following thermal loading initiation. The stress profiles were generated at approximately 5°C intervals, corresponding to incremental changes in the average pile temperature recorded by all VWGSGs during operation. The computed axial stresses show excellent agreement with measured values, successfully capturing the general stress distribution trend. The close correlation between measured and computed values validates the numerical model's ability to simulate thermal stress development in energy piles under thermal loading conditions.

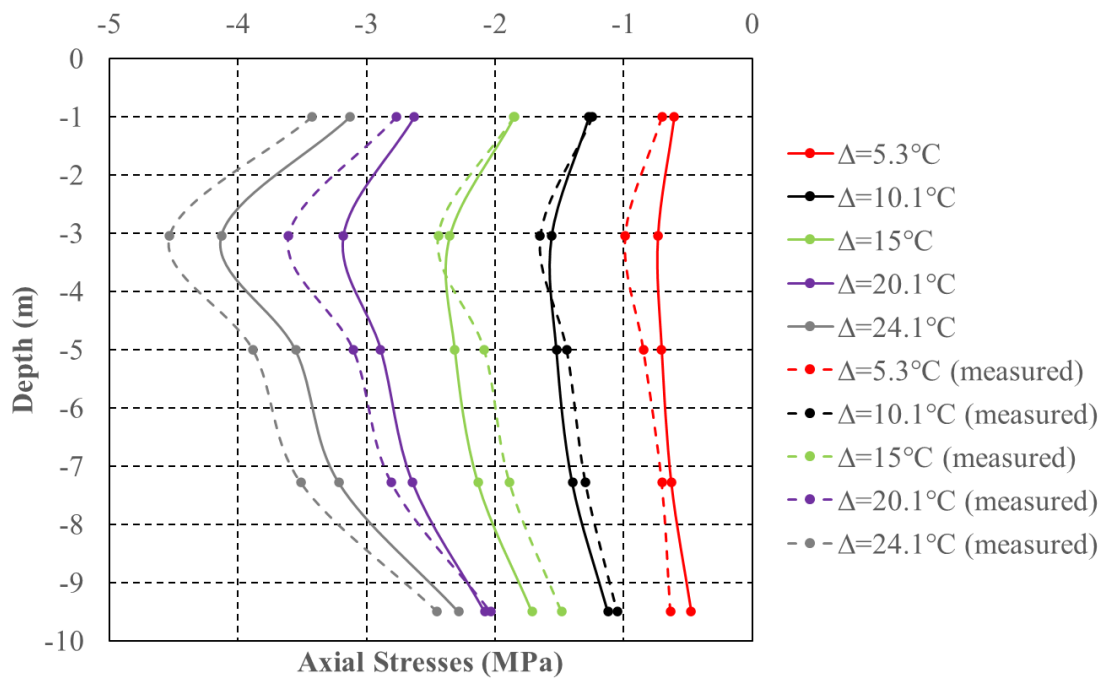


Figure 5.12. Thermally induced axial stresses along the pile (modified after Faizal et al., 2019).

6. DEFINITION OF THE PROBLEM

This chapter presents a comprehensive investigation into the effects of reinforcement and surcharge loading on thermally-induced hoop stresses in energy pile systems. The study methodology involves developing and analyzing three distinct numerical model configurations: a baseline unreinforced model without surcharge loading, a reinforced model incorporating steel rebar elements, and a surcharged model simulating typical overburden conditions. Through systematic comparison of these models, the analysis establishes optimal modeling approaches that achieve an appropriate equilibrium between numerical accuracy and computational efficiency. Following this comparative assessment, detailed sensitivity analyses are performed using a thoroughly validated finite element model to systematically identify and rank the most influential parameters governing hoop stress development. The research methodology further includes extensive sensitivity study to quantify characteristic ranges of hoop stress magnitudes under various practical scenarios, examining combinations of: (i) diverse material properties, (ii) operational conditions, and (iii) geometric configurations.

6.1. Numerical Modelling

A three-dimensional finite element analysis was performed using COMSOL Multiphysics Software v6.3 (2025) to investigate the thermo-mechanical behavior of an individual energy pile. The numerical methodology was verified against experimental data obtained from a field investigation previously reported by Polat et al. (Polat et al., 2025).

The numerical analysis examines temperature distribution and thermally-induced stress patterns across pile cross-sections during operational conditions, while determining critical governing parameters through systematic sensitivity studies. Due to the significant computational demands of such simulations, careful optimization of model sophistication becomes crucial to maintain computational tractability while preserving result reliability.

To systematically address this objective, two primary factors contributing to model complexity are identified and evaluated. The first critical consideration involves the steel

reinforcement embedded within energy piles. Extensive material property comparisons reveal that construction-grade steel possesses a thermal expansion coefficient that is comparable to, yet marginally higher than, that of conventional concrete, while demonstrating substantially greater thermal conductivity characteristics (Laloui and Rotta Loria, 2020). This combination of material properties suggests that the inclusion of reinforcement cages should theoretically exert only minimal influence on the development of thermal hoop stresses within the unprotected concrete cover region. While the steel's superior thermal conductivity promotes more efficient heat distribution throughout the pile cross-section, its slightly elevated expansion coefficient creates compensating effects. These opposing phenomena - improved thermal equilibration versus increased expansion potential - effectively neutralize each other's impact, resulting in an insignificant overall effect on stress generation within the exposed cover concrete. Furthermore, the typical placement of reinforcement cages at some distance inward from the pile periphery ensures that the clear cover remains mechanically unconstrained, allowing it to respond primarily to the localized thermal gradients created by the adjacent heat exchange pipes.

The second factor involves surface surcharge loading. Although surcharge increases lateral soil pressures on the pile, these pressures act perpendicular to the pile surface and remain independent of hoop stresses. When evaluating both their directional orientation and comparative magnitude relative to hoop stresses, the surcharge effect proves negligible in practical applications.

To systematically evaluate the thermo-mechanical behavior of energy piles under different design conditions, three distinct numerical model configurations were developed and analyzed: (i) Basic Model: A simplified representation excluding both reinforcement and surcharge loading, serving as the reference case for comparative analysis, (ii) Reinforced Model: Incorporating steel reinforcement to assess its influence on stress distribution and thermal response and (iii) Surcharged Model: Including surface loading to examine its effects on lateral earth pressures and pile-soil interaction. A detailed comparison of these models was conducted to determine the optimal balance between computational efficiency and simulation accuracy. The inclusion of reinforcement necessitated a significantly refined mesh resolution near the steel-concrete interfaces to accurately capture localized stress gradients, which substantially increased computational runtime. Similarly, modeling

surcharge effects required the implementation of the Mohr-Coulomb elastoplastic constitutive model to represent nonlinear soil behavior, further escalating computational demands due to the iterative nature of plasticity calculations. This section first presents the fundamental modeling assumptions and parameters common to all three reference cases. Subsequently, it provides a comprehensive discussion of the specific modifications and considerations implemented in the reinforced and surcharged models, highlighting their respective impacts on simulation outcomes.

6.1.1. Common Features of all Reference Case Models

The model dimensions are $50\text{m} \times 50\text{m} \times 40\text{m}$ in the x, y and z directions, respectively, as shown in Figure 6.1. The comprehensive finite element mesh consists of a total of 871582 discrete elements encompassing eight distinct element types: tetrahedral, pyramidal, prismatic, hexahedral, triangular, quadrilateral, linear, and vertex elements. Within this extensive mesh framework, the energy pile itself is represented by 611327 specifically dedicated elements to ensure accurate resolution of its structural behavior.

To optimize the mesh configuration for the pile's cylindrical geometry, a specialized polar grid mapping technique was strategically implemented. This approach provides two key advantages: (i) it properly accounts for the inherent radial symmetry of the pile system, and (ii) enables controlled mesh refinement in critical regions adjacent to the heat exchanger pipes, as clearly illustrated in Figure 6.1b. The latter feature is particularly important for capturing the steep thermal gradients that develop near these pipe interfaces.

A rigorous mesh sensitivity analysis was conducted with particular attention to the clear concrete cover region. This focused investigation guided the selection of the final mesh configuration, balancing computational efficiency with solution accuracy. The concrete cover received special consideration because it represents the most structurally vulnerable location where hoop stresses typically reach their peak magnitudes. These circumferential stresses have been identified as potentially governing factors in the design and performance assessment of energy pile systems.

The energy pile in the reference case has a diameter of 0.80 m, a length of 20 m, and is made of C40/50 concrete. To mitigate boundary effects, a minimum distance of 20 meters is maintained between the model's boundaries and the energy pile. The reference case (Polat et al. 2025) uses a single U-shaped pipe configuration, employing PEX pipes with nominal diameter of 25.4 mm and 3.2 mm wall thickness. These heat exchanger pipes are positioned within the reinforcement cages of the energy piles, consistent with common field practices (Mimouni and Laloui, 2015; Ren et al., 2023; Sutman et al., 2019). The net clear concrete cover thickness between the pile edge and the outer surface of the pipe is 7.5 cm, which is typical in field applications and aligns with BS EN 1536:2010+A1:2015 (European Committee for Standardization 2015), which specifies a minimum clear cover of 6.0 cm for piles with diameters exceeding 60 cm.

The numerical model assumes isotropic material behavior for both the energy pile and surrounding soil domain. For computational efficiency, the geological stratification is represented as a homogeneous layer of fully saturated clay. Under constant temperature conditions, the soil matrix is modeled with two key simplifications: (i) the solid particles themselves are considered incompressible, and (ii) inertial effects within the soil skeleton are assumed insignificant. The analysis is conducted using a quasi-static formulation, which is appropriate for simulating the slow, mechanically-driven processes characteristic of geothermal pile operations.

The energy pile is modeled as an isotropic linear elastic material, whereas the surrounding soil is characterized using the Mohr-Coulomb constitutive model. Consistent with established methodologies in energy pile research (Batini et al., 2015; Heidari et al., 2022; Moradshahi et al., 2021a; b; Rotta Loria and Laloui, 2018) the interface between the pile and soil is assumed to be perfectly bonded without explicit interface elements. This conventional approach, which neglects potential slippage at the pile-soil boundary, has been widely adopted in studies investigating the thermomechanical behavior of energy piles. In keeping with these standard modeling practices, the current analysis similarly employs the fully bonded assumption (Batini et al., 2015; Heidari et al., 2022; Moradshahi et al., 2021b, 2022a; Rotta Loria and Laloui, 2018).

The numerical simulation represents heat exchanger pipes using one-dimensional line elements, with their three-dimensional geometrical and thermal characteristics modeled through the specialized Heat Transfer in Pipes module. The heat transfer fluid dynamics within the pipes are simulated using coupled convective heat and mass transfer formulations.

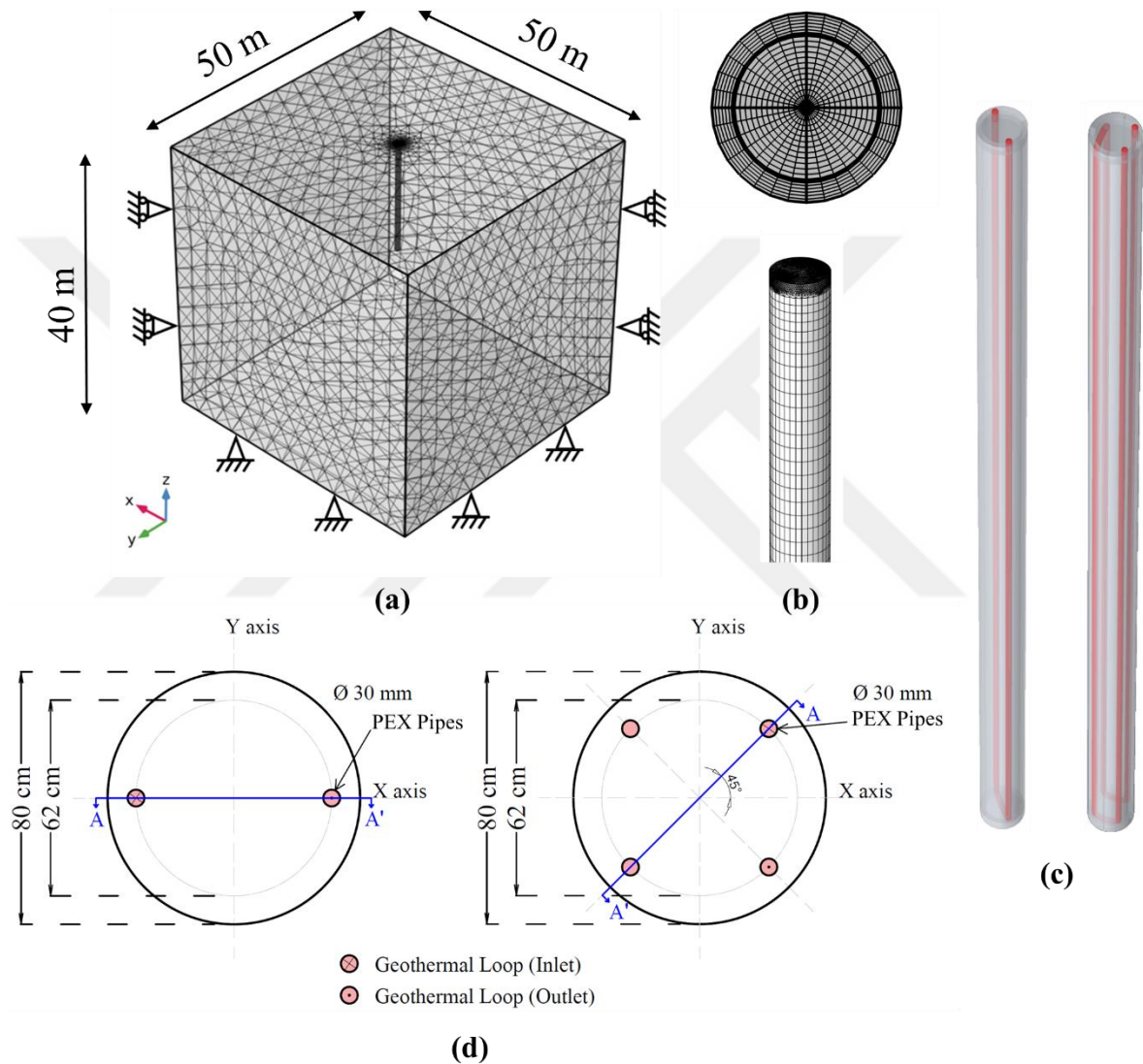


Figure 6.1. Finite element numerical model: (a) 3D perspective view, (b) pile meshing strategy, (c) W (on the left) and U (on the right) shaped pipe configurations, and (d) cross-sectional axes of the energy pile with U and W shaped pipe configurations, respectively.

6.1.2. Boundary and Initial Conditions

The numerical model employed the following boundary conditions: (i) Fully fixed support at the bottom (all DOFs constrained), (ii) laterally constrained roller boundaries (restricting horizontal motion but allowing vertical settlement) and (iii) unrestrained top boundary to replicate free-field ground surface conditions.

The initial thermal conditions for the numerical model were carefully defined based on Istanbul's characteristic geothermal profile. Both the energy pile and surrounding soil domain were initialized with a uniform temperature field of 16.3°C , corresponding to the region's annual average ground temperature as reported by (Aydın et al., 2013). This isothermal assumption was applied throughout the entire depth of the model, reflecting typical conditions for shallow geothermal systems where vertical temperature variations are minimal.

To properly isolate the thermal behavior of the energy pile system, specialized boundary conditions were implemented. All lateral boundaries and the bottom surface were assigned thermally insulated (adiabatic) conditions, effectively preventing any artificial heat transfer across these interfaces. This modeling approach follows established methodologies in geothermal pile simulations, as demonstrated in recent studies (Erginag et al., 2025; Gerola et al., 2025; Polat et al., 2025). The model's extensive spatial dimensions ($50\text{m} \times 50\text{m} \times 40\text{m}$) ensured that these insulated boundaries had no measurable influence on the results, as confirmed through preliminary sensitivity analyses.

The initial mechanical state was carefully configured to represent realistic in-situ conditions. The soil mass was initialized with conventional geostatic stresses, accounting for the self-weight of overlying material. For the concrete pile, an isotropic stress state was prescribed considering only its self-weight loading. This simplified mechanical initialization was deemed appropriate as it focuses the analysis on thermally-induced effects while providing a stable baseline for subsequent thermo-mechanical coupling.

The specification of pipe inlet temperatures constitutes a fundamental modeling consideration given their substantial influence on the coupled thermal-mechanical response

of energy piles (Laloui and Rotta Loria, 2020). To systematically assess worst-case operational scenarios, the reference analysis incorporated two distinct thermal loading conditions: (i) a heating phase with constant 45°C fluid input, and (ii) a cooling phase maintained at 5°C. These extreme temperature values were deliberately selected as they represent the upper and lower bounds of typical operating ranges reported in experimental and numerical studies of energy pile systems (Bourne-Webb et al., 2009; Faizal et al., 2016, 2019; Rotta Loria and Laloui, 2018). By employing these conservative boundary conditions, the analysis captures the maximum potential thermo-mechanical effects that could develop under severe but plausible operational circumstances.

The numerical simulation spanned a three-month operational duration (90 days), with output intervals intentionally refined during the initial stages to better capture transient thermal-mechanical responses. The heat transfer fluid was modeled with a constant flow velocity of 0.7 m/s throughout the analysis period. Complete material property specifications for both the reinforced concrete pile and surrounding soil strata in the baseline scenario are systematically tabulated in Table 6.1, providing all necessary parameters for the thermo-hydro-mechanical coupling analysis.

Table 6.1. Material properties for the reference case.

Properties	Clay	Pile	PEX Pipes
Elastic modulus, E (MPa)	45	35200	-
Poisson's ratio, ν	0.495	0.20	-
Total density, ρ (kg/m ³)	2005	2400	-
Specific heat capacity, C_p (MJ/m ³ °C)	2.25	1.90	-
Thermal conductivity, λ (W/m°C)	2.0	1.5	0.40
Linear coefficient of thermal expansion, α ($\mu\epsilon/^\circ\text{C}$)	15	10	-
Undrained shear strength (kPa)	110	-	-
Elastic modulus, E (MPa)	45	35200	-

6.1.3. Boundary and Initial Conditions

A thermo-mechanical formulation is applied through the use of COMSOL Multiphysics Software to develop time-dependent finite element models. The model incorporates the following mechanical equilibrium equation as

$$\nabla \cdot \sigma_{ij} + F_v = 0, \quad (6.1)$$

where ∇ denotes the divergence, σ_{ij} represents the total stress tensor, and F_v is the volume force factor. To account for the impact of thermal loading on the energy pile, the total stress tensor is calculated using the following equation

$$d\sigma_{ij} = D_{ijkl}(d\varepsilon_{kl} - \beta_{kl}dT), \quad (6.2)$$

where D_{ijkl} the elastic stiffness tensor, ε_{kl} is the total strain tensor, β_{kl} is a vector that includes the linear thermal expansion coefficient of the material, and T is the temperature.

The heat transfer mechanism considered for the soil and pile is thermal conduction, governed by the energy conservation equation

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot (\lambda \nabla T) = 0, \quad (6.3)$$

where ρ , C , T , and λ denote the density, specific heat capacity, temperature and thermal conductivity of the material, respectively.

The energy conservation equation for the liquid flowing through the pipes can be formulated as

$$\rho_l A_p C_l \frac{\partial T_l}{\partial t} + \rho_l A_p C_l u_l \cdot \nabla T_l - \nabla \cdot [A_p \lambda_l \nabla (T_l)] - Q_{wall} = 0, \quad (6.4)$$

where ρ_l , C_l , A_p , T_l , u_l and λ_l the density, specific heat, pipe cross sectional area, temperature, velocity and thermal conductivity of the circulating liquid through pipe, respectively. Q_{wall} is the heat flux per unit pipe length

$$Q_{wall} = h_{eff}(T_{ext} - T_l), \quad (6.5)$$

where h_{eff} is a coefficient related to the circular shaped pipe's wetted perimeter for heat transfer, and T_{ext} is the temperature of the outer surface of the pipe. The pipe heat transfer coefficient is obtained as

$$h_{eff} = \frac{2\pi r_{int}}{\frac{r_{int}}{\lambda_p} \ln\left(\frac{r_{ext}}{r_{int}}\right) + \frac{1}{h_{int}}}, \quad (6.6)$$

where r_{int} , r_{ext} , λ_p and h_{int} are the internal pipe radius, external pipe radius, thermal conductivity of the pipe and the coefficient for convective heat transfer of the internal surface of the pipe, respectively. The latter term depends on the pipe and liquid properties as

$$h_{int} = \frac{Nu\lambda_l}{\frac{4A}{2\pi r_{int}}}, \quad (6.7)$$

$$Nu = \max(3.66; Nu_{turbulent}), \quad (6.8)$$

$$Nu_{turbulent} = \frac{\left(\frac{f_d}{8}\right) \left(\frac{\rho V D}{\mu} - 1000\right) \left(\frac{\mu C_l}{\lambda_l}\right)}{1 + 12.7 \sqrt{\frac{f_d}{8}} \left[\left(\frac{\mu C_l}{\lambda_l}\right)^{\frac{2}{3}} - 1\right]}, \quad (6.9)$$

$$f_d = \left[-1.8 \log \left(\frac{6.9}{\frac{\rho V D}{\mu}} \right) \right]^{-1}, \quad (6.10)$$

where $Nu_{turbulent}$, f_d , μ , V , D , C_l and λ_l are Nusselt number for turbulent flow in pipes, coefficient of friction, liquid dynamic viscosity, velocity of fluid, pipe diameter, liquid specific heat and thermal conductivity of the liquid, respectively.

6.1.4. Variations of the Reference Case Model: Steel Reinforcements and Mechanical Loading

The numerical modeling approach incorporated detailed representation of both longitudinal and transverse reinforcement to properly evaluate steel's influence on thermo-mechanical behavior. The reinforcement cage was explicitly modeled using solid elements, consisting of: (i) twelve 24-mm-diameter longitudinal bars and (ii) 10-mm-diameter stirrups spaced at 150 mm centers (Figure 6.2). This configuration provides a 1% longitudinal reinforcement ratio, deliberately exceeding the 0.5% minimum specified in both ACI 318-19 (American Concrete Institute Committee, 2019) and BS EN 1536:2010+A1:2015 (European Committee for Standardization 2015) standards. The transverse reinforcement design similarly complies with these code requirements.

For precise numerical simulation, each longitudinal rebar was discretized into 130968 tetrahedral elements, while each stirrup contained 2536 elements. Mesh quality assessment employed COMSOL's standard evaluation metrics, with particular attention to skewness due to its significant impact on thermal analysis accuracy. Careful matching of mesh quality parameters between reinforcement and adjacent concrete elements ensured consistent numerical performance and solution stability throughout the coupled analysis.

While concrete and steel exhibit comparable coefficients of thermal expansion, their thermal conductivity properties differ substantially. To examine the potential effects of this dissimilarity on circumferential stress development, the auxiliary numerical model was employed to analyze reinforcement impacts. The thermal parameters specified for the steel reinforcement elements in these simulations are comprehensively detailed in Table 6.2.

Table 6.2. Material properties for steel reinforcements.

Properties	Values
Elastic modulus, E (MPa)	200
Poisson's ratio, ν	0.30
Total density, ρ (kg/m ³)	7850
Specific heat capacity, C_p (MJ/m ³ °C)	3.73
Thermal conductivity, λ (W/m°C)	44.5
Linear coefficient of thermal expansion, α ($\mu\epsilon/^\circ\text{C}$)	12.3

A secondary model configuration was developed to investigate the effects of structural loading by incorporating two additional mechanical components: (i) a concentrated static load applied directly at the pile head, and (ii) a distributed surface load representing superstructure weight. This dual-loading approach serves to simultaneously evaluate both axial load transfer mechanisms and the consequent increase in lateral soil confinement pressure along the pile shaft. The supplementary analysis provides critical insights into the combined thermo-mechanical behavior of energy piles under realistic service conditions.

The applied pile head load was derived from the pile's design bearing capacity. Following design procedures (U.S. Department of Transportation Federal Highway Administration, 2010), the ultimate axial capacity was computed as 3700 kN. Employing conventional ASD methodology with a safety factor of 3.0, the serviceable load was determined to be 1200 kN. This calculated working load was subsequently implemented as the pile head boundary condition in the numerical simulation.

To simulate the load transfer mechanism of a raft foundation, a uniformly distributed surface pressure was applied across the entire model domain. This loading approach provides two key advantages: (i) it generates a controlled, axisymmetric increase in both vertical and lateral soil stresses surrounding the pile, and (ii) eliminates confounding effects from localized footing interactions. The uniform pressure application particularly enhances the

confining pressure development around the pile shaft, which was maximized by applying the highest practicable load magnitude.

The soil's ultimate bearing capacity was calculated following recommendations for shallow foundation design (API, 2000), using conventional rectangular footing assumptions. Consistent with the pile loading methodology, an ASD safety factor of 3.0 was employed, yielding a design bearing pressure of 235 kPa. This computed allowable pressure was implemented as the initial mechanical boundary condition prior to subsequent thermal loading simulations.

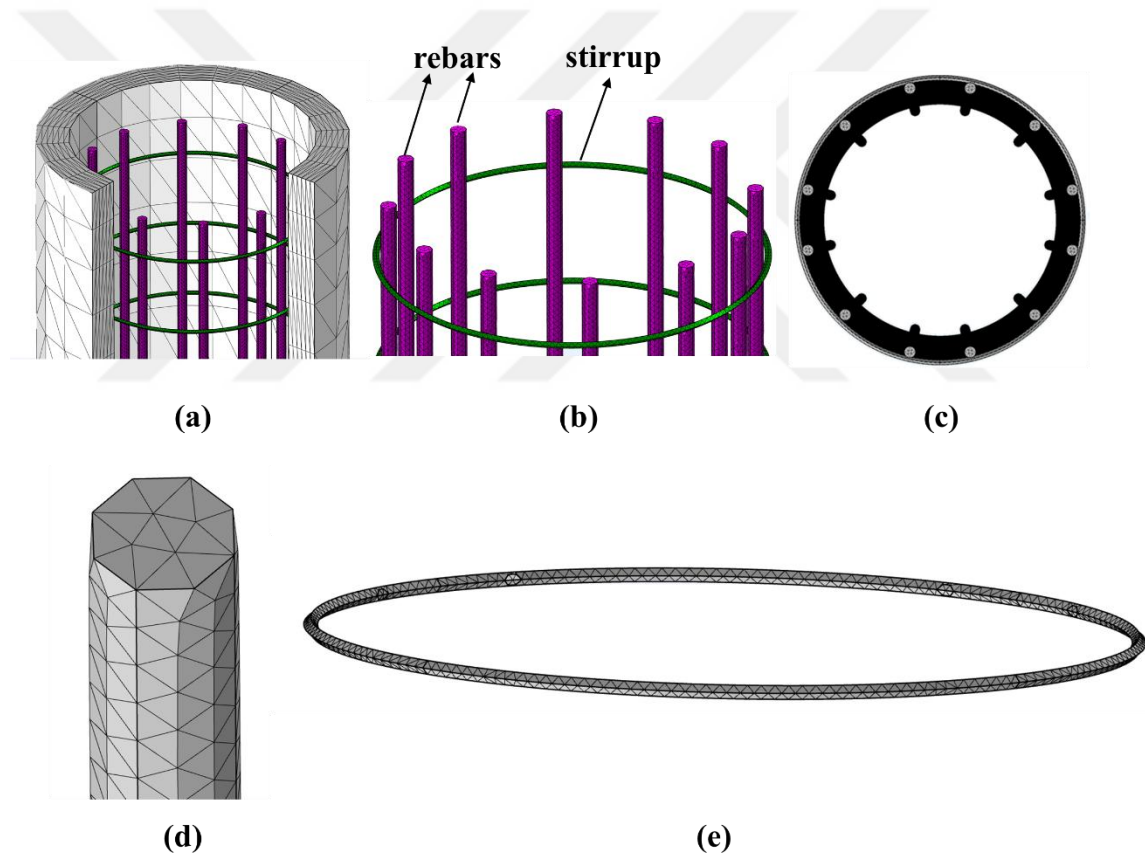


Figure 6.2. Auxiliary numerical model with steel reinforcements: (a) 3D view, (b) rebar cage only, (c) rebar cage (top view), (d) a single rebar, and (e) a single stirrup.

6.1.5. Details of the Sensitivity

The magnitude and distribution of thermally induced hoop stresses are influenced by various parameters spanning material properties, geometric factors, and operational

conditions. Key material parameters include the elastic modulus, Poisson's ratio, thermal conductivity, thermal expansion coefficient, and heat capacity of the concrete, as well as the thermal conductivity and heat capacity of the surrounding soil. Geometric considerations encompass the pile diameter and the configuration of the embedded heat exchanger pipes, particularly comparing U-shaped and W-shaped layouts. Operational variables involve the flow rate of the heat transfer fluid and site-specific climatic conditions, which affect the thermal loading imposed on the pile. Together, these parameters collectively govern the thermo-mechanical response of energy piles under operational conditions.

A systematic sensitivity analysis was conducted to evaluate the individual influence of each parameter on thermal hoop stress development. The investigated variables and their respective value ranges are detailed in Table 6.3 through 6.5. The parameter ranges in Table 6.3 were selected based on well-established values from existing literature (Laloui and Rotta Loria, 2020).

Table 6.4 reflect typical values encountered in practical engineering applications. Three distinct geographical locations were considered in addition to Istanbul, Türkiye (Aydın et al., 2013), Halden, Norway (NGI, 2019) and Houston, Texas, USA (Sutman, 2016). While actual field applications experience variable inlet temperatures depending on climate and operational requirements, this study employs constant temperature values to create a standardized framework for hoop stress evaluation. Subsequent research should examine time-dependent, climate-adaptive operational scenarios to provide more complete insights into energy pile behavior.

A sensitivity study was performed by systematically varying each individual parameter across both heating and cooling operational modes, while keeping all other variables fixed at their baseline values. This controlled approach enabled isolation of each factor's specific influence on the system response. The comprehensive analysis required execution of 40 distinct numerical simulations to adequately explore the full parameter space under investigation.

Table 6.3. Material properties for the sensitivity analysis.

Properties	Reference Value	Sensitivity Analysis Value
Elastic modulus E (GPa) and concrete grade	35.2 (C40/50)	32.8 (C30/37) 37.3 (C50/60)
Poisson's ratio, ν	0.20	0.15, 0.25
Pile specific heat capacity, $C_{p,p}$ (MJ/m ³ °C)	1.9	1.8, 2.0
Soil specific heat capacity, $C_{p,s}$ (MJ/m ³ °C)	2.25	1.5, 3.0
Pile thermal conductivity, λ_p (W/m°C)	1.5	1.0, 2.0
Soil thermal conductivity, λ_s (W/m°C)	2.0	1.0, 3.0
Linear expansion coefficient of concrete, α ($\mu\epsilon/^\circ\text{C}$)	1.0	0.8, 1.2

Table 6.4. Geometrical parameters for the sensitivity analysis.

Properties	Reference Value	Sensitivity Analysis Value
Pile diameter, D (m)	0.80	0.65, 1.0
Pipe configuration	U-shaped	W-shaped

Table 6.5. Operational parameters for the sensitivity analysis.

Properties	Reference Value	Sensitivity Analysis Value
Flow rate of the heat exchanger fluid, u (m/s)	0.7	0.4, 1.0
Average ground temperature, T (°C)	16.3 (Istanbul)	8.0 (Halden), 21.6 (Houston)

7. RESULTS AND DISCUSSION

The numerical model was employed to analyze the progressive development of thermal stresses in energy piles under distinct summer (heating) and winter (cooling) operational conditions. This section presents a comprehensive examination of the resulting stress distributions, with particular emphasis on hoop stresses within the unprotected concrete cover region. These stresses originate primarily from non-uniform temperature distributions across the pile section and the consequent differential thermal expansion/contraction effects.

Stress analysis followed standardized reference conditions to evaluate three key characteristics: (i) peak stress magnitudes, (ii) critical stress locations, and (iii) time-dependent stress evolution. The parametric influences on these stress patterns are systematically examined in later sections. Consistent with engineering convention, tensile stresses are denoted as positive values throughout this investigation.

The results demonstrate significant spatial variations in thermal gradients, with maximum differentials occurring between the heat exchanger pipes and pile periphery - especially during early heating phases and within the concrete cover zone. These localized gradients can induce stress concentrations capable of exceeding the concrete's tensile strength capacity, as detailed in subsequent sections.

7.1. Reference Case

This section details the findings obtained from the reference case simulations. The analysis begins by examining the baseline model configuration, which excludes both reinforcement and mechanical loading, to establish fundamental behavioral trends. Subsequently, a comparative evaluation is performed across three distinct model variants: (i) the unreinforced, unloaded reference case, (ii) a reinforced model without surface loading, and (iii) an unreinforced model incorporating mechanical loading. This systematic comparison enables quantitative assessment of how steel reinforcement and applied mechanical loads independently influence the system's thermo-mechanical response.

All numerical simulations maintain consistent boundary conditions with prescribed inlet temperatures of 45°C (summer operation) and 5°C (winter operation), while keeping all other parameters unchanged according to the specifications provided in Table 6.3 through 6.5. The 90-day simulation period enables comprehensive evaluation of both spatial and temporal evolution of temperature fields and associated stress distributions.

For summer operating conditions, the analysis focuses on critical cross-sections exhibiting peak thermal hoop stresses: (i) a shallow section at 2 m depth representing pile head behavior, and (ii) an intermediate section at 10 m depth characterizing mid-pile response (Figure 7.1). The 2 m depth was strategically selected to examine near-surface thermo-mechanical interactions while minimizing confounding effects from foundation boundary conditions. Conversely, the 10 m section provides insight into stable thermal regime behavior dominated by subsurface heat transfer mechanisms, representing characteristic energy pile performance under operational conditions.

The comprehensive numerical investigation yields several critical findings regarding the thermo-mechanical behavior of energy piles under operational conditions. As demonstrated in Figures 7.1a and 7.1c, the most substantial temperature gradients consistently develop within the clear concrete cover region, with the maximum differentials occurring along the radial path between the heat exchanger pipes and the nearest pile periphery. These thermal gradients directly induce corresponding hoop stresses (Figs. 7.1b, d), which reach their peak magnitudes in this same vulnerable zone. Of particular concern for structural integrity, the analysis confirms that these maximum hoop stresses are tensile in nature, with values approaching the typical tensile capacity of conventional concrete mixes. This finding has significant implications for the long-term durability design of energy pile systems, as repeated thermal cycling may lead to progressive microcracking in this critical region.

Quantitative analysis reveals maximum tensile hoop stresses of +3.58 MPa at the shallow depth (2 m) and +3.43 MPa at the intermediate depth (10 m), as clearly illustrated in Figure 7.1. These stress peaks correlate precisely with the observed maximum temperature differentials of 13.2°C (2 m depth) and 12.9°C (10 m depth) between the pipe outer surfaces

and adjacent pile edge. The slight reduction in stress magnitude with depth reflects the moderating influence of more stable geothermal conditions at greater elevations.

For enhanced understanding of the cross-sectional behavior, Figure 7.2 provides detailed contour plots of the A-A' section (defined in Figure 6.1) captured at the critical time instant of peak hoop stress development. These visualizations clearly show the non-uniform stress distribution patterns, with stress concentrations forming near the pipe locations and gradually dissipating toward the pile centerline. The plots further confirm that while the entire cross-section experiences some degree of thermal stress, the most severe effects remain localized within the outer 25% of the pile radius - precisely where the clear concrete cover provides essential protection to the reinforcement system.

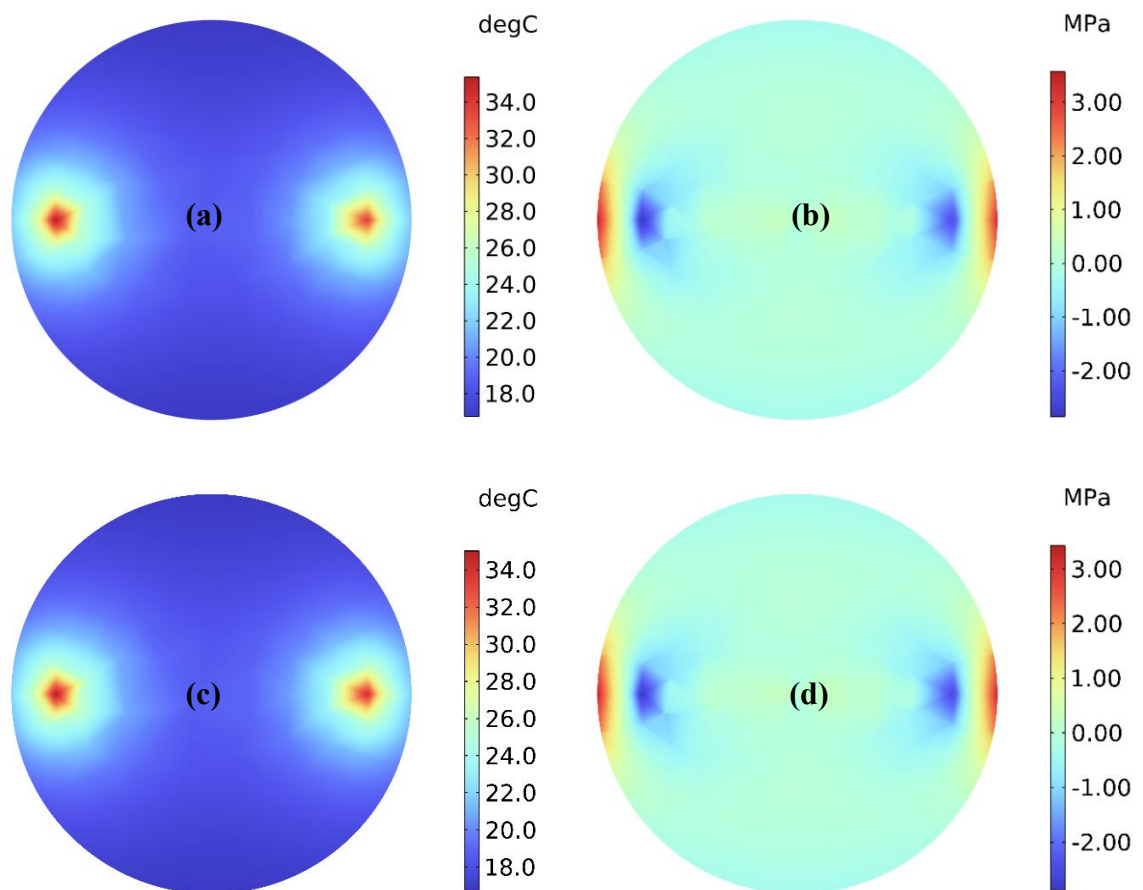


Figure 7.1. The results for the reference case-summer season: (a) temperature distribution at 2 m depth, (b) hoop stresses at 2 m depth, (c) temperature distribution at 10 m depth, and (d) hoop stresses at 10 m depth.

This depth-dependent analysis provides valuable insights for practical design considerations. The shallow zone (2 m depth) results are particularly relevant for assessing potential distress near structural connections, while the intermediate depth (10 m) represents more typical operational behavior. Both cases demonstrate that even under controlled reference conditions, the induced thermal stresses approach levels that warrant careful consideration in the structural design process, particularly with regard to concrete mix selection, cover thickness determination, and potential crack control measures.

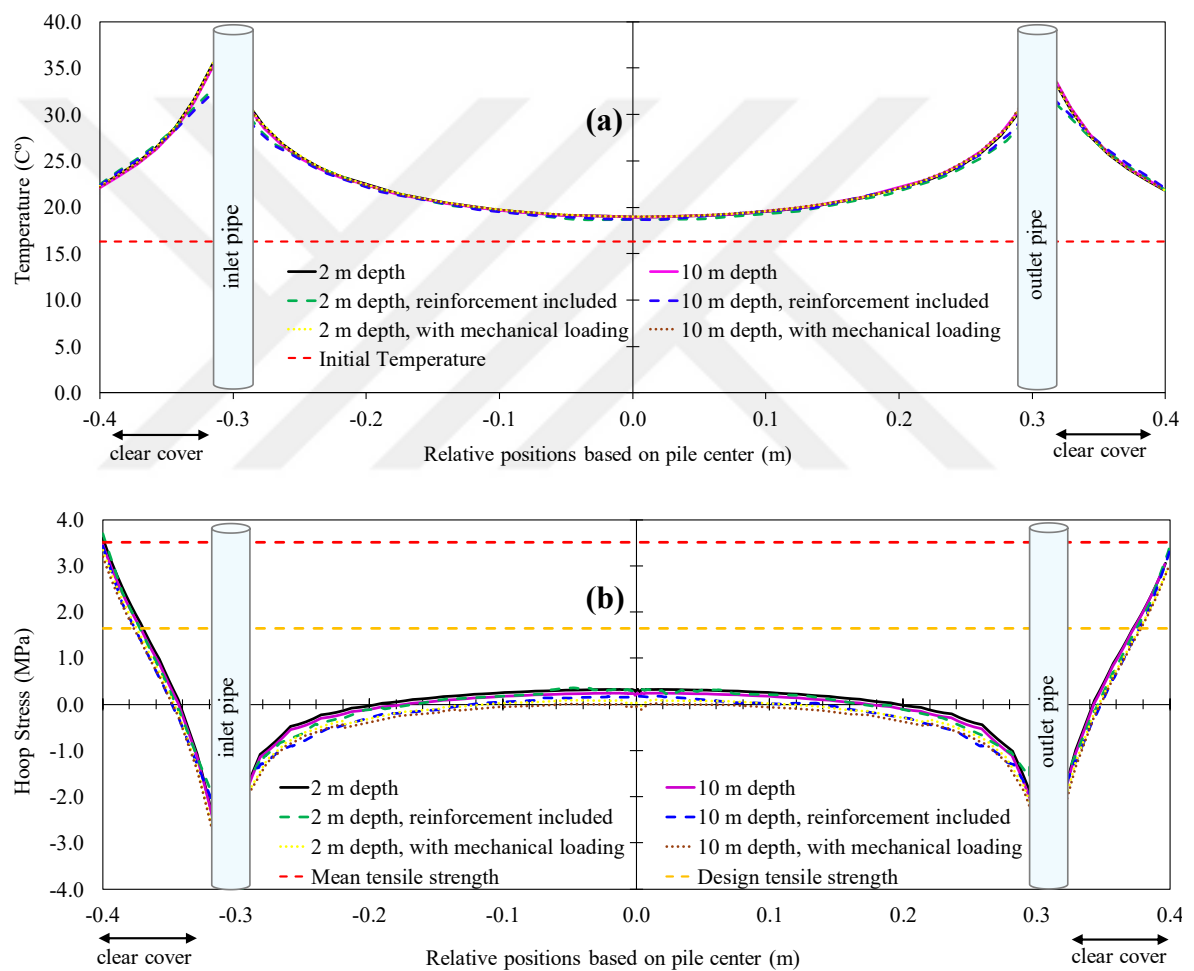


Figure 7.2. The evolution of the temperatures and the hoop stresses during summer season along the cross section passing through the pile center and the pipes when the greatest hoop stresses occur (for A-A' section): (a) temperature, and (b) hoop stresses.

The thermo-mechanical behavior during winter operation demonstrates markedly different stress patterns compared to summer conditions, as illustrated in Figures 7.3 and 7.4.

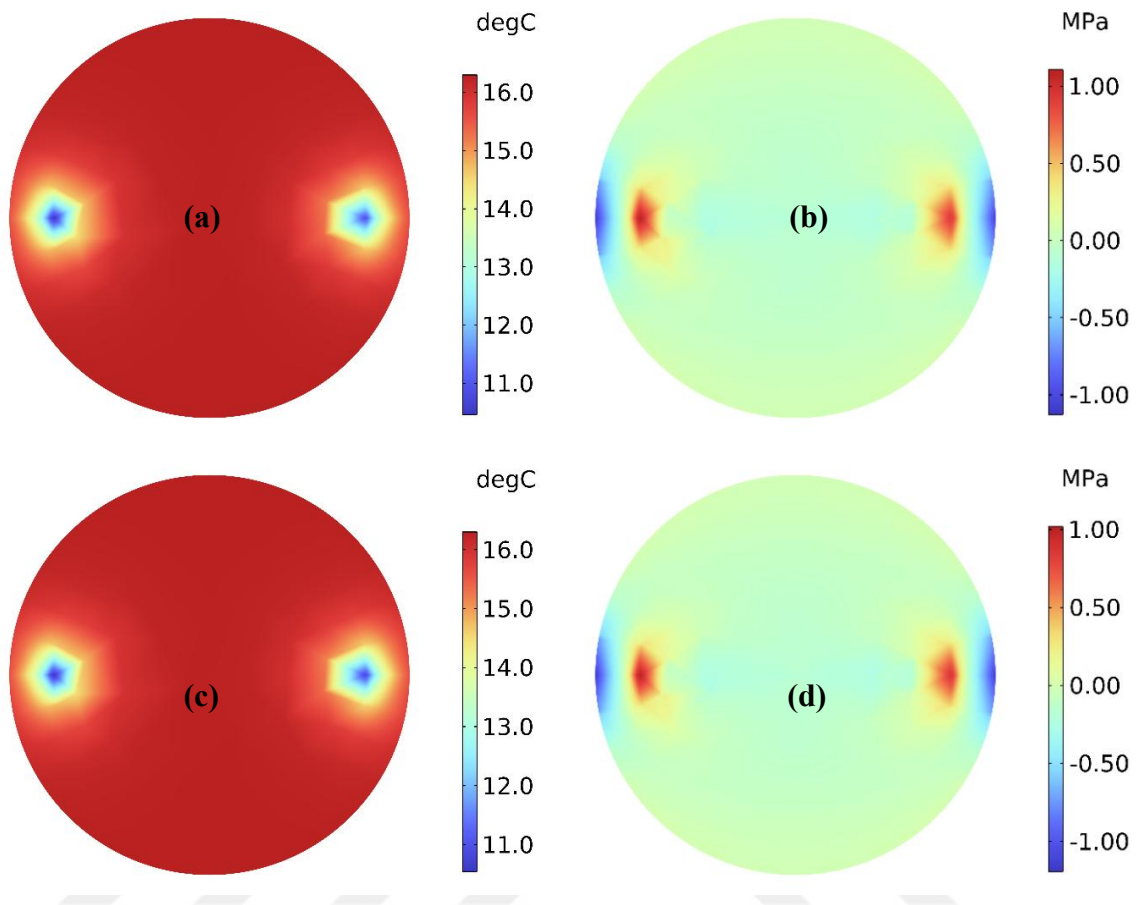


Figure 7.3. The results for the reference case-winter season: (a) temperature distribution at 2 m depth, (b) hoop stresses at 2 m depth, (c) temperature distribution at 10 m depth, and (d) hoop stresses at 10 m depth.

A complete reversal of thermal gradients occurs seasonally, transforming the stress distribution within the concrete cover. During winter months, compressive hoop stresses develop in the outer regions of the concrete cover along the pile perimeter, while tensile stresses concentrate around the heat exchanger pipes. This represents an inverse scenario to summer operation, where maximum tensile stresses occur at the pile periphery. The stress reversal causes the outermost concrete cover, which endured peak tensile stresses during summer, to become compressed in winter, while the concrete surrounding the pipes transitions into tension due to thermal contraction effects. This phenomenon creates an inward migration of tensile stresses from the pile edge toward the interior as conditions change from summer to winter. The compressive stresses developing along the outer surface during winter typically reach 65-75% of the magnitude of summer tensile stresses, indicating significant cyclic loading variations. These alternating stress patterns have important

implications for long-term structural performance, particularly regarding potential fatigue effects in the concrete cover under repeated seasonal thermal cycling. The complete stress reversal between operational phases underscores the need to consider both heating and cooling scenarios in energy pile design to ensure adequate durability throughout the structure's service life.

During winter operations, peak tensile hoop stresses within the concrete cover reached +0.61 MPa at the shallow 2-meter depth and +0.52 MPa at the deeper 10-meter section, as documented in Figure 7.4. These stress maxima coincided with thermal gradients of -3.8°C (upper section) and -3.7°C (mid-section), where the negative values signify heat transfer occurring from the surrounding soil mass toward the heat exchanger pipes. This inverse thermal flow direction during cooling operations creates fundamentally different stress patterns compared to summer conditions, with the modest temperature differentials generating proportionally lower tensile stresses than observed during heating cycles. The depth-dependent variation in stress magnitude reflects the moderating influence of more stable geothermal conditions at greater depths, while the consistent negative thermal gradients confirm the expected inward heat flow characteristic of winter operation when the pile functions as a heat extraction system.

The systematic comparison between summer (Figures 7.1-7.2) and winter (Figures 7.3-7.4) operational conditions reveals two fundamental distinctions in the energy pile's response. First, summer operations generate substantially greater thermal differentials between the pile and surrounding soil, resulting in more severe hoop stress development. Although winter-induced tensile stresses remain below the concrete's design capacity, measurable tension persists in specific regions of the unprotected cover. Second, the spatial distribution of tensile stresses undergoes complete seasonal reversal. Summer conditions produce peak tensile stresses at the unconfined pile perimeter, where thermal expansion is least constrained. Conversely, winter operation shifts the tensile zone inward to pipe-adjacent regions, where cooling-induced contraction creates localized tension against the restrained concrete matrix. This alternating stress pattern demonstrates the complex, seasonally-dependent nature of thermo-mechanical interactions in energy piles.

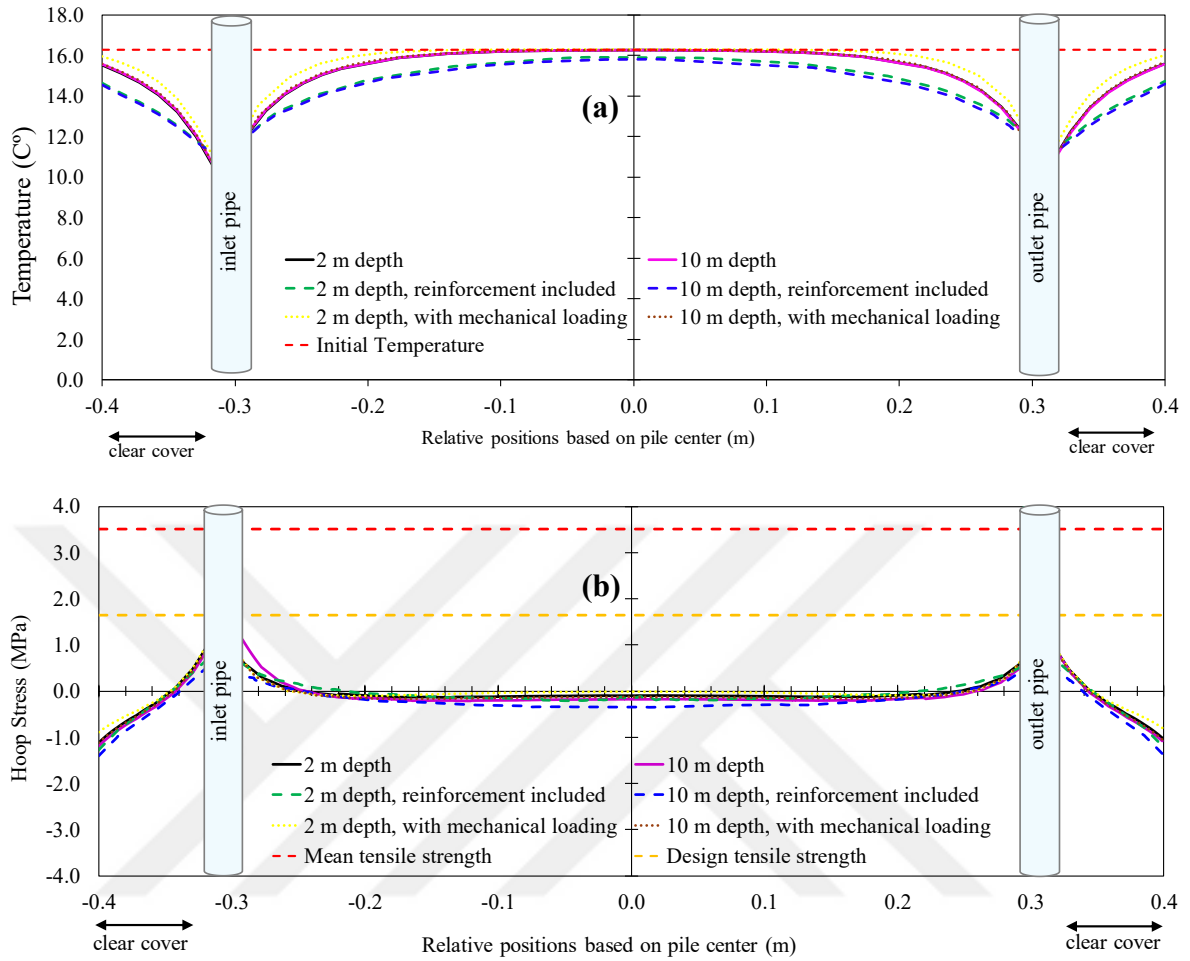


Figure 7.4. The evolution of the temperatures and the hoop stresses during winter season along the cross section passing through the pile center and the pipes when the greatest hoop stresses occur (for A-A' section): (a) temperature, and (b) hoop stresses.

The investigation of axial stresses under self-weight conditions revealed depth- and season-dependent behavior. At the analyzed depths (2 m and 10 m), summer operations produced characteristic compressive axial stresses (-6.24 MPa and -6.57 MPa respectively), though localized tensile zones developed where thermal expansion dominated gravitational effects. This contrasts with concurrent summer hoop stresses, which showed significant tension at the pile periphery due to radial thermal gradients.

Winter conditions fundamentally altered this stress distribution. Axial stresses transitioned to tension near pipes (+2.27 MPa at 2 m, +2.12 MPa at 10 m) as thermal contraction overcame gravitational compression. Notably, both stress components became tensile in pipe-adjacent regions during cooling, with axial stresses exhibiting greater

magnitude. These findings emphasize the necessity of combined stress evaluation during cooling operations.

Important limitations warrant consideration: First, these results exclude surcharge effects - in practice, structural loads would mitigate thermal axial tension through superposition of compressive stresses. Second, as demonstrated in Figures 7.2 and 7.4, hoop stresses remain mechanically uncoupled, maintaining their thermal origin regardless of applied loads. Consequently, while axial thermal stresses may be structurally compensated, thermally-induced hoop tension persists as an independent design consideration requiring specific attention in energy pile engineering. Moreover, axial stress distribution are shown in Figure 7.5.

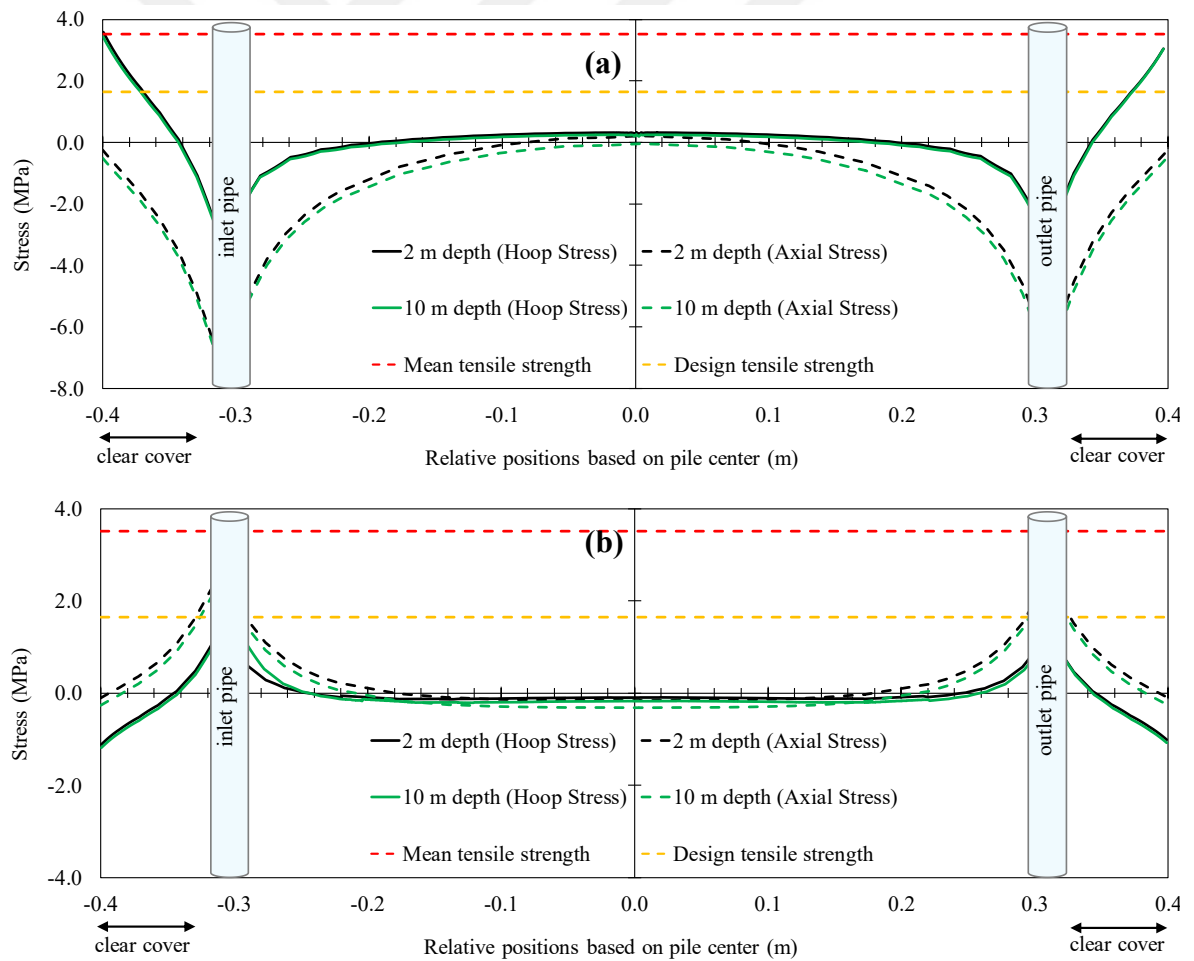


Figure 7.5. The evolution of the hoop and axial stresses along the cross section passing through the pile center and the pipes when the greatest hoop stresses occur for summer episode (for A-A'): (a) summer season, and (b) winter season.

7.2. Effects of Steel Reinforcements and Mechanical Loading on Hoop Stresses

This analysis investigates the thermo-mechanical influence of steel reinforcement and superimposed mechanical loading on circumferential stress development during summer operation. The study employs a comparative methodology, contrasting results from enhanced configurations (incorporating either reinforcement cages or surface loads) against baseline simulations of an unreinforced, mechanically unloaded energy pile system. This systematic approach enables isolation and quantification of each parameter's individual contribution to the overall stress state.

Figure 7.6 presents the temperature and hoop stress profiles for the reinforced pile model at critical depths of 2 m and 10 m, captured during peak stress conditions. Comparative examination with the unreinforced case (Figure 7.1) demonstrates that steel reinforcement induces modest thermal homogenization across the pile cross-section. This enhanced temperature uniformity is particularly evident in the sectional view provided by Figure 7.2 (A-A' plane), where the thermal smoothing effect of the reinforcement cage becomes pronounced. The underlying mechanism stems from steel's superior thermal conductivity, which promotes more efficient heat redistribution throughout the composite structural system. While the reinforcement moderates thermal gradients, the fundamental stress distribution patterns maintain their characteristic profiles, with peak hoop stresses remaining concentrated in the concrete cover region.

The presence of steel reinforcement, while producing a more homogeneous temperature field, fails to reduce circumferential stress magnitudes in the concrete cover. As evidenced by comparative analysis of Figures 7.1 (unreinforced configuration) and 7.6 (reinforced configuration), both the peak values and spatial distribution of hoop stresses show remarkable consistency between cases. This stress invariance becomes particularly conspicuous in the cross-sectional view presented in Figure 7.2. The underlying physical mechanism involves two competing phenomena: (i) thermal gradient reduction due to steel's superior conductivity ($\approx 50 \text{ W/m}\cdot\text{K}$ versus concrete's $1.6 \text{ W/m}\cdot\text{K}$), and (ii) stress amplification from steel's greater thermal expansion ($\alpha_{\text{steel}} \approx 12 \times 10^{-6}/^{\circ}\text{C}$ versus $\alpha_{\text{concrete}} \approx 10 \times 10^{-6}/^{\circ}\text{C}$). The circumferential restraint provided by heated stirrups proves particularly

influential, as their radial expansion directly contributes to increased hoop stress development in the surrounding concrete matrix.

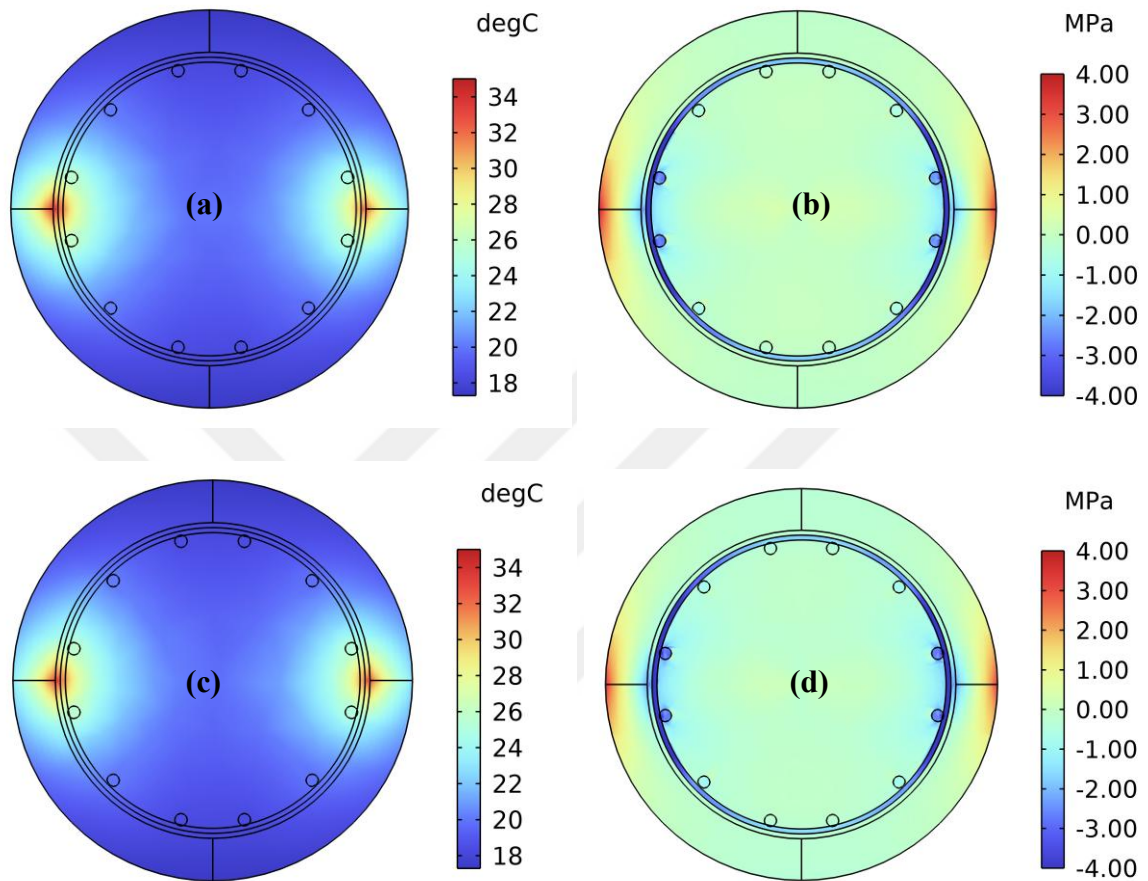


Figure 7.6. The results for the reference case as obtained from the model with reinforcement - summer season: (a) temperature distribution at 2 m depth, (b) hoop stresses at 2 m depth, (c) temperature distribution at 10 m depth, and (d) hoop stresses at 10 m depth.

These findings demonstrate the fundamentally different roles of steel reinforcement in energy pile systems. While essential for structural resistance to mechanical loads, the reinforcement system provides negligible benefit in alleviating thermally-induced stresses. The comprehensive comparison across Figures 7.1, 7.2, 7.4 and 7.6 consistently reveals that both the magnitude and spatial distribution of hoop stresses in the critical clear cover region remain virtually unchanged regardless of reinforcement presence.

This behavior is well-supported by existing research (Vkr, 2008; Wu and Sun, 2012), which establishes that reinforcement primarily modifies internal stress redistribution while exerting minimal influence on boundary-dominated thermal stress regimes. The physical explanation lies in the different governing mechanisms: mechanical load transfer occurs through steel-concrete composite action, while thermal stresses in the cover zone are predominantly controlled by radial temperature gradients at the pile-soil interface. Consequently, conventional reinforcement design, while crucial for structural integrity, cannot be relied upon to mitigate thermal cracking risks in the concrete cover.

To evaluate potential surcharge influences, the reference case was extended to incorporate superstructure loading conditions following the methodology outlined in Section 6.1.4. The results demonstrate minimal variation in thermal stress behavior, as evidenced by Figure 7.2 showing nearly identical temperature and hoop stress distributions between loaded and unloaded cases. Crucially, both the peak hoop stress magnitudes and their critical locations remain effectively unchanged under mechanical loading, confirming that surface surcharges and structural loads have negligible influence on thermally-induced circumferential stresses.

For comprehensive stress analysis, Figure 7.7 presents the major principal stress distributions during peak hoop stress conditions. The results reveal that in pipe-adjacent concrete cover regions, hoop stresses consistently govern the principal stress field regardless of reinforcement or loading conditions. This dominance of hoop stresses underscores how thermal gradients, rather than mechanical factors, control the critical stress state in these vulnerable zones. The persistent thermal stress patterns across all modeled configurations suggest that conventional load-resisting elements provide limited mitigation of temperature-driven stress concentrations.

Comparative evaluation of the three reference model configurations revealed that sensitivity studies could be conducted effectively while omitting both reinforcement elements and mechanical loading. This strategic simplification yields substantial computational savings without sacrificing result validity, as the fundamental thermo-mechanical behavior remains adequately captured. The exclusion of reinforcement eliminates the need for computationally intensive mesh refinement at steel-concrete

interfaces, which would otherwise be required to resolve the high thermal conductivity contrast and complex geometrical details of the cage assembly. Similarly, neglecting surcharge loading avoids the numerical overhead associated with implementing Mohr-Coulomb plasticity in the soil domain. This judicious simplification represents an optimal balance between numerical efficiency and model fidelity, carefully preserving the essential physics governing thermal stress development while dramatically reducing solution times.

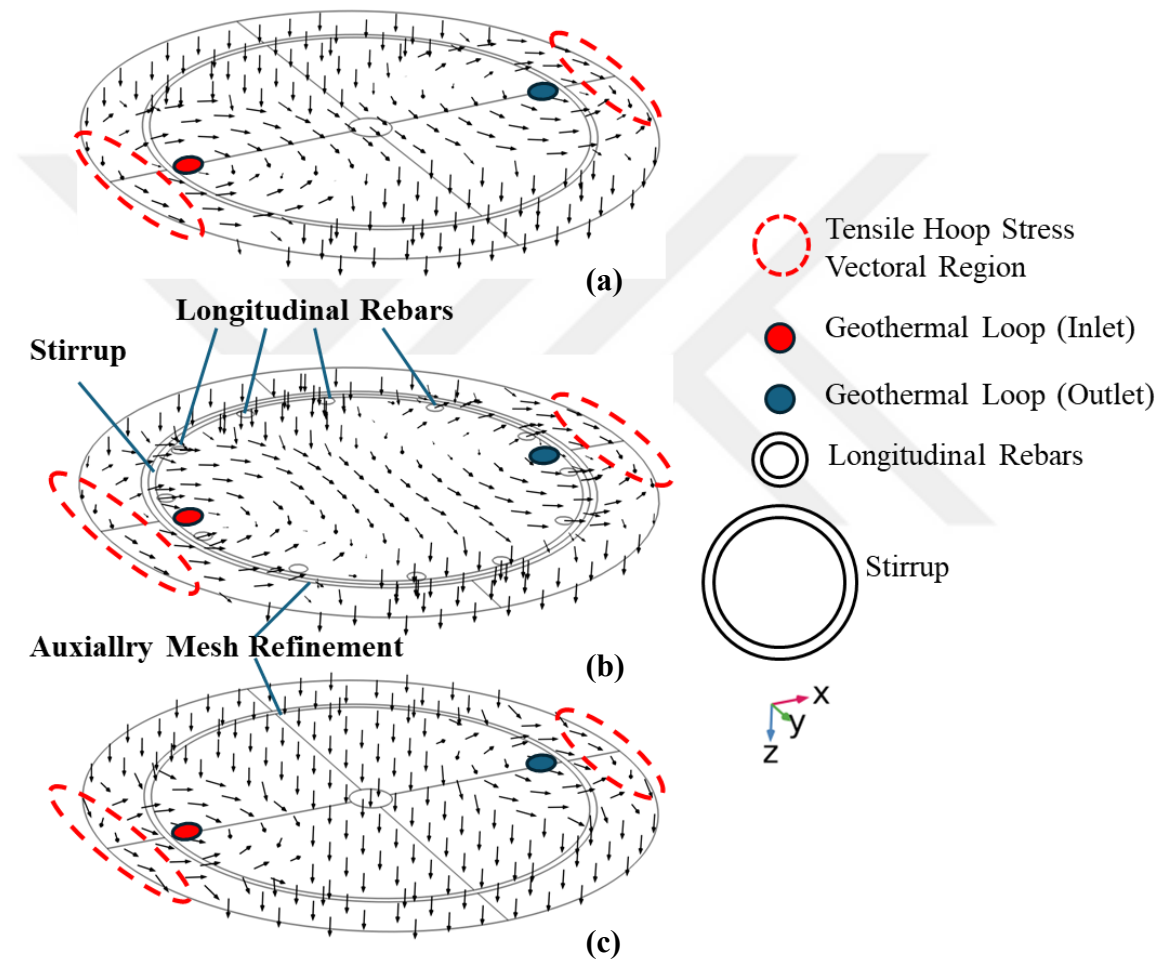


Figure 7.7. The tensile hoop stress vectoral region: (a) reference case, (b) the case involving steel reinforcement, and (c) the case involving mechanical loading.

7.3. Analytical Calculation of Hoop Stresses

Complementary to numerical modeling approaches, thermal-induced hoop stresses can be estimated through analytical solutions. The classical work of Timoshenko and Goodier (1951) presents a fundamental formulation for determining circumferential stresses in an

infinitely long cylindrical body containing a circular hole along its axis under thermal loading. This analytical framework provides the hoop stress (σ_θ) expression

$$\sigma_\theta = \frac{\alpha E}{1 - \nu} \frac{1}{r^2} \left(\frac{r^2 + a^2}{b^2 - a^2} \int_a^b T r dr + \int_a^r T r dr - T r^2 \right), \quad (7.1)$$

where α , E , ν , r , a , b and T represent the thermal expansion coefficient, modulus of elasticity, Poisson's ratio, the distance between the point of interest and center of the pipe, the distance between pipe center and pipe edge, the distance between pipe center and pile edge, and temperature difference, respectively. Using this analytical method, maximum hoop stresses in the clear concrete cover were calculated as +3.48 MPa and +3.40 MPa at depths of 2 meters and 10 meters, respectively.

Both numerical and analytical approaches demonstrate that summer operational conditions induce critical hoop stresses in the concrete cover region. The predicted stress magnitudes of +3.58 MPa (2 m depth) and +3.43 MPa (10 m depth) substantially exceed the characteristic tensile strength of +3.51 MPa specified for C40/50 concrete in Eurocode 2 (2004). When considering design conditions, these values surpass the recommended design tensile stress limit of +1.64 MPa for C40/50 concrete by approximately 120%. Furthermore, Eurocode 2 (2023) stipulates an additional 10% reduction (factor of 1.1) for foundation elements, making the observed thermal stresses even more critical from a design perspective.

Conversely, winter operations produce significantly lower tensile stresses adjacent to the pipes, with values of +0.64 MPa (2 m depth) and +0.62 MPa (10 m depth). These magnitudes remain safely below the design tensile capacity, representing approximately 60% of the reduced allowable stress for foundations. The marked seasonal variation in stress levels highlights the importance of considering both heating and cooling scenarios in energy pile design, with summer conditions proving particularly demanding for concrete durability.

The comparative analysis reveals excellent agreement between numerically simulated and analytically predicted maximum hoop stresses in the concrete cover region. While the analytical solution (Equation 7.1) was originally derived for centrally-located pipes, it demonstrates practical accuracy when incorporating the appropriate temperature differential - in this case, the peak thermal gradient obtained from COMSOL simulations at maximum stress occurrence.

Several important limitations of the analytical method should be noted: (i) it exclusively calculates hoop stresses, (ii) these stresses only equate to principal stresses at the pile perimeter, and (iii) shear stresses render hoop stresses non-principal at interior locations. However, along the critical section A-A' (Figures 6 and 8) - both the symmetry axis and location of maximum hoop stress - the circumferential stress indeed represents a principal stress component due to the absence of shear effects. This correspondence between methods confirms the analytical solution's utility for preliminary stress estimation while highlighting the need for numerical modeling to capture full stress tensor behavior throughout the cross-section.

The analytical solution serves as an important theoretical reference for preliminary verification and fundamental understanding of thermal stress mechanisms. However, its practical application is constrained by idealized assumptions regarding geometry, material homogeneity, and thermal boundary conditions. These simplifications restrict its accuracy when applied to actual energy pile systems characterized by complex configurations and operational variability.

A comprehensive numerical approach becomes indispensable to properly account for the multidimensional complexities inherent in energy pile applications. Finite element modeling enables precise representation of realistic geometric details, spatially non-uniform temperature fields, and transient thermal loading patterns. This computational capability is particularly crucial for capturing the coupled thermo-mechanical behavior that develops under cyclic operating conditions, where time-dependent effects significantly influence stress evolution. The numerical framework thus provides an essential tool for reliable performance assessment and design optimization of energy pile systems in engineering practice.

7.4. Discussion of the thermal behavior of the clear concrete cover

The time-dependent behavior of circumferential stresses in the concrete cover is examined at the 2-meter depth cross-section through Figures 7.8 (summer operation) and 7.9 (winter operation). These figures chronologically depict the stress evolution patterns, capturing the progressive development of thermal-induced hoop stresses during seasonal

operational periods. The shallow depth selection (2 m) provides critical insights into near-surface stress behavior while minimizing boundary effect complications from surface conditions.

The summer heating cycle generates distinct hoop stress patterns within the concrete cover, characterized by maximum tensile stresses at the pile periphery that gradually diminish toward the interior. This stress distribution develops through a time-dependent mechanism initiated when heat transfer fluid circulation begins. The pipe-adjacent concrete immediately attempts to expand radially, but this expansion is resisted by the outer cover region, creating competing stress zones: tension develops at the unconstrained outer edge while compression forms in the restricted interior.

The stress evolution follows a predictable temporal sequence, reaching peak conditions several hours after heating commencement. This delay occurs as thermal energy propagates outward, progressively enlarging the warm concrete zone while simultaneously intensifying the radial temperature gradient. Maximum tensile stresses coincide with the optimal combination of two factors: (i) sufficient spatial extent of the heated region and (ii) peak thermal differential between the pipe vicinity and pile edge. During this phase, the outer cover behaves essentially as a tension membrane, while the inner region remains in compression due to constrained expansion.

As shown in Figure 7.8, the compressive stresses initiate at their maximum magnitude and decay steadily as heat diffuses through the cross-section. Conversely, tensile stresses at the periphery exhibit a more complex trajectory - increasing gradually to a peak value before declining during the thermal equilibration phase. This behavior persists throughout the summer operational period, maintaining constant tensile hoop stresses at the pile edge, with the exact magnitudes and evolution rates being governed by the relative thermal properties of the concrete and surrounding soil matrix.

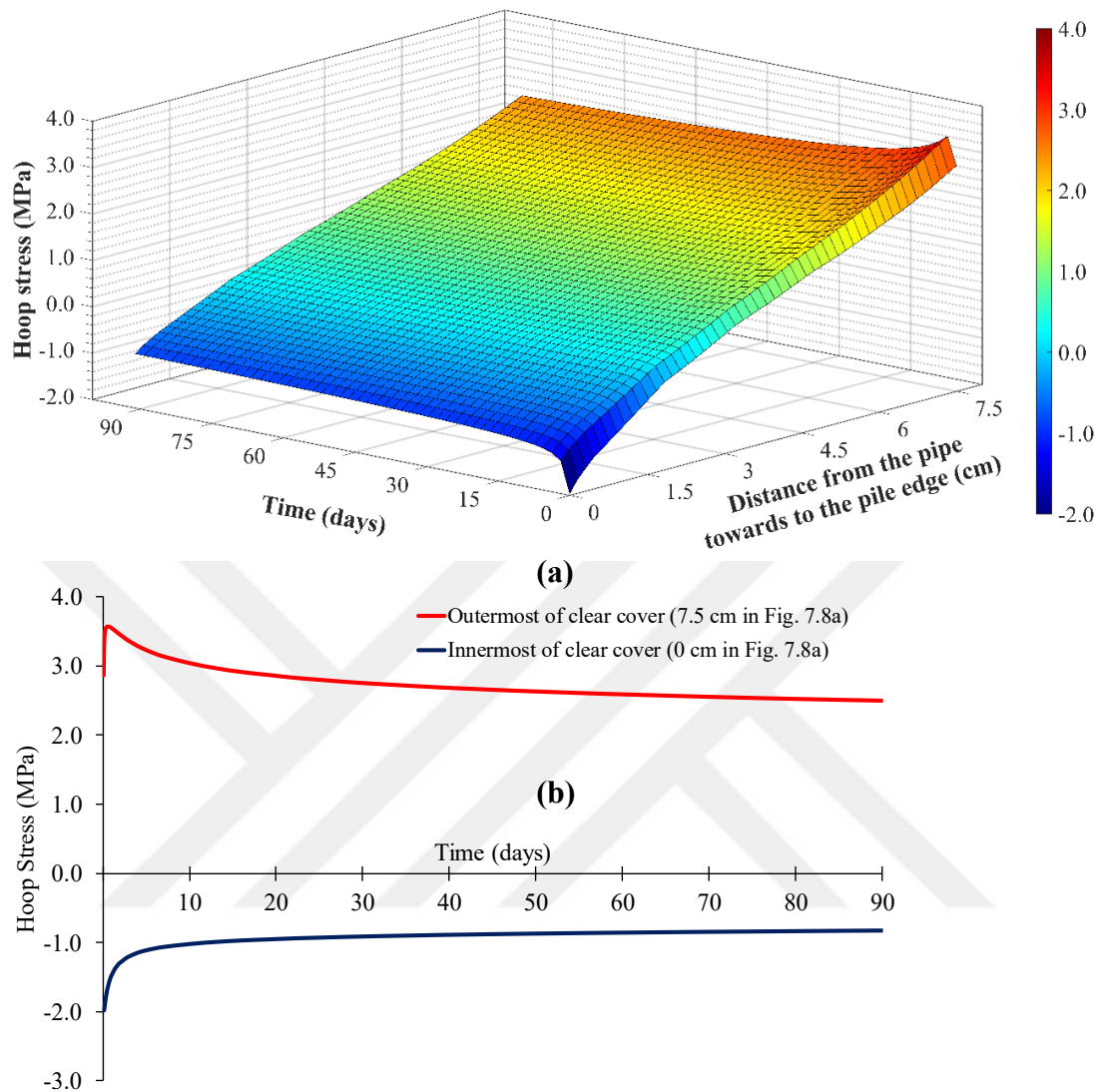


Figure 7.8. The hoop stress evolution in the clear concrete cover during summer season implementation: (a) for the clear concrete cover next to inlet pipe on the A-A' section (7.5 cm being the pile edge), and (b) for both innermost and outermost of the clear concrete cover.

During the winter season, the heat flow direction is opposite to that in summer. Consequently, the edge of the clear concrete cover no longer functions as a tension membrane but instead acts like a compressed shell. This behavior arises because cooling begins at the pipe, causing the surrounding area to attempt to shrink. However, this contraction is resisted by the warmer outer regions, creating tension in the cooled zone and compression in the outer shell. As anticipated, the tension levels in winter are lower compared to those in summer. Both tension and compression peak quickly after the onset of winter conditions, occurring when a sufficiently large area has cooled and the thermal

gradient is at its highest. Over time, as the system approaches thermal equilibrium, these stresses diminish, as illustrated in Figure 7.9. Much like the summer scenario, this mechanism relies on the thermal properties of the materials, and tensile stresses persist within the inner regions of the clear concrete cover. This is important because it demonstrates that every part of the clear concrete cover undergoes tension at some point during the operational life of an energy pile used for both heating and cooling.

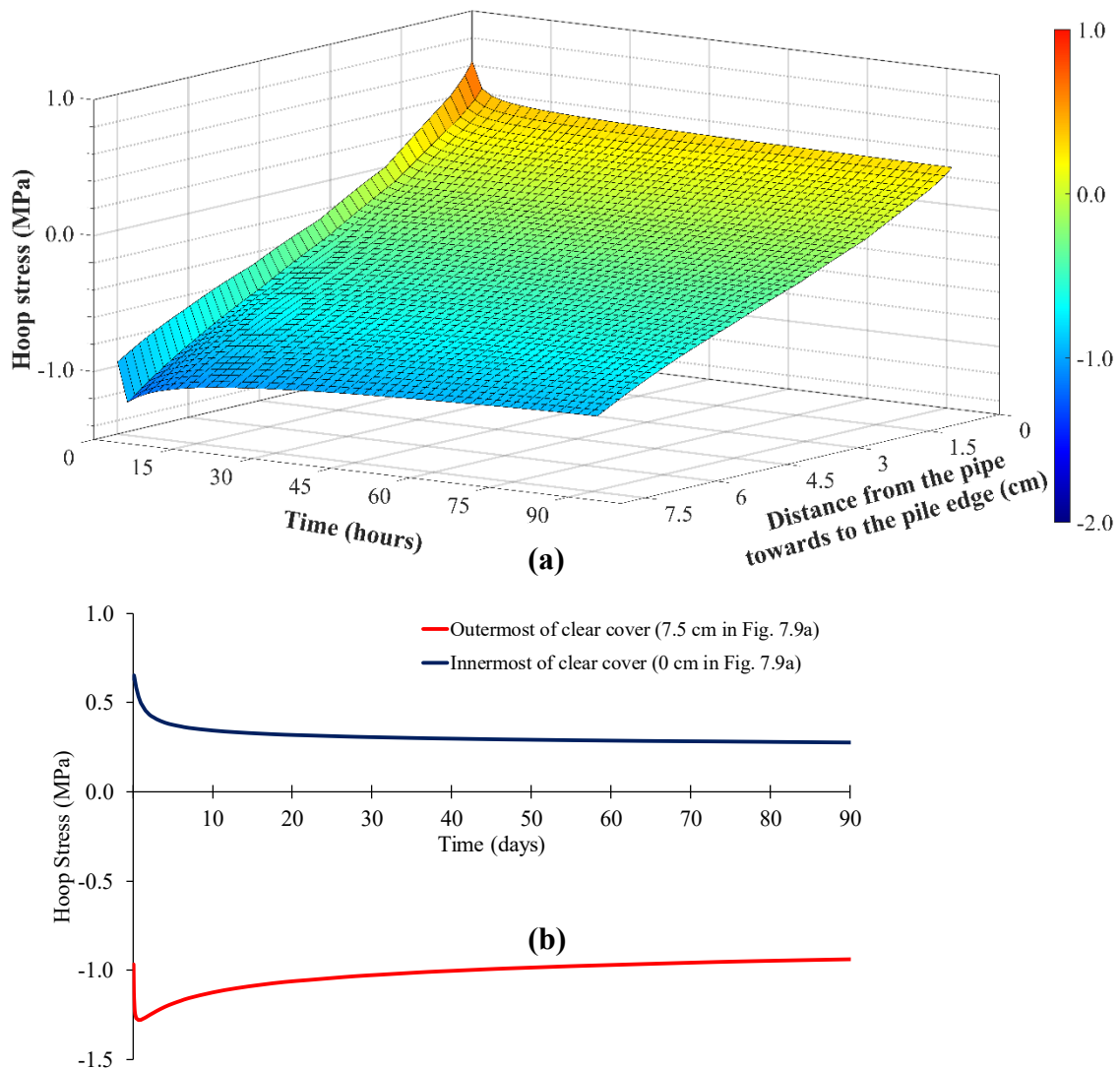


Figure 7.9. The hoop stress evolution in the clear concrete cover during winter season implementation (a) for the clear concrete cover next to inlet pipe on the A-A' section (7.5 cm being the pile edge), (b) for both innermost and outermost of the clear concrete cover.

7.5. Design Considerations

Expanding on the provided results, a thorough examination reveals that tensile stresses develop at every location within the clear concrete cover over time when considering the combined effects of both summer and winter operational conditions. In the reference case analysis, the summer scenario emerges as the more structurally demanding condition due to its generation of significantly greater tensile stresses compared to winter operations. This difference in stress magnitude can be attributed directly to the thermal loading conditions, with the summer scenario producing a more severe temperature gradient across the concrete section.

The fundamental relationship between thermal gradient and induced stresses becomes particularly evident in these results. The reference case demonstrates that when subjected to the maximum expected temperature differential (as occurs in summer conditions), the resulting tensile stresses reach their highest magnitudes. This phenomenon occurs because the steeper thermal gradient creates greater differential expansion between the inner and outer concrete regions, leading to more pronounced tensile strains at the cover's exterior surfaces.

However, it's crucial to recognize that while the absolute stress values vary between scenarios, the persistent presence of tensile stresses remains a constant design consideration. Even in winter conditions or alternative operational modes where temperature gradients may be less severe, the clear concrete cover still experiences tensile loading—albeit at reduced magnitudes. This cyclic nature of stress reversal between summer and winter operations means that the entire cover region will be subjected to fluctuating tensile forces throughout the system's service life.

From a structural integrity perspective, these findings carry significant implications for design practice. The clear concrete cover represents a potentially vulnerable zone in the energy pile's cross-section, as its unreinforced condition provides no resistance against crack initiation when tensile stresses exceed the concrete's capacity. This vulnerability persists regardless of whether the maximum stresses occur at the surface or within the interior regions

of the cover, or whether they develop during initial thermal transients or under sustained temperature differentials.

Consequently, these results underscore the necessity of incorporating tensile stress analysis into the design process for energy pile systems. Design approaches must account for both the peak stress conditions (typically occurring in summer) and the cumulative fatigue effects of repeated thermal cycling. This comprehensive stress evaluation becomes particularly critical when considering the long-term durability requirements of geothermal energy piles, where crack formation in the clear concrete cover could potentially compromise both structural performance and hydraulic containment functions over decades of operation.

An important factor to examine is the movement of tension areas within the clear concrete cover. The reference case indicates that summer operations produce tensile stresses far greater than the concrete's strength, meaning cracks will inevitably form in the cover. When winter and summer conditions alternate repeatedly, these cracks grow deeper as stress focuses on the already damaged areas. This ongoing process can eventually cause steel reinforcement to corrode, reduce the structure's longevity, and weaken the connection between concrete and steel – all consequences that designs must prevent from occurring.

It is crucial to highlight that the mean tensile strength and corresponding design strength of the concrete, as presented in Figures 7.1 and 7.3 for the reference case, are related exclusively to uniaxial loading conditions. However, in practical applications, piles are seldom subjected to purely uniaxial loading. Multiaxial loading scenarios must also be incorporated into the design considerations. This is particularly relevant for energy piles, which inherently experience multiaxial loading.

When axial stresses coexist with radial and hoop stresses, the resulting stress state becomes multiaxial, necessitating consideration of the Kupfer effect (Kupfer and Gestier, 1973). This research demonstrates that under multiaxial loading conditions—where tensile and compressive stresses act in orthogonal directions—the effective strength of concrete is reduced. This phenomenon is especially pertinent for axially loaded energy piles, which typically undergo axial compression while simultaneously developing tensile hoop stresses

within the clear concrete cover. Consequently, the tensile capacity of the concrete is diminished, increasing the likelihood of cracking in the clear concrete cover.

Usually, design criteria against cracking of clear concrete cover are not clearly identified in standards and guidelines where the focus is more on the causes, evaluation and repair. For example, in the standard ACI PRC-207.1-21 by the American Concrete Institute (2022), considers tensile stresses caused by differential volume changes that surpass the tensile strength of concrete as a reason for crack formation. The same report also notes that cracks may propagate at stresses much lower than the one required to cause crack initiation. Considering this warning in the light of the results of this study, the idea regarding the likelihood of crack propagation towards the interior region of the clear concrete cover in subsequent cycles of summer and winter scenarios, is a reasonable mechanism that requires further investigation. On the other hand, according to the report, CIRIA C660 (2007), a document on early-age thermal crack control in concrete, when the thermal gradient exceeds 20°C for plain concrete, thermal cracking is expected to occur.

From serviceability and performance perspective for structural elements, JSCE (2010) recommends controlling the possibility of thermally induced cracks. This control is achieved by calculating the thermal crack index (I_{cr})

$$I_{cr} = \frac{f_{ct}}{\sigma_t}, \quad (7.2)$$

where f_{ct} is the tensile strength and σ_t is the maximum principal tensile stress. The calculated value of I_{cr} is then compared to the typical values provided in Table 7.1 (JSCE, 2010). For the reference case in this study, thermal crack index values were found to be 0.98 for the summer scenario and 3.35 for the winter scenario. Therefore, especially for the summer scenario, there is a high probability of crack formation. It is also important to note that this consideration does not account for the possible reduction in f_{ct} due to the Kupfer effect.

Table 7.1. Thermal crack index and the corresponding consequences.

Cracking case	Thermal crack index (I_{cr})
No crack	$1.75 \leq I_{cr}$
Limited crack	$1.45 \leq I_{cr} < 1.75$
Restricted or minimized harmful cracking	$I_{cr} \leq 1.0$

Therefore, the subsequent presentation of results will concentrate specifically on hoop stresses. The data shown in Figures 7.1 through 7.4 indicate that thermally generated stresses reach their highest magnitude in two locations: the upper portions of the pile and the zone adjacent to the inlet pipe. This phenomenon results from the progressive cooling of the inlet fluid as it moves through the pile system, caused by heat exchange between the fluid, the pile material, and the surrounding soil. This heat transfer process gradually reduces the temperature differential until the fluid exits the system. It should be noted that for energy piles and comparable thermal geostructures, insulating materials can be installed around pipes near ground surface areas. For these reasons, the analysis that follows will emphasize the stress conditions observed in the central segment of the pile.

7.6. Results of the Sensitivity Analyses

The current section systematically presents and discusses the comprehensive results obtained from the detailed sensitivity analysis performed to quantitatively assess and evaluate the relative influence of multiple governing parameters and boundary conditions on the development and magnitude of thermally induced hoop stresses within the clear concrete cover region of energy piles. The extensive sensitivity investigation was carefully designed to encompass and examine three distinct categories of influential variables: (i) material properties, including the thermal and mechanical characteristics of constituent materials; (ii) geometric parameters, comprising the dimensional and configurational aspects of the pile system; and (iii) operational conditions, covering the various thermal loading scenarios and functional parameters that may occur during service life.

The material properties examined comprised the thermal conductivity and specific heat capacity of both soil and pile materials, as these characteristics govern heat transfer processes and thus determine the temporal evolution of temperature fields. Furthermore, the investigation included the pile's elastic modulus, Poisson's ratio, and coefficient of thermal expansion, since these mechanical properties directly affect the development of constrained thermal strains and their corresponding stress responses relative to the established temperature profiles.

The geometric parameters examined in the study consisted of pile diameter and pipe configuration, as these dimensions influence the time-dependent temperature variations within the system. Regarding operational factors, the analysis incorporated both the flow rate of the heat-transfer fluid and prevailing climatic conditions. The complete set of parameter values used in this investigation can be found in Tables 6.3 through 6.5. For each parameter variation, systematic modifications were implemented separately for heating and cooling modes, while maintaining all other variables at their baseline values as defined in the reference case. Through careful observation of variations in peak tensile hoop stress occurring in the clear concrete cover region, the relative impact of each individual parameter was quantitatively determined.

Figure 7.10 displays the outcomes of the sensitivity analyses conducted for both summer and winter operating conditions. The results are plotted as hoop stress against normalized parameters, where each parameter value is expressed relative to its reference case magnitude. The investigation demonstrated that the coefficient of thermal expansion emerges as the most significant parameter affecting stress development. This finding aligns with fundamental thermo-mechanical principles, since materials with higher thermal expansion coefficients experience greater constrained thermal strains when subjected to non-uniform temperature fields, consequently generating more substantial stresses during both heating (summer) and cooling (winter) operational modes.

In contrast, the thermal conductivity of the pile represents the second most critical parameter, exhibiting an inverse relationship with hoop stress magnitude. Higher thermal conductivity promotes greater uniformity in cross-sectional temperature distribution, thereby diminishing potential constrained thermal strains. Furthermore, the specific heat capacities of both soil and pile materials demonstrate negligible influence on hoop stress development. Nevertheless, soil thermal conductivity exhibits a modest effect during summer conditions, where increased conductivity exacerbates non-uniform temperature fields by facilitating more efficient heat transfer from the pile to the surrounding soil. This thermal gradient maintains cooler temperatures in the tension membrane region.

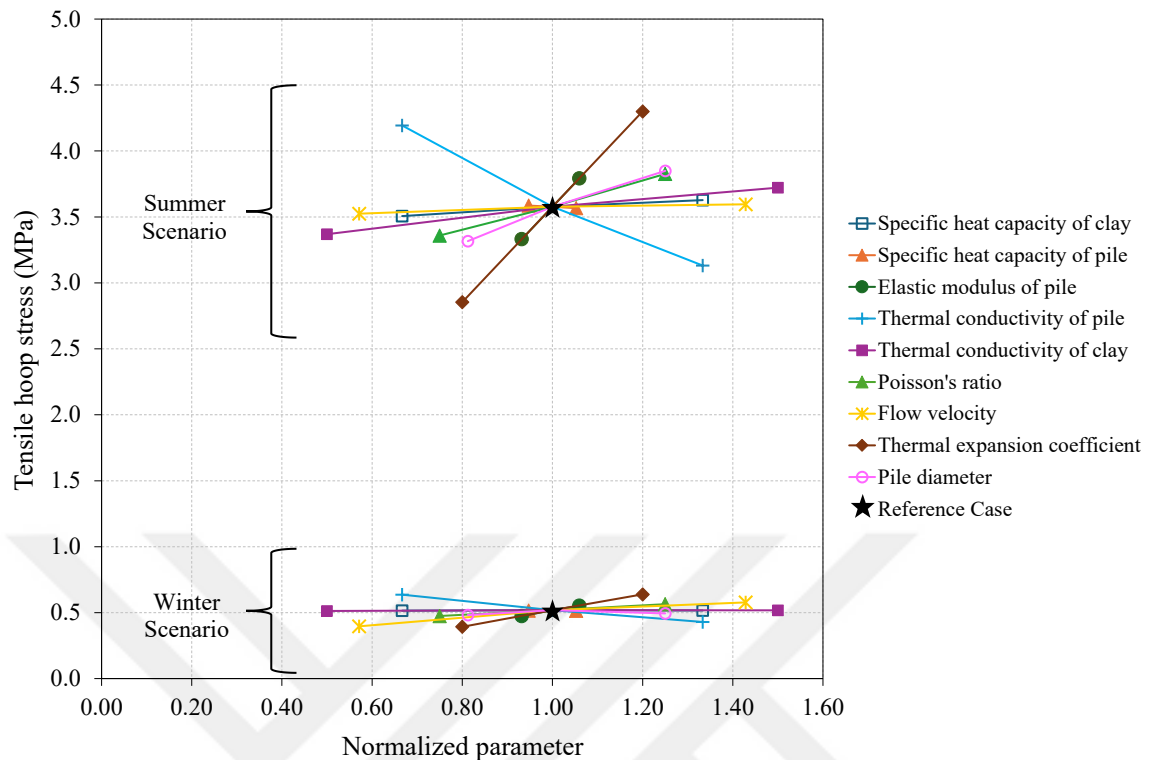


Figure 7.10. Hoop stresses for both summer and winter scenarios.

The analysis also identifies Poisson's ratio and elastic modulus as materially significant contributors to hoop stress generation. As fundamental constitutive properties governing concrete's stress-strain response, these parameters directly influence thermally induced stresses. Specifically, greater structural stiffness elevates hoop stresses when subjected to equivalent constrained strains. Similarly, elevated Poisson's ratios amplify average strain magnitudes, consequently intensifying stress development under thermal loading.

The study also examined the effect of heat-transfer fluid flow velocity on system behavior. Analysis shows that elevated flow velocities produce a modest but consistent rise in tensile hoop stresses under both winter and summer operating conditions. This correlation stems from enhanced thermal energy transport at higher flow rates, which establishes more pronounced temperature differentials within the system.

The sensitivity study revealed distinct diameter-dependent behavior in thermally-induced tensile hoop stresses. During summer operations, larger pile diameters consistently produced elevated hoop stress magnitudes, as demonstrated in Figure 14. This correlation

aligns with the fundamental stress generation mechanisms previously established. In contrast, winter operating conditions showed no statistically significant diameter-stress relationship, indicating seasonal dependence in the geometric influence.

The analysis further demonstrates the significant impact of geographical location on stress development through its effect on local climatic conditions. Comparative evaluation of the selected locations revealed Halden, Norway as the most critical case for summer operations, attributable to the substantial thermal differential between the ground and circulating fluid temperatures. The resulting tensile hoop stresses during summer conditions were quantified at +4.83 MPa (Halden), +3.43 MPa (Istanbul), and +2.78 MPa (Houston). Conversely, winter conditions produced maximum stresses in Houston (+0.81 MPa), followed by Halden (+0.63 MPa) and Istanbul (+0.52 MPa), with this stress hierarchy directly correlating with the observed temperature differentials during cooling operations.

The investigation additionally examined the influence of pipe geometry by analyzing an alternative W-shaped configuration compared to the conventional U-shaped reference case. The analysis yielded maximum tensile hoop stresses of +3.12 MPa during summer operation and +0.60 MPa in winter conditions. This stress reduction primarily stems from the W-configuration's enhanced capacity to establish more uniform cross-sectional temperature distributions, thereby mitigating thermal gradients and their corresponding stress effects.

7.7. Possible Precautions against Tensile Hoop Stress Danger

In this part of the chapter, possible precautions against tensile hoop stresses will be presented.

7.7.1. Boundary and Initial Conditions

The primary driver of tensile hoop stresses in energy piles is the non-uniform temperature distribution across the pile's cross-section. When heat exchange fluid circulates through the embedded pipes, the concrete near the pipes heats up faster than peripheral regions, creating radial temperature gradients. This differential thermal expansion induces

self-equilibrating stresses, where warmer inner regions attempt to expand but are constrained by cooler outer concrete, generating compressive stresses at the core and tensile hoop stresses near the perimeter. These tensile stresses are particularly critical as concrete has limited tensile capacity. In extreme cases, uncontrolled thermal gradients exceeding 15-20°C across the radius can initiate radial cracking, compromising structural integrity and long-term durability.

To mitigate these effects, controlled step-wise loading protocols should be implemented. Rather than applying full design temperatures immediately, incremental increases of about 5°C per hour allow heat to dissipate more evenly through the concrete mass. This gradual approach reduces the maximum temperature differential from potentially critical levels (>15°C) to more manageable ranges (5-8°C). The exact ramp rate should be determined through 3D coupled thermo-mechanical analysis that considers the pile's specific geometry, concrete thermal properties, and soil interaction. Numerical modeling can identify the threshold where faster heating rates would produce unacceptable stress concentrations while balancing operational efficiency requirements.

The absolute temperature of the circulating fluid must be carefully regulated relative to the native ground temperature. Maintaining inlet temperatures as compared to the ambient soil temperature minimizes the thermal shock potential while still enabling effective heat exchange. For example, in soils at 15°C, limiting maximum inlet temperatures to 25-30°C rather than 40-45°C can reduce hoop stresses by 30-40%. Concurrently, flow rate adjustments provide secondary control - reducing flow velocities from typical 0.6-1.0 m/s to 0.3-0.5 m/s decreases the convective heat transfer coefficient, resulting in more gradual temperature changes throughout the pile section. This combined approach of moderated temperature differentials and controlled flow rates synergistically limits both the magnitude and rate of hoop stress development.

7.7.2. Fiber Reinforcement Usage

It was shown experimentally that steel fiber usage increases tensile strength the concrete (Olivito and Zuccarello, 2010). The experimental results demonstrated that the addition of steel fibers significantly improved the tensile strength of concrete, with the extent

of improvement depending on fiber length and volume content. Fibers (1% volume content) increased the mean tensile strength of the concrete tensile strength as 40%.

The hoop stress-strain behavior of fiber-reinforced cementitious composite thin-walled cylindrical shells under uniform internal hydrostatic loading was investigated (Ghasemzadeh Mosavinejad et al., 2018). It was demonstrated that silica fume significantly enhances mechanical properties, increasing compressive strength by up to 27% and flexural strength by up to 32% when added at 10% by weight of cement. In terms of hoop stress, silica fume improved tensile strength by 10% but reduced strain capacity by 28%, resulting in more brittle failure. Furthermore, the addition of glass fibers, particularly at 0.5–2.5% by volume, substantially improves ductility, with hoop ultimate strain increasing by up to 7.4 times compared to non-fiber specimens. Fibers also enhance hoop tensile strength by up to 37%, though they have minimal effect on compressive strength. The study noted that fibers help distribute microcracks and delay visible cracking. However, samples with glass fibers did not provide post-crack strain hardening, meaning the material still fails in a relatively brittle manner after cracking.

7.7.3. Concrete Thermal Conductivity Adjustment

According to sensitivity analyses, increase in concrete thermal conductivity causes less tensile hoop stresses within concrete. Therefore, in the section, factors affecting concrete thermal conductivity will be presented.

Several parameters influencing the thermal conductivity of concrete, with some leading to an increase in its value was identified (Asadi et al., 2018). Moisture content is a significant factor; concrete in saturated conditions exhibits higher thermal conductivity compared to dry conditions due to water's superior thermal conductivity. Furthermore, the type and volume of aggregate used in concrete significantly affect thermal conductivity. Normal-weight aggregates, such as crushed stone, increase thermal conductivity compared to lightweight aggregates like expanded perlite or oil palm shell. Coarse aggregate volume fraction is particularly influential; higher fractions generally lead to higher thermal conductivity values. Moreover, the presence of PCMs typically reduces thermal conductivity, but the specific impact depends on the PCM type and incorporation method.

For example, paraffin in liquid phase has lower thermal conductivity than in solid phase, but its interaction with the concrete matrix can alter overall heat transfer properties.

It was shown that the addition of steel fibers also elevates thermal conductivity, particularly when the volume fraction exceeds 0.25%. Steel fibers create a percolation network within the concrete matrix, enhancing heat transfer (Sargam et al., 2020). At a 2% volume fraction, thermal conductivity can increase by approximately 10–15% compared to fiber-free concrete. In contrast, polypropylene fibers have negligible impact due to their low thermal conductivity.



8. CONCLUSION

This research employs numerical methods to analyze the fundamental mechanisms responsible for thermally-induced hoop stresses in energy pile systems. Using a verified computational model, the investigation first examines these thermo-mechanical interactions through a baseline reference case. The results demonstrate that active thermal loading through embedded heat exchange pipes creates temporally evolving, non-uniform temperature fields within the pile structure. During heating operations, pipe-adjacent zones experience temperature increases prior to outer concrete regions, creating differential expansion conditions. The resulting constraint of warmer inner regions by cooler outer material produces a characteristic stress distribution featuring tensile stresses at the periphery and compressive stresses in interior zones of the concrete cover. Under cooling conditions, this stress pattern undergoes complete reversal. The reference case analysis notably shows that peak thermal tensile hoop stresses may approach or surpass both the mean and design tensile capacities of concrete, representing a crucial structural consideration for energy pile design and implementation.

The sensitivity analysis examined variations in material properties, operational parameters, geometric factors, and climate conditions. Results indicated that higher values of thermal expansion coefficient, elastic modulus, and Poisson's ratio increased thermal hoop stresses, whereas pile diameter only significantly affected stresses during summer conditions. In contrast, pile thermal conductivity showed an inverse correlation with stress levels. This parameter also governs internal temperature distribution and heat transfer to the surrounding soil, where greater conductivity produces more uniform temperature fields, minimizing differential expansion and resulting stress. These findings imply that concrete with improved thermal properties could reduce tensile stresses in the clear cover. For piles undergoing repeated thermal cycles, conductivity optimization might enhance fatigue life and long-term durability. The study found negligible impacts from: (i) soil heat capacity, (ii) pile heat capacity, and (iii) fluid flow velocity. Climate conditions substantially affected stress magnitudes, with larger temperature differences creating higher stresses - particularly during heat injection in Halden, Norway and heat extraction in Houston, USA. Pipe geometry also affected stresses through its influence on temporal temperature distribution, with W-shaped configurations producing lower stresses than U-shaped designs.

The findings collectively emphasize the critical need to account for thermal hoop stresses in energy pile design. The simultaneous occurrence of compressive and tensile stresses within the same cross-section - characteristic of multiaxial loading conditions - presents particular concern due to concrete's reduced strength under such stress states. This includes both structural axial loads and thermally induced axial stresses, which vary according to pile restraint conditions. Consequently, the design tensile strength of concrete for energy piles should be conservatively reduced compared to uniaxial loading scenarios. Furthermore, additional stress contributions from environmental and operational factors must be incorporated in the design framework.

The results verify that structural reinforcement designed for mechanical loads does not effectively counteract thermal stresses. Accordingly, an essential design requirement is limiting tensile stresses to remain beneath the concrete's design tensile strength for the system's operational lifetime. This can be accomplished by improving concrete's tensile capacity using higher-strength concrete mixtures or fiber reinforcement. Alternative solutions involve altering pile properties - including decreasing diameter, optimizing pipe layouts for better temperature uniformity, or adding conductivity-enhancing materials. Operational adjustments, like lowering heat-transfer fluid temperatures to decrease thermal gradients or reducing flow speeds, may also help control stress variations.

8.1. Recommendations for Future Research

This study adopts a strength-based approach for evaluating hoop stresses in energy piles. However, to better represent real behavior, future research could implement a displacement-based approach combined with advanced constitutive modeling. The use of sophisticated material models such as CDP would enable more accurate simulation of crack initiation and propagation under thermal loading. Such refined modeling approaches could provide more realistic stress distributions throughout the pile cross-section, potentially leading to more economical design solutions by optimizing reinforcement requirements.

Furthermore, given that energy piles experience cyclic thermal loading in service (Bourne-Webb et al., 2016), future studies should investigate the progressive damage accumulation and crack widening under repeated thermal cycles. This is particularly

important for durability considerations with respect to find out progressive crack development in concrete. The quantification of crack opening displacements would be especially valuable for assessing corrosion risks in high groundwater table conditions, where chloride penetration through cracks could accelerate reinforcement deterioration (Bertolini et al., 2016). Such analyses would provide crucial insights for long-term performance assessment and maintenance planning of energy pile systems.

Hoop stresses develop in structures of any geometry when subjected to thermal loading because its dependence on the thermal gradient. Regardless of the shape, temperature gradients form along the radial direction, inducing thermally induced hoop stresses. These stresses are particularly significant in energy walls and energy tunnels, where the combined mechanical and thermal loads influence structural behavior. Given the similarities in thermo-mechanical response, the same analytical and numerical approaches used for energy piles can be extended to these energy geostructures.

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