

Performance of Soil Borehole Thermal Energy Storage System under Different Natural and Engineered Subsurface Conditions

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Upasana Pandey

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner	Dr. John S. McCartney Professor, Department of Structural Engineering, Jacobs School of Engineering, University of California San Diego
Supervisor	Dr. Dipanjan Basu Professor, Department of Civil and Environmental Engineering, University of Waterloo
Internal Member	Dr. Maurice B. Dusseault Professor, Department of Earth and Environmental Sciences, University of Waterloo
Internal Member	Dr. Shunde Yin Associate Professor, Department of Civil and Environmental Engineering, University of Waterloo
Internal-external Member	Dr. Roydon Fraser Professor, Department of Mechanical and Mechatronics Engineering, University of Waterloo

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Borehole thermal energy storage (BTES) system, a type of underground thermal energy storage (UTES) systems, is a promising technology for sustainable space heating. BTES stores thermal energy in subsurface media (rock or soil) using borehole heat exchangers (BHEs). BTES installed in soil are specifically known as soil borehole thermal energy storage (SBTES) system. In SBTES, a heat carrier fluid (HCF) collects thermal energy from various heat sources such as solar energy and industrial waste heat, circulating it through the BHEs. The heat from the BHEs is transferred to the surrounding soil and stored as thermal energy in the soil deposits, thereby increasing its temperature. Subsequently, the stored energy is extracted through BHEs for space heating applications.

The ability to retain stored energy in soil deposits depends on subsurface thermal and hydraulic conditions. Previous studies have explored various subsurface conditions (saturated, unsaturated, and groundwater flow) to capture their influence on the thermal performance of SBTES system. While previous studies focused specifically on the role of soil thermal conductivity under saturated soil conditions, the influence of other soil properties, particularly under different SBTES design conditions, has not been systematically explored. In unsaturated subsurface conditions, studies have concentrated on assessing the thermal performance of SBTES systems under varying moisture content conditions, while considering different water retention parameters. However, the understanding of the role of soil porosity in the thermal performance of SBTES in unsaturated soil, particularly under long-term operation scenarios, is limited. Additionally, existing studies have predominantly examined homogeneous soil conditions and have not accounted for soil layering. Further, while some studies have explored the impact of seasonal climatic fluctuations, they have primarily focused on variations in seasonal surface temperatures alone. The effect of surface pressure variations induced by factors such as evapotranspiration, groundwater table fluctuations, and other climatic conditions has not been thoroughly investigated. Previous studies regarding groundwater flow consideration often assumed the groundwater table to be flush with the ground surface, with the BHEs completely submerged into the groundwater. However, when different groundwater table depths are considered, where the BHEs are partially submerged, these studies did not take into account the influence of flow velocity. Previous studies have established that the consideration of groundwater flow is important in the analysis and design of SBTES systems. However, there is no systematic study available that explores the SBTES performance for a

wide range of flow velocities and for multiple groundwater table depths considered in conjunction. Additionally, in the presence of high velocity groundwater flow, it is commonly recommended to avoid installing SBTES at the location without proper engineering modifications. However, currently no strategies exist to effectively mitigate the adverse effects of groundwater flow on the thermal performance of SBTES systems.

The aim of this study is to develop better understanding of the influence of different subsurface conditions on the thermal performance of SBTES system through rigorous numerical analysis. The analysis incorporates saturated, unsaturated, and groundwater flow conditions to capture their respective impacts. Initially, a simplified conduction-based model is used to investigate the influence of physical and thermal properties of soil under different BHE spacing and injection heat flux scenarios for saturated soil condition. Subsequently, for unsaturated soil conditions, a coupled heat and mass transfer based numerical model is used to investigate the thermal behavior of SBTES systems under various subsurface moisture conditions, encompassing fully dry, fully saturated, and varying moisture content scenarios with different depths of the saturated soil zone. Additionally, the study examines the impact of seasonal surface pressure variations on the thermal performance of the SBTES system in unsaturated soil. Further, the role of soil porosity under different soil stratifications and soil moisture conditions on the thermal performance of the SBTES system in unsaturated soil is investigated to augment the existing knowledge in this area.

The effects of groundwater flow on the short- and long-term performances of SBTES systems under fixed- and variable-energy supply and demand conditions are studied for different groundwater velocities and different groundwater table depths. Numerical simulations of a SBTES system are performed for four groundwater table depths and with four groundwater velocities ranging from 0 m s^{-1} to $1 \times 10^{-5} \text{ m s}^{-1}$. The study aimed to highlight the importance of conducting long-term analyses and quantifies the adverse effects of groundwater flow on the thermal performance of SBTES.

Finally, a design aid is proposed in the form of vertical barriers to be installed within the SBTES domain, aimed at mitigating thermal losses resulting from groundwater flow. A comprehensive study is conducted to provide recommendations regarding the suitable type of vertical barriers, their appropriate positioning with respect to SBTES domain, and the anticipated improvement in thermal performance of SBTES system upon integration with the vertical barrier as a design aid. A detailed analysis is conducted for small, medium, and large-

scale SBTES domain to provide a suitable range of vertical barrier design components, refining the geometry of the vertical barrier to achieve optimal thermal performance.

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Dedication

To my family

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List of Symbols

θ	Volumetric water content
θ_r	Residual water content
θ_s	Saturated water content
ϕ	Soil porosity
λ	Thermal conductivity of the soil
λ_{dry}	Dry thermal conductivity of soil
λ_{sat}	Saturated thermal conductivity of soil
ρ_b	Total density of the soil
ρ_w	Density of water
μ_w	Dynamic viscosity of water
B_{TH}	Thickness of the vertical barrier
B_z	Depth of the vertical barrier
C_p	Effective volumetric heat capacity of soil
$C_{p,\text{dry}}$	Dry volumetric heat capacities of soil
$C_{p,\text{sat}}$	Saturated volumetric heat capacities of soil
C_s	Specific heat capacity of soil
D_L	Distances between longitudinal barriers from the BHE array
D_{Tr}	Distances between transverse barriers from the BHE array
g	Acceleration due to gravity
K_0	Saturated hydraulic conductivity of soil
k_{int}	Intrinsic permeability of soil
k_{rw}	Relative permeability of water
L_{BHE}	Length of the BHEs
N_{BHE}	Number of BHEs
NES	Normalized energy storage
P_B	Outer perimeter of the barriers

P_c	Capillary pressure
P_w	Pore-water pressure
$P_{w,surface}$	Surface pressure function
Q	Injection heat flux
$Q_{\text{extraction}}$	Total extracted heat
Q_{injected}	Total injected heat
Q_m	Mass source
Q_s	Heat source
Q_{stored}	Heat stored in the SBTES domain
S_f	Soil saturation parameter defined at the onset of funicular regime
S_p	BHE spacing
S_w	Degree of saturation
T	Soil temperature
t	Time
T_{avg}	Average temperature of the SBTES domain
TD	Temperature density
T_e	Temperature of SBTES domain at the end of heat injection-extraction cycle
T_i	Initial ground temperature
u_w	Groundwater flow velocity
V	Volume of SBTES domain
V_B	Construction material volume of the barriers
W_L	Width of the longitudinal barriers
W_{Tr}	Width of the transverse barriers
z	Depth
z_w	Groundwater table depth

CHAPTER 1

Introduction

1.1 Motivation

Globally, more than 50% of the final energy consumption is attributed to thermal energy (IRENA, 2020). Approximately half of this consumption is allocated to space and water heating in buildings as well as in cooking, while the remaining portion fuels various industrial processes (IRENA, 2020). Presently, a mere 9% of this extensive global heat demand is met by renewable sources, including direct heating and heat generated from renewable electricity (Collier, 2018). The high demand for heat significantly contributes to CO₂ emissions, accounting for approximately 12.5 gigatons of CO₂ or 39% of annual energy-related emissions in 2015 (Collier, 2018). Thus, considering thermal energy's crucial role as both a major end-use commodity and contributor to emissions, undertaking effective heat decarbonization measures becomes imperative.

Within the European Union and North America, buildings consume nearly 60% of the total heat consumption, primarily for space heating (IRENA, 2020). Therefore, this substantial segment specifically requires attention for heat decarbonization. Although there is no single straightforward solution to make heating more sustainable, the integration of *thermal energy storage* (TES) that is configured to accommodate diurnal and seasonal fluctuations, can be an effective solution.

TES is a technology that stores thermal energy by changing the temperature of the storage medium for later use in heating, cooling, or power generation applications (EASE, 2017). TES not only provides a solution to the mismatch between thermal supply and demand requirements as conventional energy storage systems do, but also empowers the heating sector by significantly reducing its reliance on conventionally generated electricity for thermal

applications. There exists a variety of TES types, applicable in power generation, industry, district heating and cooling, buildings, and cold chain logistics (see Figure 1.1).

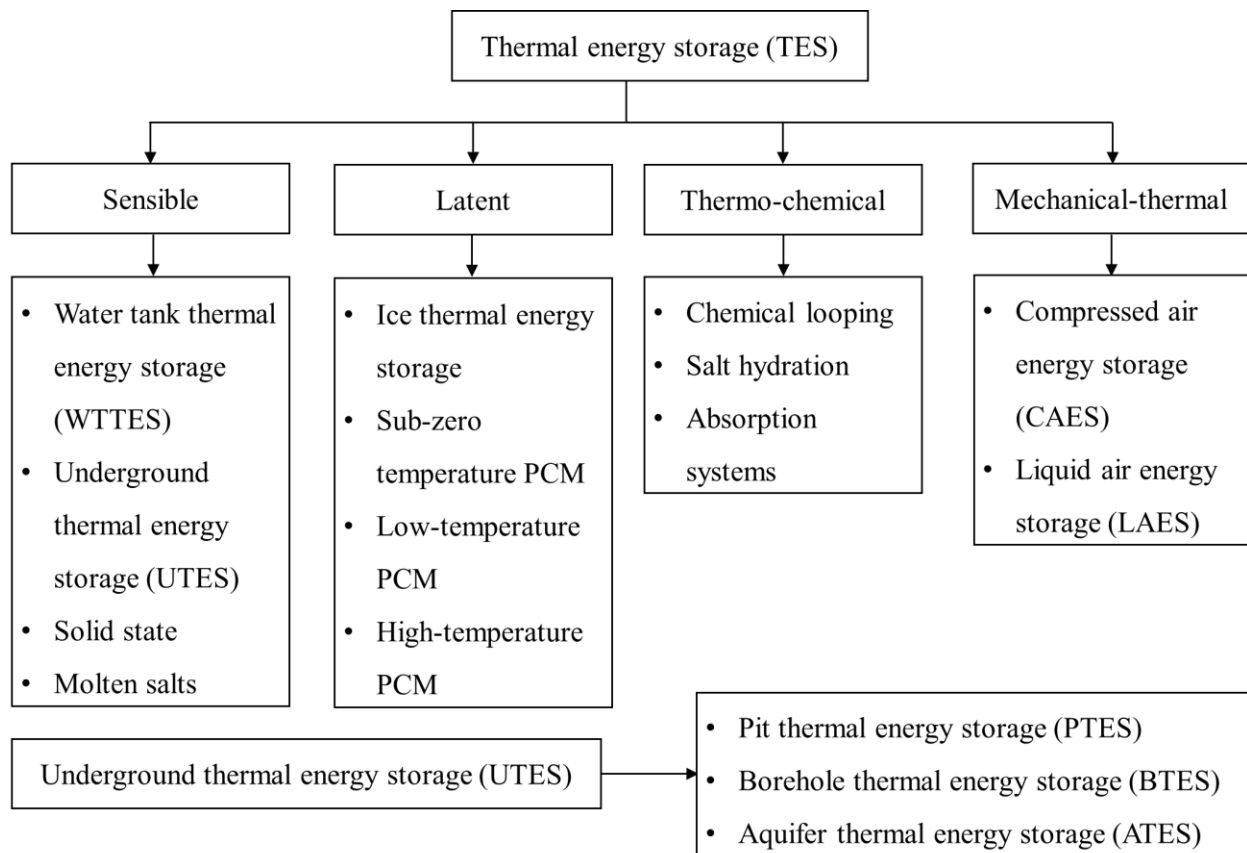


Figure 1.1: Overview of various types of TES systems.

This dissertation focusses on *Soil Borehole Thermal Energy Storage* (SBTES) system, a subtype of *Underground Thermal Energy Storage* (UTES), and a promising TES that offers a sustainable solution for building space heating applications. Details on SBTES are provided in the subsequent section.

1.2 Background

Borehole thermal energy storage (BTES) system is a type of underground thermal energy storage (UTES) technology that is used to store thermal energy in underground geologic media (rock or soil) using borehole heat exchangers (BHEs) (Gehlin, 2016). The depth of BTES system ranges from tens of meters to more than 1000 m with the shallower systems installed in soil deposits and the deeper systems installed in rock (Bär et al., 2015; Mesquita et

al., 2017). Those installed in soil are known as soil borehole thermal energy storage (SBTES) systems (McCartney et al., 2017).

SBTES is constructed by installing arrays of vertical boreholes that are equipped with heat exchanger pipes (U-tube, double U-tube, coaxial) (Figure 1.2). The single U-tube BHEs are the most prevalent and reliable heat exchanger pipes as they are easy to install and simple to operate (Gehlin, 2016). Once the heat exchanger pipes are placed within the boreholes, they are subsequently surrounded with a backfill material or grout, creating a network of subsurface heat exchangers. Commonly, SBTES boreholes are backfilled with soil or grout (Nilsson, 2020). The backfill material serves a dual purpose, facilitating the thermal contact between the BHE and surrounding soil while also supporting the structural stability of the boreholes, which makes grouting a more suitable backfill option (Cruickshank and Baldwin, 2016). To ensure excellent thermal contact between BHE and the surrounding soil, grouts with high thermal conductivity are preferred as backfill materials (Velraj, 2016). An insulation layer is applied to the top of the thermal storage volume (Figure 1.3) to minimize heat loss to the surrounding environment (Başer et al., 2016; Giordano et al., 2016). Finally, the layer of insulation on the SBTES domain is overlain by ~1.5 m of native topsoil from the surrounding earthwork (Mielke et al., 2014). Typically, extruded polystyrene (XPS) insulation is used, due to its resistance to moisture and its high compressive strength, effectively withstanding the stresses exerted by the overlying native topsoil layer (Sibbitt et al., 2014).

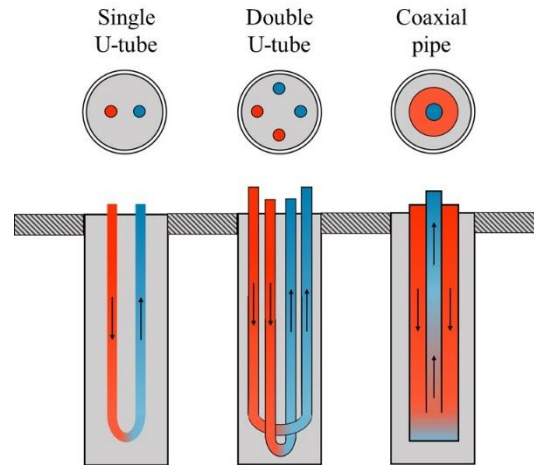


Figure 1.2: Single U-tube, double U-tube, and coaxial borehole heat exchanger pipes used in SBTES

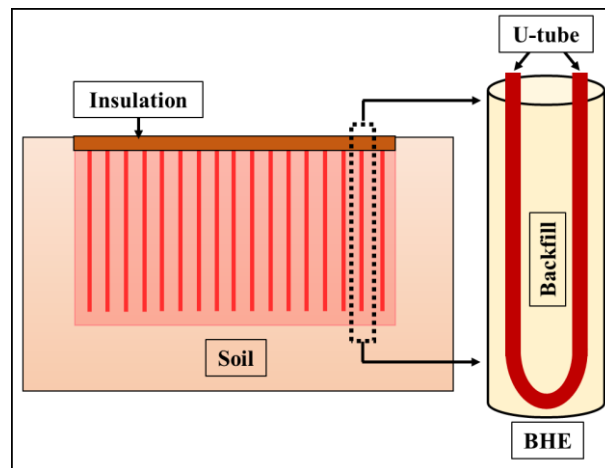


Figure 1.3: Schematic representation of construction elements of SBTES.

SBTES system shares common design components such as the BHE with ground source heat pump (GSHP) systems. However, SBTES and GSHP systems differ with respect to their operations, functionality, and scale of the design components. The GSHP system operates by utilizing the ground as a heat source or sink depending on the seasonal requirements for heating (or cooling). This results in a constant mean ground temperature maintained throughout its operational period (specifically under conditions where heating and cooling demands are balanced). This is achieved by using a heat pump that adjusts the collected ground temperature to meet the required heating or cooling demand. Therefore, a GSHP system is not systematically designed to store heat in the subsurface media. In contrast, the primary objective

of SBTES systems is to store heat within the subsurface media, facilitating an increase in the ground temperature from its initial value for space heating application. To achieve this, the design components of SBTES system, such as the number of BHE and the total length of BHE, typically need to be larger compared to those of a GSHP system. Additionally, the operation of an SBTES system may or may not involve the integration of a heat pump. For instance, a low-temperature SBTES system would require a heat pump to level up the extracted heat from the stored thermal energy for space heating application. On the other hand, a high-temperature SBTES system can provide direct heating without the need for integration with a heat pump. The Drake Landing Solar Community (DLSC) in Alberta, Canada and BTES in Crailsheim, Germany are examples of operational SBTES systems that demonstrate the prospects of SBTES systems as a feasible and efficient thermal energy storage (TES) technology (Mesquita et al., 2017; Mielke et al., 2014). Table 1.1 provides details on various SBTES applications worldwide.

Table 1.1: Details of the notable SBTES projects.

Plant, location	Year of first operation	Facility	Thermal source	Number of boreholes	Storage volume, V (m ³)	Borehole length, L_{BHE} (m)	Temperature (°C)	Source
Kungsbacka, Suncly, Sweden	1980	School building	Solar	612	80000	35	15 - 30	Hultmark, 1981
Vaulruz Project, Switzerland	1982	Maintenance building, garage	Solar		3300	Horizontal tubing	45	Chuard et al., 1983
Innsbruck, Austria	1983	Military barracks	Solar		65000	Horizontal tubing		Chuard and Hadorn, 1983
Treviglio, Italy	1985	Existing residential area	Solar	414	43000	11		Fisch et al., 1998; Jan-Olaf Dalenback, 1990
Groningen, Netherlands	1985	Domestic (44 houses)	Solar	20	23000	20	50	Anders Juhl Kallesøe et al., 2019
Lidköping, Sweden		Residential area	Solar		15000			Fisch et al., 1998; Jan -Olaf Dalenback, 1990
Neckarsulm, Germany	1997	Domestic (300 homes, shops)	Solar	528	63000	30	63	Nußbicker et al., 2003; Schmidt et al., 2004
Attenkirchen, Germany	2001	Domestic (30 houses)	Solar - hybrid	90	10000	30		Reuß et al., 2006; Schmidt et al., 2004
Mol, Belgium	2002	Building	Waste heat	144	16000	30	80	Hoes et al., 2005
DLSC, Canada	2007	Domestic (52 houses)	Solar	144	34000	37	80	Mesquita et al., 2017
Crailsheim, Germany	2008	District heating	Solar	80	39000	55	75	Mielke et al., 2014
Brædstrup, Denmark	2013	District heating	Solar	48	19000	45	70	Gauthier and PlanEnergi, 2020

Among various types of TES systems, SBTES is distinguished as a low enthalpy thermal energy system, as its operational temperature is below 95 °C (Ali et al., 2021). Currently, well-suited for this specified operational temperature limit, SBTES is primarily utilized for building space heating applications. Nevertheless, significant potential exists for expanding its usage to include diverse applications, such as providing heating for facilities like greenhouses, swimming pools, and pavement de-icing, as well as facilitating the process of food dehydration (Figure 1.4).

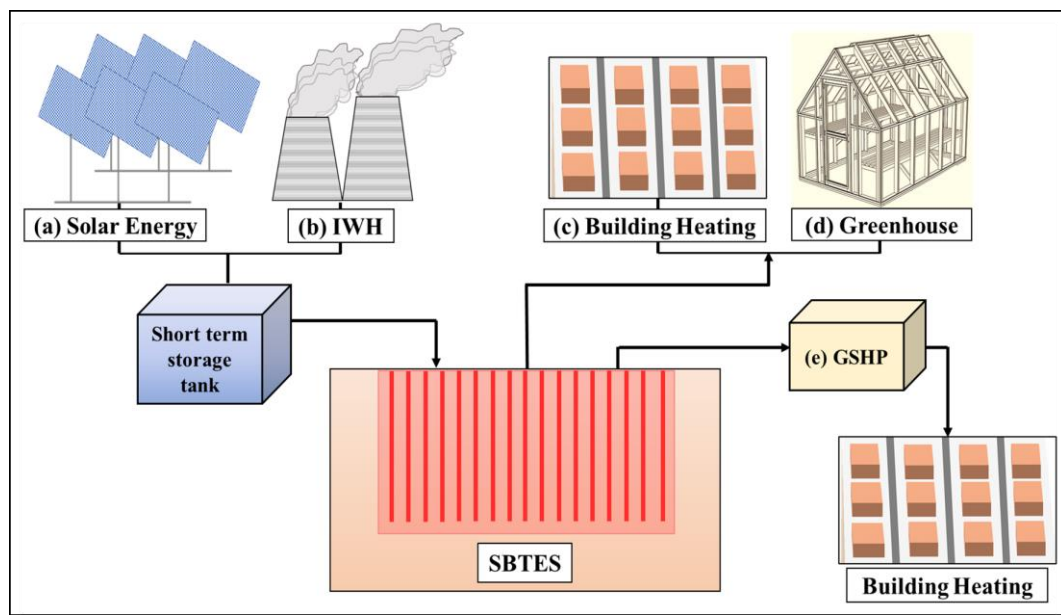


Figure 1.4: Schematic representation of SBTES system and its diverse applications

1.3 Recent development and challenges

Albeit a promising thermal energy storage technology, SBTES system comes with thermal performance challenges such as heat loss and low system efficiency (Sibbitt et al., 2012). A notable SBTES application in Alberta, Drake Landing Solar Community (DLSC) SBTES system delivered 6% to 35% of efficiency during its first three years of operation (Sibbitt et al., 2012). Another SBTES plant in Neckarsulm, Germany did not provide any heat extraction for the first five years of operation (Bauer et al., 2010). These observations suggest that the challenges associated with thermal performance are more pronounced during the initial years of operation (Zhu et al., 2019).

Attaining a high thermal performance in SBTES is the primary objective that has been explored in numerous studies investigating the influence of ground, design, and operational parameters on the thermal performance of SBTES (Başer and McCartney, 2020; Moradi et al., 2015a; Zhu and Chen, 2019). Boukelia et al., (2019) identified the soil thermal conductivity, specific heat capacity, and thermal diffusivity as the soil properties that influence the thermal performance of SBTES. Skarphagen et al., (2019) identified BHE spacing, BHE depth, number of BHEs, and the arrangement as important design parameters that influence the thermal performance of SBTES. Baser and McCartney (2015) conducted a parametric evaluation to study the influence of soil thermal conductivity, BHE spacing, and the amount of heat injection on the thermal performance. Baser and McCartney (2015) found that a smaller BHE spacing yields a higher energy density in the BTES domain but increases the heat loss. Catolico et al., (2016) found that a low soil thermal conductivity enables superior heat recovery during the extraction phase.

While the foregoing studies made significant contributions in advancing the understanding of SBTES system performance, the influence of soil parameters other than soil thermal conductivity remain largely unexplored. Specific heat capacity and total density are the other soil properties that may play important roles in thermal applications (Abed Gatea Al-Shammary et al., 2020; Alnefaie and Abu-hamdeh, 2020; Abu-hamdeh and Reeder 2000). At the same time, the influence of soil properties under different SBTES design conditions are not well known — the existing studies are often constrained by narrow parameter ranges and site-specific considerations (Guo and Yang, 2021).

Many researchers have recognized unsaturated soil in the vadose zone as a favourable medium to install SBTES systems (McCartney et al., 2013; Reuss et al., 1997; Wang and Qi, 2011). The idea of storing heat in the vadose zone is based on the existing understanding of the correlation between unsaturated soil-specific hydraulic properties and soil thermal properties,

particularly under non-isothermal conditions. From the early 20th century, various studies have examined the coupled nature of heat and mass transfer in unsaturated soils under non-isothermal conditions (Boyucos, 1915; Philip and De Vries, 1957; Smith, 1943). Such unsaturated soil-specific heat- and mass-transfer phenomena are expected to have an influence on the thermal response of BTES when installed in unsaturated soil in the vadose zone. The suggestion of installing SBTES in unsaturated soil in the vadose zone is based on the idea of exploiting the heat and mass transfer processes in unsaturated soil to increase the thermal storage capacity of the SBTES system (McCartney et al., 2013).

Previous studies have focused on assessing the thermal performance of SBTES systems under varying moisture content conditions in unsaturated soil, taking into account the different water retention parameters. However, there is limited understanding of the role of soil porosity on the thermal performance of SBTES in unsaturated soil, particularly under long-term operation scenarios. Further, the existing studies have predominantly examined homogeneous soil conditions and have not accounted for soil stratification, which is contrary to real-world field situations. No studies have considered the effect of a wide range of soil porosities arising from soil stratification within the thermal energy storage domain. Additionally, while some studies have explored the impact of seasonal climatic fluctuations, such studies have primarily focused on seasonal surface temperature variations only (Başer and McCartney, 2020). The effect of surface pressure variations, induced by factors like evapotranspiration, groundwater table fluctuations, and other climatic conditions, have not been investigated (Ito et al., 2022). Several studies have found the significant role of surface pressure variations on subsurface moisture content and other hydraulic properties (Ahmed et al., 2018; Fredlund, 2006; Mabirizi and Bulut, 2011; Totoev and Kleeman, 1998).

It is observed in various studies that the magnitude of stored energy and the storage efficiency are influenced by groundwater flow (Behbehani and McCartney, 2022; Catolico et

al., 2016; Lanahan and Tabares-Velasco, 2017; Zhang et al., 2015). In fact, it has been observed that the efficiency of SBTES systems can be significantly reduced if the groundwater flow rate is excessively high (Skarphagen et al., 2019). Consideration of groundwater flow is important in the analysis and design of SBTES systems. However, there is no systematic study available that quantifies the SBTES performance for a wide range of flow velocities and for multiple groundwater table depths considered in conjunction. Also, in the presence of high velocity groundwater flow, it is commonly recommended to avoid installing SBTES in locations without proper engineering modifications. Currently no strategies exist to effectively mitigate the adverse effects of groundwater flow on the thermal performance of SBTES systems.

In the forthcoming chapters, a rigorous literature review is provided, complementing the study addressed within each respective chapter. The literature reviews in each chapter complements the literature review presented above.

1.4 Objectives of present study

In consideration of the limitations identified in the previous section, the aim of this study is to enhance the understanding of how different subsurface conditions influence the thermal performance of the SBTES system and to provide engineering solutions to enhance the performance of the SBTES system. To achieve this goal, the objectives outlined in this dissertation are:

- (i) To investigate the influence of selected thermal and physical soil parameters on thermal performance of SBTES system in fully saturated soil under various SBTES design conditions for the first phase of heat injection.
- (ii) To investigate the long-term thermal performance under diverse subsurface moisture conditions, determine the effects of seasonal surface pressure fluctuations, and study the influence of soil porosity across different soil stratifications. This objective aims to

address knowledge gaps pertaining to the thermal performance of BTES systems in unsaturated soil.

- (iii) To assess the adverse effects of groundwater flow on SBTES thermal performance by investigating the influence of different groundwater velocities and groundwater table depths on the short- and long-term performance of SBTES systems, accounting for fixed- and variable-energy demand-supply conditions.
- (iv) To investigate the effectiveness of integrating vertical barriers in the SBTES domain to mitigate groundwater flow effects, this study identifies the suitable barrier type and its strategic positioning relative to the BHE array. The research concludes with the development of design recommendations for these vertical barriers.

1.5 Dissertation outline

The dissertation has six chapters and is organized as follows:

Chapter 1: This chapter establishes the motivation of the study and provides a general introduction of the SBTES system. It outlines the research objectives to be addressed.

Chapter 2: This chapter delves into the investigation of SBTES system performance in saturated soil, using a simplified conduction-based model during the first phase of heat injection. It examines the sensitivity of various ground parameters under different SBTES design conditions.

Chapter 3: This chapter explores the thermal behavior of SBTES systems in unsaturated soil, for various subsurface moisture conditions, encompassing fully dry, fully saturated, and varying moisture content scenarios with different depths of the saturated soil zone. The influence of seasonal surface pressure variations is assessed and the role of soil porosity on the thermal performance of SBTES in unsaturated soil is investigated.

Chapter 4: This chapter deals with the impact of different groundwater velocities and table depths on the short- and long-term performance of SBTES systems under fixed- and

variable-energy supply and demand conditions. It highlights the importance of conducting long-term analyses and quantifies the adverse effects of groundwater flow on SBTES thermal performance.

Chapter 5: Focused on mitigating negative groundwater flow effects, this chapter presents the integration of vertical barriers into the SBTES domain. It addresses issues related to vertical barrier selection and positioning relative to the BHE array. Additionally, a systematic numerical analysis across various SBTES configurations is conducted, and design recommendations for vertical barriers are provided.

Chapter 6: The final chapter presents the conclusions drawn from the study and offers recommendations for future research studies. It synthesizes the findings and suggests potential areas for further exploration.

CHAPTER 2

Thermal Analysis of Borehole Thermal Energy Storage in Saturated Soil

2.1 Introduction

In this chapter, the thermal performance of soil borehole thermal energy storage (SBTES) systems installed in saturated soil is studied considering the first phase of heat injection. In particular, the sensitivity of BTES responses to various ground parameters under different SBTES design conditions is investigated. The ground parameters considered are soil thermal conductivity, specific heat capacity, total density, and initial ground temperature. The influence of these selected parameters on the thermal performance of SBTES is studied for different borehole heat exchanger (BHE) spacings and injection heat fluxes. The numerical simulations of SBTES system are performed with COMSOL Multiphysics® v. 5.6 (2019). The results are presented in terms of various performance indicators such as average temperature T_{avg} , heat stored Q_{stored} , temperature density TD , normalized energy storage NES .

2.2 Overview of existing studies on the analysis of SBTES system in saturated soil

Attaining a high thermal performance in SBTES is the primary objective that has been explored in numerous studies investigating the influence of ground, design, and operational parameters on the thermal performance of SBTES (Başer and McCartney, 2020; Moradi et al., 2015; Zhu and Chen, 2019). Boukelia et al., (2019) identified soil thermal conductivity, specific heat capacity, and thermal diffusivity as the soil properties that influence the thermal performance of SBTES. Skarphagen et al., (2019) identified BHE spacing, BHE depth, number of BHEs, and borehole arrangement as important design parameters that influence the thermal performance of SBTES. Baser and McCartney (2015) conducted a parametric evaluation to study the influence of soil thermal conductivity, BHE spacing, and the amount of heat injection on the thermal performance. Baser and McCartney (2015) found that a smaller BHE spacing yields a higher energy density in the BTES domain but increases the heat loss (Baser and

McCartney, 2015). Catolico et al., (2016) found that a low soil thermal conductivity enables superior heat recovery during the extraction phase. Zhu et al., (2019) conducted a global sensitivity analysis to observe the influence of the interaction between different design parameters on thermal performance of BTES system in soil and highlighted the importance of soil thermal conductivity and BHE spacing. Rosato et al., (2019) found that a high soil thermal conductivity has a positive effect on the thermal performance of SBTES. Nilsson and Rohdin (2019) emphasized the importance of detailed numerical analysis for selecting appropriate BHE spacing to achieve the desired thermal performance. Guo and Yang (2021) conducted parametric analysis of SBTES and found that a high thermal conductivity of soil provides an enhanced heat transfer in BTES but can also enhance thermal dissipation. Guo and Yang (2021) found that, for large-scale BTES applications, soils with high thermal conductivity and specific heat capacity should be preferred.

It is important to note that SBTES system comes with thermal performance challenges such as heat loss and low system efficiency (Sibbitt et al., 2012). Also, as discussed in Chapter 1, the challenges associated with thermal performance are more pronounced during the initial years of operation (Zhu et al., 2019). While the foregoing studies made significant contributions in advancing the understanding of SBTES system performance, the influence of soil parameters other than soil thermal conductivity remains largely unexplored. Specific heat capacity and total density are the other soil properties that may play important roles in thermal applications (Al-Shammary et al., 2020; Alnefaie and Abu-hamdeh, 2020; Abu-hamdeh and Reeder 2000). At the same time, the influence of soil properties under different SBTES design conditions are not well known (the existing studies are often constrained by narrow parameter ranges and site-specific considerations (Guo and Yang, 2021)).

To address the identified research gaps, the present study has two primary objectives related to the thermal performance of SBTES systems in fully saturated soil. First, the impacts

of selected thermal and physical soil parameters, such as soil thermal conductivity, specific heat capacity, total density, and initial ground temperature on the thermal performance of SBTES systems are investigated under various SBTES design conditions. For the design conditions, different BHE spacings and injection heat fluxes are considered. Four performance indicators, namely, average temperature T_{avg} , heat stored Q_{stored} , temperature density TD , normalized energy storage NES , are used to quantify the thermal performance of SBTES system. The second objective of this study is to provide recommendations on the most suitable performance indicators, based on their ability to accurately assess the thermal performance of the SBTES system.

2.3 Numerical analysis

2.3.1 Governing differential equation

In soil, heat transfer can happen by conduction, convection, vaporization, and condensation depending on the subsurface moisture content, hydraulic conductivity, degree of saturation, and thermal properties (Deru and Kirkpatrick, 2001; Farouki, 1981; Moradi et al., 2015, 2016). Commonly, conduction is adapted as the heat transfer mechanism in soil media (Baser and McCartney, 2015; Zhu et al., 2019; Zhu and Chen, 2019). Moradi et al., (2016) found that when soil sample reaches a saturation of 95%, the heat transfer takes place in pure conduction mode. Farouki (1981) mentioned that, as soil dry density and degree of saturation increases, the heat transfer process in soil is predominantly governed by pure conduction. In this study, a saturated soil condition with no ground water flow is considered. Thus, the heat transfer process is modeled as a purely conductive process.

The governing differential equation that describes the transient heat conduction process in the saturated soil is given by

$$\frac{\partial^2 T(x, y, z, t)}{\partial x^2} + \frac{\partial^2 T(x, y, z, t)}{\partial y^2} + \frac{\partial^2 T(x, y, z, t)}{\partial z^2} = \frac{\rho_b C_s}{\lambda} \frac{\partial T(x, y, z, t)}{\partial t} \quad (2.1)$$

where T is the absolute temperature, ρ_b is the total density of the soil (kg m^{-3}), C_s is the specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$), λ is the thermal conductivity of the soil ($\text{W m}^{-1} \text{K}^{-1}$), t is the time (s).

2.3.2 SBTES performance parameters

The SBTES performance is quantified in terms of average temperature T_{avg} of the domain, the total heat stored Q_{stored} in the domain, temperature density (TD) in the thermal storage volume, and normalized energy storage (NES). These metrics are used as performance indicators to assess the feasibility of the SBTES system. The average temperature is defined as

$$T_{\text{avg}} = \frac{1}{V} \int_V T(x, y, z) dx dy dz \quad (2.2)$$

where $T(x, y, z)$ is the temperature of the domain varying spatially in the x , y , and z directions and V is the volume of SBTES thermal storage domain (m^3) enclosed within the BHE array.

The heat stored Q_{stored} in the domain is given by

$$Q_{\text{stored}} = \rho_b C_s V (T_e - T_i) \quad (2.3)$$

where T_i is the initial temperature of SBTES ($^{\circ}\text{C}$), and T_e is the temperature of SBTES at the end of heat injection period ($^{\circ}\text{C}$). The temperature density (TD) is defined as

$$TD = \frac{T_{\text{avg}}}{V} \quad (2.4)$$

The normalized energy storage (NES) is defined as the ratio of heat stored (Q_{stored}) and total heat injected (Q_{injected}) in the SBTES domain (Başer and McCartney, 2015; Zhu and Chen, 2019). The total injected heat (Q_{injected}) and NES are given by

$$Q_{\text{injected}} = N_{\text{BHE}} \int_0^{t_i} Q dt \quad (2.5)$$

$$NES = \frac{Q_{\text{stored}}}{Q_{\text{injected}}} \quad (2.6)$$

where N_{BHE} is number of boreholes, Q is the injection heat flux applied at the BHE (Wm^{-1}), and t_i is the period of heat injection.

2.3.3 Problem description

The SBTES configuration considered in this study is a three-dimensional (3D) domain (of size $30 \times 30 \times 15 \text{ m}^3$) consisting of 9 BHEs of 10 m length, arranged in a rectangular pattern (Figure 2.1). The analysis domain is fully saturated with no groundwater flow. The size of the analysis domain is carefully chosen to minimize the boundary effects. Tetrahedral elements are used to discretize the domain. A mesh convergence study is conducted to ensure that the results are independent of mesh size. The element size is successively reduced until the average soil temperature T_{avg} in the SBTES domain reaches a stable value. Figure 2.2 describes the mesh convergence study performed over five successive iterations.

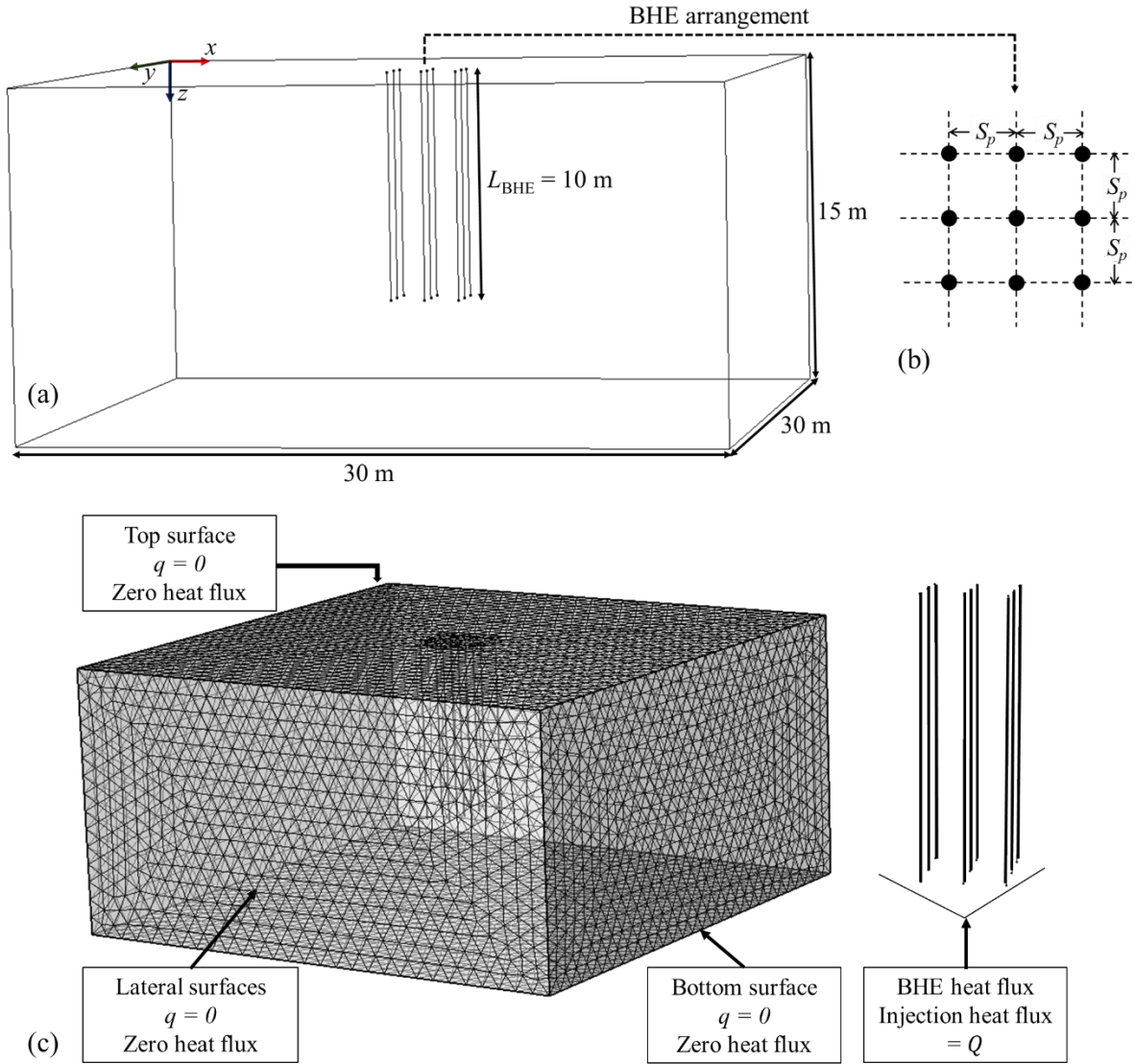


Figure 2.1: (a) Schematic of SBTES domain for numerical analysis, (b) BHE arrangement and spacing, and (c) 3D mesh for numerical analysis.

The soil properties used in this study are given in Table 2.1. The initial ground temperature of the domain is set at 10 °C (Hanova and Dowlatabadi, 2007). The thermal response resulting from the spatio-temporal variation of domain temperature, caused by seasonal surface temperature variation, is neglected by applying a zero-heat flux boundary condition at the top surface. The far-field vertical and bottom horizontal boundaries are set to zero heat flux conditions ensuring no heat transfer across the vertical and bottom boundaries. The heat transfer process from the BHE to the surrounding soil is simulated by modelling the

BHE as a line heat source with a constant injection heat flux (Wm^{-1}) emanating from the BHEs (Başer et al., 2016; Baser and McCartney, 2015; Erol and François, 2016).

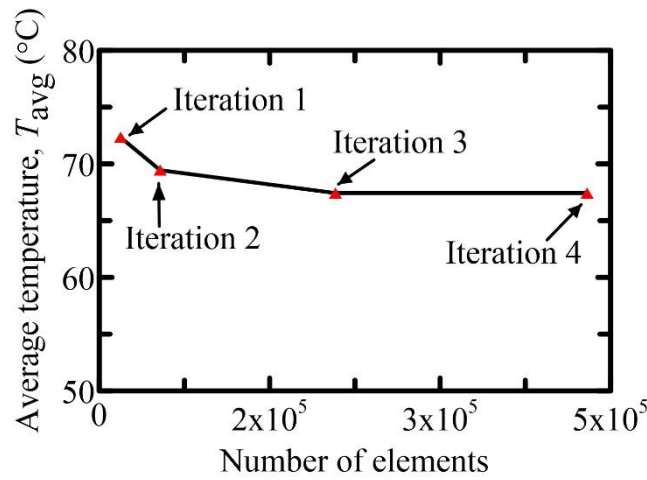


Figure 2.2: Mesh convergence study.

Table 2.1: Range of input parameters

Parameter	Range	Source
Thermal conductivity, λ ($\text{W m}^{-1} \text{K}^{-1}$)	0.5 – 5	Wang et al., (2021)
Specific heat capacity, C_s ($\text{J kg}^{-1} \text{K}^{-1}$)	700 – 3200	Wang et al., (2019)
Total density, ρ_b (kg m^{-3})	800 – 2050	Herder (2019); Xie et al., (2018)
Initial ground temperature, T_i (°C)	7 – 21	Williams and Gold (1976)
BHE spacing, S_p (m)	0.5 – 5	Zhu et al., (2019)
Injection heat flux, Q (W m^{-1})	10 – 100	Baser and McCartney (2015); Bristow and White (1994)

2.3.4 Analysis of SBTES

The influence of soil parameters on the thermal performance of SBTES is investigated during the first heat injection phase. The soil parameters selected for the parametric study are soil thermal conductivity λ , specific heat capacity C_s , total density ρ_b , and initial ground temperature T_i . These parameters are varied within the specified ranges as listed in Table 2.1. The first phase of heat injection is assumed to span over a duration of 150 days, during which a constant injection heat flux Q is applied to simulate the heat injection process. To assess the

influence of the selected parameters under various design conditions, the analysis is performed for different BHE spacing S_p and injection heat flux Q . The one-at-one (OAT) technique (Papaćanin, 2019) is adopted for the parametric study in which the effects of variation of one input parameter are studied one at a time with the remaining input parameters held constant at the default values listed in Table 2.2.

Table 2.2: Default values of input parameters

Parameter	Default value
Thermal conductivity, λ ($\text{W m}^{-1} \text{K}^{-1}$)	1.5
Specific heat capacity, C_s ($\text{J kg}^{-1} \text{K}^{-1}$)	1230
Total density, ρ_b (kg m^{-3})	1350
Initial ground temperature, T_i ($^{\circ}\text{C}$)	10
BHE spacing, S_p (m)	1.5
Injection heat flux, Q (W m^{-1})	30

2.4 Results

2.4.1 Verification

The accuracy of the present analysis is verified by comparing with the results obtained from the studies performed by Baser and McCartney (2015a, b). Baser and McCartney (2015a) evaluated the design and construction processes of SBTES systems using a series of numerical analyses and full-scale SBTES installation. A transient conductive heat transfer-based model was used to conduct a parametric analysis on five BHEs, and the influence of amount of heat injection and BHE spacings on soil temperature in SBTES domain was studied (Baser and McCartney 2015a). Figures 2.3(a)-(b) show the soil temperature distribution profiles for different heat injection cases and different BHE spacings, as obtained from the present study

and from Baser and McCartney (2015a). The match is well with the maximum difference being 4.3%.

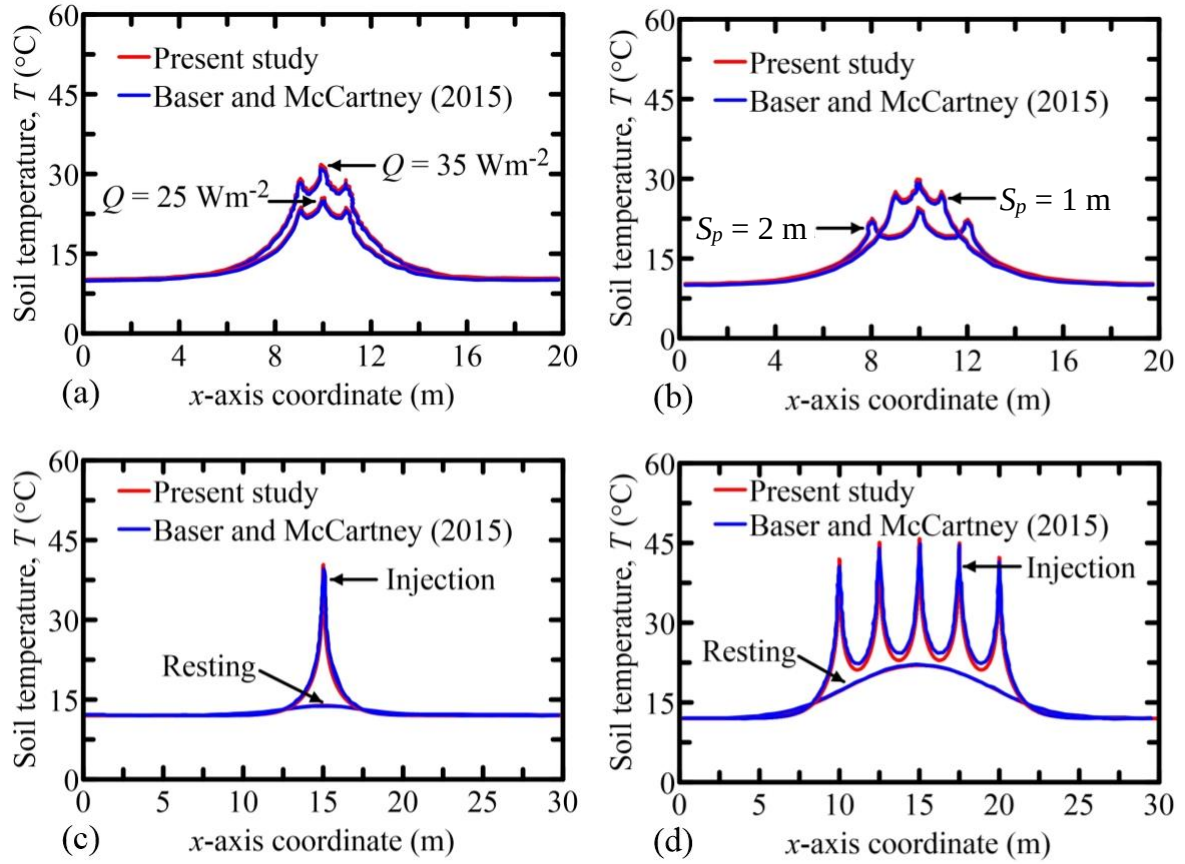


Figure 2.3: Comparison of soil temperature distribution profiles (a) for different heat injection rates, (b) BHE spacings, (c) for a single borehole at the end of injection and resting periods, and (d) for a thirteen borehole configuration at the end of injection and resting period.

Başer and McCartney (2015b) evaluated (with single and thirteen boreholes) the role of different array sizes on the performance of the SBTES systems focusing on different operational timelines, specifically at the end of heating and resting periods. Comparisons of the soil temperature distribution profiles obtained from the present study and from Baser and McCartney (2015b) at the end of resting period following the first heating phase are shown in Figures 2.3(c)-(d) for the BHEs with a single borehole and thirteen borehole configurations, respectively. The match is good with a maximum difference of 6.3%.

2.4.2 Influence of thermal conductivity

Figures 2.4(a)-(d) show the effect of thermal conductivity λ on the thermal performance of SBTES. The performance indicators are T_{avg} , Q_{stored} , TD , and NES plotted as functions of time for different soil thermal conductivities. The highest values of the performance indicators are observed in soils with the lowest thermal conductivity at the end of the first phase of heat injection. This observation highlights the preference for soils characterized by lower thermal conductivity, as they enable superior thermal performance for SBTES.

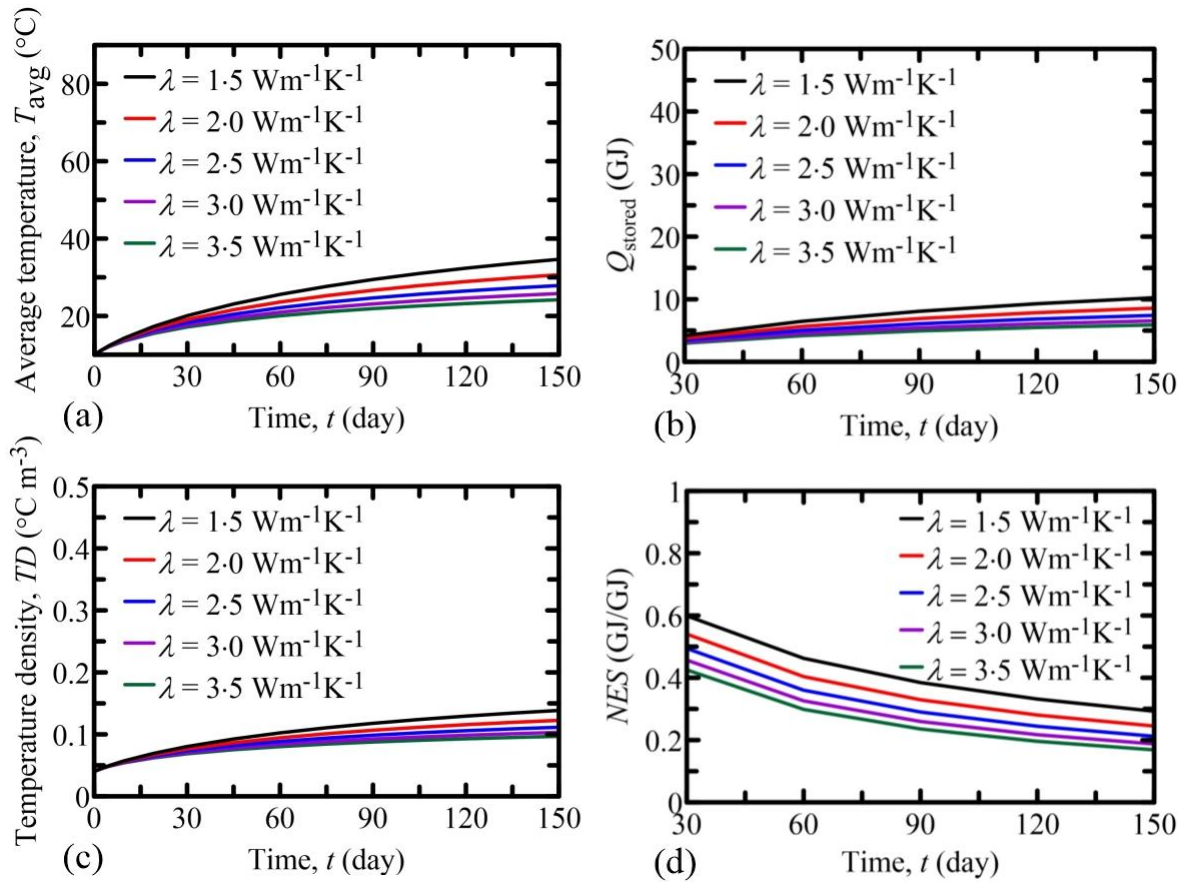


Figure 2.4(a)-(d): Performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES versus time during the first phase of heat injection for different soil thermal conductivity λ values. In this analysis, λ is varied while keeping other parameters fixed at the default value given in Table 2.2 to provide insights into the influence of soil thermal conductivity λ on SBTES performance.

Further investigation into the influence of thermal conductivity λ is carried out by varying the injection heat flux Q and BHE spacing S_p . Figure 2.5(a)-(d) show respectively T_{avg} , Q_{stored} , TD , and NES as functions of soil thermal conductivity λ for different injection heat

fluxes at the end of first phase of heat injection ($t = 150$ days). The results show a direct correlation between a higher injection heat flux and greater T_{avg} , Q_{stored} , and TD . Interestingly, NES is unaffected by changes in Q . Figure 2.6 shows the performance indicators as functions of thermal conductivity under various BHE spacings. Closely spaced BHEs resulted in a substantial increase in T_{avg} and TD . Higher values for Q_{stored} and NES are observed for widely spaced BHEs. This observation can be attributed to the enhanced thermal storage volume achieved with widely spaced BHEs, resulting in higher Q_{stored} . The greater thermal storage volume associated with widely spaced BHEs led to lower TD . Interestingly, in spite of a decrease in T_{avg} and TD with an increase in soil thermal conductivity, these performance indicators exhibit relative independence from soil thermal conductivity when BHEs are widely spaced. Furthermore, the gain in T_{avg} is significantly lower for SBTES domains with widely spaced BHEs compared to that for closely spaced BHEs. This is attributed to the enhanced thermal dissipation in the widely spaced BHE domains, which hinders heat accumulation. In contrast, closely spaced BHEs enable heat accumulation.

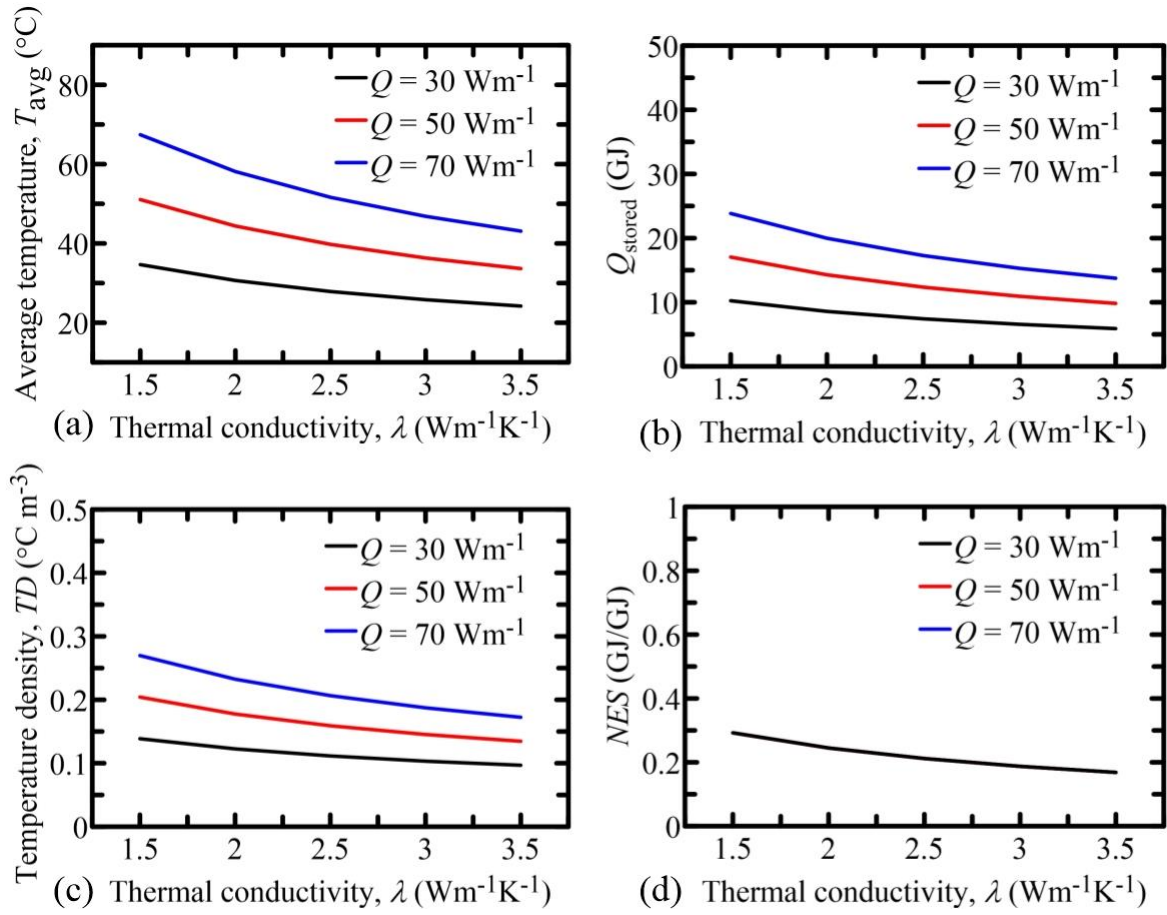


Figure 2.5(a)-(d): Thermal performance of SBTES as a function of soil thermal conductivity λ . The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES are investigated as a function of λ after the first phase of heat injection (at $t = 150$ days). Analyses are conducted under different injection heat flux Q while keeping all other parameters fixed at the default values (Table 2.2). This analysis provides insights into the influence of soil thermal conductivity λ on the performance indicators under different injection heat flux Q .

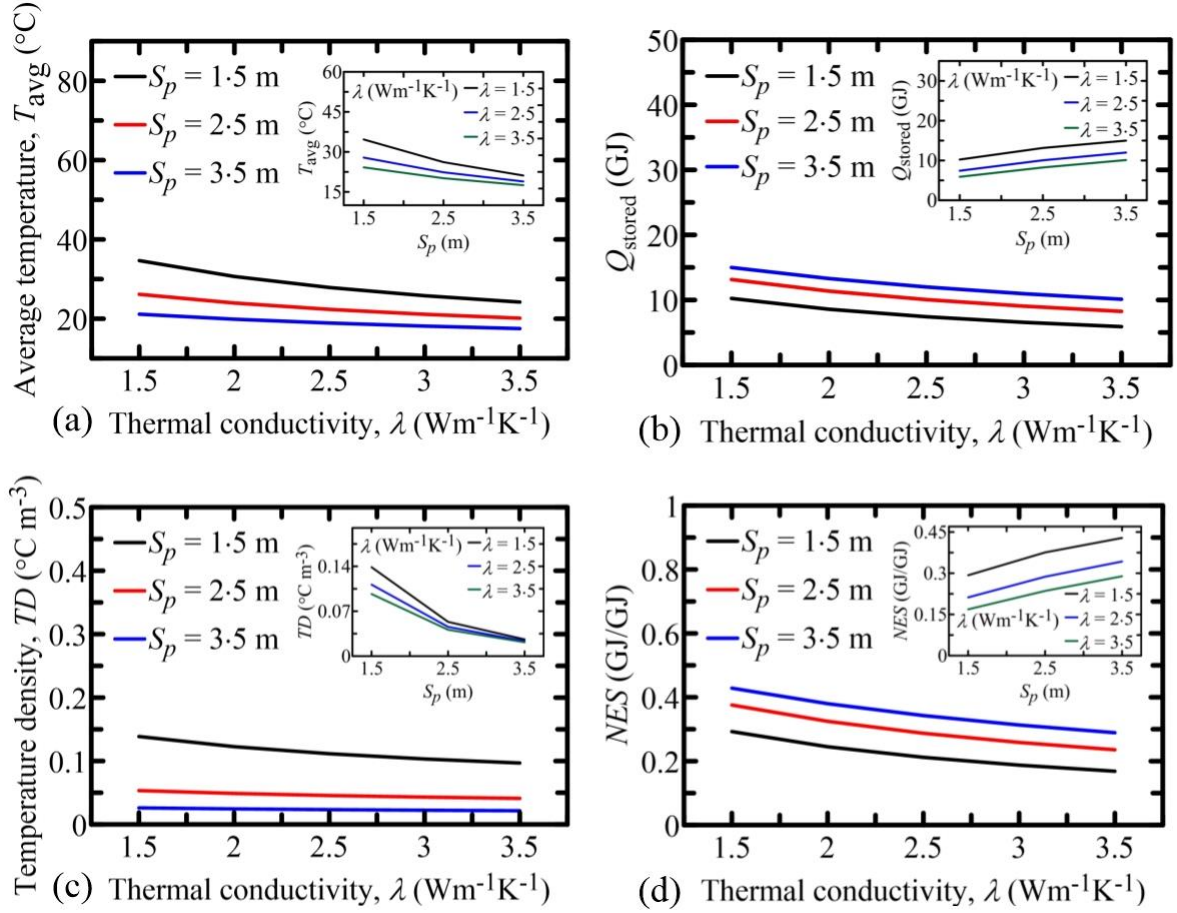


Figure 2.6(a)-(d): Thermal performance of SBTES as a function of soil thermal conductivity λ . The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES are plotted as functions of λ after the first phase of heat injection (at $t = 150$ days). Analyses are conducted for different values of BHE spacing S_p while keeping all other parameters fixed at their default values (Table 2.2). The figures provide insights into the influence of soil thermal conductivity λ on the performance indicators under different BHE spacings.

2.4.3 Influence of specific heat capacity

Figures 2.7(a)-(d) show the results of numerical simulations conducted to investigate the influence of specific heat capacity C_s on thermal performance of SBTES. In these analyses, specific heat capacity of soil is systematically varied while keeping other parameters constant. In Figures 2.7(a)-(d), performance indicators are plotted as functions of time for different soil specific heat capacities. At the end of the first phase of heat injection, the lowest specific heat capacity soil exhibits the highest values for T_{avg} and TD . The highest values for Q_{stored} and NES are observed in soils characterized by the highest specific heat capacities. Therefore, while

soils with low specific heat capacities contribute to higher T_{avg} , those with higher specific heat capacities provide superior heat storage capacity, a favourable attribute for efficient SBTES system.

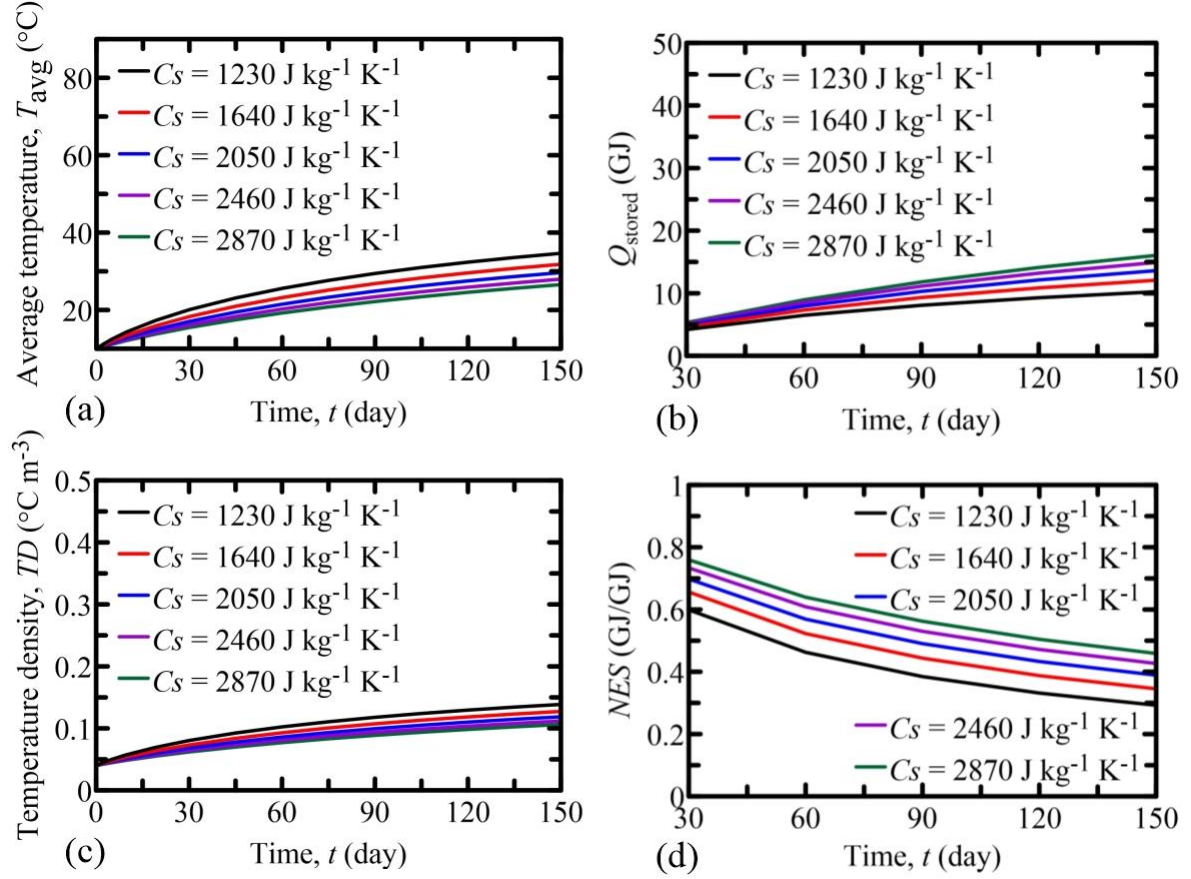


Figure 2.7(a)-(d): Performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES versus time during first phase of heat injection for different values of specific heat capacity C_s of soil. In this analysis C_s is varied while keeping the other parameters fixed at their default values (Table 2.2) to provide insights into the influence of specific heat capacity C_s of soil on SBTES performance.

To further investigate the influence of C_s under varying design conditions, analyses are carried out by varying the injection heat flux Q and BHE spacing S_p . Figures 2.8(a)-(d) show the performance indicators as functions of specific heat capacity of soil C_s for different injection heat fluxes Q . The results show a direct correlation between injection heat flux and T_{avg} , Q_{stored} , and TD , while NES remained unaffected by the changes in Q . Figures 2.9(a)-(d) show the performance indicators as functions of specific heat capacity C_s under various BHE

spacings. Closely spaced BHEs resulted in a substantial increase in T_{avg} and TD . Conversely, in accordance with earlier observations regarding BHE spacing, higher values for Q_{stored} and NES are observed for widely spaced BHEs because of the larger thermal storage volume they have. Again, T_{avg} and TD exhibit relative independence from the specific heat capacity of soil when BHEs are widely spaced.

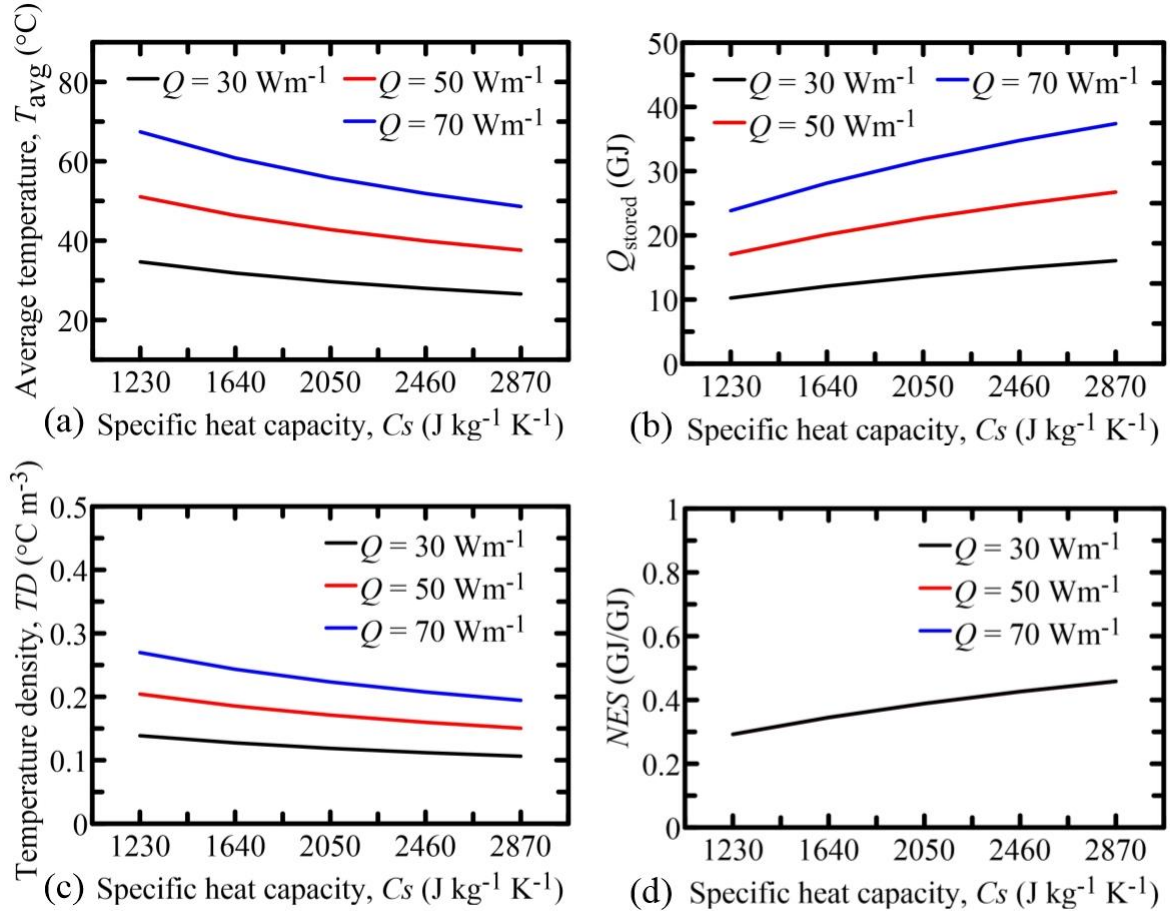


Figure 2.8(a)-(d): Thermal performance of SBTES as a function of specific heat capacity C_s of soil. The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES are plotted as functions of C_s after the first phase of heat injection (at $t = 150$ days). Analyses are conducted under different injection heat flux Q values keeping all the other parameters fixed at their default values (Table 2.2). This analysis provides insights into the influence of specific heat capacity of soil on the performance indicators under different injection heat flux Q .

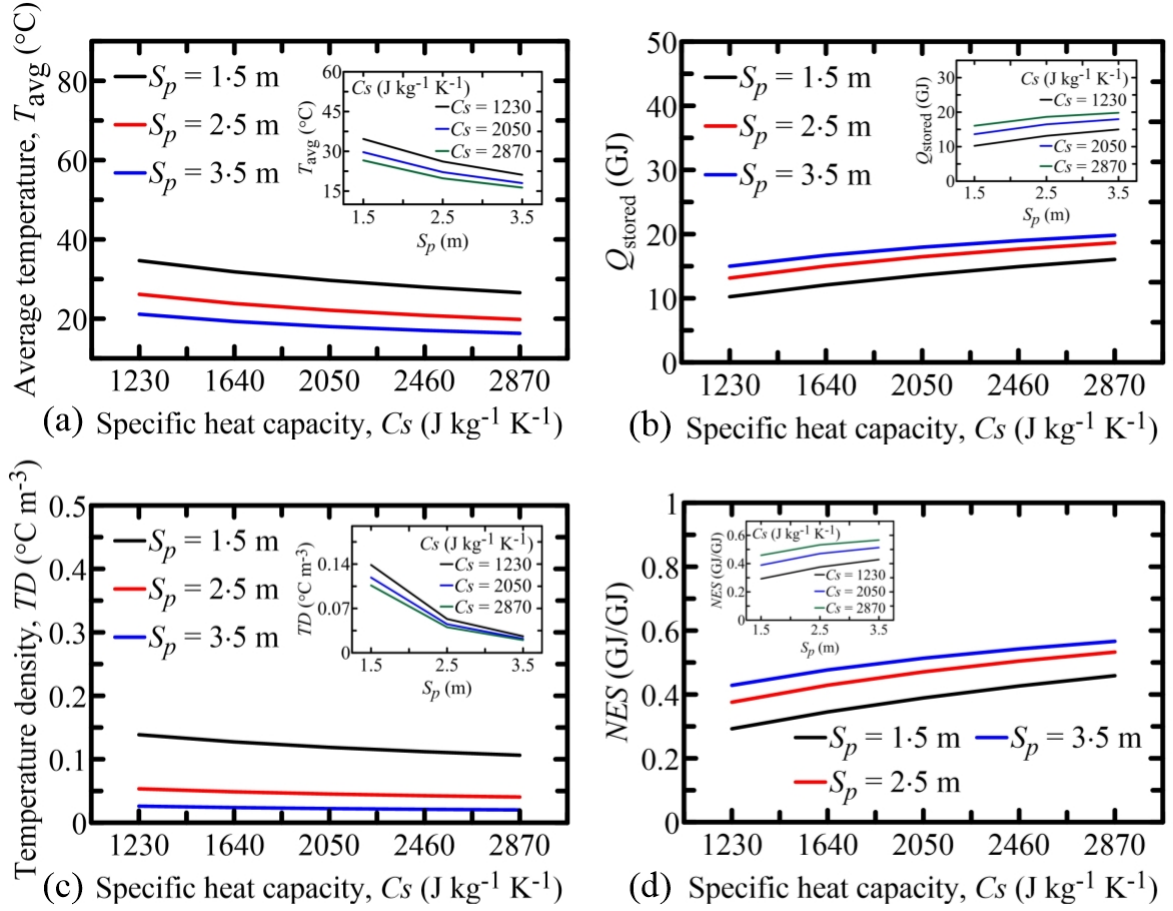


Figure 2.9(a)-(d): Thermal performance of SBTES as a function of specific heat capacity C_s of soil. The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES are plotted as functions of C_s after the first phase of heat injection (at $t = 150$ days). Analyses are conducted under different BHE spacing S_p values while keeping all other parameters fixed at their default values (Table 2.2). This analysis provides insights into the influence of specific heat capacity of soil on the performance indicators under different BHE spacing S_p .

2.4.4 Influence of total density

Figures 2.10(a)-(d) show the influence of soil total density ρ_b on the thermal performance of SBTES. The performance indicators are plotted as functions of time for different soil total densities. In these analyses, total density of soil is systematically varied while keeping the other parameters constant. At the end of the first phase of heat injection, the soil with the lowest total density exhibits the highest values for T_{avg} and TD . Highest values for Q_{stored} and NES are observed in soils characterized by the highest total density. Therefore,

while soils with low total density contribute to higher T_{avg} , those with higher total density provide superior heat storage capacity.

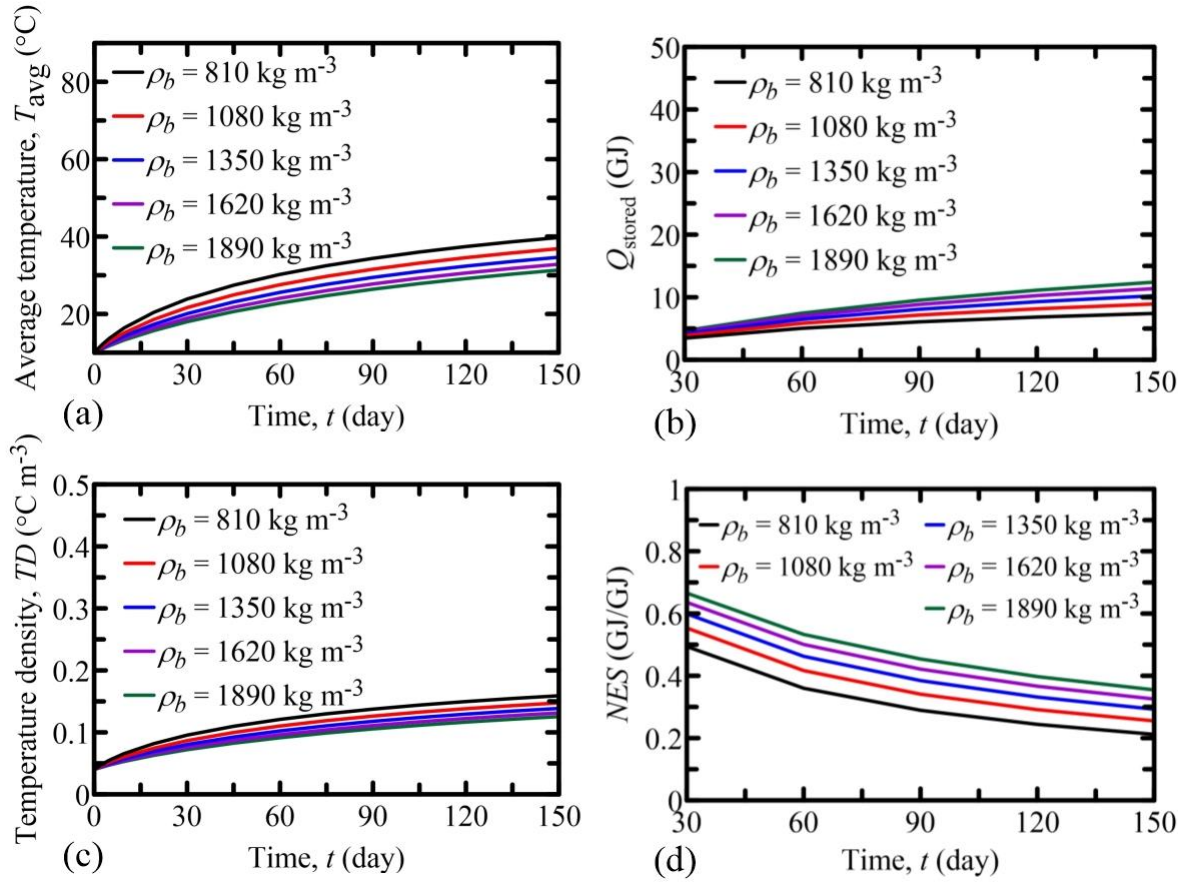


Figure 2.10(a)-(d): Performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES versus time for different values of soil total density ρ_b during the first phase of heat injection. In this analysis ρ_b is varied while keeping the other parameters fixed at their default values (Table 2.2) to provide insights into the influence of soil total density ρ_b on SBTES performance.

To further investigate the influence of total density under varying design conditions, analyses are carried out by varying the injection heat flux Q and BHE spacing S_p . Figures 2.11(a)-(d) show the performance indicators as functions of total density of soil for different injection heat fluxes. The results show a direct correlation between higher injection heat flux and greater values for T_{avg} , Q_{stored} and TD , while NES remains unaffected. Figures 2.12(a)-(d) show the performance indicators as functions of total density under different BHE spacings. Closely spaced BHEs resulted in a substantial increase in T_{avg} and TD . Conversely, in accordance with earlier observations regarding BHE spacing, higher values for Q_{stored} and NES

are observed for widely spaced BHEs, attributed to the larger thermal storage volume they have. T_{avg} and TD exhibit relative independence from total density of soil when BHEs are widely spaced.

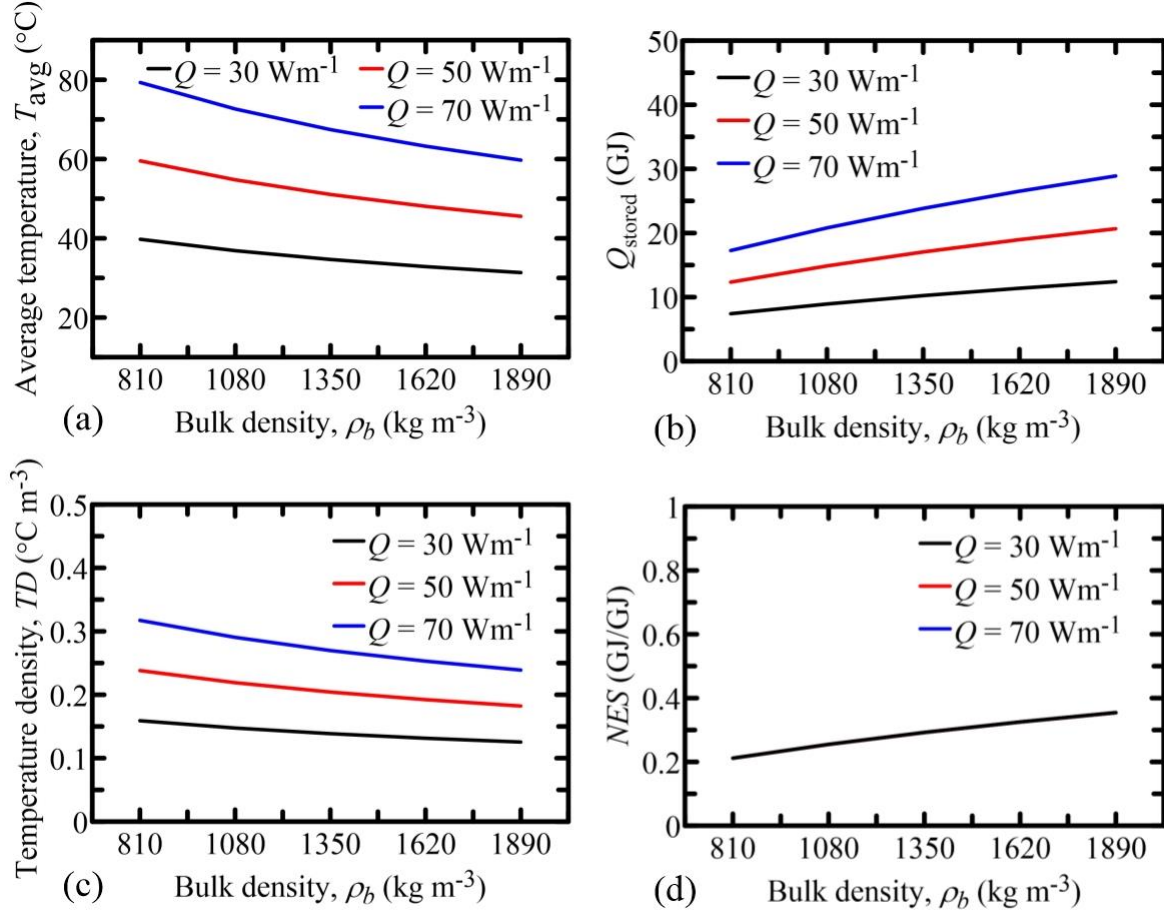


Figure 2.11(a)-(d): Thermal performance of SBTES as a function of soil total density ρ_b . The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES are plotted as functions of ρ_b after the first phase of heat injection (at $t = 150$ days). Analyses are conducted under different injection heat flux Q values while keeping all the other parameters fixed at their default values (Table 2.2). This analysis provides insights into the influence of soil total density on the performance indicators under different injection heat flux Q .

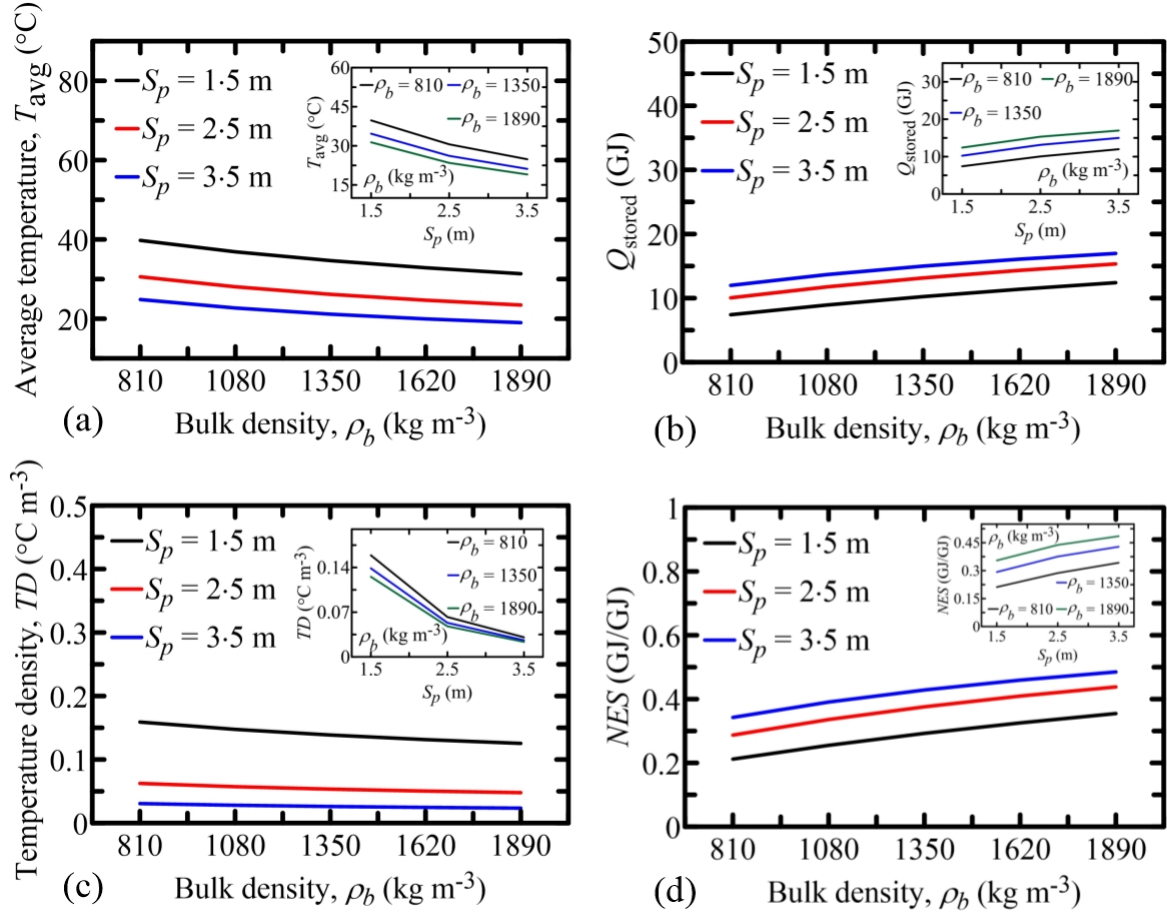


Figure 2.12(a)-(d): Thermal performance of SBTES as a function of soil total density ρ_b . The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES as a function of ρ_b after the first phase of heat injection (at $t = 150$ days). Analyses are conducted under different BHE spacing S_p values while keeping all the other parameters fixed at their default values (Table 2.2). This analysis provides insights into the influence of soil total density on the performance indicators under different BHE spacings.

2.4.5 Influence of initial ground temperature

Figures 2.13(a)-(d) show the effect of initial ground temperature T_i on the thermal performance of SBTES. The performance indicators are plotted as functions of time for different initial ground temperature. The initial ground temperature T_i is systematically varied while keeping other parameters constant. The highest initial ground temperature results in the highest values for T_{avg} , Q_{stored} , TD , and NES at the end of the first phase of heat injection.

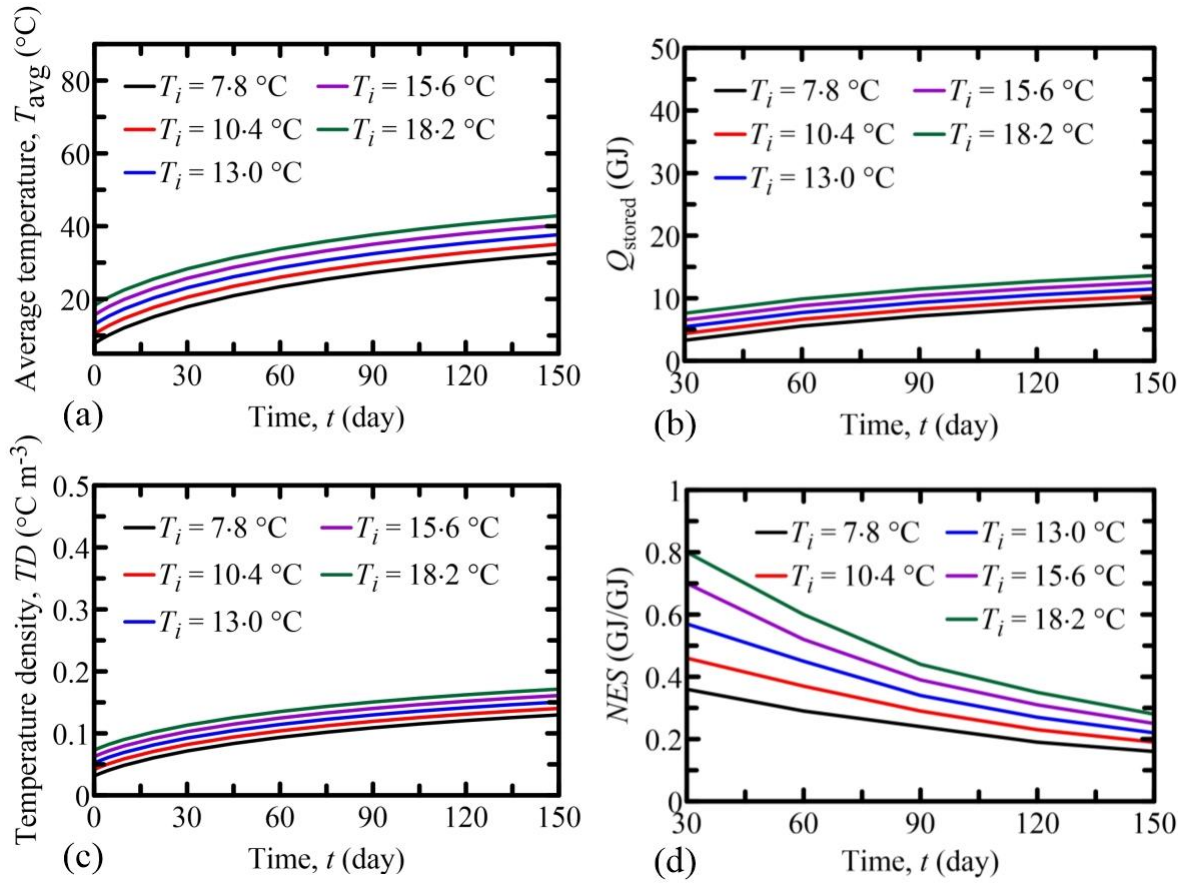


Figure 2.13(a)-(d): Performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES versus time during the first phase of heat injection for different values of initial ground temperature T_i . In this analysis T_i is varied while keeping other parameters fixed at their default values (Table 2.2) to provide insights into the influence of initial ground temperature T_i on SBTES performance.

Furthermore, to investigate the influence of initial ground temperature T_i under varying design conditions, analyses are carried out by varying the injection heat flux Q and BHE spacing S_p . Figures 2.14(a)-(d) show the performance indicators as functions of initial ground temperature T_i of soil for different injection heat fluxes. The results show a direct correlation between higher injection heat flux and greater values for T_{avg} , Q_{stored} , and TD , while NES remains unaffected by changes in injection heat flux. Figures 2.15(a)-(d) show the performance indicators as functions of initial ground temperature T_i under different BHE spacings. Closely spaced BHEs resulted in a substantial increase in T_{avg} and TD . Similar to earlier observations regarding BHE spacing, higher values for Q_{stored} and NES are observed for widely spaced

BHEs, attributed to the larger thermal storage volume they have. Only TD exhibits relative independence from initial ground temperature T_i of soil when BHEs are widely spaced.

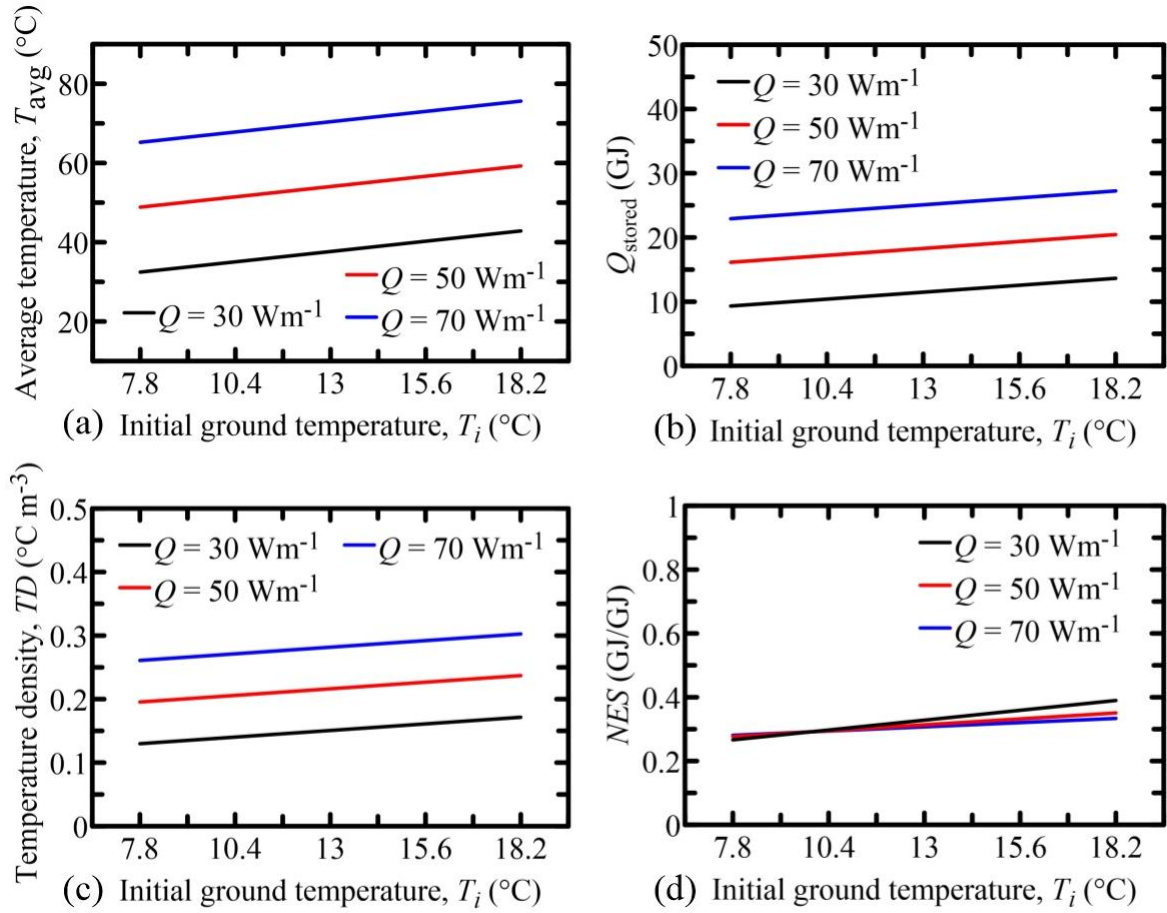


Figure 2.14(a)-(d): Thermal performance of SBTES as a function of initial ground temperature T_i . The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES as a function of T_i after the first phase of heat injection (at $t = 150$ days). Analyses are conducted under different injection heat flux Q values while keeping all other parameters fixed at their default values (Table 2.2). This analysis provides insights into the influence of initial ground temperature on the performance indicators under different injection heat flux Q .

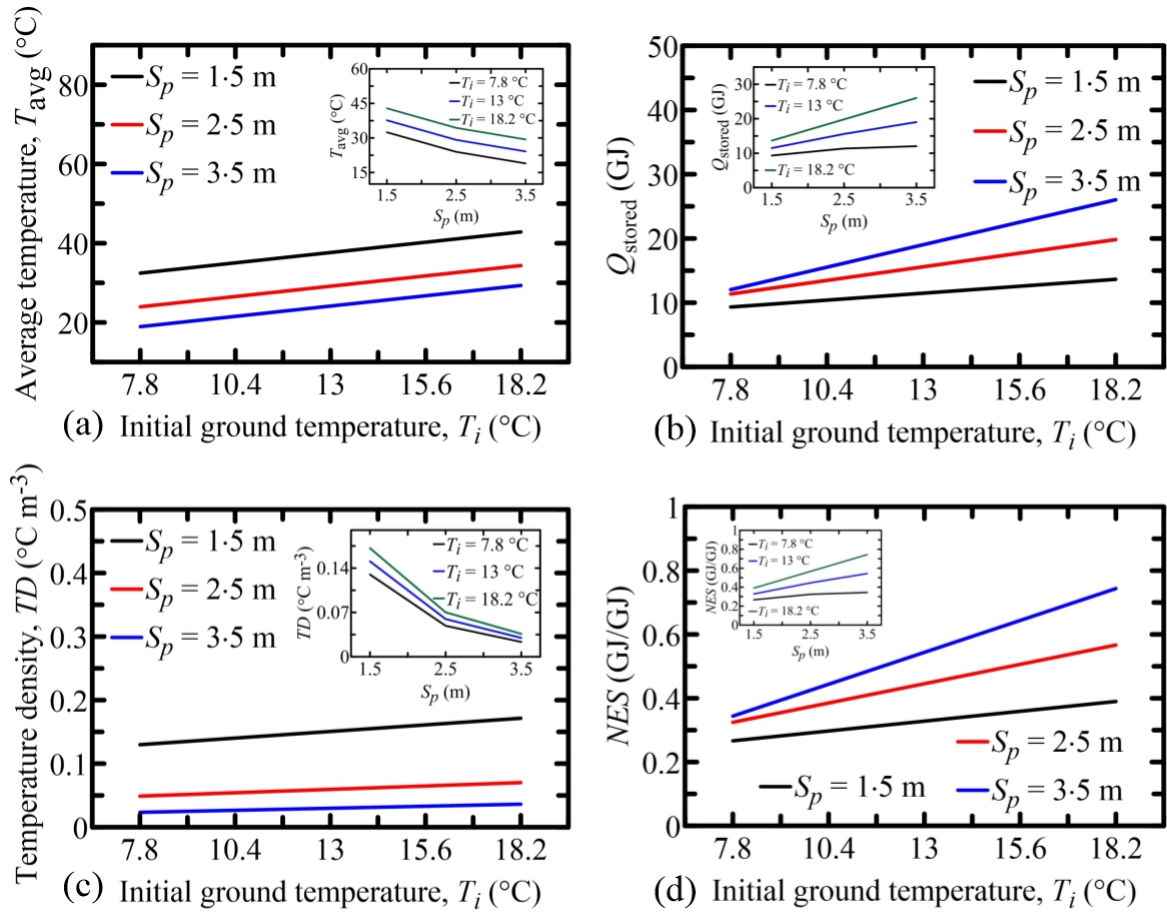


Figure 2.15(a)-(d): Thermal performance analysis with respect to initial ground temperature T_i . The performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES as a function of T_i after the first phase of heat injection (at $t = 150$ days). Analyses are conducted under different BHE spacing S_p values while keeping all the other parameters fixed at their default values (Table 2.2). This analysis provides insights into the effect of initial ground temperature on the performance indicators under different BHE spacing S_p .

2.4.6 Parametric sensitivity analysis

To determine the parameters with the most substantial influence on the performance indicators, an analysis is performed to assess the percentage change in performance indicators corresponding to a percentage change in the parameters. Figures 2.16(a)-(d) show that the most substantial influence on T_{avg} , resulting in the largest variation of nearly 25%, is caused by soil thermal conductivity λ . Subsequently, T_{avg} is influenced, in descending order, by specific heat capacity C_s , total density ρ_b , and initial ground temperature T_i , yielding percentage variations of approximately 17%, 15%, and 13%, respectively, in response to a 40% variation in these

parameters. Similarly, for Q_{stored} , soil thermal conductivity λ is the parameter with the most significant influence, leading to a substantial variation of approximately 37%. It is closely followed by total density ρ_b , responsible for a 27% variation, and specific heat capacity C_s , contributing to a 24% variation in Q_{stored} . Initial ground temperature T_i induces an 18% variation in Q_{stored} . Notably, the percentage variation trends in TD and NES are identical to those observed for T_{avg} and Q_{stored} , respectively. This indicates that a comprehensive understanding of thermal performance can be effectively attained by the exclusive evaluation of T_{avg} and Q_{stored} , as TD and NES do not provide additional insights for performance evaluation within the context of parametric analysis.

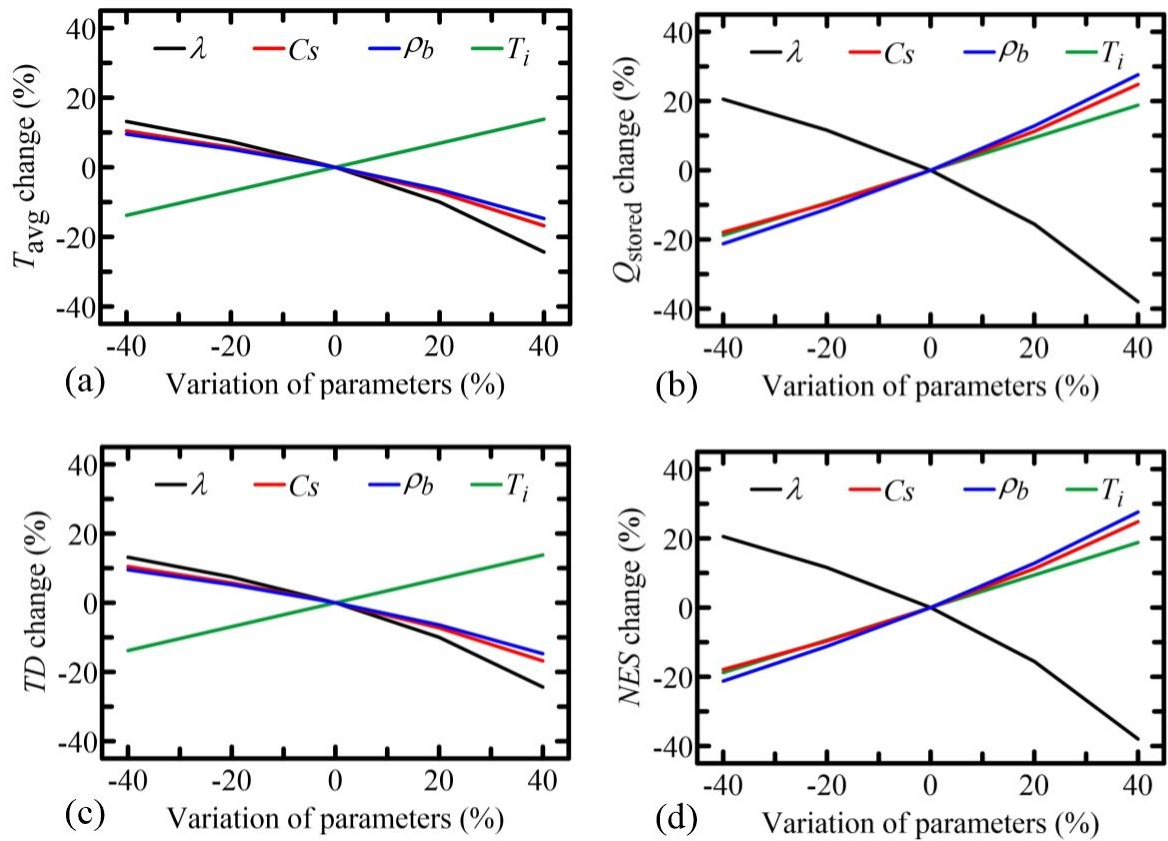


Figure 2.16(a)-(d): Result of parametric sensitivity analysis. The percentage changes in performance indicators (a) T_{avg} , (b) Q_{stored} , (c) TD , and (d) NES are presented in response to a percentage variation in each parameter studied.

2.5 Conclusions and limitations

In this chapter, the influence of selected soil parameters, namely thermal conductivity λ , specific heat capacity C_s , total density ρ_b , and initial ground temperature T_i on the thermal performance of SBTES are studied under different design conditions considering different BHE spacings S_p and different injection heat fluxes Q . The performance indicators used to assess the SBTES performance are T_{avg} , Q_{stored} , TD , and NES .

Findings from this study highlight the importance of the influence of ground parameters on SBTES thermal performance under different design scenarios. It is observed that a lower soil thermal conductivity provides enhanced thermal performance, resulting in higher values of T_{avg} , Q_{stored} , TD , and NES . Higher specific heat capacity C_s results in lower T_{avg} however it provides enhanced Q_{stored} . Similarly, lower total density provides higher values of T_{avg} , but low Q_{stored} . Higher initial ground temperature T_i enables enhanced T_{avg} , Q_{stored} , TD , and NES . Moreover, the significance of BHE spacing S_p and injection heat flux Q in designing SBTES systems is investigated. The study indicated that widely spaced BHEs promoted enhanced temperature distribution within a larger thermal volume. On the other hand, closely spaced BHEs are associated with increased heat loss due to enhanced heat accumulation. These findings suggest that the thermal performance corresponding to ground parameters can significantly vary under different design scenarios and therefor requires careful evaluation in the SBTES design process.

In the performance indicators used to assess the thermal performance of SBTES system, T_{avg} and Q_{stored} stand out as a reliable performance indicator, providing a clear understanding of the thermal performance of SBTES system. The results from parametric analysis show that TD and NES do not provide substantial insights into the thermal performance of SBTES. Furthermore, there are instances where TD and NES inaccurately represent the thermal performance of SBTES. For instance, TD appears to be unaffected by changes in ground

thermal and physical parameters when BHE are widely spaced within the SBTES domain. However, this observation can be attributed to the significantly increased thermal storage volume associated with the widely spaced BHE, resulting in notably reduced TD values. Moreover, the variation of NES with time for all studied cases (Figures 2.4(d), 2.7(d), 2.10(d), and 2.13(d)) shows a consistent reduction in NES over time. In a time-dependent study, both the numerator (Q_{stored}) and denominator (Q_{injected}) components of the NES vary temporally, leading to less reliable results. Therefore, TD and NES are less effective as performance indicators compared to T_{avg} and Q_{stored} , which provide more reliable assessments of SBTES performance. Therefore, in subsequent chapters, T_{avg} and Q_{stored} will be used for the evaluation of the thermal performance of SBTES systems.

It is essential to acknowledge the limitations of the present study. Saturated soil conditions and pure conduction heat transfer are assumed, which do not represent all real-world scenarios characterized by variations in subsurface moisture conditions, groundwater flow, and associated heat transfer mechanisms. Limiting the study to pure conduction heat transfer in saturated soil narrowed down the parameters under investigation. However, this approach doesn't cover the full range of soil-related parameters that can influence SBTES performance. Furthermore, the study is only conducted for the first phase of heat injection, whereas SBTES systems operate for years with heat injection-extraction cycle. Additionally, the present study is conducted within a theoretical framework wherein one parameter is varied while keeping other parameters fixed. This approach assists in understanding the effects of the selected parameter under investigation. However, such an approach can lead to parameter combinations that may not exist in practical scenarios. It is also possible that strong correlations exist between different variables, and simultaneous variations may occur in a practical scenario. Therefore, solely varying one parameter while holding others constant may not reflect the realistic conditions accurately. In summary, while valuable insights into the influence of soil parameters

on SBTES thermal performance for saturated soil condition are provided by this study, these findings should be considered within the context of these limitations. Subsequent chapters are designed to address these limitations and refine the existing understanding of SBTES system.

CHAPTER 3

Thermal analysis of Borehole Thermal Energy Storage in Unsaturated Soil

3.1 Introduction

In this chapter, the thermal performance of SBTES system in unsaturated soil is investigated. This covers evaluation of diverse subsurface conditions that potentially influence the thermal performance of SBTES, ultimately leading to more precise portrayal of subsurface conditions. To achieve this, three primary objectives are focused on: (1) to explore the impact of subsurface moisture content condition on the SBTES thermal performance, (2) to assess the effect of seasonal surface pressure variation on the SBTES thermal performance, and (3) to examine the influence of soil porosity on the thermal performance of SBTES in homogeneous and layered soils. By addressing these objectives, this study aims to augment the existing knowledge on the thermal performance of BTES systems in unsaturated soil.

3.2 Overview of existing studies on the thermal analysis of SBTES system in unsaturated soil

Researchers continue to explore methods of enhancing the thermal efficiency of SBTES systems, which is influenced by BTES design parameters (such as borehole spacing, depth, and arrangement), ground material parameters (such as soil thermal conductivity, volumetric heat capacity, hydraulic conductivity, density, porosity, and moisture content), and operating parameters (such as injection-extraction heat fluxes and time-period) (Wołoszyn, 2020). Many researchers have recognized the unsaturated soil in the vadose zone as a favorable medium to install SBTES systems (McCartney et al., 2013; Reuss et al., 1997; Wang and Qi, 2011). The idea of storing heat in the vadose zone is based on the existing understanding of the correlation between unsaturated soil-specific hydraulic properties and soil thermal properties, particularly under non-isothermal conditions. From the early 20th century, various studies have examined the coupled nature of heat and mass transfer in unsaturated soils under non-isothermal

conditions (Boyoucos, 1915; Philip and De Vries, 1957; Smith, 1943). Such unsaturated soil-specific heat- and mass-transfer phenomena are expected to have an influence on the thermal response of BTES when installed in unsaturated soil in the vadose zone. The suggestion of installing SBTES in unsaturated soil in the vadose zone is based on the idea of exploiting the heat and mass transfer processes in unsaturated soil to increase the thermal storage capacity of the SBTES system (McCartney et al., 2013).

A range of field, experimental, and numerical studies have been conducted to develop an in-depth understanding of the role of unsaturated hydraulic and thermal properties on the thermal performance of SBTES systems. Reuss et al., (1997) conducted an experimental study with a single borehole installed in unsaturated soil sample and associated numerical studies considering coupled heat- and mass-transfer in unsaturated soil domains to develop a design of a pilot BTES system. Although the numerical model in Reuss et al., (1997) did not account for the dependency of thermal parameters such as soil thermal conductivity on the subsurface hydraulic conditions, the numerical and experimental results provided insights into the role of moisture content in unsaturated soil on the heat-transfer process and, thus, laid a strong foundation for the study of BTES in unsaturated soils. Wang and Qi (2011) studied the performance of BTES in unsaturated soils with the help of an experimental setup consisting of a single borehole installed in an unsaturated soil sample and provided strong evidence of the importance of the initial moisture content of unsaturated soil on the complex heat transfer in BTES. Moradi et al., (2016) conducted a comprehensive numerical and experimental study on heat and mass transfer in unsaturated soil that provided valuable insights into the thermal response of multi-borehole BTES system in unsaturated soil. The study highlighted the significance of the degree of saturation in driving the different heat transfer mechanism within the soil domain. Additionally, the research suggested that to accurately analyze the BTES performance in unsaturated soil, it is essential to consider the dependence of soil thermal

conductivity on the degree of saturation (Moradi et al., 2016). Moradi et al., (2015) also explored the influence of soil porosity, saturated hydraulic conductivity, and soil thermal conductivity on the thermal response of SBTES for a short operational period of seven days. The results indicated that soil porosity and saturated hydraulic conductivity do not have significant effects on temperature, while soil thermal conductivity is an important factor that significantly affects the temperature achieved in BTES after heat injection. Catolico et al., (2016) have investigated the influence of intrinsic permeability of soil on the performance of BTES in unsaturated soil and the results showed that a higher intrinsic permeability condition gives rise to lateral heat loss for saturated soils, while providing improved heat transfer in the soil domain for unsaturated conditions. Behbehani and McCartney (2022) investigated the thermal performance of BTES in dry, saturated, and unsaturated soils with varying moisture content through a combination of numerical and experimental analysis. The study focused on the impact of different groundwater table levels (i.e., depths of saturated zone), particularly in the case of unsaturated soil, and different water retention parameters on the SBTES thermal performance over a period of five years. While the study did not take into account the effect of different soil thermo-hydraulic and physical parameters, it nonetheless yielded insights regarding the influence of the depth of the saturated zone and of water retention parameters on the temperature and heat stored in the SBTES (Behbehani and McCartney, 2022). Başer and McCartney (2020) conducted experimental and numerical studies on closely spaced BTES in unsaturated soil with consideration of the impact of seasonal fluctuations of the ambient temperature on the surface of SBTES. The study captured the coupled effect of variation of thermal and hydraulic parameters in the BTES domain as a result of heating and cooling on the thermal response of BTES in unsaturated soil. To minimize the effect of seasonal temperature fluctuation on thermal performance of SBTES, Başer et al., (2016) studied the performance of

SBTES in unsaturated soil domains with and without surficial insulation conditions and showed that the stored heat is higher in SBTES when surface insulation on top is present.

The foregoing literature review reveals several significant research gaps that require further investigation. Previous studies have focused on assessing the thermal performance of SBTES systems under varying moisture content conditions in unsaturated soil, taking into account different water retention parameters. However, there is limited understanding of the role of soil porosity on the thermal performance of SBTES in unsaturated soil, particularly under long-term operation scenarios. Furthermore, the existing studies have predominantly examined homogeneous soil conditions and have not accounted for soil stratification, which is contrary to real-world field situations. No studies have considered the effect of a wide range of soil porosities arising from soil stratification within the thermal energy storage domain. Additionally, while some studies have explored the impact of seasonal climatic fluctuations, such studies have primarily focused on seasonal surface temperature variations only (Başer and McCartney, 2020). The effect of surface pressure variations, induced by factors like evapotranspiration, groundwater table fluctuations, and other climatic conditions, have not been investigated (Ito et al., 2022). Several studies have found the significant role of surface pressure variations on subsurface moisture content and other hydraulic properties (Ahmed et al., 2018; Fredlund, 2006; Mabirizi and Bulut, 2011; Totoev and Kleeman, 1998).

To address the identified research gaps, the present study has three primary objectives related to the thermal performance of BTES systems in unsaturated soil. First, the thermal behavior of SBTES systems is investigated under various subsurface moisture conditions, encompassing fully dry, fully saturated, and varying moisture content scenarios with different depths of the saturated soil zone. Second, the impact of seasonal surface pressure variation on the thermal performance of the BTES system is examined in unsaturated soil. For this, a study is conducted by selecting a variable moisture content subsurface condition in the unsaturated

soil which is subjected to seasonal surface pressure variations applied to the upper surface of the SBTES system. Third, the role of soil porosity under different soil stratifications and soil moisture conditions on the thermal performance of the BTES system in unsaturated soil is investigated. Thus, this study augments the existing knowledge on the thermal performance of BTES systems in unsaturated soil.

3.3 Numerical analysis

3.3.1 Governing thermo-hydraulic processes and differential equations

The SBTES system is simulated in this study using COMSOL Multiphysics® v. 5.6 (2019) with a coupled heat and mass transfer model (Başer et al., 2019) quantified in terms of a set of differential equations, which are described in this section. The governing differential equation for heat transfer in soil (porous medium) is given by (Başer et al., 2019; Nield and Bejan, 2008)

$$\left(\rho C_p\right)\left(\frac{\partial T}{\partial t}\right)+\nabla \cdot\left(\left(\rho C_p\right)_w u_w T-(\lambda \nabla T)\right)=Q_s \quad (3.1)$$

where ρ is the density of soil (kg m^{-3}), C_p is the effective volumetric heat capacity of soil ($\text{J m}^{-3} \text{K}^{-1}$), u_w is the velocity of groundwater flow in the saturated domain (m s^{-1}), λ is the effective thermal conductivity of soil ($\text{W m}^{-1} \text{K}^{-1}$), T is the absolute temperature (K), and Q_s is the heat source ($\text{J m}^{-3} \text{s}^{-1}$). The ground above the saturated zone is considered unsaturated and moisture content in this part is modeled using Richards' equation given by (Richards', 1931)

$$\phi\left(\frac{dS_w}{dP_c}\right)\left(\frac{\partial \rho_w P_c}{\partial t}\right)+\nabla \cdot\left[\left(-\frac{\rho_w k_{rw} k_{int}}{\mu_w}\right)(\nabla P_w+\rho_w g)\right]=-Q_m \quad (3.2)$$

where ϕ is the porosity of soil, S_w is the degree of saturation of soil, ρ_w is the density of water (kg m^{-3}), μ_w is the dynamic viscosity of water (Pa s), P_c is the capillary pressure in unsaturated soil (Pa), P_w is the pore-water pressure (Pa), k_{int} is the intrinsic permeability of soil (m^2), k_{rw} is the relative permeability of water, g is the acceleration due to gravity ($\text{m}^2 \text{s}^{-1}$), and Q_m is the

mass source ($\text{kg m}^{-3} \text{ s}^{-1}$), which is assumed to be zero in this study. The relative permeability k_{rw} and degree of saturation S_w are respectively quantified in the simulations using the van Genuchten-Mualem and van Genuchten models (van Genuchten, 1980) given by

$$k_{rw}(S_w) = \begin{cases} K_0 S_w^{1/2} \left[1 - (1 - S_w^{n/n-1})^{1-1/n} \right]^2 & P_c \leq 0 \\ K_0 & P_c > 0 \end{cases} \quad (3.3)$$

$$S_w(P_c) = \begin{cases} \left[\frac{1}{1 + (\alpha P_c)^n} \right]^{1-1/n} & P_c \leq 0 \\ 1 & P_c > 0 \end{cases} \quad (3.4)$$

where K_0 is the saturated hydraulic conductivity of soil (m s^{-1}), and α and n are empirical, fitted parameters. The degree of saturation S_w is related with volumetric water content θ , residual water content θ_r , and saturated water content θ_s as

$$S_w = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (3.5)$$

The thermal properties of soil are also dependent on soil moisture content (Farouki, 1981; Moradi et al., 2015). To establish quantitative relationships between soil moisture content and thermal parameters, the models proposed by Lu and Dong (2015) and Başer et al., (2018) are respectively used for effective thermal conductivity λ and effective volumetric heat capacity C_p as

$$\frac{\lambda - \lambda_{\text{dry}}}{\lambda_{\text{sat}} - \lambda_{\text{dry}}} = 1 - \left[1 + \left(\frac{S_w}{S_f} \right)^m \right]^{\frac{1}{m-1}} \quad (3.6)$$

$$\frac{C_p - C_{p,\text{dry}}}{C_{p,\text{sat}} - C_{p,\text{dry}}} = 1 - \left[1 + \left(\frac{S_w}{S_f} \right)^m \right]^{\frac{1}{m-1}} \quad (3.7)$$

where λ_{dry} and λ_{sat} are the dry and saturated thermal conductivities of soil ($\text{W m}^{-1} \text{ K}^{-1}$), respectively, S_f is a soil saturation parameter defined at the onset of funicular regime, m is a

fitted parameter, and $C_{p,dry}$ and $C_{p,sat}$ are the dry and saturated volumetric heat capacities of soil ($J m^{-3} K^{-1}$), respectively.

3.3.2 SBTES performance parameters

For the thermal analysis, the average temperature T_{avg} of soil thermal storage domain, soil temperature distribution in SBTES domain, and heat stored Q_{stored} are used to analyze the SBTES thermal performance. The average temperature is defined as

$$T_{avg} = \frac{1}{V} \int_V T(x, y, z) dx dy dz \quad (3.8)$$

where $T(x, y, z)$ is the temperature of the domain varying spatially in the x , y , and z direction and V is the volume of SBTES thermal storage domain (m^3). The heat stored Q_{stored} in the domain is given by

$$Q_{stored} = \rho C_p V (T_e - T_i) \quad (3.9)$$

where T_i is the initial temperature of SBTES ($^{\circ}C$), and T_e is the temperature of SBTES at the end of annual heat injection-extraction cycle ($^{\circ}C$).

3.3.3 Problem description

The present study examines the thermal performance of a SBTES system using a three-dimensional (3D) domain (of size $150 \times 80 \times 80 m^3$) composed of 23 boreholes of 35 m length, with a center-to-center distance of 2.25 m, as shown in Figure 3.1. The soil thermo-hydraulic properties used in this study are given in Table 3.1 (Başer et al., 2016). The initial ground temperature of the domain is set at $12^{\circ}C$ (Majorowicz et al., 2009).

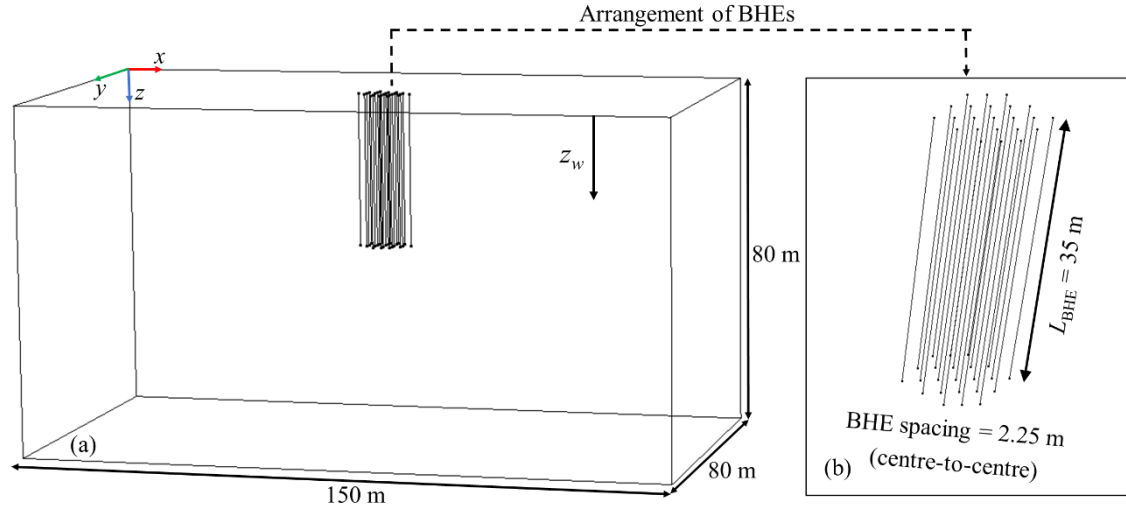


Figure 3.1: (a) SBTES domain geometry, and (b) BHE arrangement and dimensions.

Table 3.1: Soil thermal, hydraulic, and physical parameters

Parameter	Value and Unit
Dry thermal conductivity (λ_{dry})	$0.67 \text{ W m}^{-1} \text{ K}^{-1}$
Saturated thermal conductivity (λ_{sat})	$1.68 \text{ W m}^{-1} \text{ K}^{-1}$
Dry volumetric heat capacity ($C_{p,\text{dry}}$)	$1.25 \text{ MJ m}^{-3} \text{ K}^{-1}$
Saturated volumetric heat capacity ($C_{p,\text{sat}}$)	$2.60 \text{ MJ m}^{-3} \text{ K}^{-1}$
Porosity (ϕ)	0.40
Saturated water content (θ_s)	$0.40 \text{ (m}^3/\text{m}^3\text{)}$
Residual water content (θ_r)	$0.08 \text{ (m}^3/\text{m}^3\text{)}$
Density of soil (ρ)	2650 kg m^{-3}
Density of water (ρ_w)	1000 kg m^{-3}

The size of the domain is selected after careful consideration to minimize the boundary effects. To ensure the independence of the results from the mesh size, a mesh convergence study is performed. The mesh is discretized using tetrahedral elements with a total of 173,034 elements. The mesh is refined around the boreholes, with a minimum element size of 0.03 m, while the maximum element size of 5.25 m is employed at the far-field boundaries.

The heat transfer process from the HCF to the surrounding soil is complex and dynamic with variations in inlet and outlet fluid temperatures over time and along the depth of the BHE (Jia et al., 2023). To save on computation time, the injection and extraction processes in the

BHEs are simulated with the BHE modelled as a line heat source. The heat transfer from HCF is simulated by applying a time varying heat flux (Wm^{-1}) at the BHEs (Başer et al., 2016a; Başer and McCartney, 2015; Erol and François, 2016; Shao et al., 2016). The initial hydraulic condition of the soil, such as volumetric water content, is determined for the selected depth of groundwater table or saturated zone (z_w) using the van Genuchten water retention model.

To address the first objective, five different cases are considered with different subsurface soil moisture conditions: case 1 – fully dry condition with degree of saturation $S_w = 0$, case 2 – varying moisture content with the groundwater table (or saturated zone) depth $z_w = 17.5$ m (z_w is half the borehole length), case 3 – varying moisture content with the groundwater table (or saturated zone) depth $z_w = 35$ m (z_w is at the base of the boreholes), case 4 – varying moisture content with the groundwater table (or saturated zone) depth $z_w = 80$ m, and case 5 – fully saturated condition with $z_w = 0$ m and $S_w = 1$. The saturated zone depths ($z_w = 17.5$ m, 35 m, 80 m) are defined in the domain with a total vertical span of 80 m and BHE length L_{BHE} of 35 m to represent scenarios where half of the BHE array is situated in unsaturated (or partially saturated) soil and half is in saturated soil ($z_w = 17.5$ m), the entire BHE array is situated in unsaturated soil with the saturated zone present at the base of the BHE array ($z_w = 35$ m), and the entire domain is in an unsaturated state with the saturated zone positioned well below the BHE array ($z_w = 80$ m). This selection of saturated zone depths allows moisture content reduction in the domain systematically with successive reduction in the depth of the saturated zone, enabling an in-depth investigation of the impact of subsurface moisture conditions on the thermal performance of the SBTES system. It is essential to recognize that, in reality, the saturated zone depth undergoes dynamic variations due to seasonal effects. The defined subsurface moisture conditions in the present study are intentionally not specific to any particular location, rather they simulate an engineered subsurface system to cover a diverse range of subsurface moisture conditions.

To address the second objective, case 3 is selected and is subjected to a surface pressure variation condition. In this case the entire BTES domain is in unsaturated soil with groundwater table z_w located at the base of the boreholes. Mitchell (1980) proposed a sinusoidal function to model the seasonal variation of suction pressure at the ground surface. Based on typical surface pressure amplitude data recorded by Ito et al., (2022), a sinusoidal function is used in this study to model the temporal variation of surface suction pressure as

$$P_{w,surface} = 180 - 165 \cos \pi \left(\frac{2t}{365} + \frac{1}{2} \right) \text{ (kPa)} \quad (3.10)$$

where t is time in days. By applying $P_{w,surface}$ as a boundary condition on the ground surface, its effects on the subsurface thermo-hydraulic properties and overall thermal performance of SBTES are explored.

To address the third objective, the influence of soil porosity on the thermal performance of the BTES system under different soil moisture conditions is investigated for cases 1-5 described above. Further, how soil porosity impacts SBTES performance under varying surface pressure is also investigated. Moreover, to explore the impact of soil porosity resulting from soil stratification, the study considers different soil stratification scenarios, as described in Figure 3.2. Soil layering cases L0-L6 with porosity ranging over 0.3-0.5 and with different layer thicknesses are considered in the study. For the base case L0 comprising a homogeneous soil deposit, an average porosity of 0.4 is assumed.

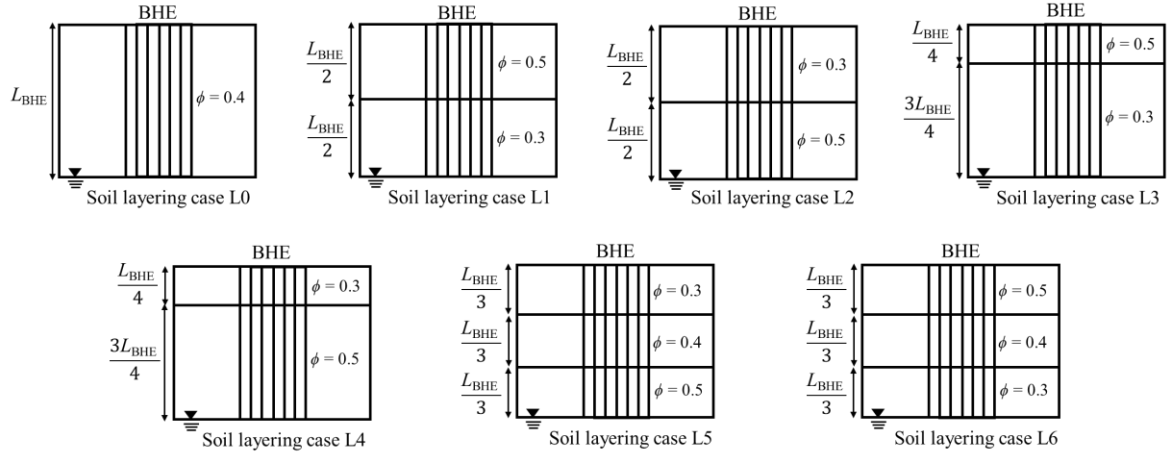


Figure 3.2: Vertical cross-section through the mid-domain parallel to the x - z plane showing the different soil stratification cases considered in this study. The figure shows the precise configuration of soil layering, illustrating the variations in soil porosity within each layer.

The heat injection and extraction scheme is maintained the same for all the subsurface conditions studied, as shown in Figure 3.3 (injected heat is denoted by $Q_{\text{injection}}$ and extracted heat is denoted by $Q_{\text{extraction}}$). The input $Q_{\text{injection}}$ and $Q_{\text{extraction}}$ vary with time (Figure 3.3). The SBTES domain is heated for 210 days (heat injection period) followed immediately (without any resting time) by heat extraction for 155 days (heat extraction period), and this cycle of heat injection and extraction (spanning over a total of 365 days) is repeated over a period of 5 years. The assumed temporal variations of $Q_{\text{injection}}$ and $Q_{\text{extraction}}$ (Figure 3.3) are typical of what can be expected under real field conditions. A fixed $Q_{\text{injection}}-Q_{\text{extraction}}$ scheme ensures that the study focuses on the effects of subsurface moisture conditions, surface pressure variation, and porosity and that the resulting differences in the observed performance indicators obtained for the different cases are not influenced by the input heat injection-extraction scheme.

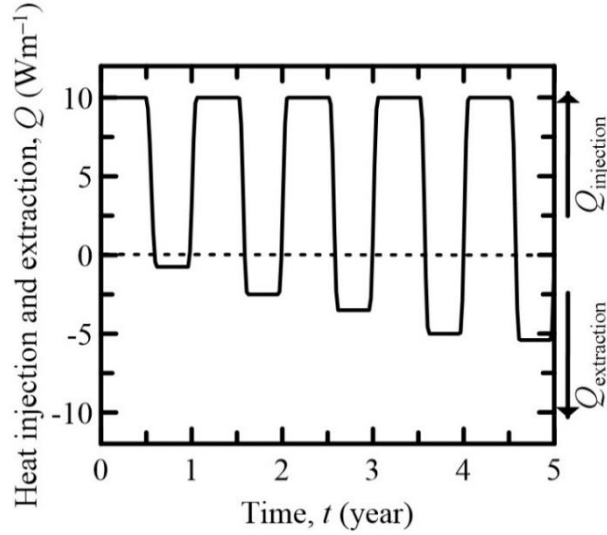


Figure 3.3: Annual heat injection-extraction scheme considered in this study.

3.4 Results

3.4.1 Verification and validation

A verification study is performed by comparing the results obtained from the present analysis with those by Başer et al., (2016) who performed numerical and field studies on a SBTES system in unsaturated soil. Figure 3.4(a) shows, for the soil deposit considered by Başer et al., (2016), a comparison of the volumetric water content θ profiles with depth z obtained by solving equation (3.2) in COMSOL and by Başer et al., (2016). Figure 3.4(a) confirms that the hydraulic part of the present simulation framework produces accurate results. Figure 3.4(b) shows the soil temperature profiles with depth obtained from the present analysis and from Başer et al., (2016) for days 1 and 90. As evident, the match in Figure 3.4(b) is good and shows that the thermal part of the present simulation framework produces accurate results.

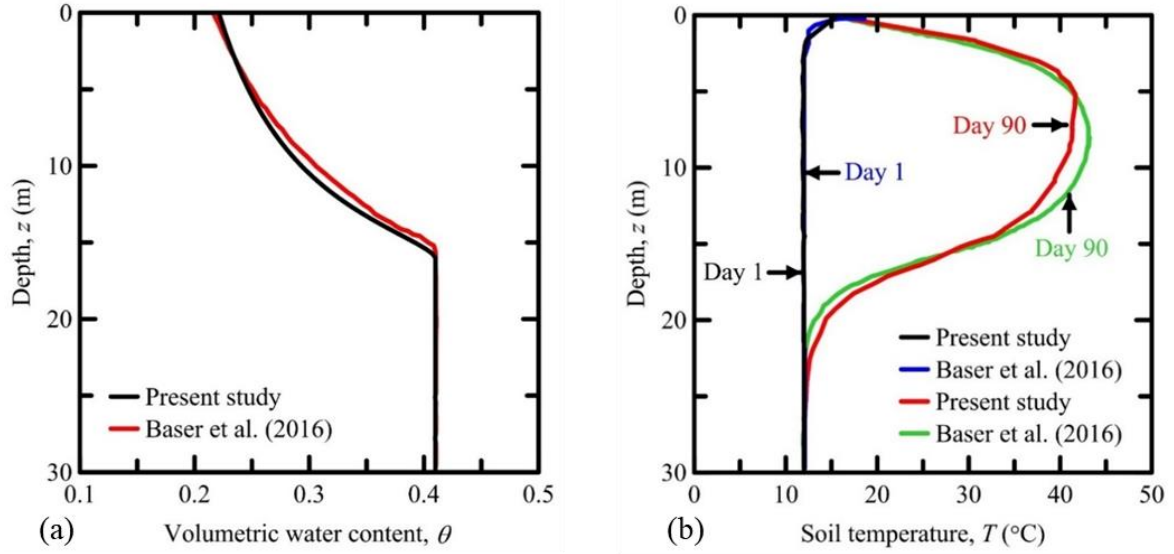
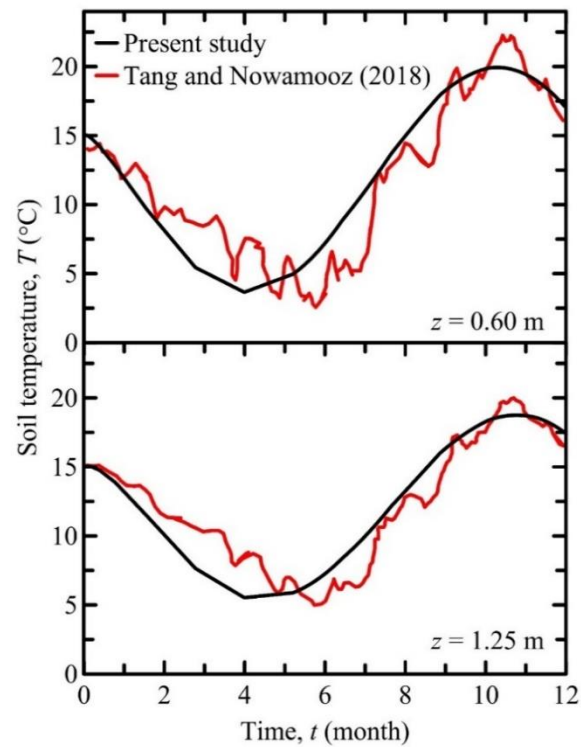


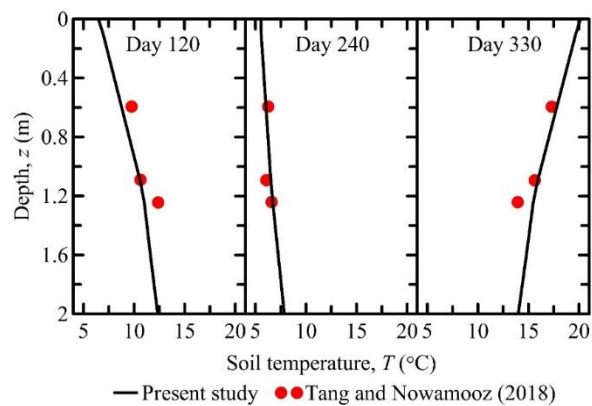
Figure 3.4: Results of verification studies: (a) volumetric water content profile and (b) soil temperature profiles for day 1 and day 90.

A field-scale study on borehole thermal behavior by Tang and Nowamooz (2018) is used for validating the applicability of the present numerical model. Tang and Nowamooz (2018) performed in-situ measurements in the Alsace region to capture the subsurface thermo-hydraulic response of unsaturated soil when used as a medium to install BHEs. Thermal probes were installed at various depths in the investigated area to monitor the subsurface temperature variation over time. The soil profile at the site has seven horizontal layers with varying thicknesses (ranging from 0.1 m to 11 m) and four different soil types (clay loam, sandy loam 1, loam, and sandy loam 2). To assess the effect of seasonal surface temperature variation on the subsurface thermal response, Tang and Nowamooz (2018) also recorded the seasonal surface temperature variation at the site. In the present study, the numerical model incorporates the same field conditions described by Tang and Nowamooz (2018), including the seasonal surface temperature variation as a surface boundary condition, the variation of subsurface thermo-hydraulic properties in unsaturated soil, and the variations in ground properties associated with the multi-layered soil condition. The recorded thermal responses from the installed thermal probes are used to validate the numerical model. Figure 3.5(a) shows the

ground temperatures at depths $z = 0.6$ m and 1.25 m over a period of twelve months as obtained from field data collected using thermal probes and from the present numerical study. Figure 3.5(b) shows the temperature profiles with depth z at 120 days, 330 days, and 440 days, as obtained from the field thermal probes and present simulations. It is evident that the present numerical framework produces reasonably accurate results and can appropriately represent field conditions.



(a)

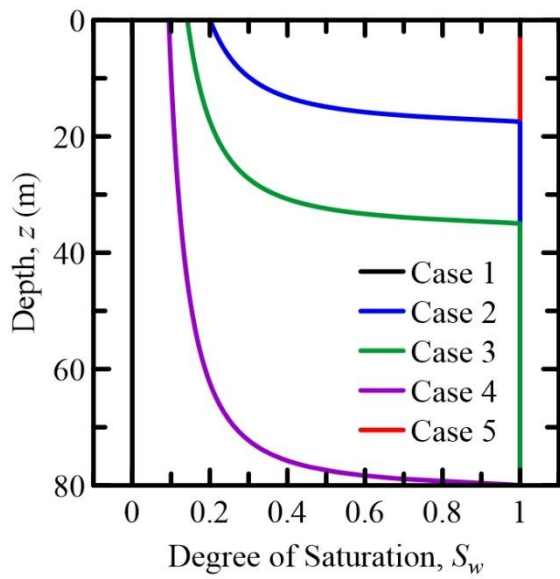


(b)

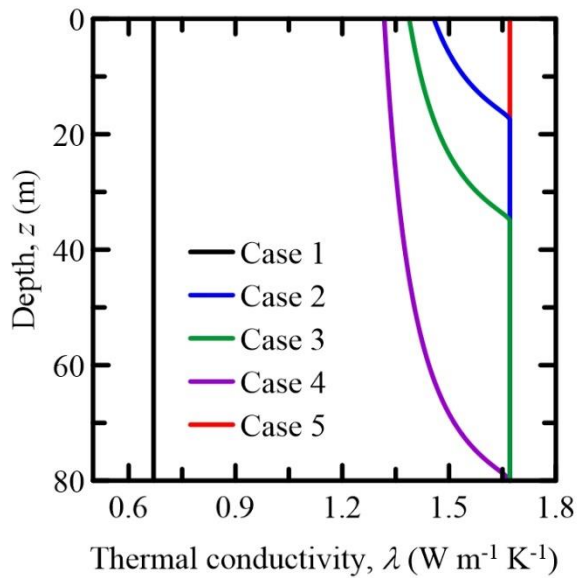
Figure 3.5: Validation study showing (a) soil temperature over 12 months at depths of 0.60 m and 1.25 m, and (b) soil temperature with depth at different days.

3.4.2 Effect of subsurface moisture conditions

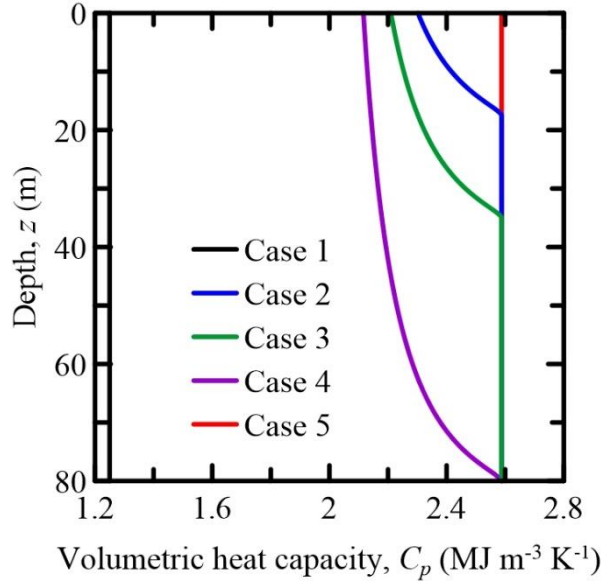
For the subsurface moisture content cases 1-5 assumed in this study, the degree of saturation S_w profiles within the SBTES domain are shown in Figure 3.6(a). This figure demonstrates the hydrostatic variation of S_w over the domain for fully dry, fully saturated, and varying moisture content subsurface conditions. Figures 3.6(b) and 3.6(c) respectively show the corresponding spatial distributions of subsurface thermal properties such as soil thermal conductivity λ and volumetric heat capacity C_p .



(a)



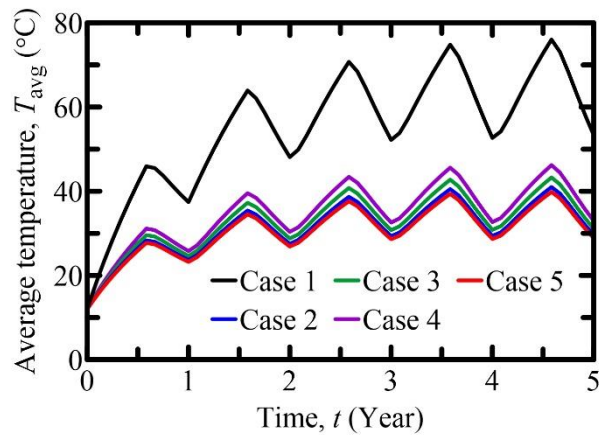
(b)



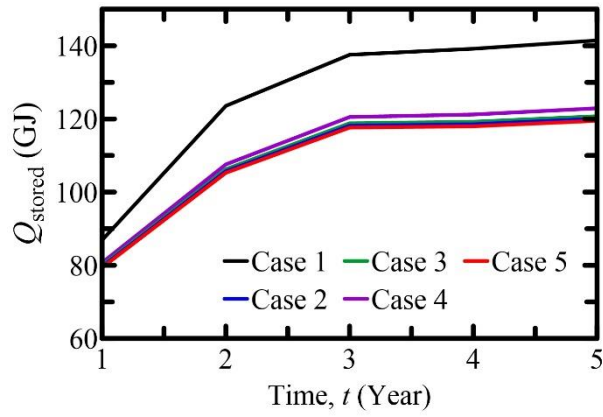
(c)
Figure 3.6: Spatial variations of (a) degree of saturation S_w , (b) thermal conductivity λ , and (c) volumetric heat capacity C_p with depth z calculated from coupled thermo-hydraulic analysis.

Figure 3.7(a) shows the variation of average temperature T_{avg} with time for different subsurface moisture conditions (cases 1-5) investigated. The results show that the highest average soil temperature T_{avg} is achieved for the SBTES installed in dry soil (case 1). As the moisture content of the subsurface increases from fully dry to fully saturated conditions, the T_{avg} of SBTES reduces, and the minimum temperature is observed for the fully saturated soil domain (case 5). A similar trend is observed for heat stored Q_{stored} , as shown in Figure 3.7(b). The temperature distribution along the x -axis at mid-depth of SBTES after one year of operation is shown in Figure 3.7(c) for cases 1-5. Highest temperature is recorded for fully dry soil (case 1) and the temperature decreases as the moisture content increases. This is attributed to the dependence of thermal conductivity on moisture content. For the fully dry condition, the soil lacks moisture leading to low thermal conductivity compared with the other cases of varying moisture content and fully saturated conditions. For the fully dry condition, the thermal conductivity of soil is the lowest, which limits heat loss but, as the moisture content increases, the thermal conductivity of soil also increases leading to greater heat loss. Figure 3.7(d) shows

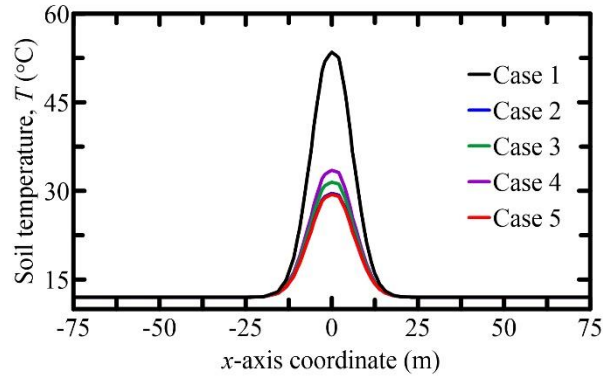
the spread of temperature at mid-depth of the SBTES domain over a period of five years of operation, based on the radius of contour corresponding to a temperature of 25°C. The result shown in Figure 3.7(d) is consistent with those shown in Figures 3.7(a)-(c). These figures highlight the importance of considering the spatial variability of soil moisture in SBTES analysis. Failing to consider the spatial variability of moisture content in the unsaturated soil domain may result in inaccurate estimations of the soil thermal properties, leading to incorrect assessments of SBTES performance.



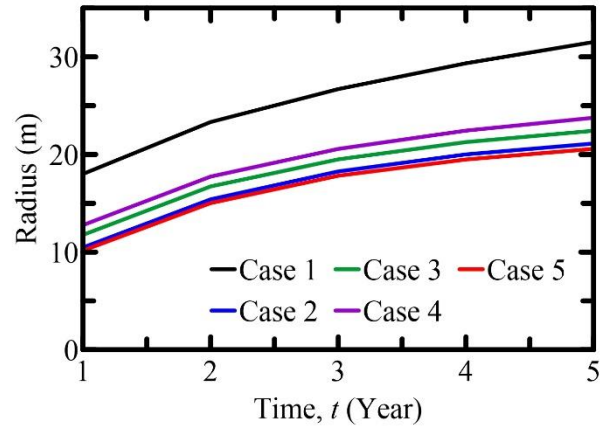
(a)



(b)



(c)



(d)

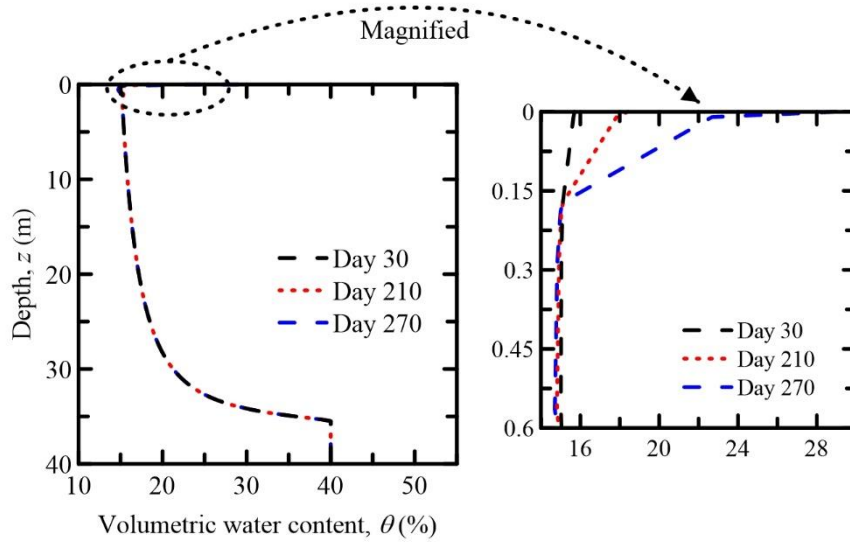
Figure 3.7: (a) Average temperature T_{avg} with time, (b) Heat stored Q_{stored} with time, (c) Soil temperature T distribution along x-axis at mid-depth of SBTES after first year of operation, (d) radius of temperature contour, corresponding to 25 °C, with time at mid-depth of SBTES.

3.4.3 Effect of varying surface pressure condition

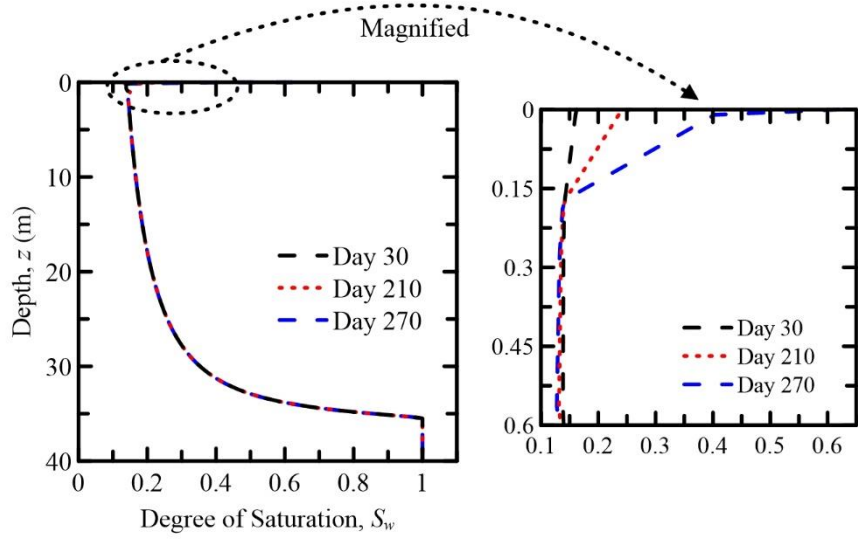
Figures 3.8(a)-(b) show the variations of volumetric water content θ and degree of saturation S_w with depth for the subsurface moisture condition case 3 at three different times, namely, $t = 30, 210$, and 270 days for the temporal variation of $P_{w,surface}$ as described in equation (3.10). It is observed that the effect of surface pressure variation on subsurface suction and moisture content diminishes with depth and is only significant in the shallow depths of the ground (~ 0.5 m), as also observed by Totoev and Kleeman (1998). Without the surface pressure fluctuation for the same moisture content condition (case 3), the degree of saturation S_w within the SBTES domain varies spatially from 0.21 to 1, as observed from the plot (Figure 3.6(a)). However, with the consideration of surface pressure variation, the degree of saturation S_w varies

temporally over 0.1 to 0.6 respectively, in the top 0.5 m. This variation in subsurface hydraulic properties (θ and S_w) reduce substantially beyond this depth ($z = 0.5$ m), eventually converging to the steady state value consistent with the hydrostatic moisture content condition case 3. Figure 3.8(c) shows the variation in volumetric water content θ with time for different depths z . Consistent with the previous figures, the most significant variation is observed at the shallowest depth of $z = 0.05$ m with the fluctuations continuing up to a depth of $z = 2.0$ m.

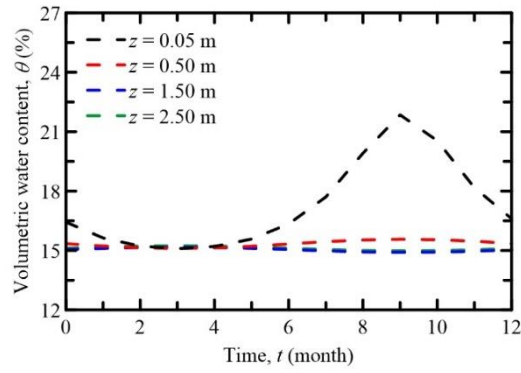
Because the thermal conductivity λ is related to θ , a similar variation of λ with depth is also observed for case 3 under the temporal variation of $P_{w,\text{surface}}$, as shown in Figure 3.8(d). Without the surface pressure variation, λ of soil varies spatially from $\sim 1.39 \text{ W m}^{-1} \text{ K}^{-1}$ to $1.67 \text{ W m}^{-1} \text{ K}^{-1}$ for case 3. However, the temporal variation in λ is observed in the range of $\sim 1.37 \text{ W m}^{-1} \text{ K}^{-1}$ to $1.67 \text{ W m}^{-1} \text{ K}^{-1}$, in the top 0.5 m when $P_{w,\text{surface}}$ is applied.



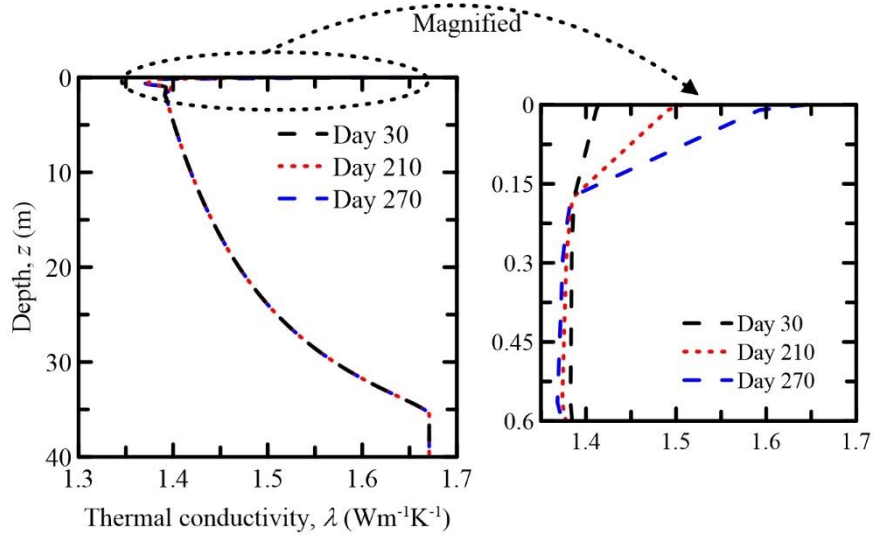
(a)



(b)



(c)



(d)

Figure 3.8: (a) Volumetric water content θ with depth z for selected days, (b) degree of saturation S_w with depth z for selected days, (c) Volumetric water content θ with time t at different depth z , and (d) thermal conductivity λ with depth z calculated for surface pressure variation study.

Figures 3.9(a)-(b) show respectively the variations of average temperature T_{avg} and heat stored Q_{stored} with time for both with and without surface pressure variation conditions. Although $P_{w,\text{surface}}$ impacts θ , S_w , and λ particularly at shallow depths, its effect on T_{avg} and Q_{stored} is rather minimal.

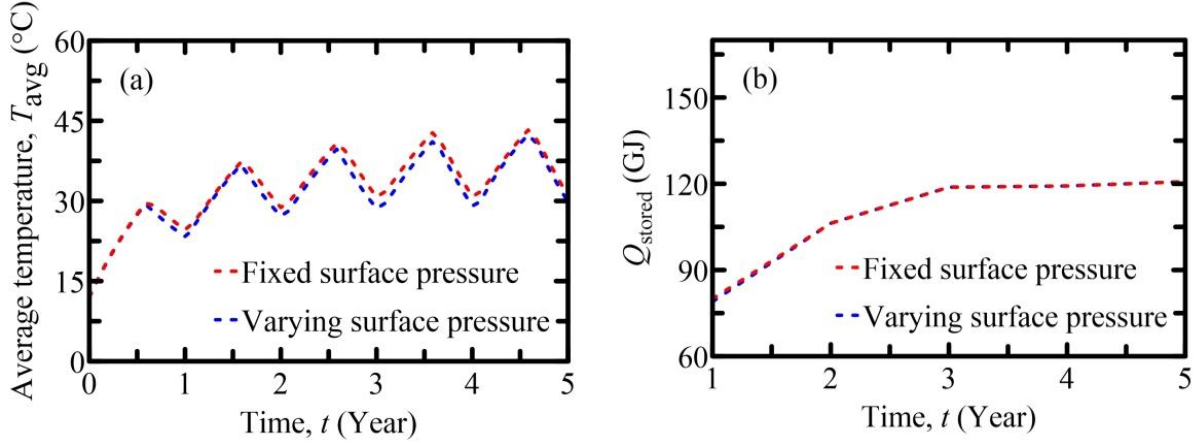


Figure 3.9: Variation of (a) average temperature T_{avg} and (b) heat stored Q_{stored} with time t with and without surface pressure variations.

3.4.4 Effect of soil porosity in homogeneous soil

Figures 3.10(a)-(c) investigate how soil porosity impacts the SBTES performance under different soil moisture conditions (cases 1-5). For all the cases 1-5, as the porosity increases, T_{avg} and Q_{stored} decrease. However, the variation of T_{avg} with porosity is more than the variation of Q_{stored} (Figure 3.10(a)-(b)). The observations for T_{avg} and Q_{stored} are consistent with the temperature distributions shown in Figure 3.10(c).

This effect of porosity on SBTES performance can be attributed to the combined effect of the variations of soil thermal conductivity λ and volumetric water content θ arising from changes in soil porosity. An increase in soil porosity results in a rise in saturated water content θ_s and, eventually, the overall moisture content within the soil. For soils with high porosities, the elevated moisture contents lead to an increased thermal conductivity λ , which results in greater heat loss Q_{stored} , and lower average temperature T_{avg} . These observations indicate that soils with low porosities are more conducive to SBTES applications.

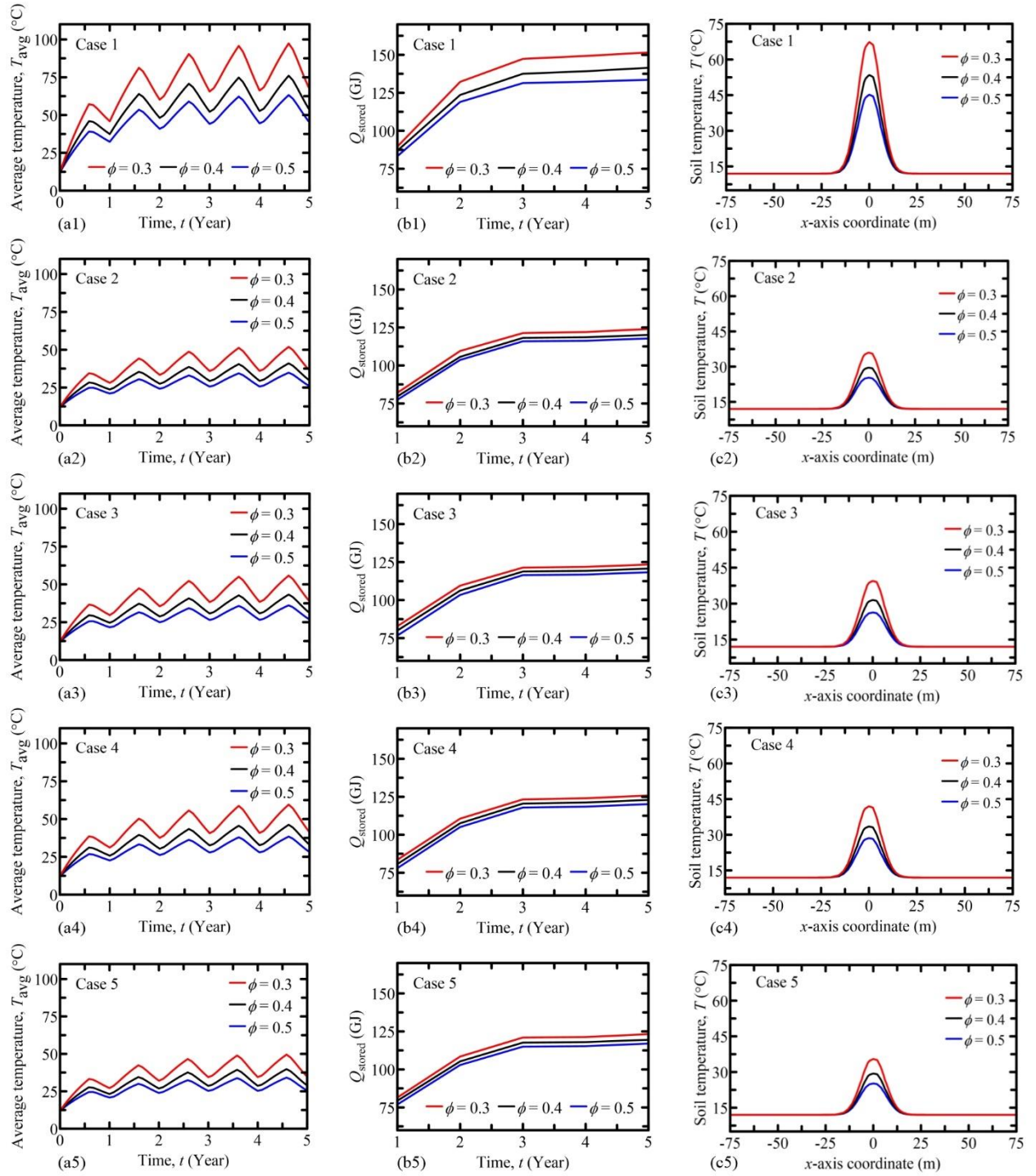


Figure 3.10: (a) Average temperature T_{avg} with time, (b) heat stored Q_{stored} with time, and (c) spatial distribution of soil temperature T along x-axis at mid-depth of SBTES after first year of operation for homogeneous soil with different moisture content variation cases 1-5.

The effect of porosity with varying surface pressure $P_{w,surface}$ in homogeneous soil (with soil moisture condition corresponding to case 3) is shown in Figures 3.11 and 3.12. For the varying surface pressure condition, soils with higher porosities exhibit a greater fluctuation in volumetric water content θ and degree of saturation S_w in the shallow depths (Figure 3.11). As a result, the soil within the shallow depths experiences greater fluctuations in thermo-hydraulic properties for higher porosities than for lower porosities. Figure 3.12(a1) - (b2) show the variations of T_{avg} and Q_{stored} with time for different porosities and surface pressure conditions. Although porosity impacts T_{avg} significantly, the variation of surface pressure does not add much to the change in T_{avg} .

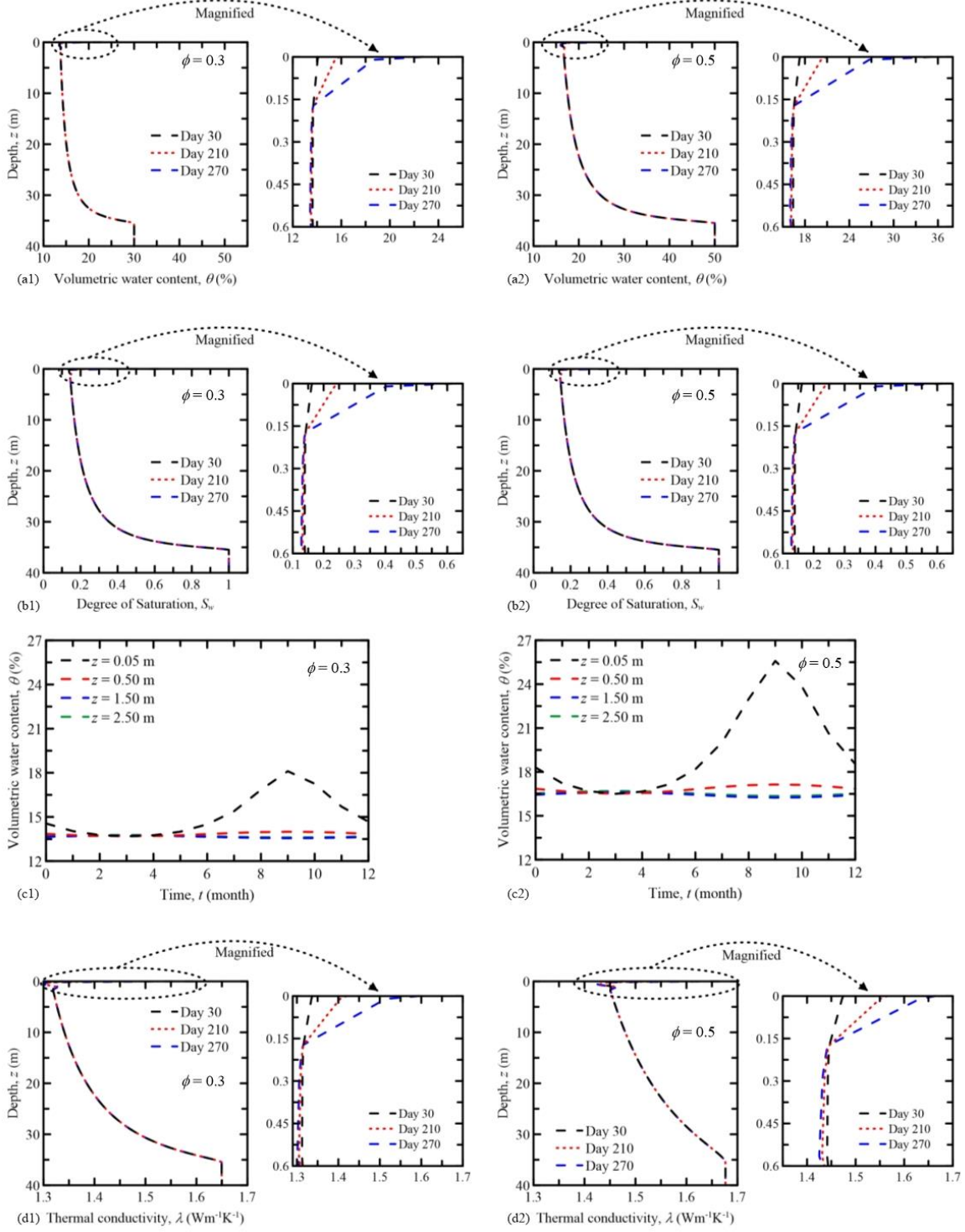


Figure 3.11: (a1) Volumetric water content θ with depth z for $\phi = 0.3$, (a2) volumetric water content θ with depth z for $\phi = 0.5$, (b1) degree of saturation S_w with depth z for $\phi = 0.3$, (b2) degree of saturation S_w with depth z for $\phi = 0.5$, (c1) volumetric water content θ with time t at different depth z for $\phi = 0.3$, (c2) volumetric water content θ with time t at different depth z for $\phi = 0.5$, (d1) thermal conductivity λ with depth z for $\phi = 0.3$, and (d2) thermal conductivity λ with depth z for $\phi = 0.5$ calculated for different surface pressure variations.

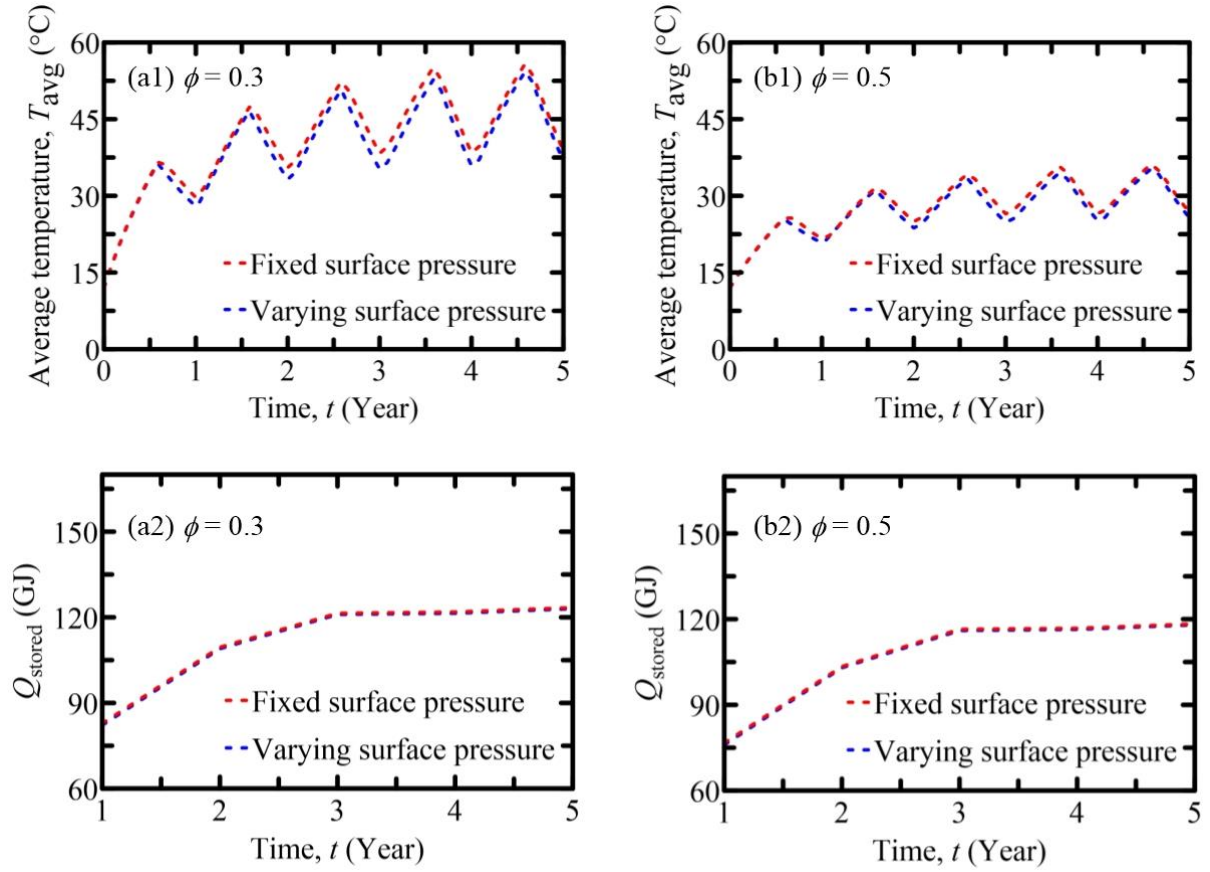
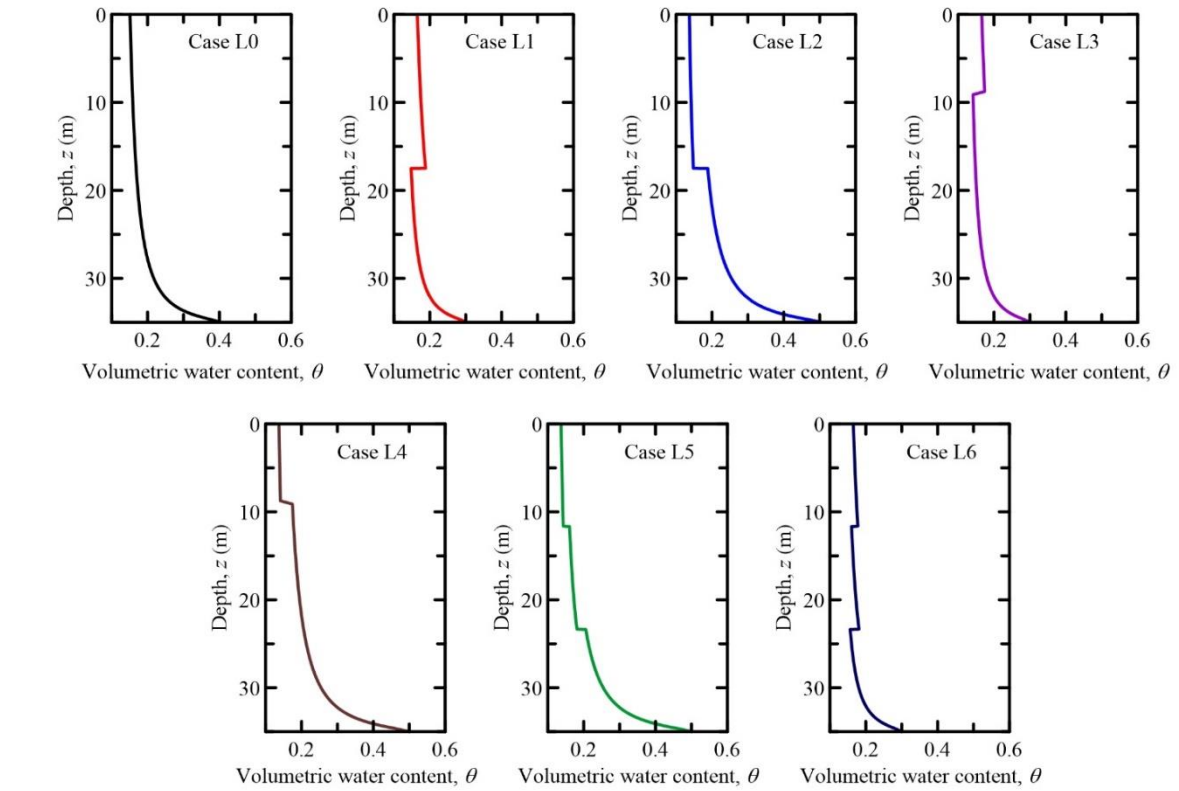


Figure 3.12: Average temperature T_{avg} and heat stored Q_{stored} with time t considering with and without surface pressure variation for (a1-a2) $\phi = 0.3$ and (b1-b2) $\phi = 0.5$.

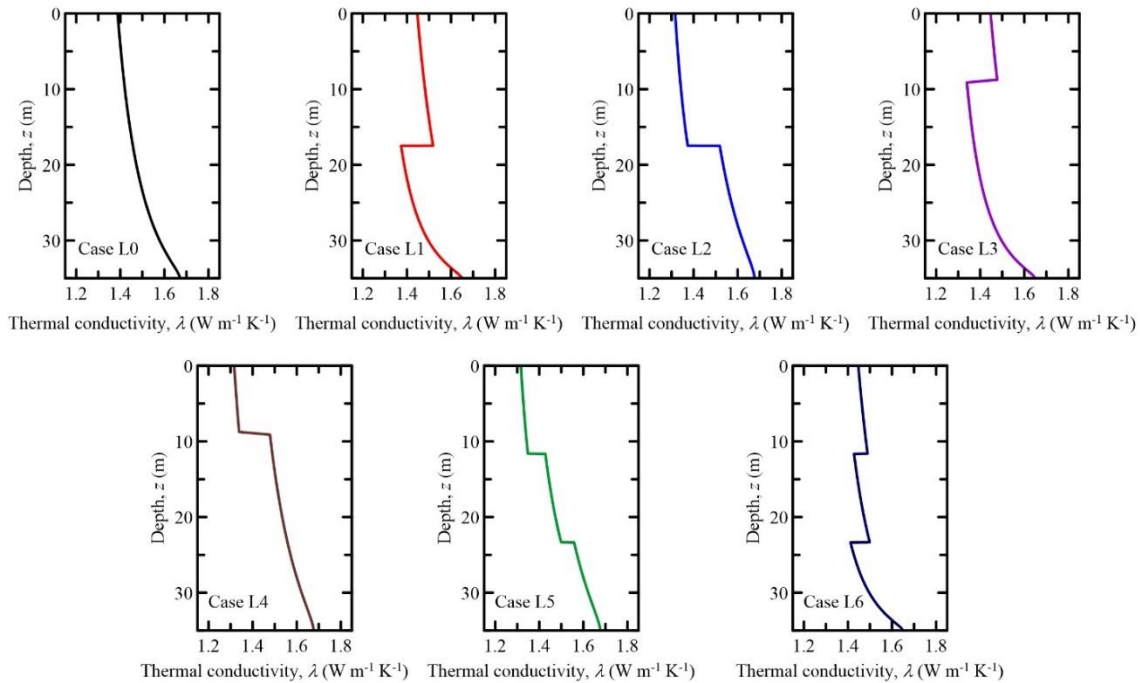
3.4.5 Effect of soil porosity in layered soil

Figures 3.13(a) and 3.13(b) show respectively the variations of volumetric water content θ and thermal conductivity λ with depth for the different soil layering cases L0-L6 with spatially varying soil porosity. A higher porosity ϕ results in a higher volumetric water content θ and a higher thermal conductivity λ , as already shown, and this is also reflected in the layered soil profiles (Figures 3.13(a) - (b)). However, the average temperature T_{avg} is an averaged response of the hydrothermal processes in soil, and because of the averaging effect, the differences exhibited in θ and λ (caused by different ϕ in different layers) is significantly reduced for T_{avg} , as evident in Figures 3.14(a1) - (a3). Notwithstanding, some differences in T_{avg} is observed between the different layering cases (Figures 3.14(a1) - (a3)). In fact, the heat

stored Q_{stored} is even less impacted by variations of ϕ (or θ and λ) because Q_{stored} is obtained by averaging the already averaged quantity T_{avg} (Figures 3.14(b1) - (b3)).



(a)



(b)

Figure 3.13: (a) Volumetric water content θ with depth z for defined soil stratification cases, (b) thermal conductivity λ with depth z for defined soil stratification cases.

Figure 3.14(a1) shows that T_{avg} is practically not impacted when the boreholes are equally divided by soil layering with reciprocal porosities and that the average porosity is a good representation for equivalent homogenization of the soil domain. Similarly, Q_{stored} for such cases is not impacted at all by soil layering, as evident from Figure 3.14(b1). Figure 3.14(a2) shows that, if a substantial part of the SBTES domain is dominated by a particular soil layer, then the corresponding ϕ (or θ and λ) has some effect on T_{avg} and may generate different T_{avg} depending on the layer thickness, although such difference completely disappears for Q_{stored} , as shown in Figure 3.14(b2). Figures 3.14(a3) and 3.14(b3) corroborate the findings of Figures 3.14(a1) and 3.14(b1).

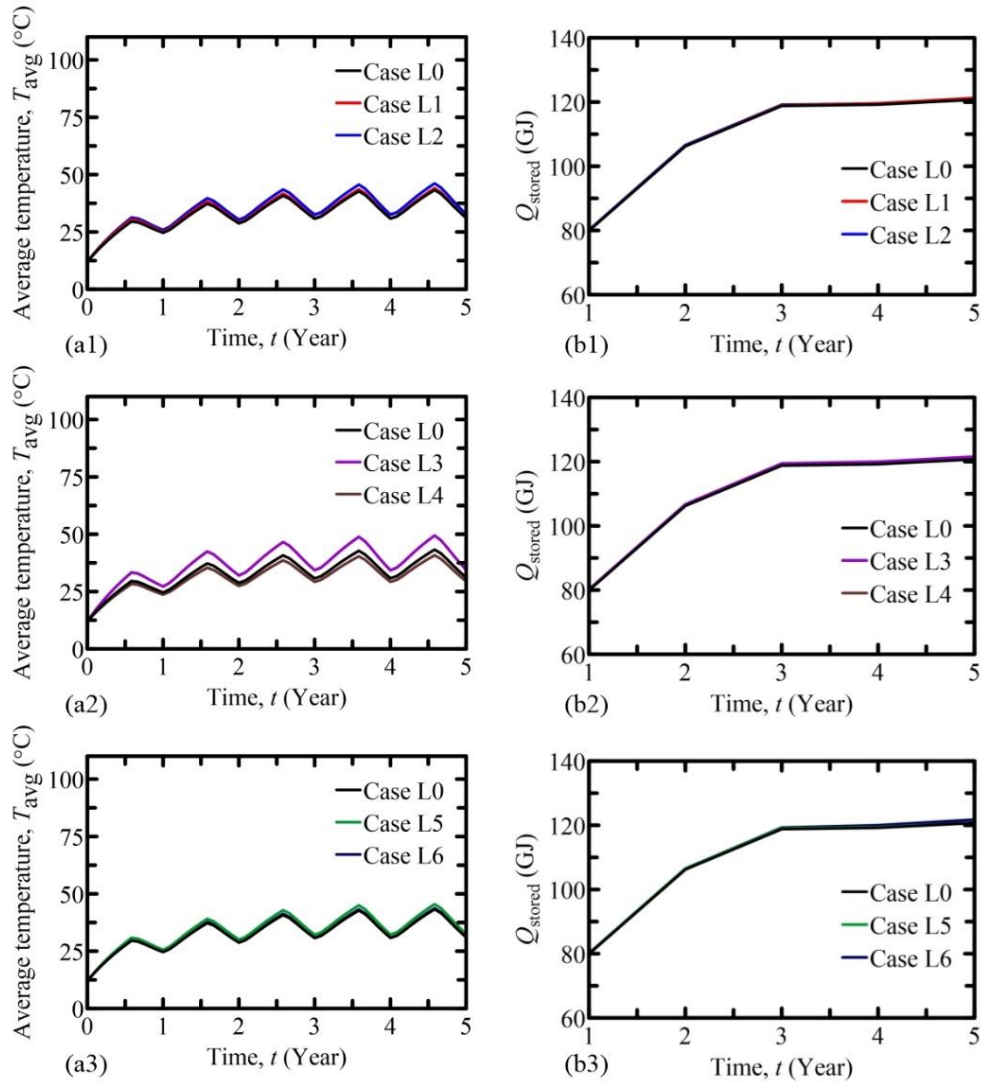


Figure 3.14: (a) Average temperature T_{avg} with time t and (b) heat stored Q_{stored} with time t for different soil layering cases L0-L6.

3.5 Conclusions

This study has three primary objectives related to the thermal performance of BTES systems in unsaturated soil. First, the thermal behavior of SBTES systems is investigated under various subsurface moisture conditions, such as fully dry soils, fully saturated soils, and soils with spatially varying moisture contents with different depths of the saturated soil zone. Second, the impact of seasonal surface pressure variation on the thermal performance of the BTES system in unsaturated soils is investigated. Finally, the role of soil porosity on the thermal performance of BTES system in unsaturated soil is examined considering both homogeneous and layered soils. Numerical simulations using COMSOL Multiphysics were performed after verifying and validating the numerical model. The numerical model uses the coupled heat and mass transfer governing equation in porous media, as developed by Nield and Bejan (2008), to conduct thermo-hydraulic numerical analysis in unsaturated soil. To accurately represent the unsaturated soil hydraulic properties, the widely acknowledged van Genuchten (1980) water retention model is used in the model. The study provides significant insights into the thermal performance of SBTES in unsaturated soil with different subsurface moisture content conditions and porosities.

Subsurface moisture content is a crucial factor that influences the subsurface thermo-hydraulic properties. The evolution of ground average temperature over time, heat stored in the domain, and temperature distribution in the domain were found to be dependent on the spatial distribution of moisture in the SBTES domain. The results show that a higher moisture content leads to a lower average temperature in the thermal storage domain. Therefore, this study emphasizes the significance of considering soil moisture content in the analysis and design of SBTES systems. Ignoring subsurface moisture content may lead to errors in performance estimation.

The results suggest that the seasonal variation in surface pressure can cause hydrodynamic changes, leading to temporal and spatial variations in the thermo-hydraulic properties of soil. However, these effects are observed only at the shallow subsurface depths (~1.5 m) and are found to be insignificant in terms of the average temperature rise in the SBTES system. Thus, there is no discernible effect of surface pressure variation on the average temperature T_{avg} and heat stored Q_{stored} of the SBTES domain. The complexity of subsurface thermo-hydraulic dynamics caused by seasonal surface pressure variation requires further investigation.

Soil porosity has a strong impact on the thermal performance of SBTES. Low soil porosity yields superior thermal performance. Under surface pressure variations, soils with high porosity experience more extensive hydrodynamic fluctuations in subsurface thermo-hydraulic properties, particularly in the shallow depths. Different soil porosities in layered soils produce different volumetric water contents and thermal conductivities in different soil layers. However, these differences caused by soil layering do not impact the thermal performance of SBTES much. The thermal performance of the SBTES system varies modestly when one soil type dominates and has a higher volume fraction than others in the soil stratification. When the different soil types have equal volume fractions, then layering has no impact on SBTES performance.

CHAPTER 4

Effect of Groundwater Flow on Thermal Performance of SBTES Systems

4.1 Introduction

In SBTES, the heat carrier fluid (HCF) collects thermal energy from heat sources such as solar energy and industrial waste heat and stores the thermal energy in the soil deposit. The magnitude of stored thermal energy and the storage efficiency of SBTES system are influenced by groundwater flow (Behbehani and McCartney, 2022; Catolico et al., 2016; Lanahan and Tabares-Velasco, 2017; Zhang et al., 2015). In fact, it has been observed that the efficiency of SBTES systems can be significantly reduced if the groundwater flow rate is excessively high (Skarphagen et al., 2019). In this chapter, the influence of different groundwater flow conditions on the short- and long-term thermal performance of SBTES system is studied. Numerical analyses of a SBTES system are performed using COMSOL Multiphysics® v. 5.6 (2019) with four groundwater table depths and with four groundwater velocities. The study evaluates the thermal performance of SBTES in terms of the average temperature T_{avg} , heat stored Q_{stored} , and system efficiency η over a 10-year operational period.

4.2 Overview of existing studies on the influence of groundwater flow on the thermal performance of SBTES system

Researchers have examined the influence of groundwater flow on the thermal performance of SBTES systems based on field observation and experimental and numerical studies. Diersch et al., (2011) observed from a field-scale SBTES installation in Crailsheim, Germany that the in-situ groundwater condition must be considered in the design process for true estimation of performance and reliability of SBTES systems. In fact, McDaniel and Kosanovic (2016) identified high groundwater flow rate as a reason for discrepancy between actual and estimated efficiencies of the SBTES installation at DLSC, Alberta. Dehkordi et al., (2015) investigated, using numerical studies, the influence of groundwater flow on the

performance of multiple SBTES configurations and observed that the outlet temperature slightly reduces under a groundwater flux of 10^{-7} m s^{-1} . Catolico et al., (2016) found from their numerical study with a groundwater velocity of $3.6 \times 10^{-8} \text{ m s}^{-1}$ that the thermal efficiency of SBTES systems reduces because of groundwater flow. Nguyen et al., (2017) found from their numerical study with two flow velocities of $1 \times 10^{-7} \text{ m s}^{-1}$ and $5 \times 10^{-7} \text{ m s}^{-1}$ as well as with no-flow condition that the stored heat reduces because of groundwater flow over an operational period of ten years. Chicco et al., (2018) conducted laboratory-scale experiments on SBTES systems installed in coarse- and fine-grained soils and found that low heat dispersion occurs in fine-grained soils because of low groundwater flow velocity, which results in higher peak temperature. In the foregoing numerical and experimental studies, the groundwater table was considered flushed with the ground surface with the BHEs completely submerged into the groundwater. Behbehani and McCartney (2022) conducted both experimental and numerical studies with multiple groundwater table depths (such that the BHEs are partially or completely submerged into the groundwater) but under no-flow condition and concluded that the efficiency of SBTES system depends on groundwater table depth (Behbehani and McCartney, 2022). These studies establish that consideration of groundwater flow is important in the analysis and design of SBTES systems. However, there is no systematic study available that quantifies the SBTES performance for a wide range of flow velocities and for multiple groundwater table depths considered in conjunction.

The objectives of the present study are to investigate the effects of different groundwater velocities and different groundwater table depths on the short- and long-term performances of SBTES systems for fixed- and variable-energy supply and demand conditions. Numerical simulations of a SBTES system are performed using COMSOL with four groundwater table depths and with four groundwater velocities ranging from 0 m s^{-1} to $1 \times 10^{-5} \text{ m s}^{-1}$. Two sets of investigations are performed on the thermal performance of SBTES. In the

first set, a fixed heat injection and extraction scheme is maintained as input to ensure that the observed performance parameters are not affected by variations of the heat injection and extraction scheme. In the second set of simulations, specific thermal design conditions are fixed in terms of a set minimum operational temperature constraint, and the system efficiency η of SBTES are studied over short- and long-term periods to investigate the effects of various groundwater flow conditions (for these simulations, the heat injection and extraction scheme varied from one case to the other). The study highlights the importance of conducting long-term analyses and quantifies the adverse effects of groundwater flow on the thermal performance of SBTES.

4.3 Numerical analysis

4.3.1 Governing thermo-hydraulic processes and differential equations

The SBTES system is simulated in this study using COMSOL Multiphysics® v. 5.6 (2019) with a coupled heat and mass transfer model (Baser et al., 2019; Behbehani and McCartney, 2022) quantified in terms of a set of differential equations, which are described in this section. The governing differential equation for heat transfer in soil (porous medium) is given by (Baser et al., 2019; Nield and Bejan, 2008)

$$\left(\rho C_p\right)\left(\frac{\partial T}{\partial t}\right)+\nabla \cdot\left(\left(\rho C_p\right)_w u_w T-(\lambda \nabla T)\right)=Q_s \quad (4.1)$$

where ρ is the density of soil (kg m^{-3}), C_p is the effective volumetric heat capacity of soil ($\text{J m}^{-3} \text{K}^{-1}$), u_w is the velocity of groundwater flow in the saturated domain (m s^{-1}), λ is the effective thermal conductivity of soil ($\text{W m}^{-1} \text{K}^{-1}$), T is the absolute temperature (K), and Q_s is the heat source ($\text{J m}^{-3} \text{s}^{-1}$). The ground above the groundwater table is considered unsaturated and moisture content in this part is modelled using Richards' equation given by (Richards', 1931)

$$\phi \left(\frac{dS_w}{dP_c} \right) \left(\frac{\partial \rho_w P_c}{\partial t} \right) + \nabla \cdot \left[\left(-\frac{\rho_w k_{rw} k_{int}}{\mu_w} \right) (\nabla P_w + \rho_w g) \right] = -Q_m \quad (4.2)$$

where ϕ is the porosity of soil, S_w is the degree of saturation of soil, ρ_w is the density of water (kg m^{-3}), μ_w is the dynamic viscosity of water (Pa s), P_c is the capillary pressure in unsaturated soil (Pa), P_w is the pore-water pressure (Pa), k_{int} is the intrinsic permeability of soil (m^2), k_{rw} is the relative permeability of water, g is the acceleration due to gravity ($\text{m}^2 \text{s}^{-1}$) and Q_m is the mass source ($\text{kg m}^{-3} \text{s}^{-1}$), which is assumed to be zero in this study. The relative permeability k_{rw} and degree of saturation S_w are respectively quantified in the simulations using the van Genuchten-Mualem and van Genuchten models (van Genuchten, 1980) given by

$$k_{rw}(S_w) = \begin{cases} K_0 S_w^{1/2} \left[1 - (1 - S_w^{n/n-1})^{1-1/n} \right]^2 & P_c \leq 0 \\ K_0 & P_c > 0 \end{cases} \quad (4.3)$$

$$S_w(P_c) = \begin{cases} \left[\frac{1}{1 + (\alpha P_c)^n} \right]^{1-1/n} & P_c \leq 0 \\ 1 & P_c > 0 \end{cases} \quad (4.4)$$

where K_0 is the saturated hydraulic conductivity of soil (m s^{-1}), and α and n are empirical, fitted parameters. The degree of saturation S_w is related with volumetric water content θ , residual water content θ_r , and saturated water content θ_s as

$$S_w = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4.5)$$

The thermal properties of soil are also dependent on soil moisture content (Farouki, 1981; Moradi et al., 2015). To establish quantitative relationships between soil moisture content and thermal parameters, the models proposed by Lu and Dong (2015) and Başer et al., (2018) are respectively used for effective thermal conductivity λ and effective volumetric heat capacity C_p as

$$\frac{\lambda - \lambda_{dry}}{\lambda_{sat} - \lambda_{dry}} = 1 - \left[1 + \left(\frac{S_w}{S_f} \right)^m \right]^{\frac{1}{m-1}} \quad (4.6)$$

$$\frac{C_p - C_{p,dry}}{C_{p,sat} - C_{p,dry}} = 1 - \left[1 + \left(\frac{S_w}{S_f} \right)^m \right]^{\frac{1}{m-1}} \quad (4.7)$$

where λ_{dry} and λ_{sat} are the dry and saturated thermal conductivities of soil ($\text{W m}^{-1} \text{K}^{-1}$), respectively, S_f is a soil saturation parameter defined at the onset of funicular regime, m is a fitted parameter, and $C_{p,dry}$ and $C_{p,sat}$ are the dry and saturated volumetric heat capacities of soil ($\text{J m}^{-3} \text{K}^{-1}$), respectively. The thermal conductivity model considered in this study simulates the variation of ground thermal conductivity based on subsurface moisture content condition. The model does not consider the influence of thermal dispersion associated with groundwater flow (Erol and François, 2016; Fujii et al., 2005; Nguyen et al., 2017).

4.3.2 SBTES performance parameters

The SBTES performance can be quantified in terms of average temperature T_{avg} of the domain, the total heat stored Q_{stored} in the domain at the end of every annual heat injection-extraction cycle, and system efficiency η of the SBTES. The average temperature is defined as

$$T_{avg} = \frac{1}{V} \int_V T(x, y, z) dx dy dz \quad (4.8)$$

where $T(x, y, z)$ is the temperature of the domain varying spatially in the x , y , and z direction and V is the volume of SBTES thermal storage domain (m^3). The heat stored Q_{stored} in the domain is given by

$$Q_{stored} = \rho C_p V (T_e - T_i) \quad (4.9)$$

where T_i is the initial temperature of SBTES ($^{\circ}\text{C}$), and T_e is the temperature of SBTES at the end of annual heat injection-extraction cycle ($^{\circ}\text{C}$). The system efficiency is defined as

$$\eta = \frac{Q_{\text{ext,annual}}}{Q_{\text{inj,annual}}} \quad (4.10)$$

where $Q_{\text{ext,annual}}$ (J) is the total energy extracted annually from the SBTES system and $Q_{\text{inj,annual}}$ (J) is the total energy injected annually to the SBTES domain (Lanahan and Tabares-Velasco, 2017).

4.3.3 Problem description

The SBTES configuration used in this study is inspired by the installation at DLSC, Alberta (Sibbitt et al., 2012). The three-dimensional (3D) domain (of size $150 \times 80 \times 80 \text{ m}^3$) consists of 72 BHEs of 35 m length, spaced at 2.25 m center to center, and arranged in a hexagonal pattern (Figure 4.1). The analysis domain is divided into unsaturated and saturated zones depending on the depth z_w of groundwater table for the different cases studied. The size of the analysis domain is carefully chosen to minimize the boundary effects. Tetrahedral elements are used to discretize the domain. A mesh convergence study is conducted to ensure that the results are independent of mesh size. The element size is successively reduced until the average soil temperature T_{avg} in the SBTES domain reaches a stable value. Figure 4.2 describes the mesh convergence study performed over five successive iterations. The final chosen mesh used in all the calculations (obtained at iteration 5) consists of a minimum element size of 0.03 m in the vicinity of the BHEs and a maximum element size of 4.25 m in the surrounding domain.

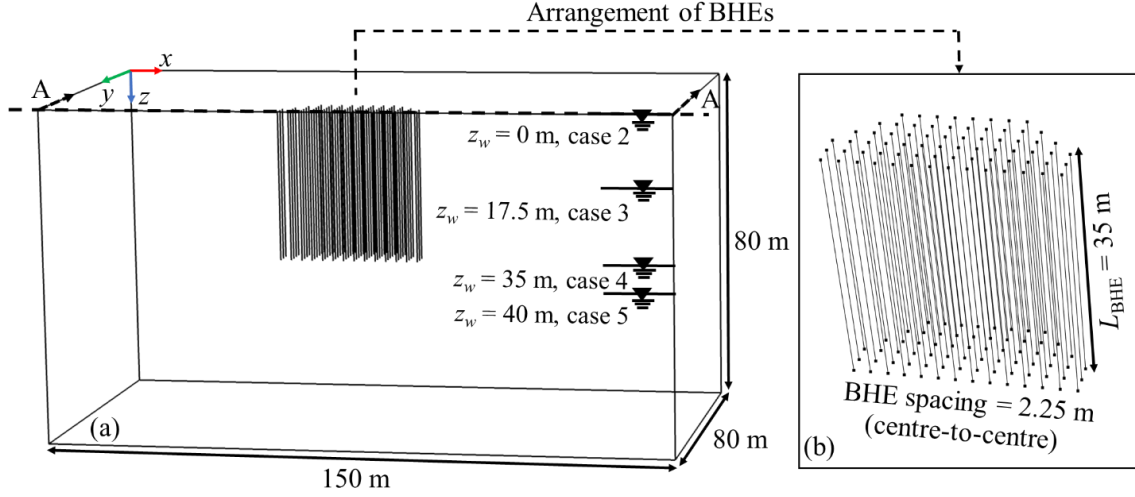


Figure 4.1: (a) SBTES domain and different cases of the groundwater table depth considered in this study, and (b) BHE arrangement and dimensions.

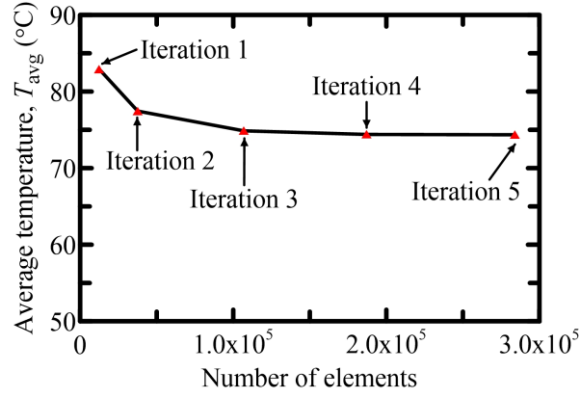


Figure 4.2: Mesh convergence study.

The soil thermo-hydraulic properties used in this study are given in Table 4.1 (Başer et al., 2016). The initial ground temperature of the domain is set at 12 °C (Majorowicz et al., 2009). To focus on the effect of groundwater flow, the thermal response resulting from the spatio-temporal variation of domain temperature caused by seasonal surface temperature variation is neglected. This is achieved by applying a zero-heat flux boundary condition at the top surface. The vertical far-field boundaries are also set to zero heat flux conditions, ensuring no heat transfer from lateral boundaries. The bottom boundary of the domain is assigned a constant temperature of 12 °C.

Table 4.1: Soil thermal, hydraulic, and physical parameters

Parameter	Value and Unit
Dry thermal conductivity (λ_{dry})	0.45 W m ⁻¹ K ⁻¹
Saturated thermal conductivity (λ_{sat})	1.75 W m ⁻¹ K ⁻¹
Dry volumetric heat capacity ($C_{p,\text{dry}}$)	0.98 MJ m ⁻³ K ⁻¹
Saturated volumetric heat capacity ($C_{p,\text{sat}}$)	1.93 MJ m ⁻³ K ⁻¹
Porosity (ϕ)	0.41
Saturated water content (θ_s)	0.41 (m ³ /m ³)
Residual water content (θ_r)	0.08 (m ³ /m ³)
Density of soil (ρ)	2650 kg m ⁻³
Density of water (ρ_w)	1000 kg m ⁻³

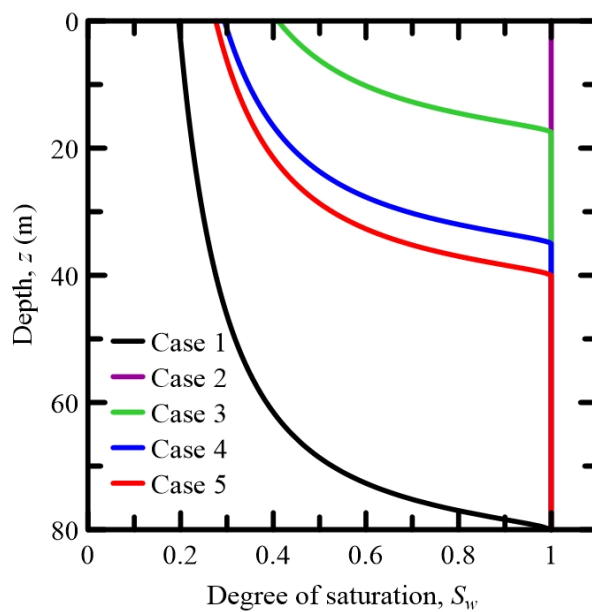
The heat transfer process from the HCF to the surrounding soil is complex and dynamic with variations in inlet and outlet fluid temperatures over time and along the depth of the BHE (Jia et al., 2023). To save on computation time, injection and extraction processes in the BHEs are simulated with the BHE modelled as a line heat source. The heat transfer from HCF is simulated by applying a time varying heat flux (Wm⁻¹) at the BHEs (Başer et al., 2016; Başer and McCartney, 2015; Erol and François, 2016; Shao et al., 2016).

The groundwater flow conditions within the domain are simulated by assigning different groundwater velocities u_w , described in Equation (4.1). In this study, four groundwater flow velocities, 0 m s⁻¹ (zero), 1×10^{-9} m s⁻¹ (low), 1×10^{-7} m s⁻¹ (medium), and 1×10^{-5} m s⁻¹ (high), are selected based on the literature that cover a wide range of conditions prevailing in the field (Angelotti et al., 2014a; Angelotti et al., 2014b; Guo et al., 2021; Michalski and Klitzsch, 2018). The top surface and vertical far-field boundaries are assigned a no-flow boundary condition, prohibiting any flow across these boundaries. The bottom boundary is subjected to a constant total head boundary condition, which is assigned depending on the depth of the groundwater table in the cases studied. Four different depths of groundwater table, $z_w = 0$ m (at the ground surface, Cases 20-2c), $z_w = 17.5$ m (at a depth corresponding to half the length

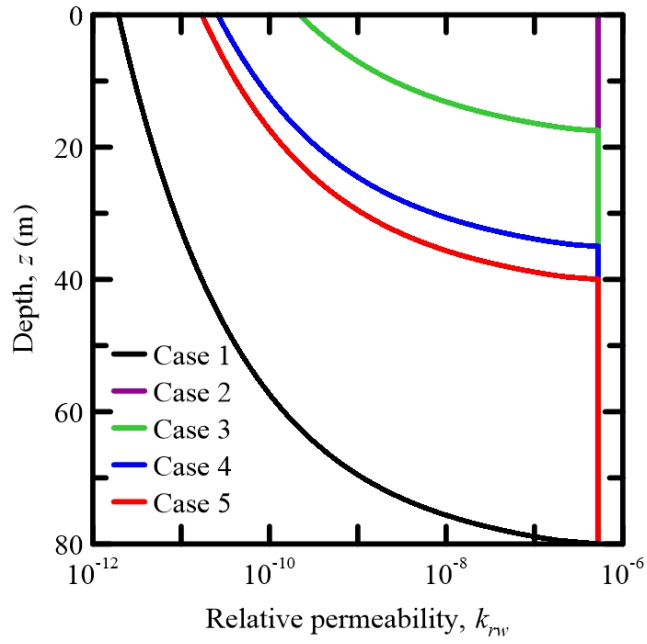
of the BHEs, Cases 3₀-3_c), $z_w = 35$ m (at a depth corresponding to the length of the BHEs, Cases 4₀-4_c), and $z_w = 40$ m (at a depth 5 m below the base of the BHEs, Cases 5₀-5_c), are considered. Further, a base case (Case 1) with the entire soil domain under unsaturated condition (i.e., with no groundwater flow) is considered (see Table 4.2 for the details of the different cases investigated).

4.3.4 Analysis of SBTES

The coupled thermo-hydraulic analysis, performed in this study using equations (4.1)-(4.7), is preceded by only hydraulic analysis (using equations (4.2)-(4.5)) to determine the initial hydraulic conditions, specifically, the spatial distributions of S_w and k_{rw} , which are given as inputs to the coupled thermo-hydraulic simulations. Figures 4.3(a)-(b) show the calculated distributions S_w and k_{rw} , which are used as initial conditions to the subsequent coupled thermo-hydraulic for all the cases studied. The effective thermal conductivity λ and effective volumetric heat capacity C_p of soil are determined from the calculated distributions of S_w based on equations (4.6) and (4.7). Figures 4.4(a)-(b) respectively show the calculated spatial distributions of λ and C_p , which are also used as initial conditions to the subsequent coupled thermo-hydraulic analysis of all the cases studied.

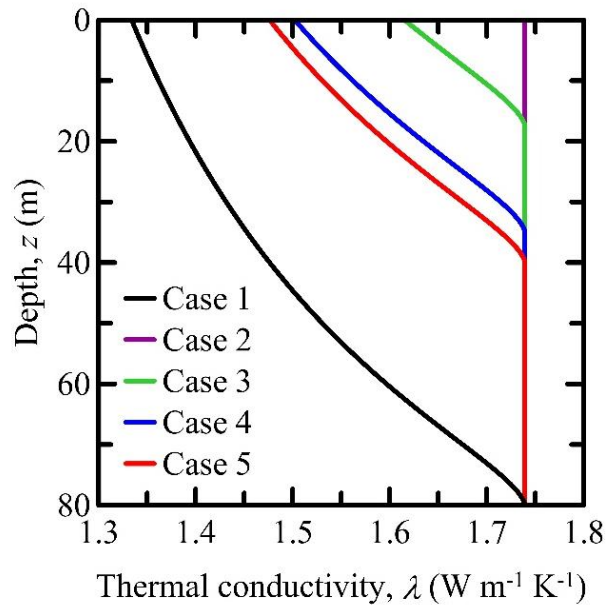


(a)

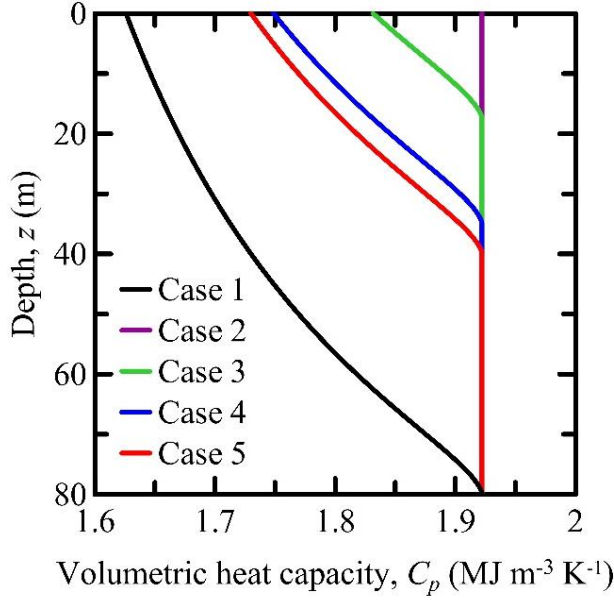


(b)

Figure 4.3: Spatial variations of (a) degree of saturation S_w and (b) relative permeability k_{rw} with depth z calculated from only hydraulic analysis and used as initial hydraulic conditions for coupled thermos-hydraulic analysis of different cases studied.



(a)



(b)

Figure 4.4: Spatial variations of (a) thermal conductivity λ and (b) volumetric heat capacity C_p with depth z calculated from hydraulic conditions and used as initial thermal conditions for coupled thermos-hydraulic analysis of different cases studied.

Two sets of investigation on the performance of SBTES are conducted in this study. In the first set (simulation set 1), the heat injection and extraction scheme is maintained the same for all the cases studied (Cases 1-5c), as shown in Figure 4.5 (injected heat is denoted by $Q_{\text{injection}}$ and extracted heat is denoted by $Q_{\text{extraction}}$). The input $Q_{\text{injection}}$ and $Q_{\text{extraction}}$ vary with time (Figure 4.5). The SBTES domain is heated for 210 days (heat injection period) followed immediately (without any resting time) by heat extraction for 155 days (heat extraction period), and this cycle of heat injection and extraction (spanning over a total of 365 days) is repeated over a period of 10 years. The assumed input temporal variations of $Q_{\text{injection}}$ and $Q_{\text{extraction}}$ (Figure 4.5) are typical of what can be expected under real field conditions. A fixed $Q_{\text{injection}}-Q_{\text{extraction}}$ scheme ensures that the effect of groundwater flow can become the focus of the study and the resulting differences in the observed performance parameters (such as T_{avg} , Q_{stored} , and temperature distribution) obtained for the different cases studied are not influenced by the input heat injection-extraction scheme.

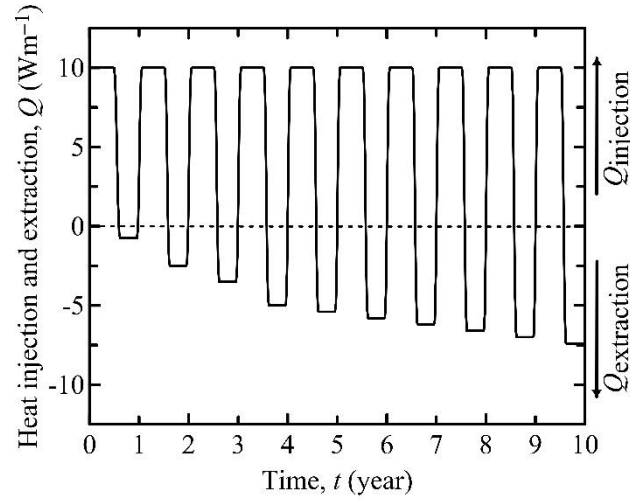


Figure 4.5: Annual heat injection-extraction scheme for first set of simulations.

In the second set of investigation (simulation set 2), the annual thermal supply and thermal demand are both assumed to be at a fixed value of 450 GJ, and the variation of SBTES system efficiency η is studied as a function of groundwater flow. The minimum operational temperature (the lower limit of the temperature range at which a system is designed to operate) of the SBTES system is assumed to be 30 °C (Behbehani and McCartney, 2022; Reuss, 2015; Skarphagen et al., 2019). Therefore, the annual heat injection of 450 GJ ($Q_{inj,annual}$) is supplied to the SBTES domain, and heat extraction is carried out in a manner that ensures that the minimum operational temperature does not fall below 30 °C. The amount of heat extracted ($Q_{ext,annual}$), which satisfies the aforementioned operational temperature constraint, is used to calculate the system efficiency η of the SBTES system for all the specified cases (Table 4.2) over the operational period of 10 years. The main question that needs to be addressed in this part of the investigation is whether the annual thermal demand can be satisfied or not under different groundwater flow regimes.

Table 4.2: Summary of groundwater (GW) flow cases studied.

Case	GW table depth, z_w (m)	GW Velocity, u_w (m s ⁻¹)
Case 1 (base case scenario)	80	0 (No groundwater flow)
Case 2 ₀	0	0
Case 2a		10 ⁻⁹
Case 2b		10 ⁻⁷
Case 2c		10 ⁻⁵
Case 3 ₀	17.5	0
Case 3a		10 ⁻⁹
Case 3b		10 ⁻⁷
Case 3c		10 ⁻⁵
Case 4 ₀	35	0
Case 4a		10 ⁻⁹
Case 4b		10 ⁻⁷
Case 4c		10 ⁻⁵
Case 5 ₀	40	0
Case 5a		10 ⁻⁹
Case 5b		10 ⁻⁷
Case 5c		10 ⁻⁵

4.4 Results

4.4.1 Verification and validation

The verification study is performed by comparing the results obtained from the present analysis with those by Başer et al., (2016) who performed numerical and field studies on a SBTES system in unsaturated soil. Figure 4.6(a) shows, for the soil deposit considered by Başer

et al., (2016), a comparison of the volumetric water content θ profiles with depth z obtained by solving equation (4.2) in COMSOL and by Başer et al., (2016). The Figure 4.6(a) confirms that the hydraulic part of the present simulation framework produces accurate results. Figure 4.6(b) shows the soil temperature profiles with depth obtained from the present analysis and from Başer et al., (2016) for days 1 and 90. As evident, the match in Figure 4.6(b) is good and shows that the thermal part of the present simulation framework produces accurate results.

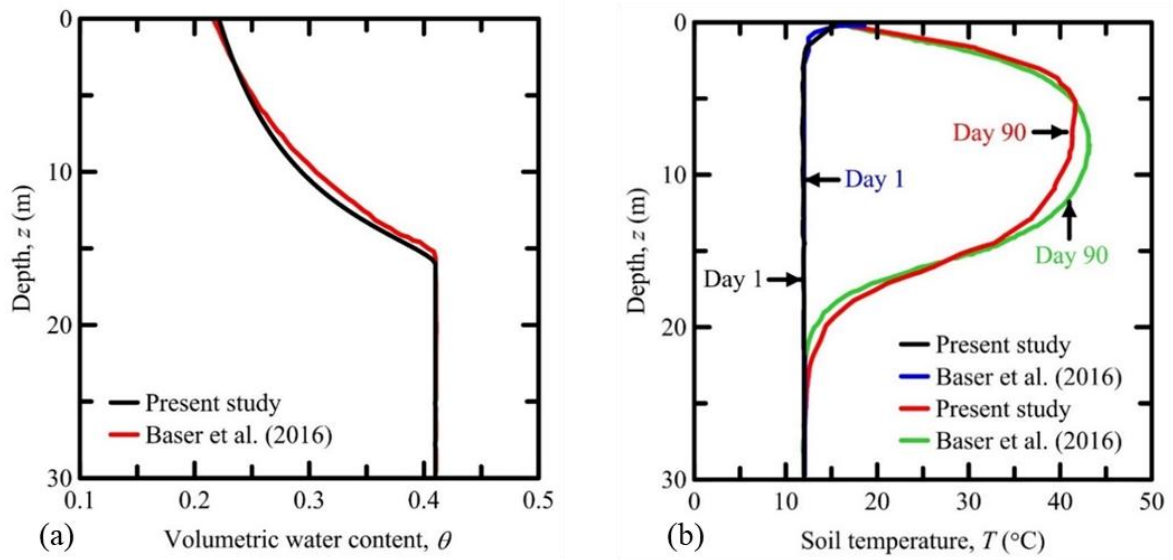
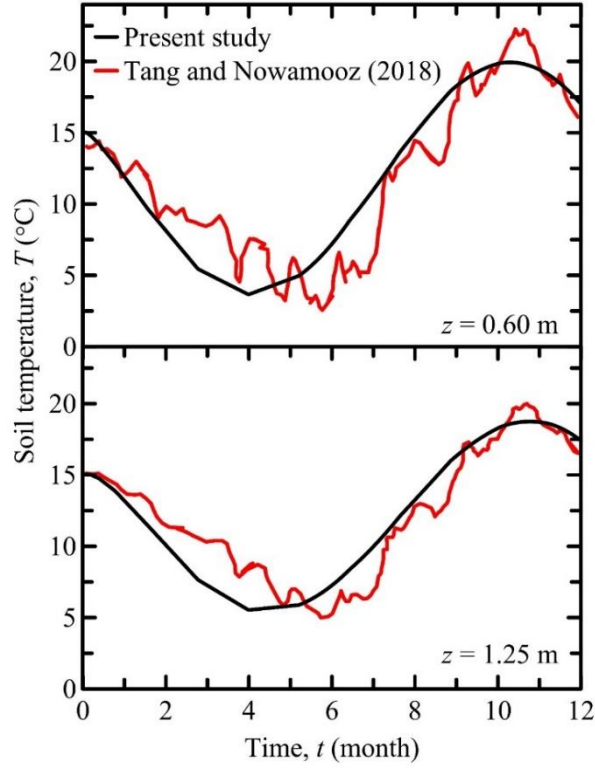


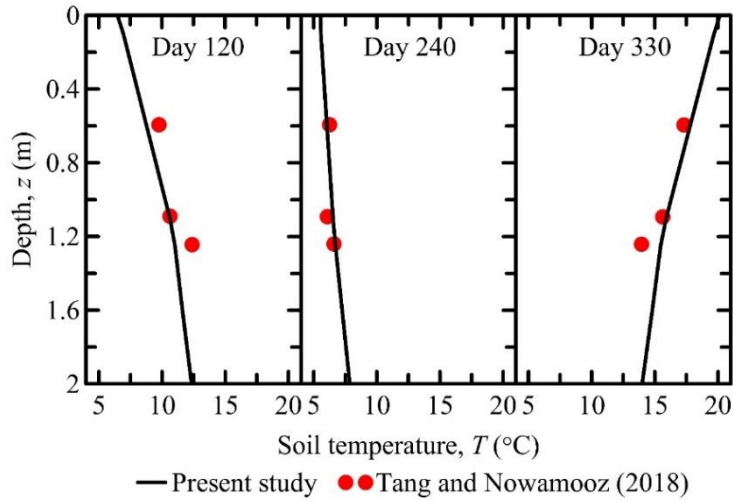
Figure 4.6: Results of verification studies: (a) volumetric water content profile and (b) soil temperature profiles for day 1 and day 90.

A field-scale study on BHE thermal behavior by Tang and Nowamooz (2018), which accounts for thermo-hydraulic variations in unsaturated soil for shallow BHE applications, is used for validating the applicability of the present numerical model. Tang and Nowamooz (2018) performed in-situ measurements in the Alsace region to capture the subsurface thermo-hydraulic response of unsaturated soil when used as a medium to install BHEs. Thermal probes were installed at various depths in the investigated area to monitor the subsurface temperature variation over time. The soil profile at the site has seven horizontal layers with varying thicknesses (ranging from 0.1 m to 11 m) and four different soil types (clay loam, sandy loam 1, loam, and sandy loam 2). To assess the effect of seasonal surface temperature variation on

the subsurface thermal response, Tang and Nowamooz (2018) also recorded the seasonal surface temperature variation at the site. Further details regarding the in-situ thermal and hydraulic properties can be obtained from Tang and Nowamooz (2018). In the present study, the numerical model incorporates the same field conditions described by Tang and Nowamooz (2018), including the seasonal surface temperature variation as a surface boundary condition, the variation of subsurface thermo-hydraulic properties in unsaturated soil, and the variations in ground properties associated with the multi-layered soil condition. The recorded thermal responses from the installed thermal probes are used to validate the numerical model. Figure 4.7(a) shows the ground temperatures at depths $z = 0.6$ m and 1.25 m over a period of twelve months as obtained from field data and from the present numerical study. Figure 4.7(b) shows the temperature profiles with depth z at 120 days, 330 days, and 440 days, as obtained from the field thermal probes and present simulations. It is evident that the present numerical framework produces reasonably accurate results and can appropriately represent field conditions. Although the developed numerical model is capable of accurately simulating horizontal soil layering and seasonal surface temperature variations, the boundary conditions used in this study align with homogeneous soil conditions in line with the objectives of the present study.



(a)



(b)

Figure 4.7: Validation study showing (a) soil temperature over 12 months at depths of 0.60 m and 1.25 m, and (b) soil temperature with depth at different days.

4.4.2 Spatial distribution of temperature

Figure 4.8 shows the temperature distribution in the SBTES domain after year 1 and year 10 of operation for cases 1, 3a-3c, and 4a-4c along the vertical section A-A of the domain (Figure 4.1) for simulation set 1. The contrasting responses of SBTES for different groundwater flow velocities and groundwater table depths are evident from the figure. For a given

groundwater table, the thermal plume shifts in the direction of flow and this shift depends on the magnitude of the groundwater velocity. The effect of low flow velocity ($1 \times 10^{-9} \text{ m s}^{-1}$) on the temperature distribution is negligible, as evident from the thermal plumes of case 1 and cases 3a and 4a. As the flow velocity increases, the plume shifts more and more with the flow and, for high velocity, the temperature rise is negligible (or, in other words, significant heat loss occurs for high velocity). This impact of groundwater flow on the thermal plume is more pronounced as time progresses (as evident from a comparison of thermal plumes after years 1 and 10 for corresponding cases).

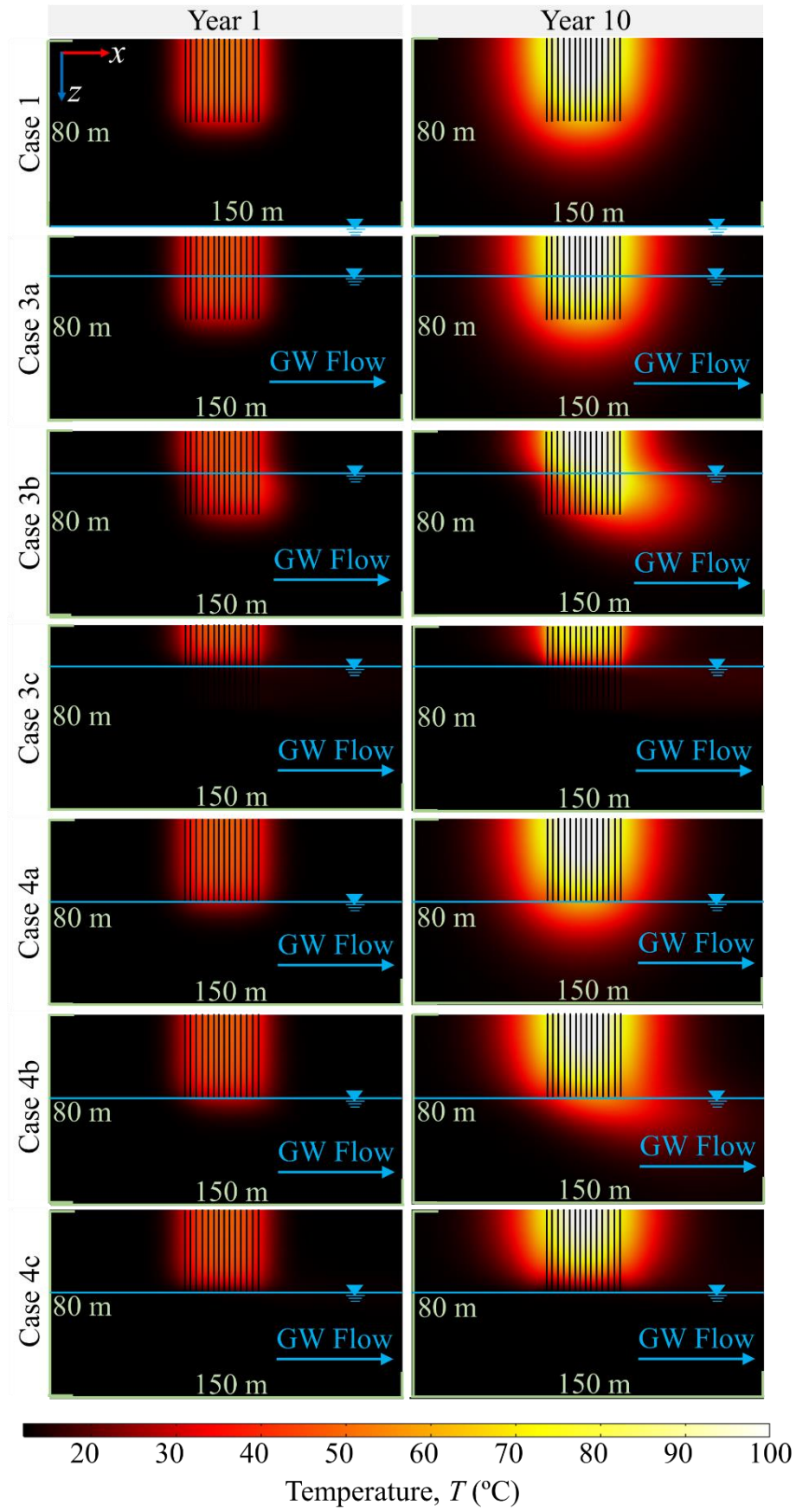


Figure 4.8: Short- and long-term temperature distributions for selected cases.

4.4.3 Average temperature and heat storage of SBTES

Figures 4.9(a)-(h) show T_{avg} and Q_{stored} as functions of time for cases 1-5c corresponding to simulation set 1. A trend exhibiting an increase in temperature with time is found with cyclic fluctuations every year because of the annual heat injection and extraction cycles (Figure 4.5). Correspondingly, the stored heat at the end of each year increases with time. Interestingly, the average temperature T_{avg} and heat stored Q_{stored} increase at the end of each year in spite of increased heat extraction over time (Figure 4.5 shows the heat injection-extraction scheme). Thus, the SBTES continues to store more and more energy with every passing year even though the heat extraction increases over time. This shows that, with proper management of heat injection and extraction, a successful SBTES system can be designed within the operational temperature range. However, groundwater flow can significantly hamper the SBTES performance if a threshold in terms of flow velocity or groundwater table depth is crossed. For example, for cases 2b-2c and 3c with the groundwater table located respectively at the top surface of SBTES and at a depth equal to one half the length of BHEs, if the velocity is medium to high ($1 \times 10^{-7} \text{ m s}^{-1}$ to $1 \times 10^{-5} \text{ m s}^{-1}$) then the increase in T_{avg} with time is marginal, which should severely impact the long term SBTES performance. Similarly, for a particular groundwater flow velocity, if the groundwater table rises too much (may be because of a change in rainfall pattern) then the stored energy significantly diminishes over the long term.

In comparison to all the cases, maximum T_{avg} is achieved for case 1, which represents the no groundwater flow condition. This observation suggests that a comparatively dry soil (case 1) sustains a higher ground temperature. For cases 5₀, 5a, 5b and 4₀, 4a, 4b, the T_{avg} is close to case 1, indicating that zero (0 m s^{-1}), low ($1 \times 10^{-9} \text{ m s}^{-1}$) and medium velocities ($1 \times 10^{-7} \text{ m s}^{-1}$) have no significant effect on T_{avg} when the groundwater table is located 5 m below or at the base of the SBTES domain. However, a visible reduction in T_{avg} is observed for cases

5c and 4c, indicating that a high groundwater flow velocity ($1 \times 10^{-5} \text{ m s}^{-1}$) reduces T_{avg} non-negligibly and contributes to heat loss.

Interestingly, the stored heat Q_{stored} for cases 2₀, 2a, 3₀, 3a, 4₀, 4a, 4b, and 5₀, 5a, 5b are higher than the Q_{stored} for case 1 after about four years of operation. This observation can be attributed to the higher volumetric heat capacity C_p for cases 2₀-2c, 3₀-3c, 4₀-4c, and 5₀-5c compared with case 1, as seen in Figure 4.4(b). Comparisons between cases 2₀ and 2a, cases 3₀ and 3a, cases 4₀ and 4a, and cases 5₀ and 5a show that Q_{stored} is the same for the corresponding pairs of compared cases. Thus, for any groundwater table depth, the thermal performance is the same for low velocity condition ($1 \times 10^{-9} \text{ m s}^{-1}$) and zero velocity conditions (0 m s^{-1}) under short- and long-term operations. For cases where a part or the full domain is completely saturated resulting in a high C_p , a better heat storage capacity ensues. However, a reduction in Q_{stored} is observed in every case with a high groundwater flow velocity ($1 \times 10^{-5} \text{ m s}^{-1}$). Therefore, it is advisable to consider the effect of groundwater flow on the thermal performance of SBTES, even if groundwater flow takes place in the near vicinity of the base of the SBTES domain. At the same time, SBTES should not be installed without adequate ground modification at sites where the groundwater velocity is high ($\sim 10^{-5} \text{ m s}^{-1}$).

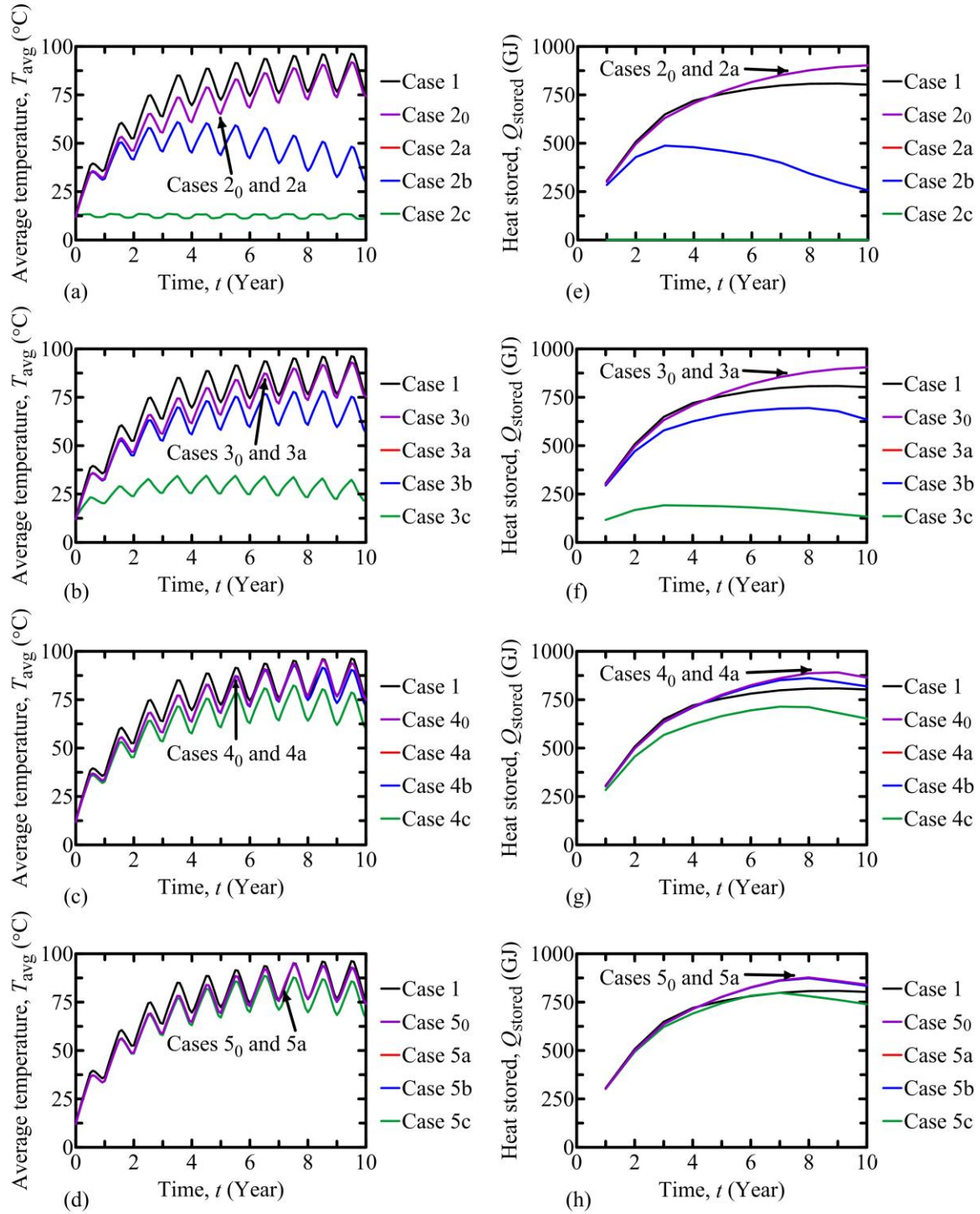


Figure 4.9: Calculated average temperature T_{avg} and heat stored Q_{stored} with time.

To further examine the short- and long-term effects of groundwater flow velocities on Q_{stored} for different groundwater table depths, the calculated Q_{stored} values for different cases are plotted as a function of groundwater velocity (Figures 4.10(a)-(d)). Specifically, the Q_{stored} for different groundwater flow cases are plotted after the first, fifth, and tenth years of

operation. These plots show that those groundwater flow conditions that exhibit not much effect during the initial years of operation can cause a significant reduction in Q_{stored} over the long term. For example, Figure 4.10(a), which is plotted for the condition when the groundwater table is at the top surface of the SBTES ($z_w = 0$ m), show that after 5 years of operation, the Q_{stored} increased for the medium velocity condition ($1 \times 10^{-7} \text{ m s}^{-1}$) but, after 10 years of operation, the Q_{stored} significantly reduced and is even lower than the Q_{stored} achieved after the first year of operation. A similar observation can be seen in Figure 4.10(b), where Q_{stored} reduced significantly over the long term for medium ($1 \times 10^{-7} \text{ m s}^{-1}$) and high ($1 \times 10^{-5} \text{ m s}^{-1}$) groundwater velocities. Figures 4.10(c)-(d) show that, after the first year of operation, the Q_{stored} is nearly independent of the variation in groundwater flow velocities. However, over the long term, Q_{stored} reduces with an increase in groundwater flow velocity. Thus, a velocity that may not show any adverse effect in the short term can have a significant adverse effect in the long term.

SBTES functions on the basis of compounding of stored heat over the operational period. Although heat loss always occurs from the SBTES to the surroundings, the accumulation of heat over multiple years of operation leads to an overall increase in the Q_{stored} in the domain. However, groundwater flow carries away a part of the stored heat from the SBTES and disrupts the compounding effect resulting in a continuous heat loss from the domain over time and ultimately leading to a reduction in the overall stored heat. Although this process is well recognized for high-velocity groundwater flow with groundwater table near or at the ground surface, the same can be true for various other groundwater flow velocity and groundwater table cases (as described above), particularly when the long-term performance is considered. As observed, the time taken for heat loss to occur is different for different cases, with some cases (cases 2b, 2c, and 3c) showing heat loss during the initial years of operation and others (cases 3b, 4c, and 5c) exhibiting pronounced heat loss after long-term operation.

These observations highlight the importance of considering the long-term effects of groundwater flow conditions on SBTES analysis and design to accurately estimate thermal performance and ensure reliable operation over the design life of the system.

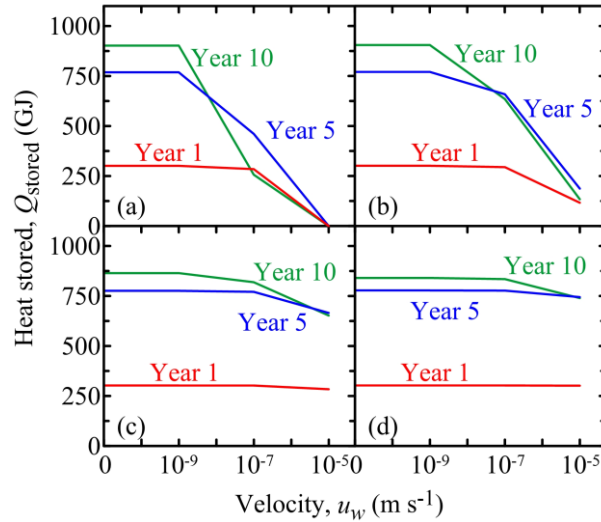


Figure 4.10: Heat stored Q_{stored} as a function of groundwater velocity u_w : (a) groundwater table at $z_w = 0$ m, (b) groundwater table at $z_w = 17.5$ m, (c) groundwater table at $z_w = 35$ m, and (d) groundwater table at $z_w = 40$ m.

4.4.4 Performance evaluation of SBTES

Figures 4.11 and 4.12(a)-(d) show the results obtained from the simulation set 2. Figure 4.11 shows the operational temperature range for all groundwater flow cases studied under simulation set 2. As mentioned before, the minimum operational temperature of 30 °C is maintained throughout to calculate system efficiency under a fixed heat supply. Figure 4.12(a)-(d) shows the SBTES system efficiency η as a function of time for all the cases considered in this study. The detrimental effect of groundwater flow, particularly for medium and high velocities, is evident from Figures 4.12(a)-(d). It is noteworthy that, in several cases (cases 2b, 3b-3c, 4c, and 5c), the decline in system efficiency η (in comparison to case 1) is not much visible during the initial years of operation, but a considerable decrease in η is observed after ten years of operation. For example, for the cases 4c and 5c, in which the effect of groundwater flow is commonly overlooked in the design process, the efficiency is reduced by 18.8% and

8%, respectively, after the tenth year of operation compared to the base case scenario. Similarly, cases 2c and 3c exhibit a reduction in efficiency from the first year of operation, while cases 2b and 3b exhibit a significant reduction of 68% and 21%, respectively, after the tenth year of operation when compared to the base case scenario. Further, for each groundwater table case, the performance recorded for the low velocity condition is the same as that of the zero velocity condition studied.

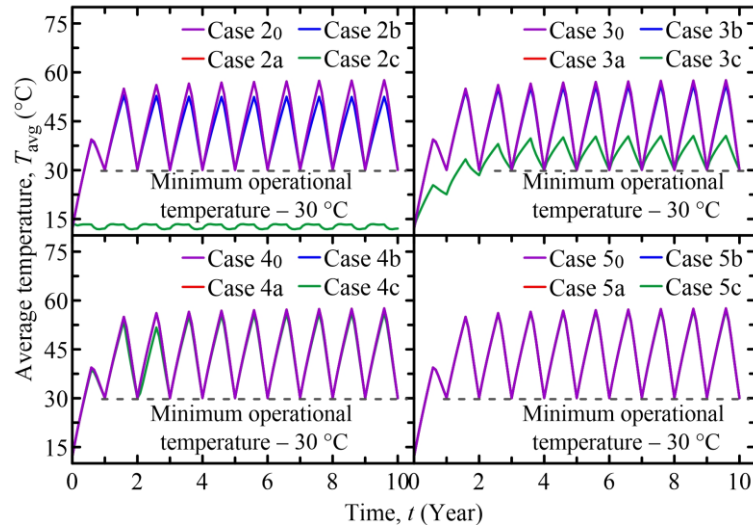


Figure 4.11: Evolution of temperature with time for simulation set 2 satisfying the minimum operational temperature constraint of 30 °C.

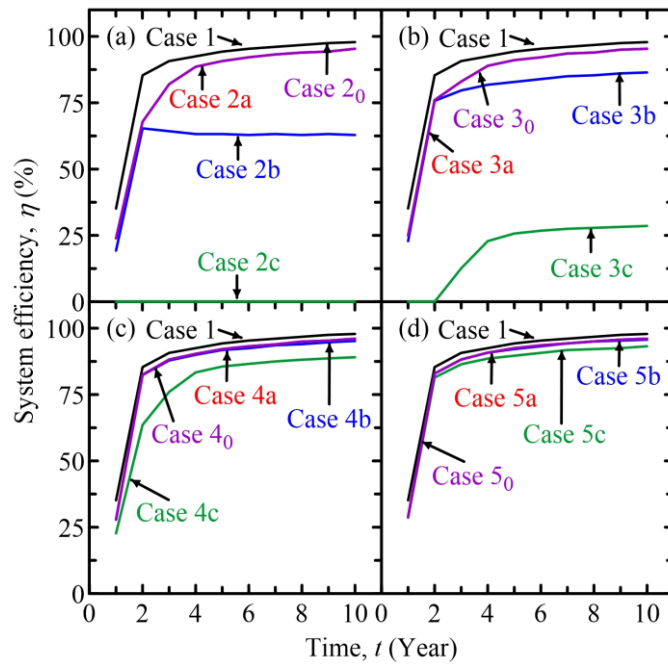


Figure 4.12: SBTES system efficiency η with time.

To observe the short- and long-term effects of groundwater flow velocities on system efficiency η for different groundwater table depths in more details, η for different cases are plotted as functions of groundwater velocity after the first, fifth, and tenth years of operation (Figures 4.13(a)-(d)). The reduction in η after fifth and tenth year of operation further emphasizes the necessity of considering long-term effects of groundwater flow for the evaluation of the thermal performance of SBTES.

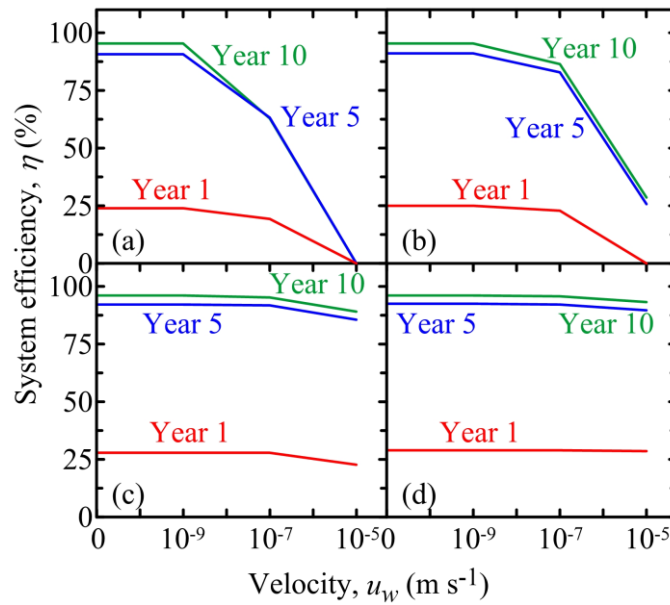


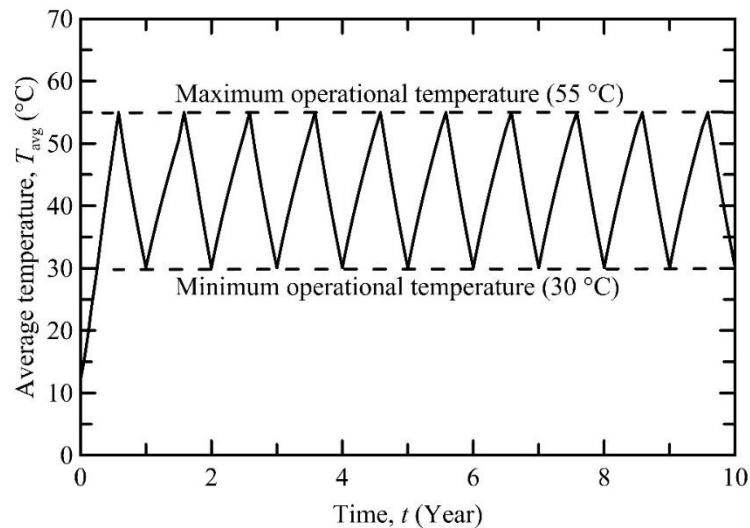
Figure 4.13: System efficiency η as a function of groundwater velocity u_w : (a) groundwater table at $z_w = 0$ m, (b) groundwater table at $z_w = 17.5$ m, (c) groundwater table at $z_w = 35$ m, and (d) groundwater table at $z_w = 40$ m.

4.4.5 Effect of borehole length on SBTES performance

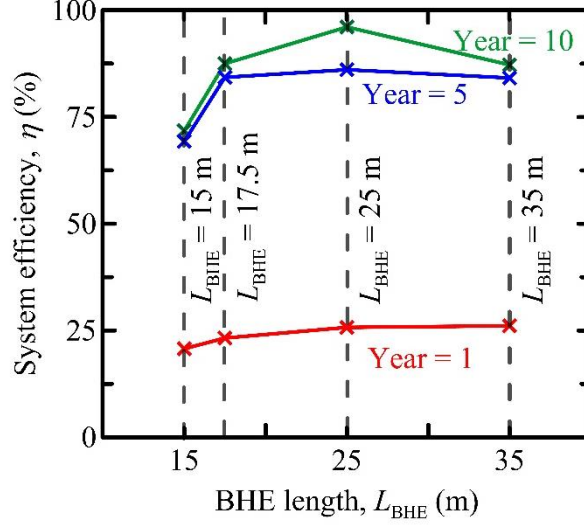
Additional simulations are performed to examine the effect of borehole heat exchanger (BHE) length L_{BHE} on the thermal performance for a fixed groundwater flow velocity of $1 \times 10^{-7} \text{ m s}^{-1}$ with the groundwater table located at 17.5 m below the top surface. The BHE spacing (2.25 m) and number (72) are kept constants at values previously mentioned (Figure 4.1), but the BHE length L_{BHE} is varied over four different values of 15 m, 17.5 m, 25 m, and 35 m. It is pertinent to note that, as other design dimensions are fixed, reducing L_{BHE} decreases the total thermal storage volume V of SBTES. To ensure a fair comparison between each L_{BHE} studied,

the operational temperature range is used as a constraint for each case, with the minimum operational temperature fixed at 30 °C and the maximum at 55 °C (Figure 4.14(a)). The system efficiency η is calculated for a 10-year operational period based on heat injection ($Q_{\text{injection}}$) and extraction ($Q_{\text{extraction}}$) that ensured the operational temperature constraint.

Figure 4.14(b) shows that, although shorter BHEs have lower thermal storage volume V , increasing BHE length L_{BHE} beyond 17.5 m (i.e., below the groundwater table) does not significantly improve the system efficiency η . This observation can be attributed to the larger vertical distances between the groundwater table and shorter BHEs. The greater the vertical distance the greater the reduction in heat loss, which benefits the shorter BHEs. However, for the cases with BHEs longer than 17.5 m, a portion of the BHE extends below the groundwater table, and get exposed to high heat loss from groundwater flow. Thus, the BHE length should be judiciously chosen ensuring that the drilling cost is kept at a minimum while maximizing efficiency as much as possible. In making such decisions, the relation between thermal storage, performance efficiency, and groundwater flow should be judiciously considered.



(a)



(b)

Figure 4.14: (a) Typical operational temperature constraint followed in the simulation conducted for four BHE lengths ($L_{BHE} = 15$ m, 17.5 m, 25 m, and 35 m), and (b) system efficiency η for different BHE lengths.

4.5 Conclusions

The effects of groundwater velocity u_w and groundwater table depth z_w on the short- and long-term performance of SBTES systems were investigated for fixed- and variable-energy supply and demand conditions. Numerical simulations were performed for four different groundwater table depths (0 m to 40 m) and four groundwater velocities u_w (0 m s^{-1} , $1 \times 10^{-9} \text{ m s}^{-1}$, 1×10^{-7} and $1 \times 10^{-5} \text{ m s}^{-1}$). The thermal performance of SBTES is evaluated in terms of the average temperature T_{avg} , heat stored Q_{stored} , and system efficiency η over a 10-year operational period.

For a given groundwater table depth under the low velocity condition ($1 \times 10^{-9} \text{ m s}^{-1}$), the thermal performance of the SBTES is same as that of the zero-velocity condition (0 m s^{-1}) both for short- and long-term operations. Further, the results indicate that low and medium groundwater flow velocities do not have a significant influence on the average temperature T_{avg} of the SBTES when the groundwater table is located either 5 m below or at the base of the SBTES domain. However, in the presence of high velocity ($1 \times 10^{-5} \text{ m s}^{-1}$) groundwater flow

below the SBTES domain (cases 4c and 5c), a notable reduction in T_{avg} is observed, particularly over the long-term operation. Generally, these groundwater flow conditions (cases 4c and 5c) are overlooked during the analysis and design of SBTES. This finding highlights the importance of heat loss resulting from high velocity groundwater flow taking place below the SBTES. Therefore, to ensure reliable performance estimates of SBTES and accurate accounting of potential heat loss, it is crucial to consider these conditions during the analysis and design processes.

The results showed that SBTES under medium velocity ($1 \times 10^{-7} \text{ m s}^{-1}$) groundwater flow conditions experiences a considerable reduction in Q_{stored} considering long-term operations when the groundwater table is at half the depth of SBTES (case 3b). For the same velocity, when groundwater table is located at the ground surface (case 2b), a substantial reduction in Q_{stored} was observed from the initial years of operation. Therefore, it can be concluded that the influence of medium-velocity groundwater flow may become evident after the first few years of operation when the entire domain is affected by groundwater flow. However, in cases where the groundwater table is located at the mid-depth of the SBTES domain, the significant influence of medium velocity flow may only become evident during long-term operation. This observation highlights the importance of considering the long-term effects of groundwater flow conditions on SBTES analysis. For the high-velocity ($1 \times 10^{-5} \text{ m s}^{-1}$) groundwater flow conditions, the results showed that such conditions lead to a massive reduction in Q_{stored} and η of SBTES, particularly when a half or the entire domain is under the influence of groundwater flow (cases 2c and 3c). Therefore, sites with such groundwater flow conditions are unsuitable for SBTES installation without proper engineering modifications.

The present study emphasizes the significance of considering groundwater flow in the analysis and design of SBTES systems. The study highlights the crucial role of groundwater flow in the thermal performance of SBTES and suggests conducting long-term analyses to

evaluate its effects. The study also suggests shortening the borehole lengths as a potential measure to mitigate the adverse effects of groundwater flow on SBTES.

CHAPTER 5

Evaluation of feasibility of subsurface vertical barriers on thermal performance of SBTES

5.1 Introduction

Numerous studies have highlighted the detrimental impact of groundwater flow on the thermal performance of SBTES (Behbehani and McCartney, 2022; Catolico et al., 2016; Lanahan and Tabares-Velasco, 2017; Zhang et al., 2015). In Chapter 4, a comprehensive study on the thermal performance of SBTES systems under groundwater flow is described. It is found that, when the entire SBTES domain is subjected to groundwater flow with velocities ranging from 10^{-7} ms^{-1} to 10^{-5} ms^{-1} , substantial heat loss occurs from the SBTES domain leading to minimal temperature rise within the domain during the heat injection period. It is commonly recommended to avoid installing SBTES in locations with high groundwater flow velocity without proper engineering modifications. However, currently no strategies exist to effectively mitigate the adverse effects of groundwater flow on the thermal performance of SBTES systems. This study proposes a novel approach by suggesting the integration of a vertical barrier within the SBTES domain to control the thermal losses resulting from groundwater flow. The objective is to offer a practical design aid in the form of a vertical barrier for the SBTES system, effectively safeguarding it against the negative effects of groundwater flow.

Vertical barriers are underground structures engineered to fulfill specific functions, such as controlling groundwater movement, mitigating contaminant migration, and ensuring waterproofing (Holtz et al., 1998). Limited studies have explored this aspect for underground thermal energy storage systems (UTES). The study conducted by Nakamura et al., (2003) investigated the effect of a cutoff wall as a hydraulic barrier provided around aquifer thermal energy storage (ATES) systems to control thermal losses resulting from groundwater flow in enclosed aquifers. Another study by Giordano et al., (2016) attempted a similar approach,

focusing on creating a thermal insulation barrier around the BHE array to reduce heat loss. Apel et al., (2017) have proposed ground improvement with the help of jet grouting and soilcrete technology to build a thermal insulator enclosing the SBTES domain to minimize the heat loss to the surrounding. However, there is currently no existing study regarding the installation of vertical barriers as a design aid to the SBTES domain to reduce thermal loss due to groundwater flow.

A systematic approach is necessary to explore the feasibility of utilizing a vertical barrier as a subsurface design aid to mitigate the thermal losses caused by groundwater flow in the SBTES system. In line with this objective, following research questions are formulated as a starting point for the investigation:

Question 1. What specific type of vertical barrier should be deployed in the SBTES domain to achieve the maximum possible enhancement in thermal performance compared to the SBTES without a vertical barrier?

Question 2. What is the effective placement position of the vertical barrier within the SBTES domain to counteract the adverse influence of groundwater flow?

Question 3. Among the various barrier types identified in the first research question, which one yields the most pronounced improvement in SBTES thermal performance when placed effectively in the SBTES domain as identified in the second research question?

Question 4. What constitutes a generalized design approach for the selection of a suitable vertical barrier within an SBTES system? Furthermore, what specific design recommendations can be outlined to assist in the selection of the efficient vertical barrier components for integration within the SBTES system?

First, the investigation focuses on selecting the most suitable type of vertical barrier. Second, the suitable positioning of the vertical barrier relative to the BHE array is explored. Third, under the most efficient vertical barrier positioning scenario, different types of vertical

barriers are rigorously assessed to determine the most efficient option. Finally, a comprehensive numerical analysis is conducted across a range of SBTES configurations, from small to large scale setups, ultimately providing design recommendations for the vertical barrier. By addressing these research questions, this study aims to provide valuable insights and design guidance for mitigating the groundwater flow effect on the thermal performance of SBTES systems through the strategic implementation of vertical barriers.

Figure 5.1 illustrates the roadmap followed to address the research questions. It outlines the specific analyses conducted for each research question, with corresponding figures and tables referenced accordingly.

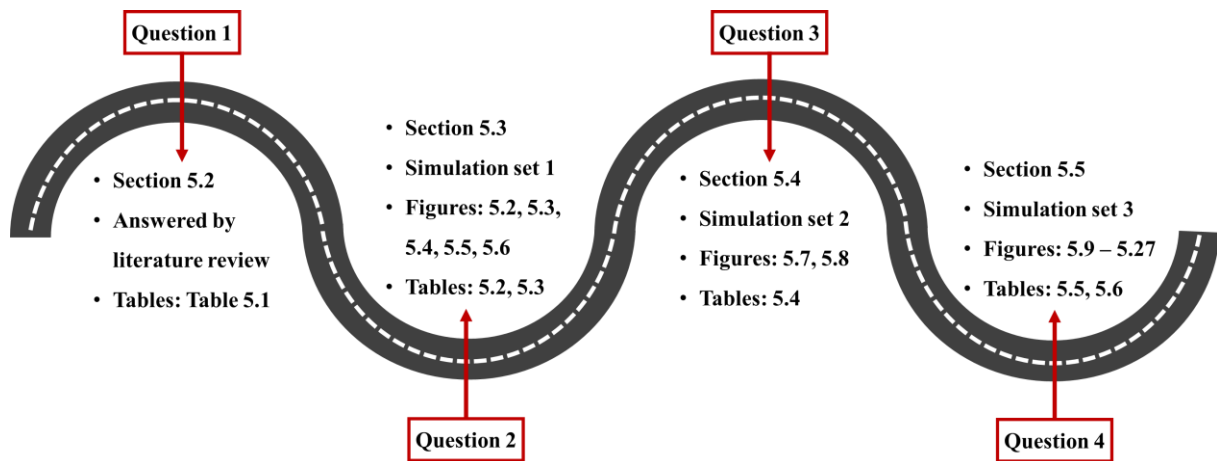


Figure 5.1: Schematic representation of the roadmap followed for vertical barrier analysis.

5.2 Addressing question 1: Selection of vertical barrier type

5.2.1 Rationale for the selection of vertical barrier type

To address the first research question, it is important to consider the rationale behind the selection of an appropriate barrier type for the designated application. The selection of appropriate barrier type is dependent on their intended functions, such as controlling groundwater movement, managing contaminant migration, and ensuring waterproofing (Holtz et al., 1998). In the context of present study, the desired function of the vertical barrier is to control and restrict groundwater flow within the SBTES domain, thereby reducing the dissipation of thermal energy from the SBTES system. This objective can be accomplished

through the installation of a *hydraulic barrier* – a subsurface structure characterized by low hydraulic conductivity, specifically designed to control groundwater flow (Holtz et al., 1998; Fan et al., 2021). Therefore, the hydraulic barrier aligns with the intended purpose of this study and requires further investigation.

While addressing the groundwater flow issue in the SBTES domain represents the primary objective of this study, it is equally important to prioritize the attainment of maximum thermal performance in SBTES system. Given the installation of a vertical barrier, an opportunity exists to utilize its potential as an insulator for the SBTES domain. Therefore, an additional type of barrier to be investigated in this study is the *thermo-hydraulic barrier*. A thermo-hydraulic barrier is characterized by low hydraulic and low thermal conductivities, enabling it to simultaneously function as an insulator that ensures reduced heat loss from SBTES to the surrounding soil. As a result, two types of vertical barriers have been selected for further investigation in the present study: *hydraulic barrier* and *thermo-hydraulic barrier*.

Table 5.1 presents a list of practical barrier types readily found in real-world applications, highlighting the emphasis on practicality in the selection process. It affirms that the chosen barrier types for further investigation, are not only theoretically sound but also viable for real-world implementation within the SBTES domain.

Table 5.1: Barrier types typically found in real-world applications

Barrier recommendation	Barrier type	Source
Concrete sheet pile wall	Hydraulic barrier	McMahon (1995)
Steel sheet piling wall	Hydraulic barrier	Evans (1993)
Soil-bentonite slurry wall	Thermo-hydraulic barrier	Evans and Ruffing (2017); Ryan et al., (2022)
Diaphragm wall	Hydraulic barrier	Bono et al., (1992); Evans (1993)

Cement-bentonite slurry trench wall	Hydraulic barrier	Evans (1993); Ramachandra and Swan (1992)
Plastic concrete wall	Hydraulic barrier	Erwin and Glenn (1992); Evans (1993)
Geomembrane walls	Hydraulic barrier	Koerner and Guglielmetti, (1995)

5.3 Addressing question 2: Comparative analysis of vertical barrier positions relative to BHE array

5.3.1 Methodology

It is an established practice to position the vertical barrier perpendicular to the direction of groundwater flow (Yihdego, 2016). Taking this into account, the second research question is addressed by defining four scenarios for positioning the vertical barrier: transverse barrier upstream, transverse barrier downstream, transverse barrier both up- and downstream, and enclosed barrier (Figure 5.2).

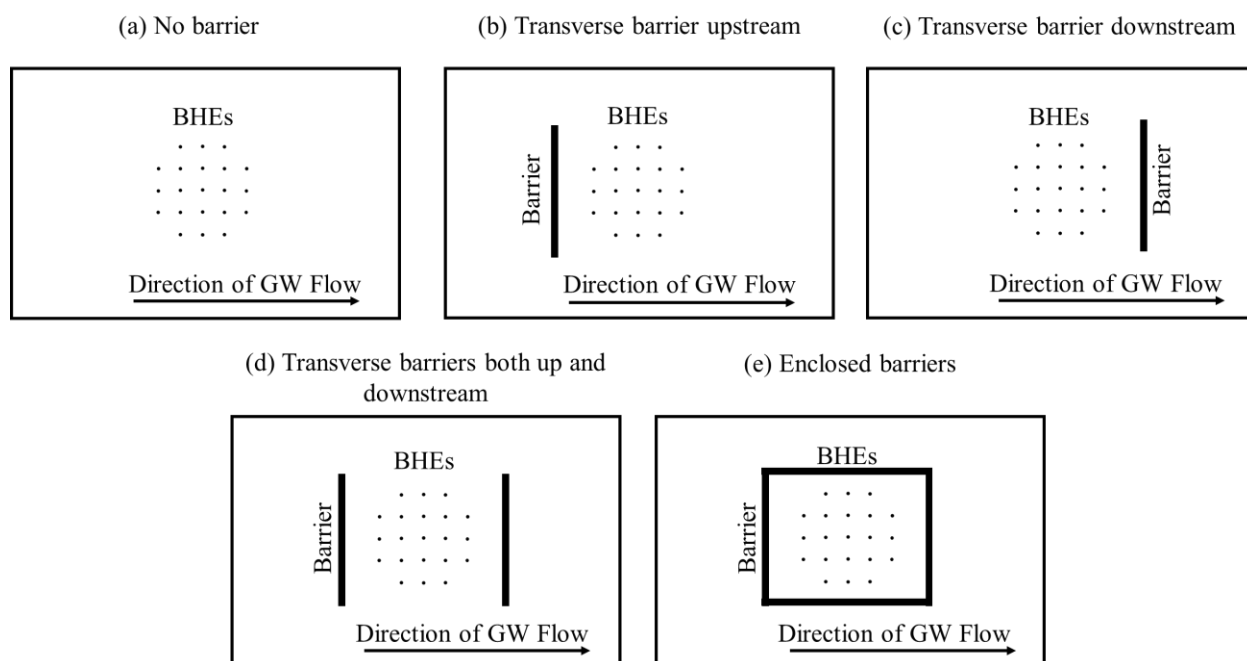


Figure 5.2: Placement of vertical barrier with respect to BHE array in SBTES domain.

Each barrier positioning scenario involves the installation of a vertical barrier at different positions relative to the BHE array in SBTES domain. In the “transverse barrier

upstream” scenario, a vertical barrier is strategically placed upstream of the BHE array, perpendicular to the direction of groundwater flow (Figure 5.2(b)). In the “transverse barrier downstream” scenario, the vertical barrier is positioned downstream of the BHE array, perpendicular to the direction of groundwater flow (Figure 5.2(c)). The “transverse barrier both up- and downstream” scenario involves the installation of vertical barriers at both upstream and downstream sides of the BHE array, perpendicular to the direction of groundwater flow (Figure 5.2(d)). The “enclosed barrier” scenario involves the installation of vertical barriers surrounding the BHE array, effectively creating a box-like enclosure around the system, as shown in Figure 5.2(e). These defined cases offer a comprehensive exploration of different barrier placements to evaluate their impact on reducing the negative effect of groundwater flow on the thermal performance of the SBTES system. Additionally, a “no barrier” scenario is defined where there is no barrier installed in the SBTES domain (Figure 5.2(a)). “No barrier” scenario serves as a base case for conducting a comparative analysis with cases involving various defined barrier positions within the SBTES domain.

5.3.2 Problem description – Simulation set 1

To investigate the effect of different barrier positions relative to BHE array in the SBTES domain on the thermal performance of SBTES under high groundwater flow, first set of analysis, simulation set 1 is defined. In simulation set 1, the thermal performance of a SBTES system is examined using a three-dimensional (3D) domain (of size $150 \times 110 \times 110 \text{ m}^3$) composed of 21 boreholes of 35 m length, with a center-to-center distance of 2 m, and arranged in a rectangular pattern, as shown in Figure 5.3. The size of the analysis domain is carefully chosen to minimize the boundary effects. Tetrahedral elements are used to discretize the domain. A mesh convergence study is conducted to ensure that the results are independent of mesh size. The final chosen mesh used in all the calculations consists of a minimum element

size of 0.03 m in the vicinity of the BHEs and a maximum element size of 3 m in the surrounding domain.

The soil thermo-hydraulic properties used in this study are given in Table 5.2 (Başer et al., 2016). The initial ground temperature of the domain is set at 12 °C (Majorowicz et al., 2009). A zero-heat flux boundary condition is applied at the top surface to eliminate the influence of seasonal surface temperature variation. The vertical far-field boundaries are also set to zero heat flux conditions, ensuring no heat transfer from lateral boundaries. The bottom boundary of the domain is assigned a constant temperature of 12 °C. The heat transfer process from the HCF to the surrounding soil is complex and dynamic with variations in inlet and outlet fluid temperatures over time and along the depth of the BHE (Jia et al., 2023). To save on computation time, injection and extraction processes in the BHEs are simulated with the BHE modelled as a line heat source. The heat transfer from HCF is simulated by applying a time varying heat flux (Wm^{-1}) at the BHEs (Başer et al., 2016; Başer and McCartney, 2015; Erol and François, 2016; Shao et al., 2016).

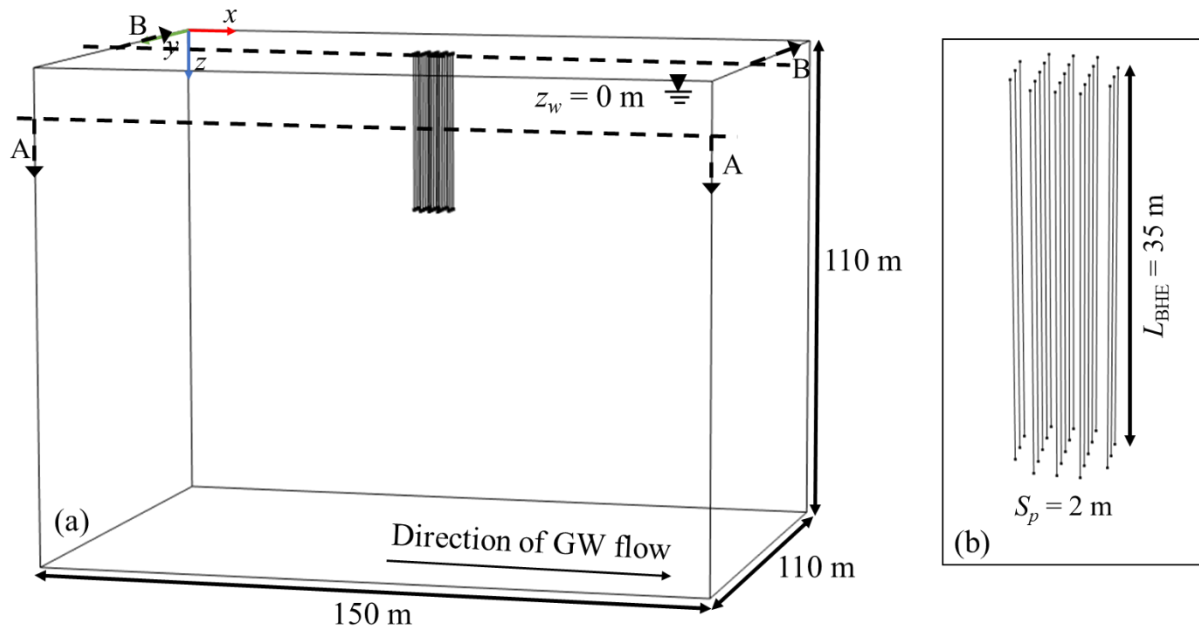


Figure 5.3: (a) SBTES domain geometry and (b) BHE arrangement and dimensions.

Table 5.2: Soil thermal, hydraulic, and physical parameters

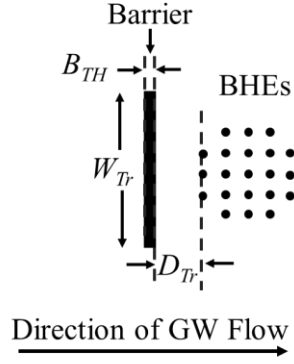
Parameter	Value and Unit
Dry thermal conductivity (λ_{dry})	0.67 W m ⁻¹ K ⁻¹
Saturated thermal conductivity (λ_{sat})	1.68 W m ⁻¹ K ⁻¹
Dry volumetric heat capacity ($C_{p,\text{dry}}$)	1.25 MJ m ⁻³ K ⁻¹
Saturated volumetric heat capacity ($C_{p,\text{sat}}$)	2.60 MJ m ⁻³ K ⁻¹
Porosity (ϕ)	0.40
Saturated water content (θ_s)	0.40 (m ³ /m ³)
Residual water content (θ_r)	0.08 (m ³ /m ³)
Density of soil (ρ)	2650 kg m ⁻³
Density of water (ρ_w)	1000 kg m ⁻³

The groundwater flow within the domain is simulated by defining a hydraulic head boundary condition on the vertical far-field boundaries, oriented perpendicular to the direction of groundwater flow. This setup establishes a hydraulic gradient of 0.5, resulting in a groundwater flow velocity u_w in the order of 1×10^{-5} m s⁻¹, with the groundwater table leveled up with the top surface of the domain ($z_w = 0$ m). This groundwater flow velocity is categorized as a high velocity groundwater flow condition in Chapter 4. The top, bottom, and vertical far-field boundaries (parallel to the direction of groundwater flow) are assigned a no-flow boundary condition, prohibiting any flow across these boundaries. Additionally, a case B0 is defined to represent a zero-velocity groundwater flow condition by assigning $u_w = 0$ m s⁻¹ to conduct a comparative analysis with the vertical barrier positioning scenarios, which will be discussed in the following section. The governing differential equation in this study is same as Chapter 4. Barriers are modelled porous media similar to the simulation approach followed for soil, as described in previous chapters.

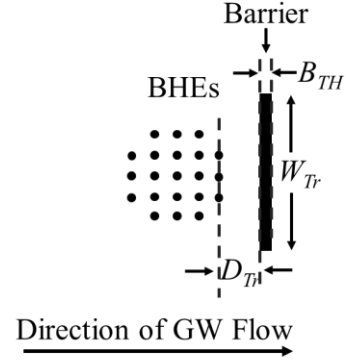
The required design specifications for the vertical barrier design components, i.e., barrier depth B_z , barrier thickness B_{TH} , its distance from the BHE array D_{Tr} and D_L , are shown in Figure 5.4. In this configuration, the depth of the barrier B_z is set equal to the length of the

BHE L_{BHE} , while the barrier thickness B_{TH} is assumed to be 1.2 meters, based on the typical values found in the literature (U.S. EPA., 1998). The distance of the barriers from the BHE array is taken to be 2.5 times the BHE spacing S_p (i.e., $2.5S_p$). Figure 5.4 provides comprehensive details of each barrier position scenario (transverse barrier upstream, transverse barrier downstream, transverse barrier both up- and downstream, and enclosed barrier), along with specifics regarding the barrier geometry. The simulation set 1 is exclusively conducted for hydraulic vertical barriers, and their properties are provided in Table 5.3. Simulation set 1 is conducted for the first phase of heat injection ($t = 150$ days) by applying a constant injection heat flux (10 Wm^{-1}) on the BHEs.

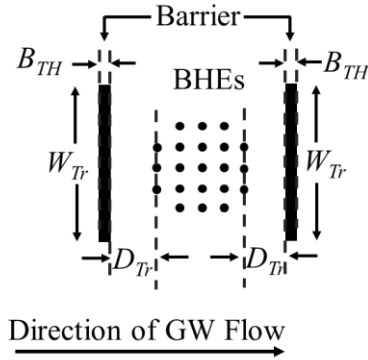
(a) Transverse barrier upstream



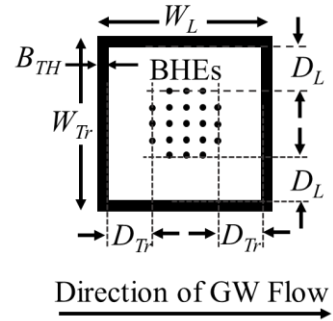
(b) Transverse barrier downstream



(c) Transverse barriers both up and downstream



(d) Enclosed barriers



SBTES domain ($N_{\text{BHE}} = 21$, $L_{\text{BHE}} = 35$, $S_p = 2$)

Barrier position	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)	W_{Tr} (m)	W_L (m)
(a) Transverse Barrier in upstream	L_{BHE}	1.2	$2.5S_p$	—	18	—
(b) Transverse Barrier in downstream	L_{BHE}	1.2	$2.5S_p$	—	18	—
(c) Transverse Barrier in both up and downstream	L_{BHE}	1.2	$2.5S_p$	—	18	—
(d) Enclosed barrier	L_{BHE}	1.2	$2.5S_p$	$2.5S_p$	18	20.4

Figure 5.4(a)-(d): Schematic representation of vertical barrier design components for each barrier placement scenario. The preliminary design specifications of the vertical barrier design components (B_z , B_{TH} , D_{Tr} , D_L) are also provided for the SBTES domain it is integrated with.

Table 5.3: Hydraulic Barrier properties

Parameter	Value and Unit	Source
Hydraulic barrier hydraulic conductivity (k_{hb})	$1 \times 10^{-10} \text{ ms}^{-1}$	Malusis et al., (2011); Takai et al., (2016)
Hydraulic barrier thermal conductivity (λ_{hb})	$1.39 \text{ W m}^{-1} \text{ K}^{-1}$	Hanson et al., (2000); Nakamura et al., (2003)
Hydraulic barrier volumetric heat capacity ($C_{p,hb}$)	$3.60 \text{ MJ m}^{-3} \text{ K}^{-1}$	Hanson et al., (2000)
Hydraulic barrier porosity (ϕ_{hb})	0.45	Malusis et al., (2011)
Density of hydraulic barrier (ρ_{hb})	2720 kg m^{-3}	Fan et al., (2021)

The thermal performance of the studied hydraulic barrier positioning scenarios (transverse barrier upstream, transverse barrier downstream, transverse barrier both up- and downstream, and enclosed barrier) is evaluated in comparison to two reference cases: the "No barrier" scenario (Figure 5.2(a)) and case B0, representing zero-velocity groundwater flow conditions. This comparison allows for insights into the expected thermal performance improvement resulting from the installation of hydraulic barriers at various positions relative to the SBTES domain. Additionally, it provides valuable information about the ability of different barrier positioning scenarios to approximate the thermal performance of the SBTES system under conditions equivalent to the absence of groundwater flow.

5.3.3 Results

Figure 5.5 shows the temperature distribution within the SBTES domain along horizontal section plane A-A and vertical section B-B (Figure 5.3) at the end of first phase of heat injection ($t = 150$ days) for the different hydraulic barrier positioning scenarios studied in simulation set 1. The contrasting responses of SBTES for different hydraulic barrier position with respect to BHE array are evident from the figure. The thermal plume shifts in the direction of flow and this shift depends on the position of hydraulic barrier with respect to BHE array.

As evident from the thermal plumes, the effect of groundwater flow on the temperature distribution is significant for the transverse barrier upstream (Figure 5.5(a)) and transverse barrier downstream (Figure 5.5(b)) scenarios. For the transverse barrier both up and downstream (Figure 5.5(c)) scenario, the temperature of SBTES domain is higher compared to the preceding barrier placements. This effect is attributed to the increasing coverage of the BHE array by the hydraulic barrier, which leads to diminished plume shifts and greater thermal retention within the domain. Notably, the enclosed barrier scenario (Figure 5.5(d)) exhibits a marked reduction in thermal plume shift, resulting in considerably higher temperatures within the SBTES domain compared to the other three barrier positioning scenarios explored.

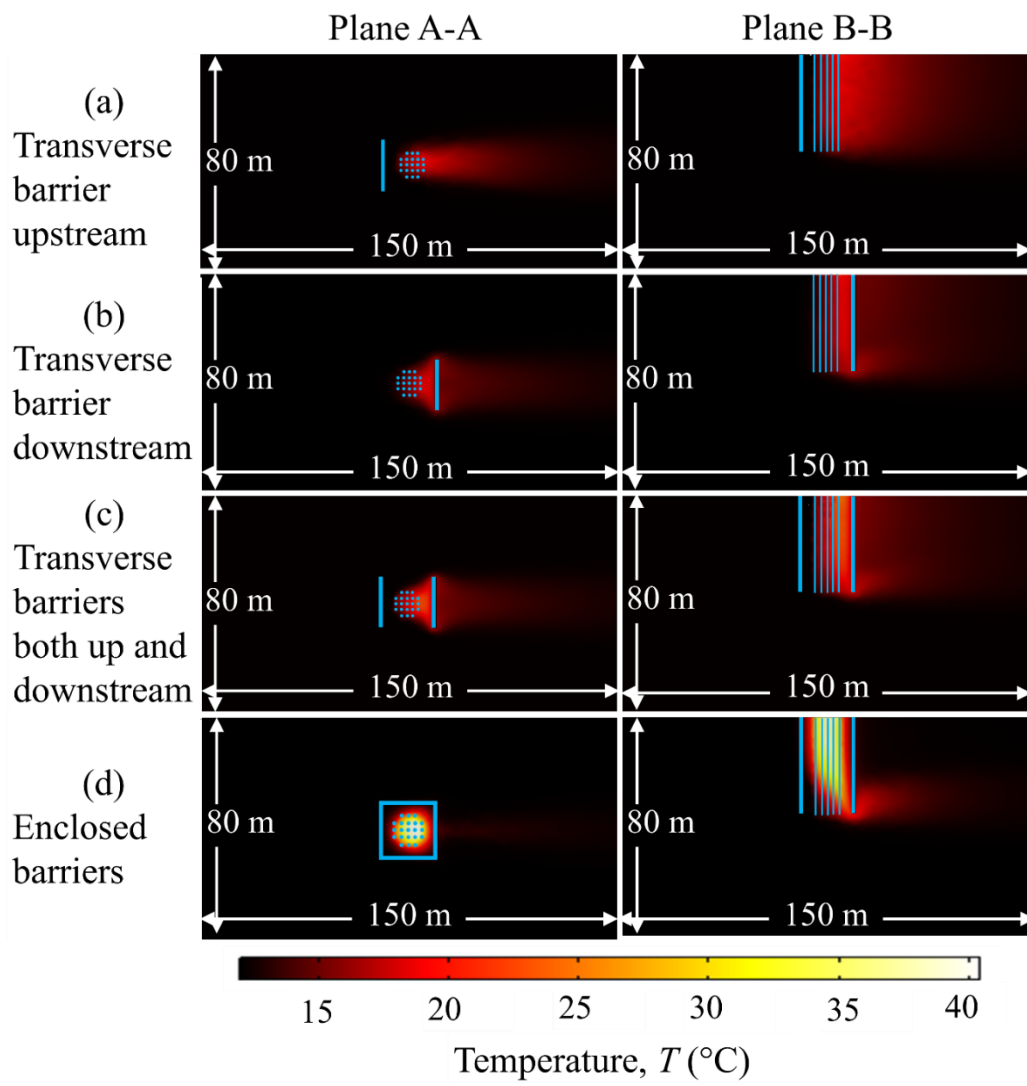


Figure 5.5: Spatial temperature distribution along horizontal plane A-A and vertical plane B-B at the end of first phase of heat injection for all the barrier positioning scenarios studied. The enclosed barrier scenario exhibits a marked reduction in thermal plume shift, resulting in considerably higher temperatures within the SBTES domain compared to the other three barrier positioning scenarios explored.

Figures 5.6(a) and (b) present T_{avg} and Q_{stored} as functions of time for the different barrier positioning scenarios (transverse barrier upstream, transverse barrier downstream, transverse barrier both up- and downstream, and enclosed barrier) studied under simulation set 1. A trend exhibiting an increase in T_{avg} and Q_{stored} with time is found for the first phase of heat injection ($t = 150$ days). When compared to all cases, case B0, representing no groundwater flow (zero-velocity) condition, achieves the highest T_{avg} and Q_{stored} . This comparison aims to

observe the extent to which hydraulic barrier integration with the SBTES domain can replicate the thermal performance achieved in the absence of groundwater flow. For the hydraulic barrier installation scenarios transverse barrier upstream, transverse barrier downstream, and transverse barrier both up- and downstream, T_{avg} and Q_{stored} closely approximate the no barrier scenario. This indicates that these barrier placements offer limited mitigation against heat loss induced by groundwater flow.

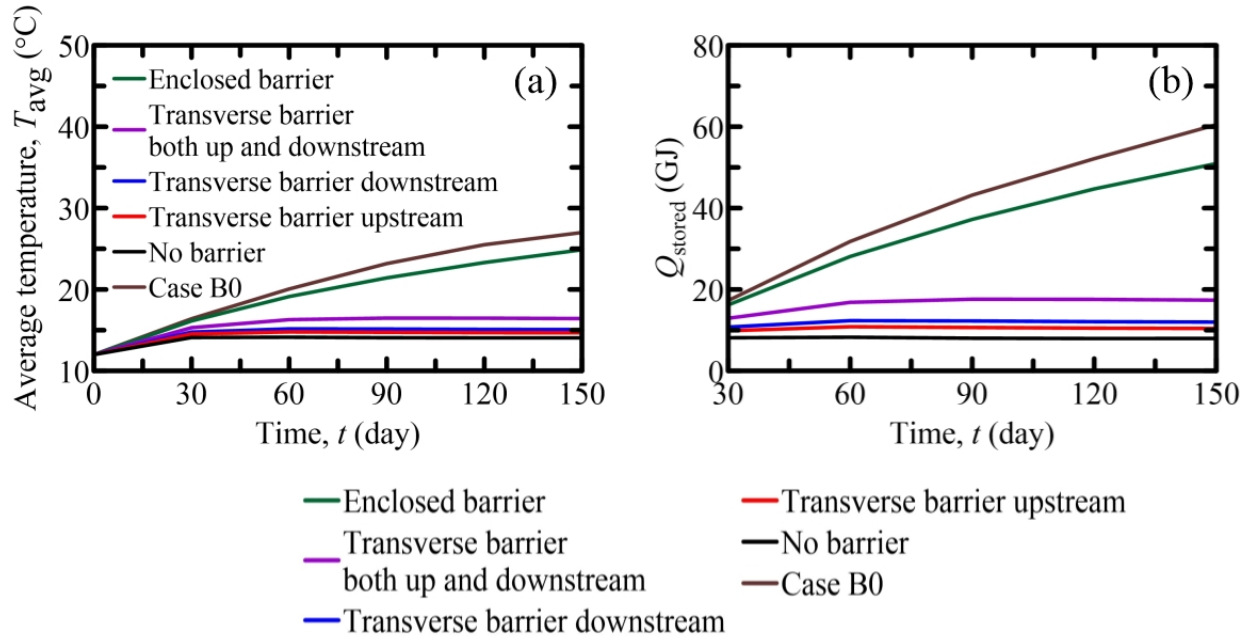


Figure 5.6: Calculated average temperature T_{avg} and heat stored Q_{stored} in SBTES domain with time for different vertical hydraulic barrier positioning scenarios. The enclosed barrier scenario provides a visible increase in both T_{avg} and Q_{stored} .

The enclosed barrier scenario provides a visible increase in both T_{avg} and Q_{stored} , signifying that covering the BHE array by a hydraulic barrier from all the sides proves to be an effective strategy in mitigating the adverse effects of groundwater flow on the thermal performance of the SBTES system. In fact, at the end of the first phase of heat injection, the T_{avg} achieved in the SBTES domain for the enclosed barrier scenario is only 8% lower than that of case B0 (no groundwater flow condition) and nearly 78% higher than the no barrier scenario.

The findings of simulation set 1 unequivocally indicate that integrating an enclosed barrier within the SBTES domain is an efficient means of reducing heat loss due to the presence of high-velocity groundwater flow. This answers the second research question, affirming that the *enclosed barrier* configuration is the most effective vertical barrier placement scenario (out of the configurations considered) within the SBTES domain for mitigating the adverse effect of groundwater flow.

5.4 Addressing question 3: Comparative analysis of hydraulic and thermo-hydraulic enclosed barriers

5.4.1 Methodology

To address the third research question, the most suitable vertical barrier positioning scenario identified in simulation set 1, is further investigated for different barrier types identified while answering the first research question. Enclosed barrier is found to be the most effective barrier positioning scenario in simulation set 1. Furthermore, hydraulic and thermo-hydraulic barrier types were identified as suitable barrier types while addressing first research question. Therefore, this study involves a comparative analysis between the influence of hydraulic enclosed barrier and the thermo-hydraulic enclosed barrier on the thermal performance of SBTES in the presence of groundwater flow over a long-term operational period (5 years).

5.4.2 Problem Description – Simulation set 2

In simulation set 2, the SBTES domain and simulation approach outlined in simulation set 1 are used (Figure 5.3). Simulation set 2 specifically focuses on the analysis of enclosed barrier scenario. The design details of enclosed barrier are given in Figure 5.4(d). The methodology for hydraulic barrier modelling remains consistent with that of simulation set 1.

To model the thermo-hydraulic barrier, the properties listed in Table 5.4 are assigned to the enclosed barrier within the SBTES domain. The heat injection-extraction scheme for the SBTES system over a 5-year operational period is shown in Figure 5.7.

Table 5.4: Thermo-hydraulic barrier properties

Parameter	Value and Unit	Source
Thermo-hydraulic barrier permeability (k_{thb})	$1 \times 10^{-10} \text{ ms}^{-1}$	Di Emidio et al., (2017); Malusis et al., (2011); Takai et al., (2016)
Thermo-hydraulic barrier thermal conductivity (λ_{thb})	$0.01 \text{ W m}^{-1} \text{ K}^{-1}$	Assumed as insulator
Thermo-hydraulic barrier volumetric heat capacity ($C_{p,thb}$)	$3.60 \text{ MJ m}^{-3} \text{ K}^{-1}$	Hanson et al., (2000)
Thermo-hydraulic barrier porosity (ϕ_{thb})	0.45	Malusis et al., (2011)
Density of thermo-hydraulic barrier (ρ_{thb})	2720 kg m^{-3}	Fan et al., (2021)

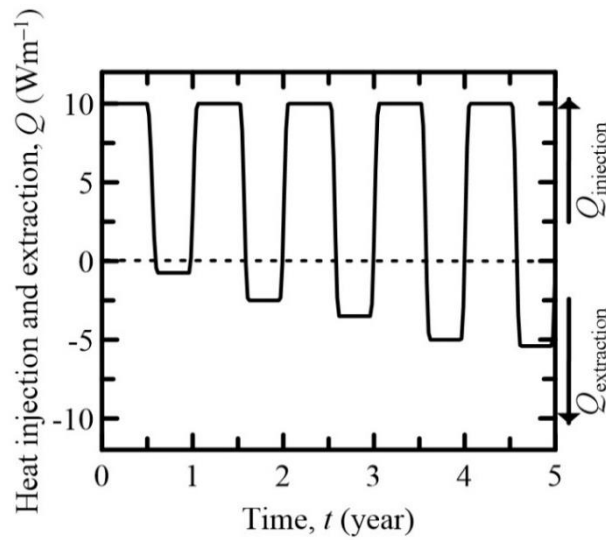


Figure 5.7: Annual heat injection-extraction scheme considered in this study.

To provide further clarification, simulation set 2 differs from simulation set 1 for following reasons. Firstly, simulation set 2 is defined as a long-term analysis (5 years), as opposed to simulation set 1 which was limited to the first phase of heat injection (150 days). Additionally, while under simulation set 1 four barrier positioning scenarios are investigated,

in simulation set 2 the enclosed barrier scenario is exclusively examined. Furthermore, in simulation set 1 only hydraulic barrier is studied, while in simulation set 2, both hydraulic and thermo-hydraulic barriers are investigated.

5.4.3 Results

The following section presents the results of simulation set 2, focusing on a comparative analysis of the impact of hydraulic enclosed barrier and the thermo-hydraulic enclosed barrier on the thermal performance SBTES system under the influence of groundwater flow.

Figure 5.8(a) and (b) show T_{avg} and Q_{stored} as functions of time for both the hydraulic enclosed barrier and the thermo-hydraulic barrier, along with no barrier scenario. Both the hydraulic and thermo-hydraulic enclosed barriers exhibit an increase in T_{avg} and Q_{stored} over time compared to the scenario with no barrier. Notably, this long-term performance analysis offers crucial insights that simulation set 1 did not capture. For the hydraulic enclosed barrier, there is significant increase in SBTES thermal performance in terms of T_{avg} and Q_{stored} during the initial years of operation (Figure 5.8). However, over the long-term, a gradual decline in T_{avg} and Q_{stored} is experienced because of groundwater flow. However, the thermo-hydraulic enclosed barrier not only outperforms the hydraulic enclosed barrier in the initial years of operation, but it also consistently retains heat within the SBTES domain, maintaining a stable temperature profile throughout its operational years. The trends showed in Figure 5.8(a) and (b) strongly endorse the thermo-hydraulic enclosed barrier as the superior choice for the enclosed barrier configuration. To quantitatively assess the extent of improvement in thermal performance of the SBTES system when integrated with the hydraulic and thermo-hydraulic enclosed barriers, relative to a scenario with no barrier, the percentage increase in T_{avg} and Q_{stored} has been plotted in Figure 5.8(c) and (d) respectively. These findings reaffirm the significance of the insights gained from the initial and long-term performance analyses.

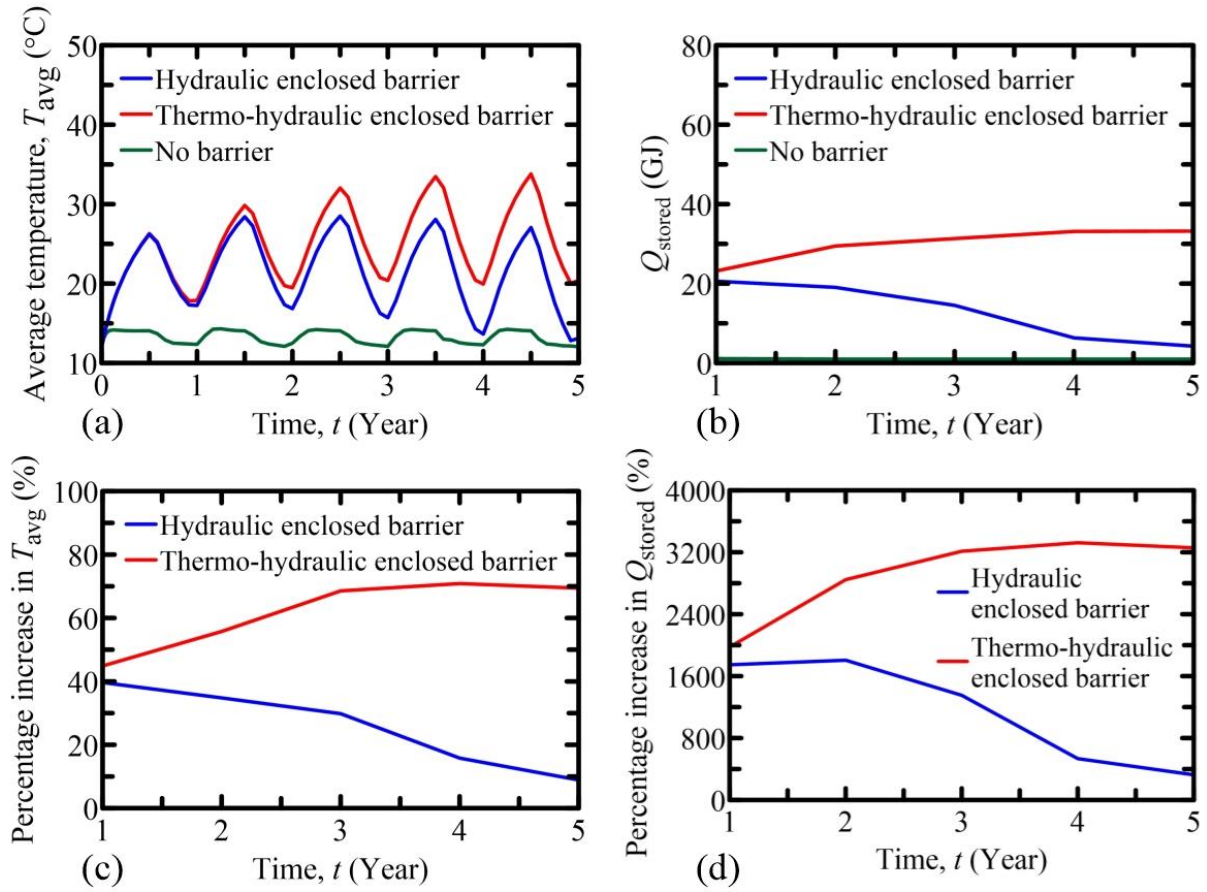


Figure 5.8: (a)-(b) Calculated T_{avg} and Q_{stored} with time, (c)-(d) percentage increase in T_{avg} and Q_{stored} with time in SBTES domain for hydraulic enclosed barrier and thermo-hydraulic enclosed barrier relative to “No barrier” scenario.

5.5 Addressing Question 4: Design assessment of thermo-hydraulic enclosed barrier

In the previous sections, a framework is established supporting the provision of thermo-hydraulic enclosed barrier as an effective design aid to mitigate the adverse impact of groundwater flow on the thermal performance of SBTES systems. In this section, the design aspect of thermo-hydraulic enclosed barrier is explored with aim of developing a systematic methodology for selecting the appropriate dimensions of thermo-hydraulic enclosed barrier for SBTES systems of different scales. Thus, in this section, design recommendations are provided for key enclosed barrier design components: barrier depth B_z , barrier thickness B_{TH} , and distances between transverse and longitudinal barriers from the BHE array D_{Tr} and D_L , and this addresses the fourth research question outlined in Section 5.1.

5.5.1 Methodology

In the preliminary enclosed barrier design (Figure 5.4(d)), the barrier design components B_z , B_{TH} , D_{Tr} and D_L are strategically defined as factors of SBTES design components L_{BHE} , S_p . Specifically, B_z is defined as a factor of L_{BHE} ($B_z = L_{BHE}$), while D_{Tr} and D_L are defined as factors of S_p ($D_{Tr} = 2.5S_p$ and $D_L = 2.5S_p$). Meanwhile, B_{TH} is assumed to be 1.2 m based on typical vertical barrier thicknesses found in literature (U.S. EPA., 1998).

Building on this approach, this part of the study aims to establish a suitable range of enclosed barrier design components (B_z , B_{TH} , D_{Tr} and D_L) in relation to SBTES design components (L_{BHE} , S_p). This range is aimed to be applicable across a spectrum of SBTES configurations, ranging from small to large scales commonly encountered in real-world applications.

To achieve this, three representative SBTES configurations have been selected to cover a variety of domain sizes, configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35$ m, $S_p = 2$ m) for small scale, Configuration 2 ($N_{BHE} = 57$, $L_{BHE} = 25$ m, $S_p = 1.5$ m) for medium scale, and configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45$ m, $S_p = 2.5$ m) for large scale (Figure 5.9 (a)-(c)). Thermo-hydraulic enclosed barriers will be integrated into all three configurations. The preliminary specifications for each enclosed barrier design components (B_z , B_{TH} , D_{Tr} and D_L) will be selected based on the SBTES design components (L_{BHE} , S_p) of the respective configuration with which the barrier is installed.

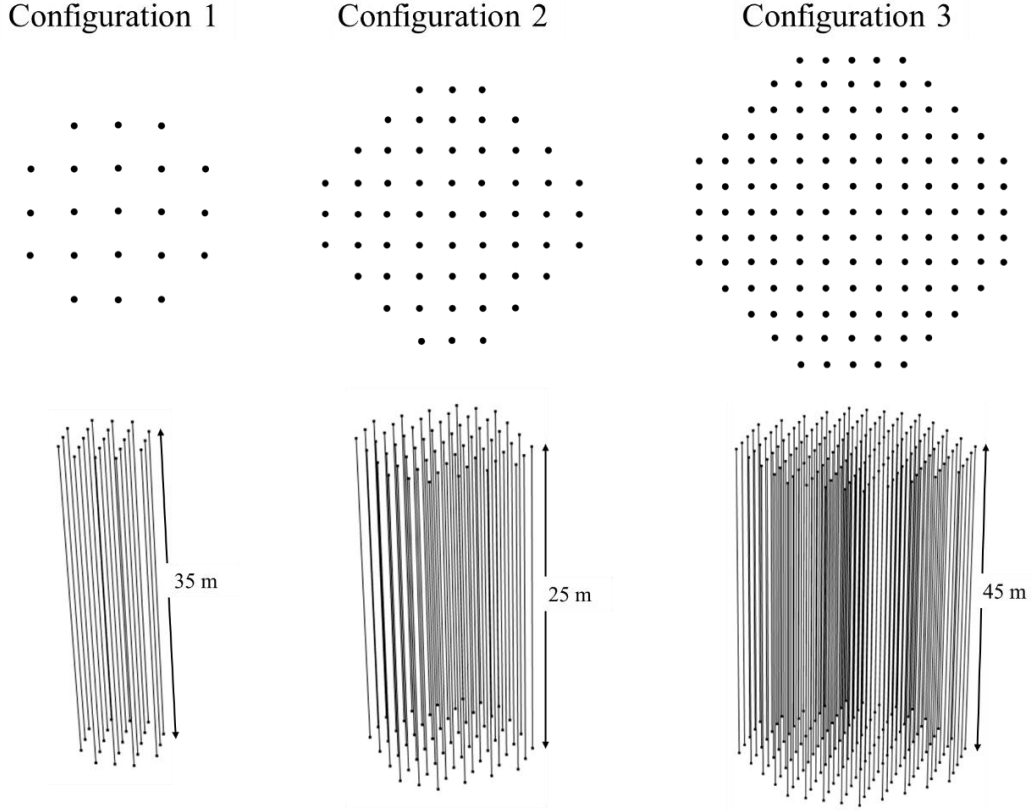


Figure 5.9: Details of SBTES configuration 1 (small scale SBTES), configuration 2 (medium scale SBTES), and configuration 3 (large scale SBTES) selected for design assessment of thermo-hydraulic enclosed barrier.

Subsequently, each enclosed barrier design components (B_z , B_{TH} , D_{Tr} and D_L) is systematically varied as a factor of the SBTES design components (L_{BHE} , S_p) to find the most efficient thermo-hydraulic enclosed barrier design specifications, ensuring optimal thermal performance for the configuration under examination. In this process, barrier design components (B_z , B_{TH} , D_{Tr} and D_L) will be incrementally increased or decreased by 25% to assess its impact on SBTES thermal performance. For instance, in the case of barrier depth B_z , after increasing B_z by 25%, the subsequent improvement in SBTES thermal performance is observed. This process is iterated in 25% increments (25%, 50%, 75%, and so forth) until thermal performance converges. The increments are chosen with practical feasibility in mind. Therefore, the maximum limit for B_z is fixed twice the length of BHE ($2L_{BHE}$) for each configuration studied. A similar approach is followed for the other barrier design components

(B_{TH} , D_{Tr} and D_L). In total, 50 cases are examined for three SBTES configurations to establish a suitable range of barrier design components based on the dimensions of SBTES design components.

5.5.2 Problem description – Simulation set 3

Under simulation set 3, the 3D SBTES domain ($150 \times 110 \times 110 \text{ m}^3$), as defined earlier in Figure 5.3, is selected for analysis. In this SBTES domain, the three BHE array configurations, as described earlier (configuration 1, configuration 2, and configuration3), are sequentially installed for their respective analysis.

For each configuration (Configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35 \text{ m}$, $S_p = 2 \text{ m}$), Configuration 2 ($N_{BHE} = 57$, $L_{BHE} = 25 \text{ m}$, $S_p = 1.5 \text{ m}$), and Configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45 \text{ m}$, $S_p = 2.5 \text{ m}$)), a thermo-hydraulic enclosed barrier is defined with barrier design components B_z , B_{TH} , D_{Tr} and D_L schematically shown in Figure 5.10, 5.11, and 5.12. Each barrier design component (B_z , B_{TH} , D_{Tr} and D_L), are systematically varied to evaluate its influence on SBTES thermal performance.

Starting with configuration 1 (Figure 5.10), the study begins with exploring the most efficient range of enclosed barrier depth B_z as a factor of L_{BHE} . This is achieved by varying enclosed barrier depth B_z as a factor of L_{BHE} ($= 35 \text{ m}$) with a fixed 25% increment. Six cases (Cases 1a-1f) are defined, each involving a different B_z while keeping other barrier components (B_{TH} , D_{Tr} , and D_L) constant. Six cases 1a, 1b, 1c, 1d, 1e, and 1f are defined by assigning B_z as $0.75L_{BHE}$, L_{BHE} , $1.25L_{BHE}$, $1.5L_{BHE}$, $1.75L_{BHE}$, and $2L_{BHE}$, respectively (Table 5.5).

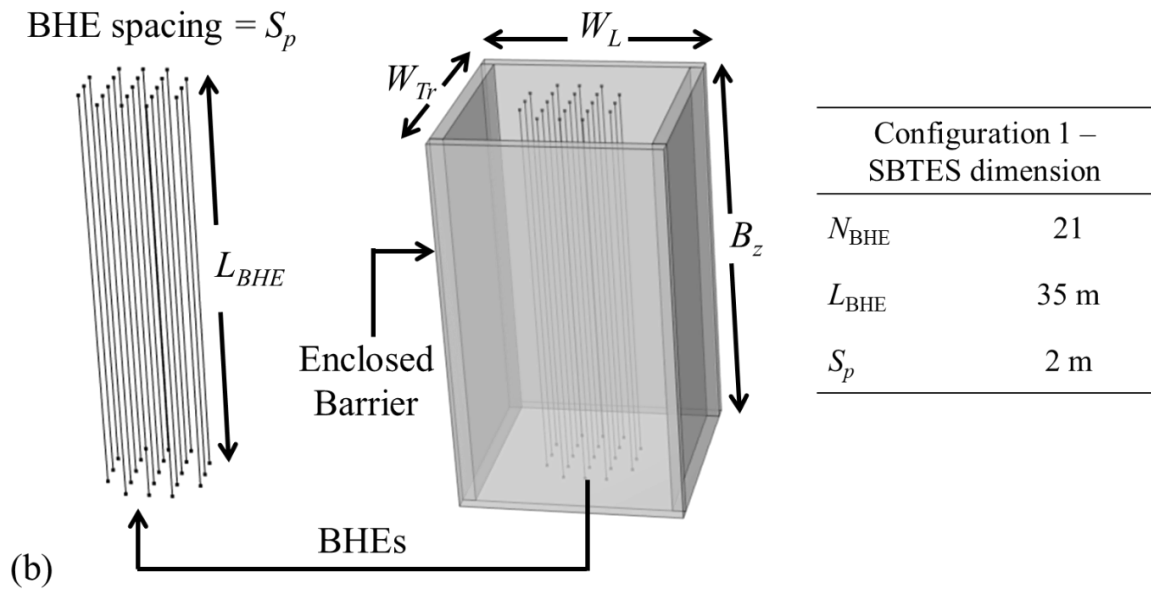
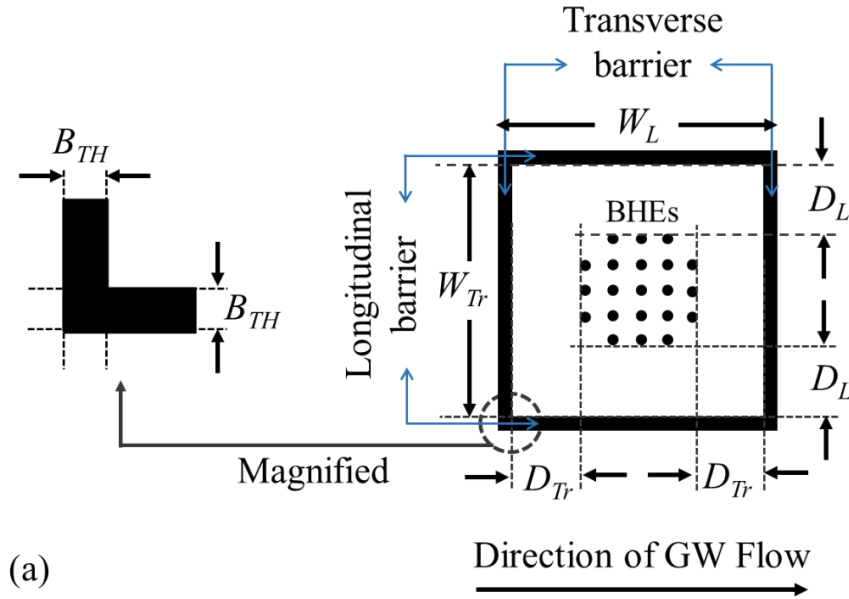


Figure 5.10: (a) Schematic representation illustrating the thermo-hydraulic enclosed barrier integrated with configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35$ m, $S_p = 2$ m) (small-scale SBTES system). It displays dimensions of the barrier design components denoted by their respective symbols, (b) 3D representation of the configuration 1 showing BHE array and thermo-hydraulic enclosed barrier integrated to it.

Table 5.5: Details of SBTES domain and thermo-hydraulic enclosed barrier dimensions for different configurations investigated

	Cases	N_{BHE}	L_{BHE} (m)	S_p (m)	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)	W_{Tr} (m)	W_L (m)	P_B (m)	V_B (m ³)
Configuration 1	1a				$0.75L_{BHE}$	1.2	$2.5S_p$	$2.5S_p$	18	20.4	81.6	2419.2
	1b				L_{BHE}	1.2	$2.5S_p$	$2.5S_p$	18	20.4	81.6	3225.6
	1c				$1.25L_{BHE}$	1.2	$2.5S_p$	$2.5S_p$	18	20.4	81.6	4032.0
	1d				$1.50 L_{BHE}$	1.2	$2.5S_p$	$2.5S_p$	18	20.4	81.6	4838.4
	1e				$1.75L_{BHE}$	1.2	$2.5S_p$	$2.5S_p$	18	20.4	81.6	5644.8
	1f				$2L_{BHE}$	1.2	$2.5S_p$	$2.5S_p$	18	20.4	81.6	6451.2
	1g				L_{BHE}	0.75×1.2	$2.5S_p$	$2.5S_p$	18	19.8	79.2	2381.4
	1h				L_{BHE}	1.25×1.2	$2.5S_p$	$2.5S_p$	18	21	84	4095.0
	1i	21	35	2	L_{BHE}	1.2	$0.25 \times 2.5S_p$	$2.5S_p$	18	12.9	66.6	2595.6
	1j				L_{BHE}	1.2	$0.50 \times 2.5S_p$	$2.5S_p$	18	15.4	71.6	2805.6
	1k				L_{BHE}	1.2	$0.75 \times 2.5S_p$	$2.5S_p$	18	17.9	75.4	3015.6
	1l				L_{BHE}	1.2	$1.25 \times 2.5S_p$	$2.5S_p$	18	22.9	86.6	3435.6
	1m				L_{BHE}	1.2	$2.5S_p$	$0.75 \times 2.5S_p$	15.5	20.4	76.6	3015.6
	1n				L_{BHE}	1.2	$2.5S_p$	$1.25 \times 2.5S_p$	20.5	20.4	86.6	3435.6
	1o				$1.75L_{BHE}$	1.2	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	10.5	12.9	51.6	3439.8
	1p				$1.50L_{BHE}$	1.2	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	10.5	12.9	51.6	2948.4
Configuration 2	2a				$0.75L_{BHE}$	1	$2.5S_p$	$2.5S_p$	19.5	21.5	86	1537.5
	2b				L_{BHE}	1	$2.5S_p$	$2.5S_p$	19.5	21.5	86	2050.0
	2c				$1.25L_{BHE}$	1	$2.5S_p$	$2.5S_p$	19.5	21.5	86	2562.5
	2d				$1.50L_{BHE}$	1	$2.5S_p$	$2.5S_p$	19.5	21.5	86	3075.0
	2e				$1.75L_{BHE}$	1	$2.5S_p$	$2.5S_p$	19.5	21.5	86	3587.5
	2f				$2L_{BHE}$	1	$2.5S_p$	$2.5S_p$	19.5	21.5	86	4100.0
	2g	57	25	1.5	L_{BHE}	0.75×1	$2.5S_p$	$2.5S_p$	19.5	21	84	1518.8
	2h				L_{BHE}	1.25×1	$2.5S_p$	$2.5S_p$	19.5	22	88	2593.8
	2i				L_{BHE}	1	$0.25 \times 2.5S_p$	$2.5S_p$	19.5	15.875	74.75	1768.8
	2j				L_{BHE}	1	$0.50 \times 2.5S_p$	$2.5S_p$	19.5	17.75	78.5	1862.5
	2k				L_{BHE}	1	$0.75 \times 2.5S_p$	$2.5S_p$	19.5	19.625	82.25	1956.3
	2l				L_{BHE}	1	$1.25 \times 2.5S_p$	$2.5S_p$	19.5	23.375	89.75	2143.8

Configuration 3	2m				L_{BHE}	1	$2.5S_p$	$0.75 \times 2.5S_p$	17.625	21.5	82.25	1956.3
	2n				L_{BHE}	1	$2.5S_p$	$1.25 \times 2.5S_p$	21.375	21.5	89.75	2143.8
	2o				$2L_{BHE}$	1	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	13.875	15.875	63.5	2975.0
	2p				$1.75L_{BHE}$	1	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	13.875	15.875	63.5	2603.1
	2q				$1.50L_{BHE}$	1	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	13.875	15.875	63.5	2231.3
	3a				$0.75L_{BHE}$	1.5	$2.5S_p$	$2.5S_p$	42.5	45.5	182	8910.0
	3b				L_{BHE}	1.5	$2.5S_p$	$2.5S_p$	42.5	45.5	182	11880.0
	3c				$1.25L_{BHE}$	1.5	$2.5S_p$	$2.5S_p$	42.5	45.5	182	14850.0
	3d				$1.50L_{BHE}$	1.5	$2.5S_p$	$2.5S_p$	42.5	45.5	182	17820.0
	3e				$1.75L_{BHE}$	1.5	$2.5S_p$	$2.5S_p$	42.5	45.5	182	20790.0
	3f				$2L_{BHE}$	1.5	$2.5S_p$	$2.5S_p$	42.5	45.5	182	23760.0
	3g				L_{BHE}	0.75×1.5	$2.5S_p$	$2.5S_p$	42.5	44.75	179	8834.1
	3h				L_{BHE}	1.25×1.5	$2.5S_p$	$2.5S_p$	42.5	46.25	185	14976.6
	3i	129	45	2.5	L_{BHE}	1.5	$0.25 \times 2.5S_p$	$2.5S_p$	42.5	36.125	163.25	10614.4
	3j				L_{BHE}	1.5	$0.50 \times 2.5S_p$	$2.5S_p$	42.5	39.25	169.5	11036.3
	3k				L_{BHE}	1.5	$0.75 \times 2.5S_p$	$2.5S_p$	42.5	42.375	175.75	11458.1
	3l				L_{BHE}	1.5	$1.25 \times 2.5S_p$	$2.5S_p$	42.5	48.625	188.25	12301.9
	3m				L_{BHE}	1.5	$2.5S_p$	$0.75 \times 2.5S_p$	39.375	45.5	175.75	11458.1
	3n				L_{BHE}	1.5	$2.5S_p$	$1.25 \times 2.5S_p$	45.625	45.5	188.25	12301.9
	3o				$2L_{BHE}$	1.5	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	33.125	36.125	144.5	18697.5
	3p				$1.75L_{BHE}$	1.5	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	33.125	36.125	144.5	16360.3
	3q				$1.50L_{BHE}$	1.5	$0.25 \times 2.5S_p$	$0.25 \times 2.5S_p$	33.125	36.125	144.5	14023.1

After this, the role of the enclosed barrier thickness B_{TH} on the thermal performance of SBTES for configuration 1 is explored. The preliminary value of B_{TH} ($= 1.2$ m) is varied with a fixed increment of 25%, while keeping other barrier design components (B_z , D_{Tr} , and D_L) constant. Three cases (cases 1g, 1b, and 1h) are defined, with B_{TH} values of 0.75×1.2 , 1.2 , and 1.25×1.2 , respectively (Table 5.5).

Similarly, the role of the distance between the transverse barrier and the BHE array D_{Tr} is investigated for configuration 1. The preliminary value of D_{Tr} ($= 2.5S_p = 2.5 \times 2$ m) is varied

as a factor of $2.5S_p$ with a fixed increment of 25% at each step, while keeping other barrier design components (B_z , B_{TH} , and D_L) constant. Five cases 1i, 1j, 1k, 1b, and 1l are defined by assigning D_{Tr} as $0.25 \times 2.5S_p$, $0.50 \times 2.5S_p$, $0.75 \times 2.5S_p$, $2.5S_p$, and $1.25 \times 2.5S_p$, respectively (Table 5.5).

Finally, the role of the distance between longitudinal barrier and BHE array D_L on the thermal performance of SBTES system is investigated for configuration 1. The preliminary value of D_L ($= 2.5S_p = 2.5 \times 2$ m) is varied as a factor of $2.5S_p$ with a fixed increment of 25% at each step, while keeping other barrier design components (B_z , B_{TH} , and D_{Tr}) constant. Three cases 1m, 1b, and 1n are defined, with D_L values as $0.75 \times 2.5S_p$, $2.5S_p$, and $1.25 \times 2.5S_p$, respectively (Table 5.5).

It is crucial to note that Case 1b represents preliminary barrier design for Configuration 1. This makes it a benchmark for comparing the effects of specific barrier design components. Case 1b is compared with Cases 1a, 1c-1f to analyze the influence of B_z , followed by comparisons with cases 1g-1h to study the impact of B_{TH} . Similarly, it's compared with Cases 1i-1l and 1m-1n to assess the influence of D_{Tr} and D_L , respectively.

This concludes the cases studied to find suitable range of barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) for configuration 1.

The same process is repeated for configuration 2 ($N_{BHE} = 57$, $L_{BHE} = 25$ m, $S_p = 1.5$ m), with barrier design components (B_{TH} , D_{Tr} , and D_L) adjusted to fit the dimensions of this configuration (Figure 5.11). Accordingly, six cases 2a, 2b, 2c, 2d, 2e, and 2f are defined, with B_z values of $0.75L_{BHE}$, L_{BHE} , $1.25L_{BHE}$, $1.5L_{BHE}$, $1.75L_{BHE}$, and $2L_{BHE}$, respectively (Table 5.5). After this, three cases (cases 2g, 2b, and 2h) are defined, with B_{TH} values as 0.75×1 m, 1 m, and 1.25×1 m, respectively. Similarly, five cases 2i, 2j, 2k, 2b, and 2l are defined, with D_{Tr} as $0.25 \times 2.5S_p$, $0.50 \times 2.5S_p$, $0.75 \times 2.5S_p$, $2.5S_p$, and $1.25 \times 2.5S_p$, respectively (Table 5.5). Finally, three cases 2m, 2b, and 2n are defined by assigning D_L as $0.75 \times 2.5S_p$, $2.5S_p$, and $1.25 \times 2.5S_p$,

respectively (Table 5.5). For configuration 2, case 2b represents preliminary barrier design and serves as a benchmark for comparing the effects of specific barrier design components. This concludes the cases studied to find suitable range of barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) corresponding to the configuration 2.

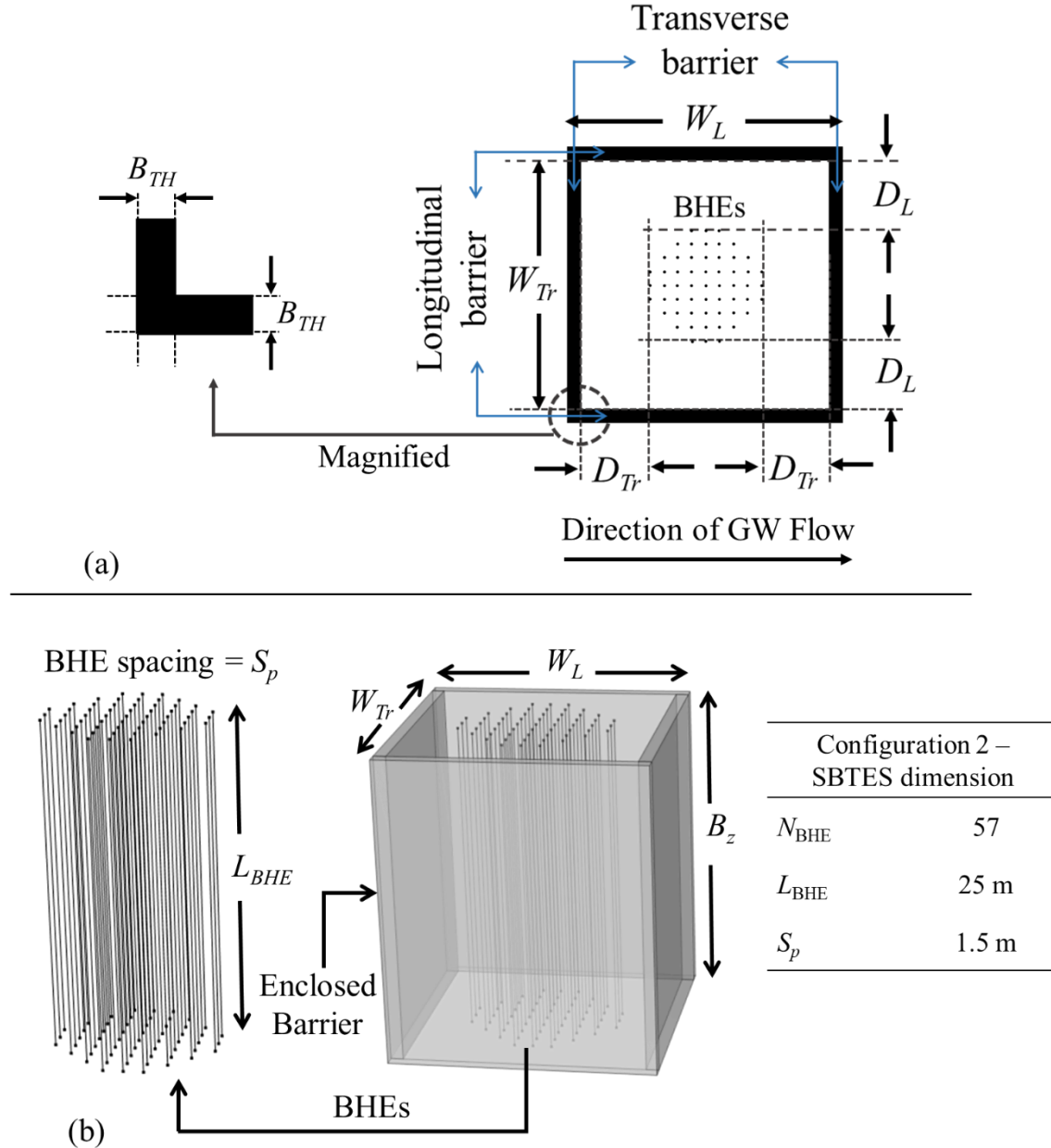


Figure 5.11: (a) Schematic representation illustrating the thermo-hydraulic enclosed barrier integrated with configuration 2 ($N_{BHE} = 57$, $L_{BHE} = 25$ m, $S_p = 1.5$ m) (medium-scale SBTES system). It displays dimensions of the barrier design components denoted by their respective symbols, (b) 3D representation of the configuration 2 showing BHE array and thermo-hydraulic enclosed barrier integrated to it.

The study concludes with configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45$ m, $S_p = 2.5$ m), again adapting the barrier components to suit this configuration (Figure 5.12). This leads to six cases 3a, 3b, 3c, 3d, 3e, and 3f defined with B_z values of $0.75L_{BHE}$, L_{BHE} , $1.25L_{BHE}$, $1.5L_{BHE}$, $1.75L_{BHE}$, and $2L_{BHE}$, respectively. Then three cases (cases 3g, 3b, and 3h) are defined, with B_{TH} values as 0.75×1 m, 1 m, and 1.25×1 m, respectively. Followed by five cases 3i, 3j, 3k, 3b, and 3l defined with D_{Tr} as $0.25 \times 2.5S_p$, $0.50 \times 2.5S_p$, $0.75 \times 2.5S_p$, $2.5S_p$, and $1.25 \times 2.5S_p$, respectively (Table 5.5). Finally, three cases 3m, 3b, and 3n are defined, with D_L values of $0.75 \times 2.5S_p$, $2.5S_p$, and $1.25 \times 2.5S_p$, respectively (Table 5.5). For configuration 3, case 3b represents preliminary barrier design and serves as a benchmark for comparing the effects of specific barrier design components. This concludes the cases studied to find suitable range of barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) corresponding to the configuration 3.

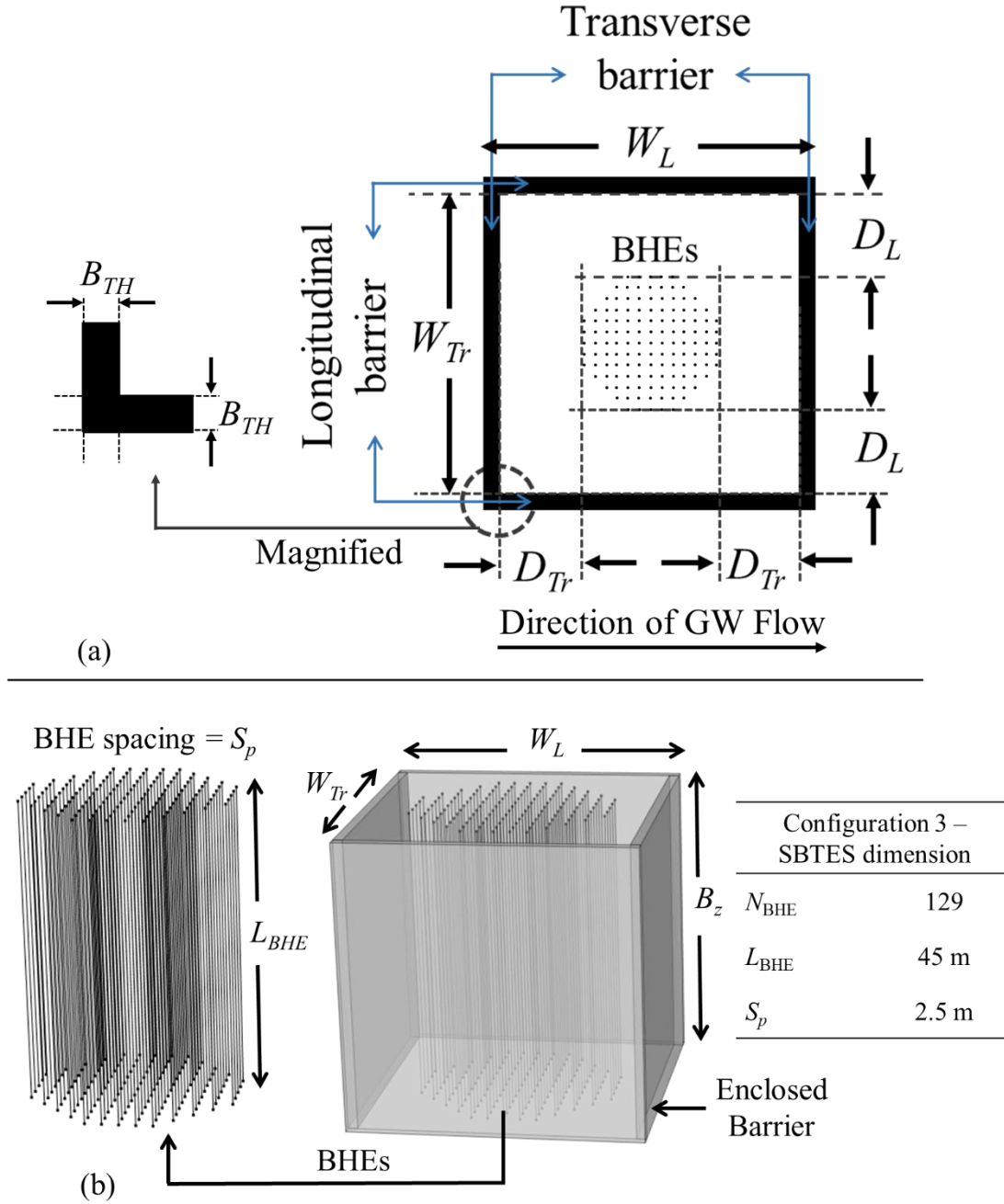


Figure 5.12: (a) Schematic representation illustrating the thermo-hydraulic enclosed barrier integrated with configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45$ m, $S_p = 2.5$ m) (large-scale SBTES system). It displays dimensions of the barrier design components denoted by their respective symbols, (b) 3D representation of the configuration 3 showing BHE array and thermo-hydraulic enclosed barrier integrated to it.

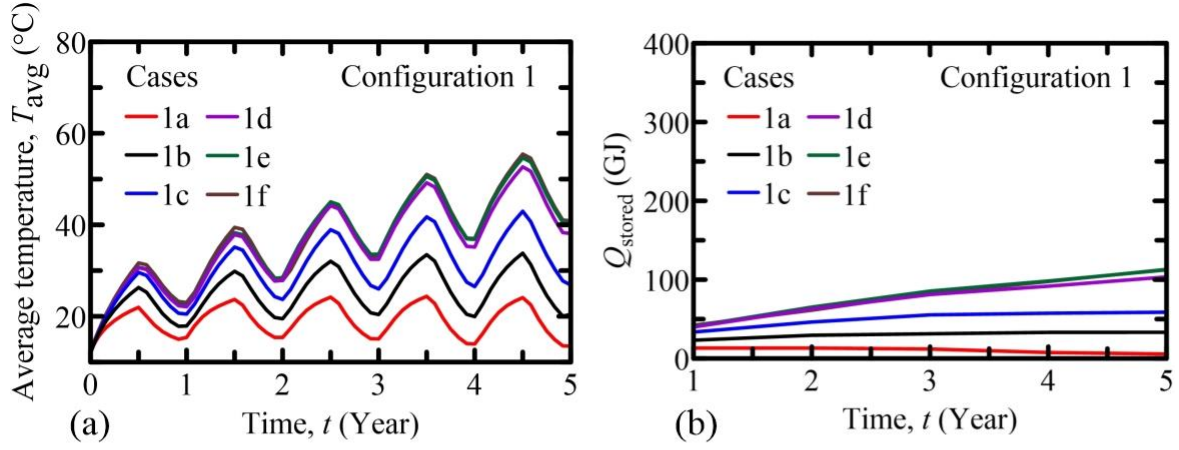
While present study specifically focuses on four enclosed barrier design components B_z , B_{TH} , D_{Tr} , and D_L , Table 5.5 provides a detailed breakdown of the geometry of the thermo-hydraulic enclosed barrier for all three configurations. The additional specifications include the

width of the transverse W_{Tr} and longitudinal W_L barriers, outer perimeter P_B , and construction material volume V_B of the enclosed thermo-hydraulic barrier in each case studied. This additional information offers a comprehensive view of the study and simultaneously provides a foundation for future studies to engage in a thorough barrier design optimization around these specifications to achieve an optimal enclosed barrier geometry that not only enhances SBTES thermal performance but also minimizes construction costs.

5.5.3 Thermal performance analysis for configurations 1, 2, and 3

5.5.3.1 Configuration 1 - Design assessment

Figures 5.13(a) and (b) show T_{avg} and Q_{stored} as functions of time for the cases (1a, 1b, 1c, 1d, 1e, 1f) exploring the influence of B_z on the thermal performance of SBTES system for configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35$ m, $S_p = 2$ m), investigated under simulation set 3. It also shows absolute values of the barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) for each case corresponding to the systematic variation of B_z as described in Table 5.5.



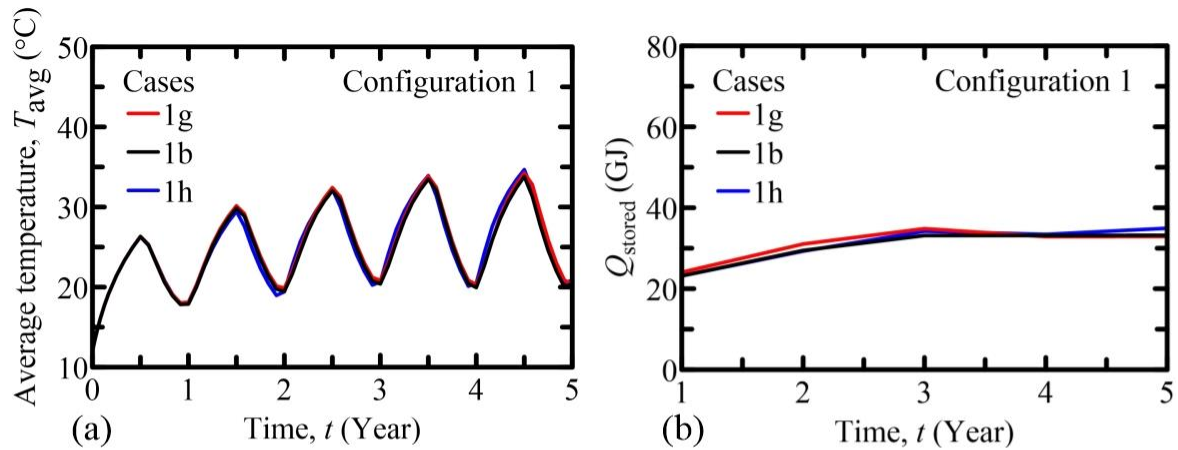
Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35$ m, $S_p = 2$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
1a	26.25 ($= 0.75L_{BHE}$)			
1b	35 ($= L_{BHE}$)			
1c	43.75 ($= 1.25L_{BHE}$)	1.2	5 ($= 2.5S_p$)	5 ($= 2.5S_p$)
1d	52.50 ($= 1.50L_{BHE}$)			
1e	61.25 ($= 1.75L_{BHE}$)			
1f	70 ($= 2L_{BHE}$)			

Figure 5.13: Comparative thermal performance analysis of configuration 1 integrated with thermo-hydraulic enclosed barrier with varying B_z Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 1 SBTES domain with time, providing a comparison of thermal performance of configuration 1 for different B_z cases (1a-1f).

Case 1a, where the depth of enclosed barrier B_z equals to 0.75 times the length of BHE L_{BHE} , achieves lowest T_{avg} and Q_{stored} among the other cases studied. Therefore, case 1a provides the poorest thermal performance among cases (1a, 1b, 1c, 1d, 1e, 1f) that explores influence of B_z on the thermal performance of SBTES for configuration 1. Furthermore, it is observed that the thermal performance in terms of T_{avg} and Q_{stored} , increases in ascending order for cases 1b, 1c, 1d, 1e, and 1f. This indicates an improvement in the thermal performance of SBTES with an increase in B_z . Interestingly, the thermal performance recorded for cases 1d, 1e, and 1f, in terms of T_{avg} and Q_{stored} , are identical, as evident from the closely overlapping plots. This observation suggests that although the thermal performance of the SBTES improves

with an increase in B_z , this improvement converges at $B_z = 1.5L_{BHE}$, corresponding to the case 1d. This implies extending B_z beyond $1.5L_{BHE}$ does not result in further improvement in the thermal performance of SBTES for configuration 1. Therefore, $B_z = 1.5L_{BHE}$ or higher ($1.75L_{BHE}$ and $2L_{BHE}$) provides equally optimal thermal performance among the cases (1a, 1b, 1c, 1d, 1e, 1f) studied to explore the influence of B_z on the thermal performance of SBTES.

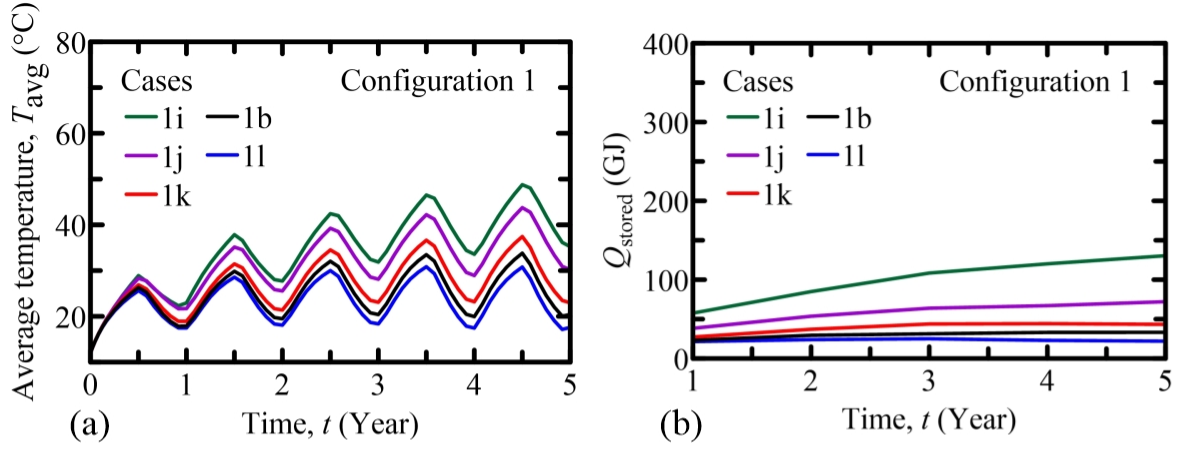
Figures 5.14(a) and (b) show T_{avg} and Q_{stored} as functions of time for the cases (1g, 1b, 1h) investigating the influence of B_{TH} on the thermal performance of SBTES system for configuration 1, studied under simulation set 3. The thermal performance observed for cases 1g, 1b, and 1h shows no variation for different B_{TH} . Therefore, for the present study, it can be concluded that thickness of the enclosed barrier B_{TH} does not have any influence on the thermal performance of SBTES for configuration 1.



Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35$ m, $S_p = 2$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
Configuration 1	1b	1.2		
	1g	35 ($= L_{BHE}$)	0.9 ($= 0.75 \times 1.2$)	5 ($= 2.5S_p$)
	1h	1.5 ($= 1.25 \times 1.2$)		

Figure 5.14: Comparative thermal performance analysis of configuration 1 integrated with thermo-hydraulic enclosed barrier with varying B_{TH} Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 1 SBTES domain with time, providing a comparison of thermal performance of configuration 1 for different B_{TH} cases (1g, 1b, 1h).

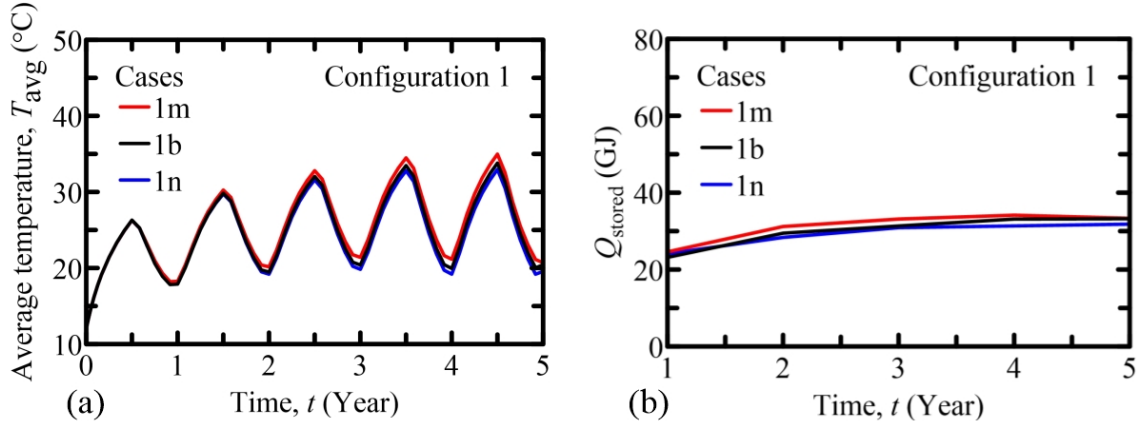
Figures 5.15(a) and (b) show T_{avg} and Q_{stored} as functions of time for the cases (1i, 1j, 1k, 1b, 1l) studying the influence of D_{Tr} on the thermal performance of SBTES system for configuration 1, investigated under simulation set 3. Case 1i, where D_{Tr} equals to 0.25 times $2.5S_p$ (preliminary selection), achieves the maximum T_{avg} and Q_{stored} among the other cases studied (1i, 1j, 1k, 1b, 1l). Among the cases (1i, 1j, 1k, 1b, 1l) studied to investigate the role of D_{Tr} , case 1i defines the shortest distance between transverse barrier and the BHE array. Furthermore, it is observed that the thermal performance in terms of T_{avg} and Q_{stored} , decreases in descending order for cases 1l, 1b, 1k, 1j, and 1i. This indicates that thermal performance of SBTES improves with reduction in D_{Tr} . This analysis concludes that the shortest D_{Tr} offers the optimal thermal performance among the cases (1i, 1j, 1k, 1b, 1l) studied to explore the influence of D_{Tr} on the thermal performance of SBTES.



Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35$ m, $S_p = 2$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
1b			5 ($= 2.5S_p$)	
1i			1.25 ($= 0.25 \times 2.5S_p$)	
1j	35 ($= L_{BHE}$)	1.2	2.5 ($= 0.50 \times 2.5S_p$)	5 ($= 2.5S_p$)
1k			3.75 ($= 0.75 \times 2.5S_p$)	
1l			6.25 ($= 1.25 \times 2.5S_p$)	

Figure 5.15: Comparative thermal performance analysis of configuration 1 integrated with thermo-hydraulic enclosed barrier with varying D_{Tr} Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 1 SBTES domain with time, providing a comparison of thermal performance of configuration 1 for different D_{Tr} cases (1i, 1j, 1k, 1b, 1l).

Figures 5.16(a) and (b) show T_{avg} and Q_{stored} as functions of time for the cases (1m, 1b, 1n) exploring the influence of D_L on the thermal performance of SBTES system for configuration 1, studied under simulation set 3. The thermal performance observed for cases 1m, 1b, and 1n shows no variation for different D_L . Therefore, for the present study, it can be concluded that the distance between longitudinal barrier and BHE array D_L does not have any influence on the thermal performance of the SBTES. This suggests that while selecting D_L , it is logical to choose shortest D_L as it will ensure lesser outer perimeter P_B of the enclosed barrier while not compromising on the thermal performance of SBTES.



Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 1 ($N_{BHE} = 21$, $L_{BHE} = 35$ m, $S_p = 2$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
Configuration 1	1b			5 ($= 2.5S_p$)
	1m	35 ($= L_{BHE}$)	1.2	5 ($= 2.5S_p$) 3.75 ($= 0.75 \times 2.5S_p$)
	1n			6.25 ($= 1.25 \times 2.5S_p$)

Figure 5.16: Comparative thermal performance analysis of configuration 1 integrated with thermo-hydraulic enclosed barrier with varying D_L Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 1 SBTES domain with time, providing a comparison of thermal performance of configuration 1 for different D_L cases (1m, 1b, 1n).

5.5.3.1.1 Design improvement for configuration 1

Additional simulations are performed to find the values of barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) that can provide best thermal performance for configuration 1, incorporating insights gained from the individual analyses of B_z , B_{TH} , D_{Tr} , and D_L on SBTES thermal performance. This is achieved by defining two additional cases, 1o and 1p, for configuration 1. These cases are thoughtfully designed by selecting values for each barrier design component (B_z , B_{TH} , D_{Tr} , and D_L) that had yielded the best thermal performance in previous individual component studies.

In this process, the values of D_{Tr} and D_L are set at 0.25 times the preliminary value (i.e., $2.5S_p$), based on the observation that the shortest D_{Tr} (case 1i) had delivered the best thermal performance. Moreover, different values of D_L did not exhibit any visible influence on thermal

performance. Thus, the shortest distances specified in case 1i are chosen for both D_{Tr} and D_L to minimize the outer perimeter P_B while maintaining consistent thermal performance (Figure 5.16). Consequently, in both cases 1o and 1p, the transverse and longitudinal barriers are positioned at the closest proximity to the BHE array, with D_{Tr} and D_L defined as $0.25 \times 2.5S_p$.

Given that B_{TH} showed no impact on the thermal performance of SBTES, its preliminary value (1.2 m) is selected for both cases 1o and 1p. Thus, in cases 1o and 1p, B_{TH} , D_{Tr} , and D_L hold identical values, with the only variation occurring in the barrier depth B_z . During the investigation of influence of B_z on thermal performance of configuration 1, it was established that extending B_z beyond $1.5L_{BHE}$ did not yield any improvements in SBTES thermal performance. To validate whether this finding holds true for cases 1o and 1p, where other barrier design components are modified, two values of B_z are explored. For case 1o, B_z is set at $1.75L_{BHE}$, and for case 1p, B_z is defined as $1.5L_{BHE}$.

Figure 5.17(a)-(b) presents a comparative analysis of these new cases, 1o and 1p, alongside the previously identified best-performing cases for configuration 1, from the individual investigations of each barrier design component (B_z , B_{TH} , D_{Tr} , and D_L). Notably, both cases 1o and 1p exhibit superior thermal performance compared to cases 1b, 1e, and 1i, which had shown the best performance in their respective component studies. This proves that cases 1o and 1p provide significant advancements in the enclosed barrier design for Configuration 1.

Furthermore, it is crucial to highlight that both cases 1o and 1p provide identical thermal performance, as evident by the overlapping plots. Therefore, the earlier observation, where extending B_z beyond $1.5L_{BHE}$ did not lead to any improvement in SBTES thermal performance, is reaffirmed in cases 1o and 1p. Consequently, as both cases 1o and 1p deliver identical thermal performance, case 1p emerges as the final and optimal enclosed barrier design for

Configuration 1. It offers reduced construction material volume compared to case 1o due to lower B_z while delivering the same level of thermal performance.

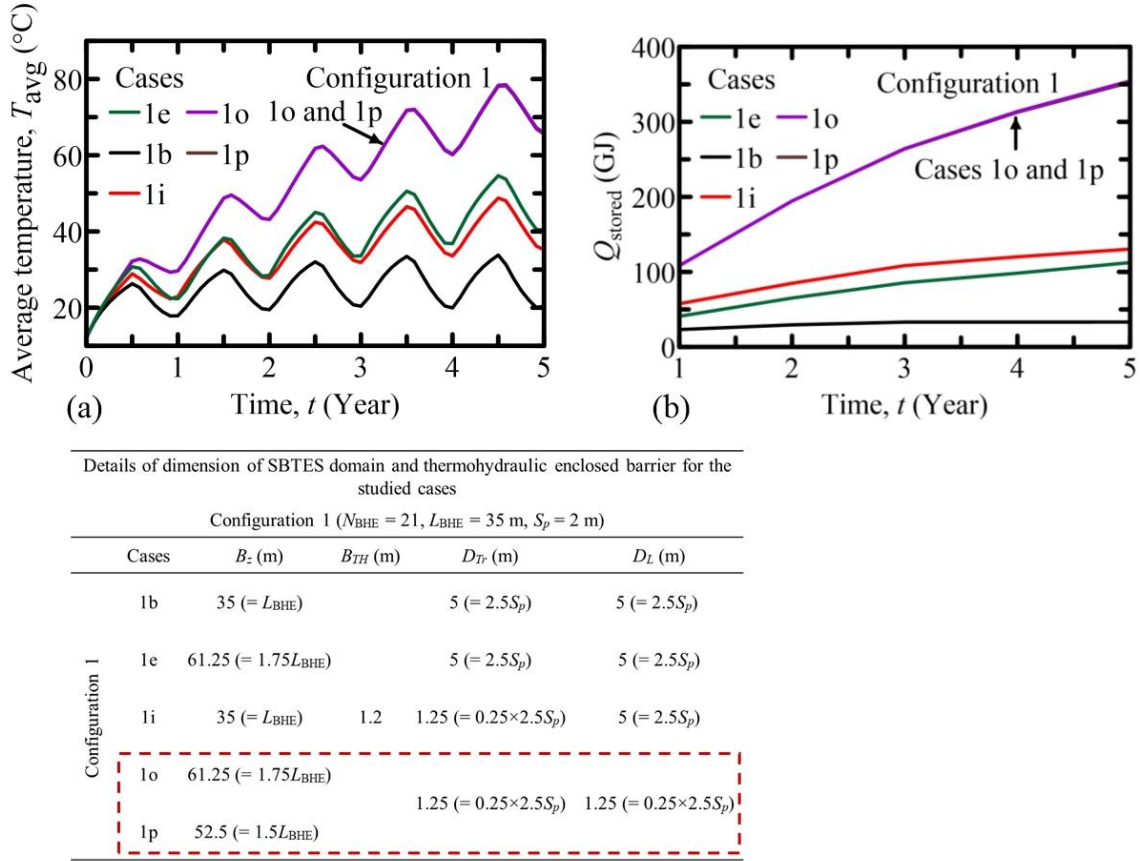
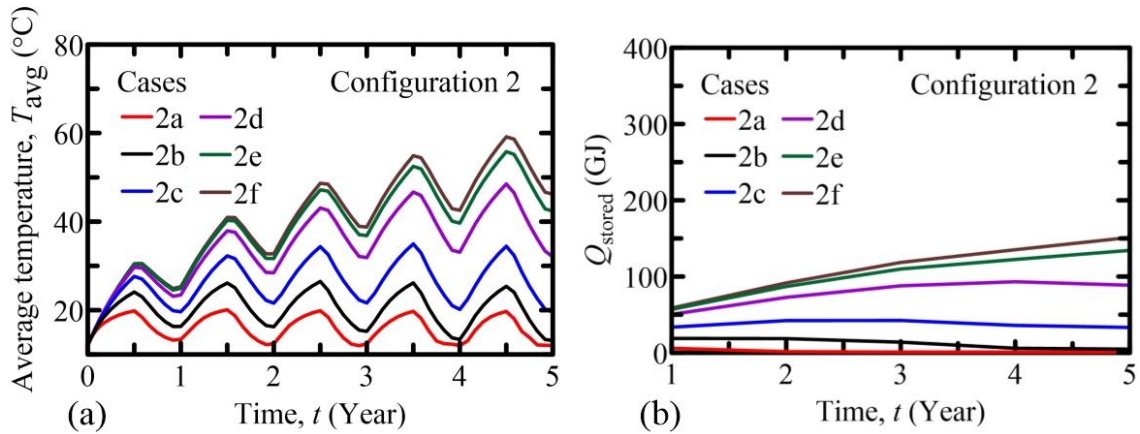


Figure 5.17: Comparative analysis of improved thermo-hydraulic enclosed barrier design for configuration 1. The plot shows calculated T_{avg} and Q_{stored} in configuration 1 SBTES domain with time. Cases 1o and 1p present performance evaluation of the improved barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) specifically customized based on their respective impact on the thermal performance of the SBTES system.

5.5.3.2 Configuration 2 – Design assessment

Figures 5.18(a)-(b) show T_{avg} and Q_{stored} as functions of time for cases (2a, 2b, 2c, 2d, 2e, 2f) investigating the influence of B_z on the thermal performance of the medium-scale SBTES system defined by Configuration 2 ($N_{BHE} = 57$, $L_{BHE} = 25$ m, $S_p = 1.5$ m), as examined under simulation set 3. Among studied cases (2a, 2b, 2c, 2d, 2e, 2f), 2a, where the depth of the enclosed barrier B_z equals 0.75 times the length of BHE (L_{BHE}), records the lowest T_{avg} and Q_{stored} . Therefore, case 2a exhibits the poorest thermal performance among the explored cases

(2a, 2b, 2c, 2d, 2e, 2f) focusing on the influence of B_z for Configuration 2. Notably, the thermal performance, indicated by T_{avg} and Q_{stored} , ascends in sequential order for cases 2b, 2c, 2d, 2e, and 2f, showing an increase in SBTES performance with an increase in B_z . Interestingly, cases 2e and 2f exhibit closely superimposing plots, indicating a convergence in thermal performance. This indicates that although SBTES performance improves with higher B_z , this enhancement stabilizes at $B_z = 1.75L_{BHE}$, corresponding to case 2e. Beyond this threshold, no further improvement in thermal performance is recorded for configuration 2. Thus, $B_z = 1.75L_{BHE}$ or higher ($2L_{BHE}$) offers comparable and optimal thermal performance among the cases (2a, 2b, 2c, 2d, 2e, 2f) examined for the influence of B_z on SBTES thermal performance for configuration 2.

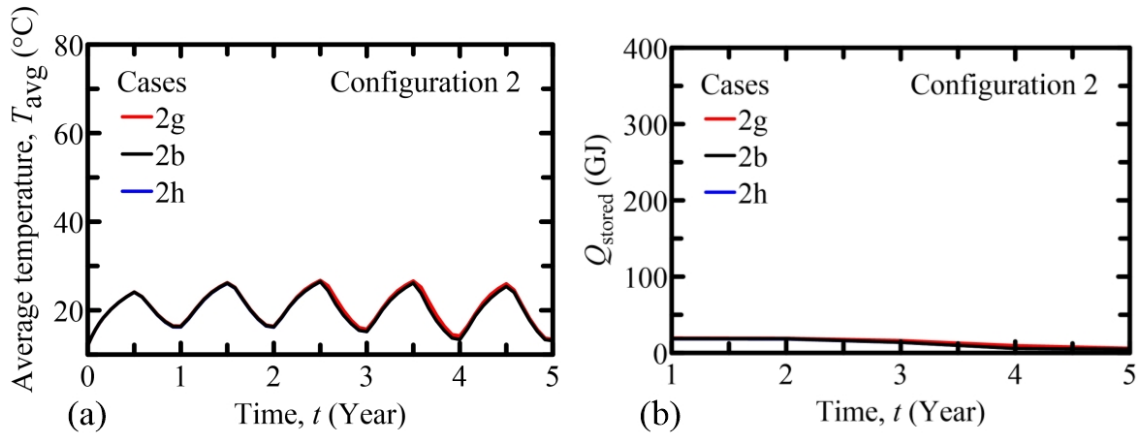


Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 2 ($N_{BHE} = 57, L_{BHE} = 25$ m, $S_p = 1.5$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
2a	18.75 (= $0.75L_{BHE}$)	1	3.75 (= $2.5S_p$)	3.75 (= $2.5S_p$)
2b	25 (= L_{BHE})			
2c	31.25 (= $1.25L_{BHE}$)			
2d	37.50 (= $1.50L_{BHE}$)			
2e	43.75 (= $1.75L_{BHE}$)			
2f	50 (= $2L_{BHE}$)			

Figure 5.18: Comparative thermal performance analysis of configuration 2 integrated with thermo-hydraulic enclosed barrier with varying B_z Values. The plot shows calculated T_{avg} and

Q_{stored} in configuration 2 SBTES domain with time, providing a comparison of thermal performance of configuration 2 for different B_z cases (2a-2f).

Figures 5.19(a)-(b) show T_{avg} and Q_{stored} over time for cases (2g, 2b, 2h), studying the impact of B_{TH} on the thermal performance of the SBTES system for configuration 2, under simulation set 3. The thermal performance observed for cases 2g, 2b, and 2h remains consistent across different B_{TH} values. Thus, it can be concluded that the thickness of the enclosed barrier B_{TH} does not have any influence on the thermal performance of the SBTES system for configuration 2.

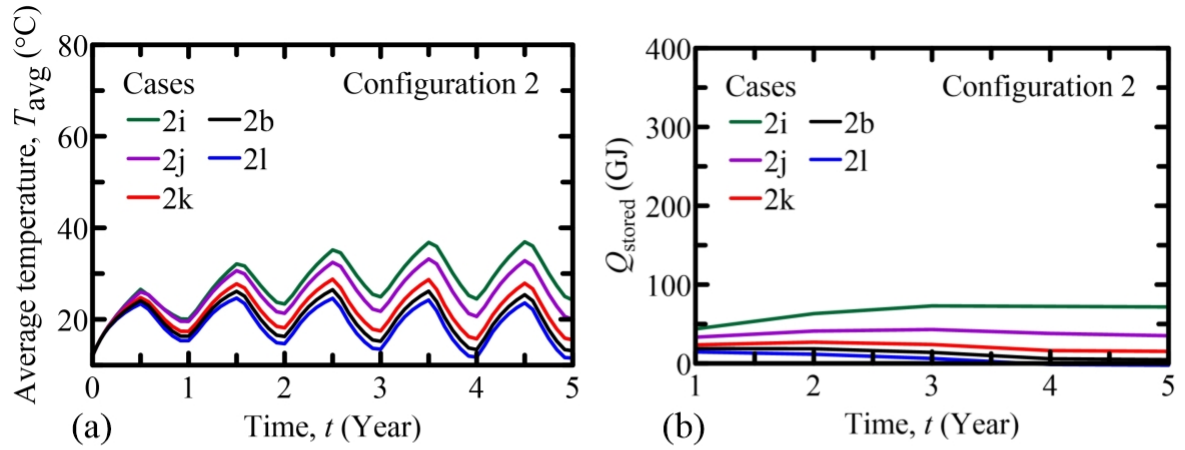


Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 2 ($N_{BHE} = 57$, $L_{BHE} = 25$ m, $S_p = 1.5$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
Configuration 2	2b	1		
	2g	25 (= L_{BHE})	0.75 (= 0.75×1)	3.75 (= $2.5 S_p$)
	2h	1.25 (= 1.25×1)		

Figure 5.19: Comparative thermal performance analysis of configuration 2 integrated with thermo-hydraulic enclosed barrier with varying B_{TH} Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 2 SBTES domain with time, providing a comparison of thermal performance of configuration 2 for different B_{TH} cases (2g, 2b, 2h).

Figures 5.20(a)-(b) show T_{avg} and Q_{stored} as functions of time for the cases (2i, 2j, 2k, 2b, 2l) investigating the influence of D_{Tr} on the thermal performance of the SBTES system for configuration 2. Among these cases (2i, 2j, 2k, 2b, 2l), 2i, where D_{Tr} equals 0.25 times the $2.5 S_p$ (preliminary design selection), attains the highest T_{avg} and Q_{stored} . Notably, case 2i establishes

the shortest distance between the transverse barrier and the BHE array within the cases (2i, 2j, 2k, 2b, 2l) studied. Furthermore, it is observed that the thermal performance descends in descending order for cases 2l, 2b, 2k, 2j, and 2i. This suggests that the thermal performance of the SBTES system improves with a reduction in D_{Tr} . This analysis leads to the conclusion that the shortest D_{Tr} offers the best thermal performance for the SBTES system for configuration 2 as well.



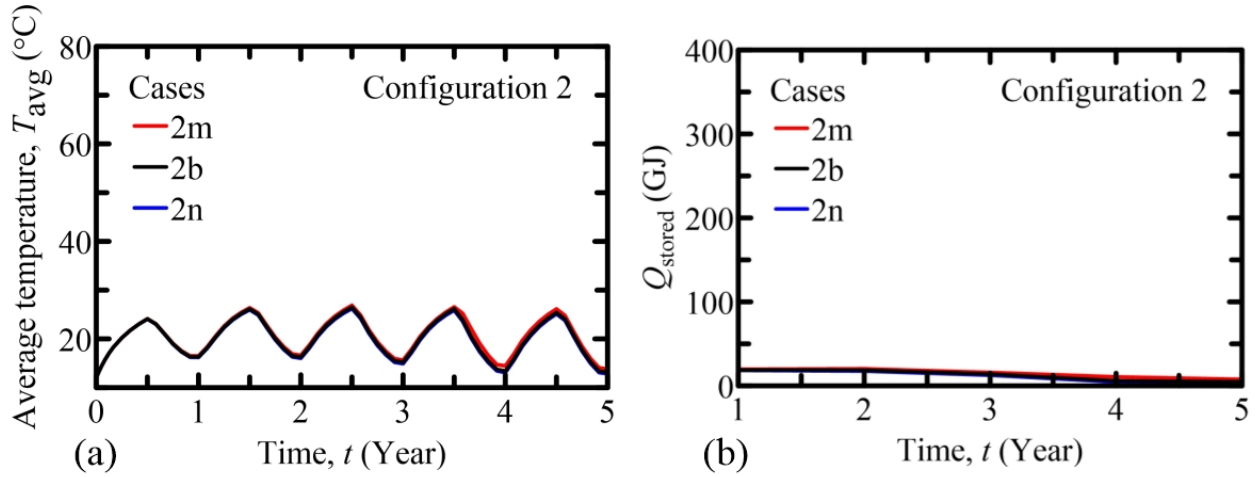
Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases

Configuration 2 ($N_{BHE} = 57, L_{BHE} = 25$ m, $S_p = 1.5$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
2b			3.75 ($= 2.5S_p$)	
2i			0.9375 ($= 0.25 \times 2.5S_p$)	
2j	25 ($= L_{BHE}$)	1	1.875 ($= 0.50 \times 2.5S_p$)	3.75 ($= 2.5S_p$)
2k			2.8125 ($= 0.75 \times 2.5S_p$)	
2l			4.6875 ($= 1.25 \times 2.5S_p$)	

Figure 5.20: Comparative thermal performance analysis of configuration 2 integrated with thermo-hydraulic enclosed barrier with varying D_{Tr} Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 2 SBTES domain with time, providing a comparison of thermal performance of configuration 2 for different D_{Tr} cases (2i, 2j, 2k, 2b, 2l).

Figures 5.21(a)-(b) present T_{avg} and Q_{stored} as functions of time for the cases (2m, 2b, 2n) exploring the influence of D_L on the thermal performance of the SBTES system for Configuration 2, investigated under simulation set 3. The thermal performance observed for cases 2m, 2b, and 2n remains consistent across different D_L values. Thus, it can be concluded

that the distance between the longitudinal barrier and BHE array D_L does not exert any influence on the thermal performance of the SBTES system for configuration 2. This suggests that, when selecting D_L , it is logical to choose the shortest D_L as it ensures a smaller outer perimeter P_B of the enclosed barrier while not compromising on the thermal performance of the SBTES system.



Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 2 ($N_{BHE} = 57$, $L_{BHE} = 25$ m, $S_p = 1.5$ m)				
	Cases	B_z (m)	B_{TH} (m)	D_L (m)
Configuration 2	2b	25 ($= L_{BHE}$)	1	3.75 ($= 2.5S_p$)
	2m			2.8125 ($= 0.75 \times 2.5S_p$)
	2n			4.6875 ($= 1.25 \times 2.5S_p$)

Figure 5.21: Comparative thermal performance analysis of configuration 2 integrated with thermo-hydraulic enclosed barrier with varying D_L Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 2 SBTES domain with time, providing a comparison of thermal performance of configuration 2 for different D_L cases (2m, 2b, 2n).

5.5.3.2.1 Design improvement for configuration 2

To further refine the design of enclosed barrier for configuration 2, additional simulations are conducted, leveraging insights gained from the individual analysis of the barrier design components (B_z , B_{TH} , D_{Tr} , and D_L). This involves defining additional cases 2o, 2p, and

2q, by selecting values for each barrier design component (B_z , B_{TH} , D_{Tr} , and D_L) that had yielded the optimal thermal performance in previous individual component studies.

In this process, D_{Tr} and D_L are set at 0.25 times their preliminary values (i.e., $2.5S_p$). This decision is supported by the outstanding performance of the shortest D_{Tr} (case 2i) and the observation that varying D_L values had no impact on the SBTES thermal performance. Thus, the minimal distance specified in case 2i is selected for both D_{Tr} and D_L , to minimize the outer perimeter P_B , while maintaining consistent thermal performance (Figure 5.21). Therefore, in cases 2o, 2p, and 2q, both transverse and longitudinal barriers are positioned in closest proximity to the BHE array, defining D_{Tr} and D_L as $0.25 \times 2.5S_p$. Furthermore, since B_{TH} showed no significant effect on the SBTES thermal performance for configuration 2, its preliminary value (1 m) is selected across these cases. Thus, in cases 2o, 2p and 2q, B_{TH} , D_{Tr} , and D_L hold identical values.

The sole variation introduced pertained to the barrier depth B_z . Upon investigating its influence for configuration 2, it was observed that extending B_z beyond $1.75L_{BHE}$ (case 2e) did not result in any additional improvements in the thermal performance of the SBTES system. Furthermore, the thermal performance recorded for $1.5L_{BHE}$ (case 2d) was marginally lower than that of $1.75L_{BHE}$ (case 2e) and $2L_{BHE}$ (case 2f) (Figure 5.18). To validate that this finding regarding B_z applies to cases 2o, 2p, and 2q, where other barrier design components are modified, three values of B_z are explored. Specifically, B_z is set to $2L_{BHE}$ for case 2o, $1.75L_{BHE}$ for case 2p, and $1.5L_{BHE}$ for case 2q.

A comparative analysis of these new cases (2o, 2p, and 2q) alongside the best-performing cases identified for configuration 2, where each barrier design component (B_z , B_{TH} , D_{Tr} , and D_L) was individually assessed, is presented in Figure 5.22(a)-(b). Cases 2o, 2p, and 2q demonstrate superior thermal performance compared to other cases (2b, 2f, 2i), proves that

cases 2o, 2p, and 2q provide considerable advancement in the enclosed barrier design for Configuration 2.

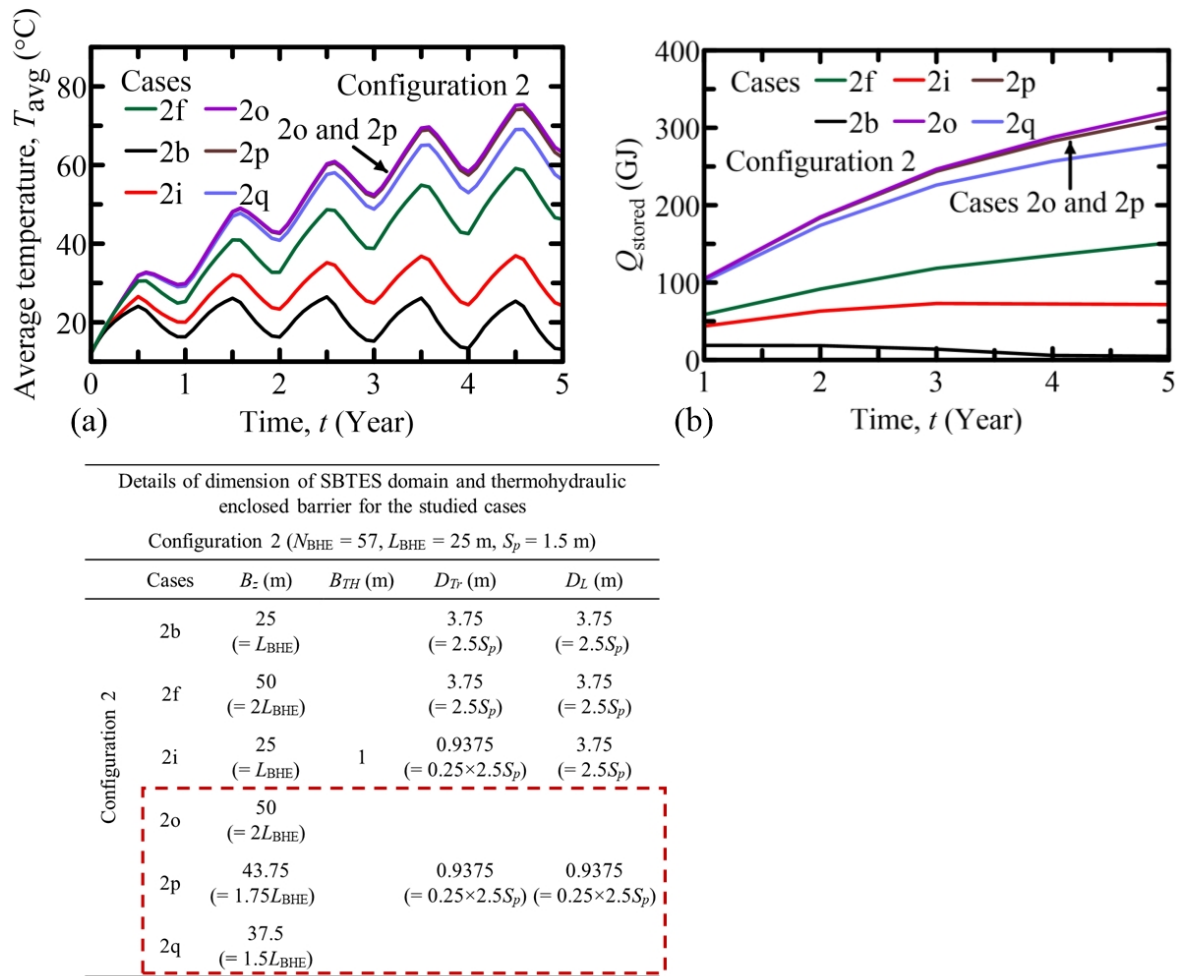


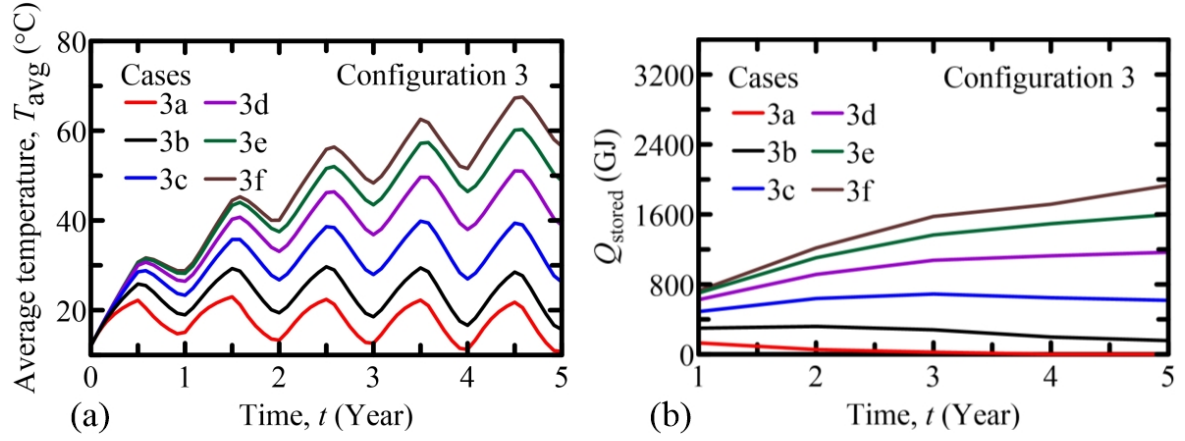
Figure 5.22: Comparative analysis of improved thermo-hydraulic enclosed barrier design for configuration 2. The plot shows calculated T_{avg} and Q_{stored} in configuration 2 SBTES domain with time. Cases 2o, 2p, and 2q present performance evaluation of the improved barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) specifically customized based on their respective impact on the thermal performance of the SBTES system.

Furthermore, both cases 2o and 2p yield identical thermal performance, as evident from the overlapping plots. Meanwhile, the thermal performance of case 2q is slightly lower than cases 2o and 2p. Thus, the earlier observation regarding configuration 2, where extending B_z beyond $1.75L_{BHE}$ failed to augment thermal performance, remains valid for cases 2o and 2p as well. Consequently, given their equivalent thermal performance, case 2p emerges as the final,

optimal enclosed barrier design for configuration 2, offering reduced construction material volume V_B compared to case 2o, while delivering the same level of thermal performance.

5.5.3.3 Configuration 3 – Design assessment

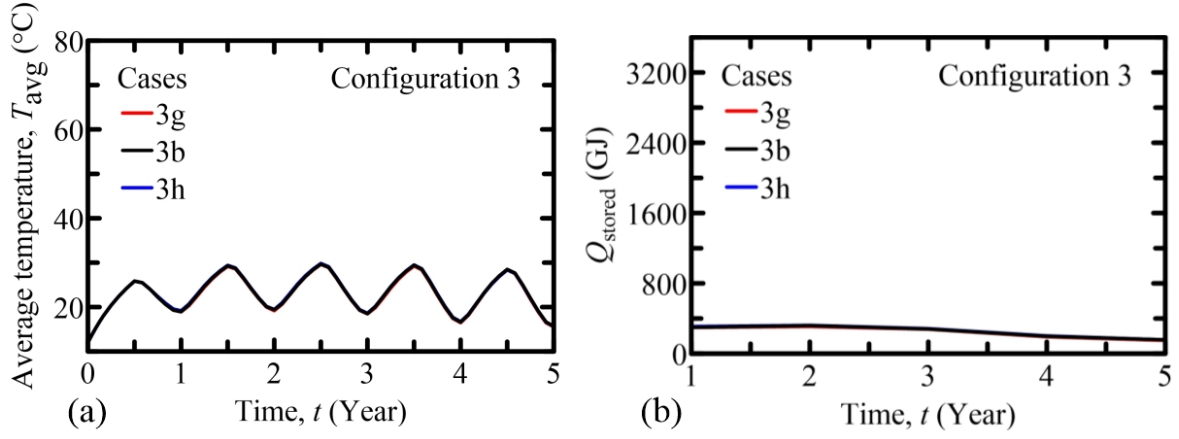
Figures 5.23(a)-(b) show T_{avg} and Q_{stored} over time for cases (3a, 3b, 3c, 3d, 3e, 3f) examining the impact of B_z on the thermal performance of a large-scale SBTES system defined by configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45$ m, $S_p = 2.5$ m), studied in simulation set 3. Case 3a, where the depth of the enclosed barrier B_z is set at 0.75 times the length of BHE L_{BHE} , provides the lowest T_{avg} and Q_{stored} among the cases studied. Case 3a exhibits the least favorable thermal performance among cases (3a, 3b, 3c, 3d, 3e, 3f) examining the influence of B_z on the thermal performance of SBTES for configuration 3. Additionally, it is noteworthy that the thermal performance, in terms of T_{avg} and Q_{stored} , displays a progressive improvement in ascending order for cases 3b, 3c, 3d, 3e, and 3f. This indicates that the thermal performance of SBTES enhances with an increase in B_z . Also, cases 3e and 3f demonstrate closely similar thermal performance, case 3f provides superior long-term thermal performance compared to any other cases (3a, 3b, 3c, 3d, 3e, 3f). Consequently, $B_z = 2L_{BHE}$ (case 3f) emerges as the optimal choice, delivering the best thermal performance among the cases (3a, 3b, 3c, 3d, 3e, 3f) studied to explore the influence of B_z on the thermal performance of SBTES for configuration 3.



Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45$ m, $S_p = 2.5$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
3a	33.75 ($= 0.75L_{BHE}$)	1.5	6.25 ($= 2.5S_p$)	6.25 ($= 2.5S_p$)
3b	45 ($= L_{BHE}$)			
3c	56.25 ($= 1.25L_{BHE}$)			
3d	67.50 ($= 1.50L_{BHE}$)			
3e	78.75 ($= 1.75L_{BHE}$)			
3f	90 ($= 2L_{BHE}$)			

Figure 5.23: Comparative thermal performance analysis of configuration 3 integrated with thermo-hydraulic enclosed barrier with varying B_z Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 3 SBTES domain with time, providing a comparison of thermal performance of configuration 3 for different B_z cases (3a-3f).

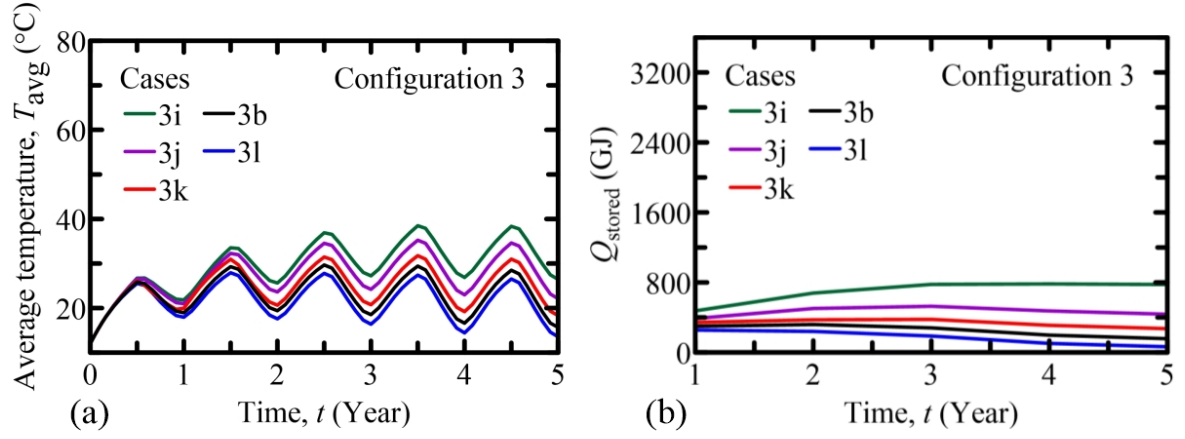
Figures 5.24(a)-(b) present T_{avg} and Q_{stored} over time for cases (3g, 3b, 3h) investigating the effect of B_{TH} on the thermal performance of the SBTES system for configuration 3. The thermal performance observed for cases 3g, 3b, and 3h exhibits no variation for different B_{TH} . Therefore, it can be concluded that the thickness of the enclosed barrier B_{TH} does not exert any influence on the thermal performance of SBTES for configuration 3.



Details of dimension of SBTES domain and thermohydraulic enclosed barrier for the studied cases				
Configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45$ m, $S_p = 2.5$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
Configuration 3	3b	1.5		
	3g	1.125 ($= 0.75 \times 1.5$)	6.25 ($= 2.5 S_p$)	6.25 ($= 2.5 S_p$)
	3h	1.875 ($= 1.25 \times 1.5$)		

Figure 5.24: Comparative thermal performance analysis of configuration 3 integrated with thermo-hydraulic enclosed barrier with varying B_{TH} Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 3 SBTES domain with time, providing a comparison of thermal performance of configuration 3 for different B_{TH} cases (3g, 3b, 3h).

Figures 5.25(a)-(b) show T_{avg} and Q_{stored} over time for cases (3i, 3j, 3k, 3b, 3l) exploring the impact of D_{Tr} on the thermal performance of the SBTES system for configuration 3. Case 3i, where D_{Tr} is set at 0.25 times $2.5S_p$ (the preliminary design selection), achieves the highest T_{avg} and Q_{stored} among the other cases (3j, 3k, 3b, 3l) studied. Among the cases (3i, 3j, 3k, 3b, 3l) studied to investigate the role of D_{Tr} , case 3i defines the shortest distance between the transverse barrier and the BHE array. Furthermore, it is observed that the thermal performance decreases in descending order for cases 3l, 3b, 3k, 3j, and 3i. This indicates that the thermal performance of SBTES improves with a reduction in D_{Tr} . This analysis concludes that the shortest D_{Tr} offers the best thermal performance for SBTES.



Details of dimension of SBTES domain and thermo-hydraulic enclosed barrier for the studied cases				
Configuration 3 ($N_{BHE} = 129$, $L_{BHE} = 45$ m, $S_p = 2.5$ m)				
Cases	B_z (m)	B_{TH} (m)	D_{Tr} (m)	D_L (m)
Configuration 3	45 ($= L_{BHE}$)	1.5	6.25 ($= 2.5S_p$)	6.25 ($= 2.5S_p$)
			1.5625 ($= 0.25 \times 2.5S_p$)	
			3.125 ($= 0.50 \times 2.5S_p$)	
			4.6875 ($= 0.75 \times 2.5S_p$)	
			7.8125 ($= 1.25 \times 2.5S_p$)	

Figure 5.25: Comparative thermal performance analysis of configuration 3 integrated with thermo-hydraulic enclosed barrier with varying D_{Tr} Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 3 SBTES domain with time, providing a comparison of thermal performance of configuration 3 for different D_{Tr} cases (3i, 3j, 3k, 3b, 3l).

Figures 5.26(a)-(b) present T_{avg} and Q_{stored} over time for cases (3m, 3b, 3n) investigating the influence of D_L on the thermal performance of the SBTES system for configuration 3. The thermal performance observed for cases 3m, 3b, and 3n exhibits no variation for different D_L . Therefore, it can be concluded that the distance between the longitudinal barrier and BHE array D_L does not have any influence on the thermal performance of SBTES for configuration 3. This suggests that while selecting D_L , it is logical to choose the shortest D_L as it will ensure a smaller outer perimeter P_B of the enclosed barrier without compromising the thermal performance of SBTES.

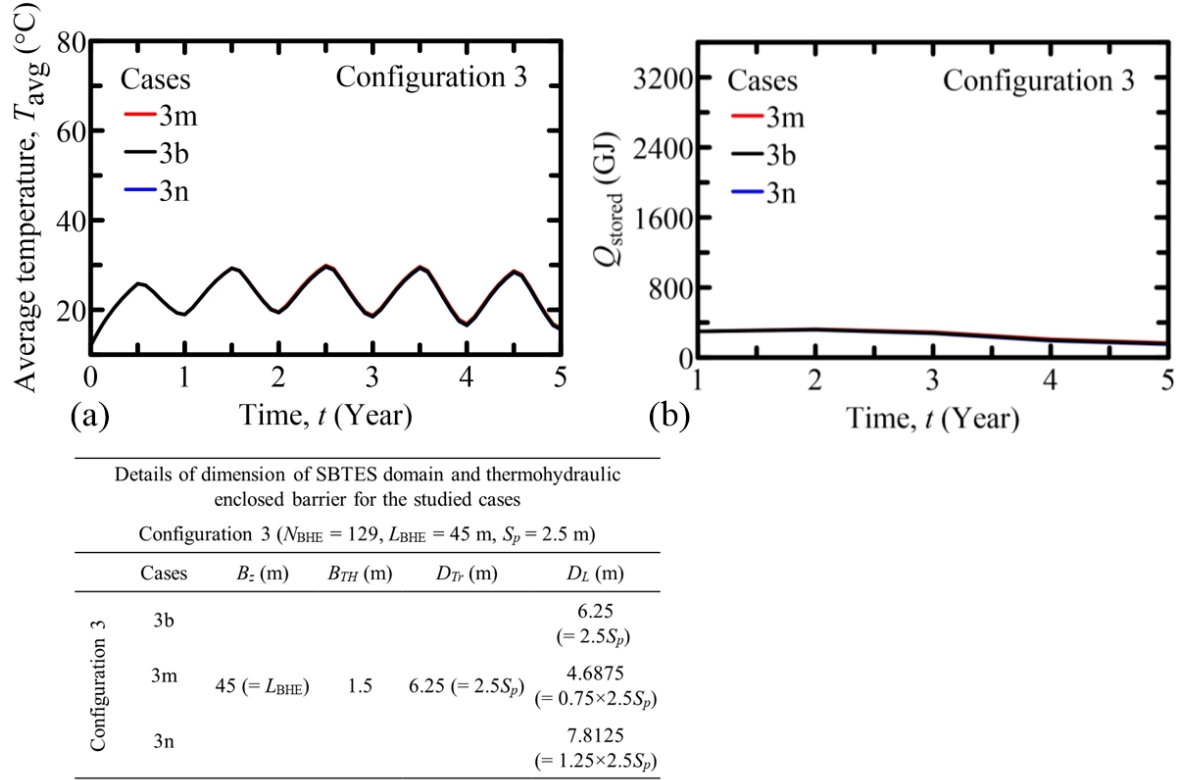


Figure 5.26: Comparative thermal performance analysis of configuration 3 integrated with thermo-hydraulic enclosed barrier with varying D_L Values. The plot shows calculated T_{avg} and Q_{stored} in configuration 3 SBTES domain with time, providing a comparison of thermal performance of configuration 3 for different D_L cases (3m, 3b, 3n).

5.5.3.3.1 Design improvement for configuration 3

Additional simulations are conducted to find the values of barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) that yield the best thermal performance for configuration 3, building upon insights gained from prior analyses investigating the influence of individual design components (B_z , B_{TH} , D_{Tr} , and D_L) on SBTES thermal performance. This is accomplished by defining additional cases 3o, 3p, and 3q for configuration 3, carefully selecting values for each barrier design component (B_z , B_{TH} , D_{Tr} , and D_L) that had demonstrated superior thermal performance in previous individual component investigations.

Initially, D_{Tr} and D_L are set at 0.25 times their preliminary values (i.e., $2.5S_p$). This decision is made following the exceptional performance of the shortest D_{Tr} (case 3i) and the observation that different D_L values did not impact thermal performance. Thus, the shortest

distances specified in case 3i is selected for both D_{Tr} and D_L , to minimize the outer perimeter P_B , as any value of D_L would yield the same thermal performance (Figure 5.26). Therefore, in cases 3o, 3p, and 3q, both transverse and longitudinal barriers are positioned in closest proximity to the BHE array, defining D_{Tr} and D_L as $0.25 \times 2.5S_p$. Given that B_{TH} demonstrated no influence on thermal performance, its preliminary value (1.5 m) is selected across these cases (3o, 3p, and 3q). So, in cases 3o, 3p, and 3q, B_{TH} , D_{Tr} , and D_L have identical values.

The sole variation introduced pertained to the barrier depth B_z . Previous study for configuration 3 indicated that the highest value explored for B_z , i.e., $2L_{BHE}$ (case 3f), provided the best thermal performance. Additionally, case 3e with B_z set at $1.75L_{BHE}$ showed a slightly lesser but comparable thermal performance to that of case 3f (Figure 5.23). To validate whether the same finding regarding B_z would apply to cases 3o, 3p, and 3q, where other barrier design components are modified, three values of B_z are explored. Specifically, B_z is set to $2L_{BHE}$ for case 3o, $1.75L_{BHE}$ for case 3p, and $1.5L_{BHE}$ for case 3q.

Figure 5.27(a)-(b) presents a comparative analysis of these new cases (3o, 3p, and 3q) alongside the best-performing cases identified for configuration 3, where each barrier design component (B_z , B_{TH} , D_{Tr} , and D_L) was individually assessed. Notably, cases 3o, 3p, and 3q demonstrate superior thermal performance compared to other cases (3b, 3f, 3i) ,proves a prominent advancement in the enclosed barrier design for configuration 3.

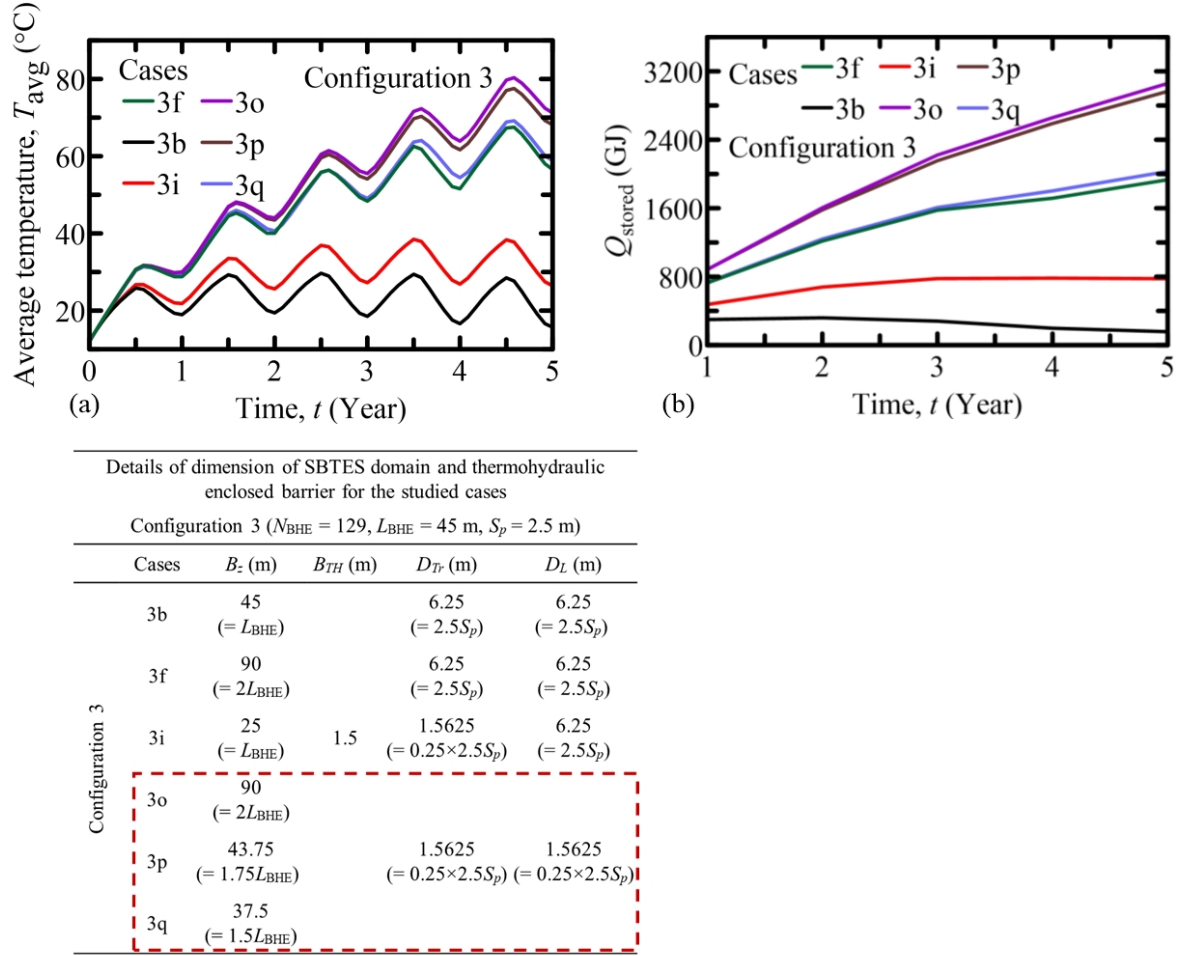


Figure 5.27: Comparative analysis of improved thermo-hydraulic enclosed barrier design for configuration 3. The plot shows calculated T_{avg} and Q_{stored} in configuration 3 SBTES domain with time. Cases 3o, 3p, and 3q present performance evaluation of the improved barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) specifically customized based on their respective impact on the thermal performance of the integrated SBTES system.

Furthermore, both cases 3o and 3p yield identical thermal performance, as evident from the superimposing plots. Meanwhile, the thermal performance of case 3q is slightly lesser than that of cases 3o and 3p. Therefore, as both cases 3o and 3p provide the same thermal performance, case 3p emerges as the final, optimal enclosed barrier design for configuration 3. It offers reduced construction material volume V_B compared to case 3o while delivering the same thermal performance.

5.5.4 Thermo-hydraulic enclosed barrier design components: Recommendations and discussion

This section offers recommendations for the suitable range of barrier design components (B_z , B_{TH} , D_{Tr} , and D_L) customized to the specific configuration of the SBTES domain. These recommendations are based on a thorough design assessment conducted across various small, medium, and large scales SBTES systems.

- Depth of enclosed barrier B_z : It is advised to maintain the depth of the enclosed barrier B_z within the range of $1.5L_{BHE}$ to $2L_{BHE}$. The analysis indicates that a B_z equal to $1.5L_{BHE}$ performs optimally for small-scale SBTES systems. For medium and large-scale systems, B_z in the range of $1.75L_{BHE}$ and $2L_{BHE}$ respectively yield the best SBTES thermal performance. When designing a thermo-hydraulic enclosed barrier for any SBTES configuration, exploration within this specified range is recommended to ascertain the optimum enclosed barrier depth.
- Distance between transverse and longitudinal barriers D_{Tr} and D_L : It is recommended to minimize this distance, keeping it as short as possible from the BHE array. Based on systematic study conducted for small, medium, and large-scale SBTES system, it is suggested to keep D_{Tr} and D_L equivalent to 0.625 times the BHE spacing S_p (i.e., $0.25 \times 2.5S_p$) distance.
- Barrier thickness B_{TH} : The analysis demonstrates that B_{TH} exerts no influence on the thermal performance of SBTES system. Therefore, it is advisable to select a typical thickness of barrier commonly used in real-life applications for the vertical barrier.

Table 5.6 summarizes the design recommendations derived from the present study.

Table 5.6: Summary of design recommendations for thermo-hydraulic enclosed barrier design components in terms of SBTES design components

Barrier design component	Recommended value
B_z	$1.5L_{BHE} - 2L_{BHE}$
D_{Tr}	$0.625S_p$
D_L	$0.625S_p$

An important discussion is required about thickness of enclosed barrier B_{TH} which showed negligible effect on the thermal performance of SBTES system. In many physical phenomena, when one dimension is significantly larger than the others, the effects of the smaller dimensions can often be considered negligible. This is because their contributions to the overall behavior of the system become proportionally smaller. Same rationale can be applied here for the observation made for the B_{TH} in the present study. This allows for simplifications in design and analysis, making it easier to focus on the most relevant barrier design factors affecting the thermal performance of SBTES. In the design, the barrier thickness can be selected keeping in mind the structural integrity, construction feasibility, or typical wall thickness applications. It won't be necessary to select an appropriate thickness to meet certain thermal performance demands for the SBTES system. While this observation holds for the specific SBTES system and the range of variations examined in present study, introduction of other influential factors may necessitate a re-evaluation of B_{TH} impact.

In addition, while enclosed barrier design specifications such as W_{Tr} , W_L , P_B , and V_B are provided for each case in Table 5.5, specific design improvements in relation to these parameters are not explored. Future studies may investigate how this information can be utilized for a rigorous optimization process, aiming to achieve an efficient enclosed barrier geometry that fulfills its function with minimal construction material, ensuring the highest degree of cost-effectiveness.

5.6 Conclusion

In this study, a novel approach has been introduced to enhance the thermal performance of SBTES system by proposing the installation of a vertical barrier within the SBTES domain. The primary objective was to mitigate thermal energy loss resulting from groundwater flow and provide a design aid to safeguard the SBTES system against the negative impacts of high-velocity groundwater flow. To achieve this goal, the study addressed four key research questions that laid the framework this study.

The first research question revolved around selecting the most suitable type of vertical barrier for further exploration. The second question sought to determine the optimal positioning of the vertical barrier relative to BHE array. The third question involved a comparative analysis to identify the most efficient type of vertical barrier within the best positioning scenario. Lastly, the fourth question aimed at conducting a rigorous numerical analysis across a range of SBTES configurations, from small to large scale, to provide comprehensive design recommendations for the vertical barrier.

These research questions are addressed by conducting a series of simulation sets. Simulation set 1 assessed the most efficient barrier positioning scenario, with the enclosed barrier emerging as the most effective option among the four different barrier placement scenarios examined. Subsequently, simulation set 2 conducted a comparison of the thermal performance of SBTES systems integrated with hydraulic enclosed barriers and thermo-hydraulic enclosed barriers. The results demonstrated that, over the long-term, the thermo-hydraulic enclosed barrier outperformed the hydraulic enclosed barrier.

With the thermo-hydraulic enclosed barrier established as the superior choice, the study progressed to explore its optimal design geometry to maximize SBTES thermal performance. The aim was to develop a generalized approach for designing thermo-hydraulic enclosed barriers applicable to various SBTES configurations. Rigorous design assessments were

conducted across small, medium, and large-scale SBTES configurations, ultimately providing recommendations for the selection of barrier design components.

Simulation set 3 is defined for conducting this design assessment, with a particular focus on determining the appropriate dimensions of thermo-hydraulic enclosed barriers for different scales of SBTES systems. This section successfully addressed the fourth objective and provided valuable design recommendations for barrier design components, including barrier depth B_z , barrier thickness B_{TH} , and distances between transverse and longitudinal barriers from the BHE array D_{Tr} and D_L .

The detailed analysis of the three selected SBTES configurations provided crucial insights. For configuration 1 and 2, barrier depth B_z beyond $1.5L_{BHE}$ and $1.75L_{BHE}$, respectively, did not result in improved SBTES thermal performance. Barrier thickness B_{TH} and distances between longitudinal barrier and BHE array D_L showed minimal influence. In both cases, the smallest value of D_{Tr} consistently provided the best thermal performance. Subsequently, additional simulations were conducted to further refine the barrier design, ultimately leading to the identification of case 1o for configuration 1 and case 1p for configuration 2 as the optimal barrier designs.

For Configuration 3, the study found that a barrier depth B_z of $2L_{BHE}$ yielded the best thermal performance, with barrier thickness B_{TH} and distances between longitudinal barrier and BHE array D_L showing no significant influence. Once again, the smallest value of D_{Tr} offered the highest thermal performance, and in the design improvement process case 3p emerged as the optimal barrier design for configuration 3.

Findings from this study has proved the effectiveness of vertical barriers as a design aid to mitigate the negative impact of groundwater flow on the thermal performance of SBTES systems. It has refined the positioning and type of vertical barrier for optimal thermal performance. Furthermore, the study recommends the integration of thermo-hydraulic enclosed

barriers to maximize the advantages of this design aid. Most notably, this research has narrowed down the range of values that should be considered when selecting thermo-hydraulic enclosed barrier design components for any SBTES domain, providing valuable design recommendations for future applications.

CHAPTER 6

Conclusions and Recommendations

This dissertation presents a detailed analysis of the impact of different subsurface conditions on the thermal performance of SBTES systems. The study covers saturated, unsaturated, and groundwater flow scenarios, using rigorous numerical analysis to evaluate their respective influences. Initially a simplified conduction-based model is used to analyze the effect of soil physical and thermal properties under different BHE spacing and injection heat flux scenarios for saturated soil conditions. Subsequently, a coupled heat and mass transfer numerical model is used for unsaturated soil conditions, examining SBTES system thermal behavior under different subsurface moisture conditions. This includes fully dry, fully saturated, and varying moisture content scenarios at different depths of the saturated soil zone. For unsaturated soil condition, the impact of seasonal surface pressure variation on the thermal performance of SBTES system is explored. Additionally, an investigation into the role of soil porosity under different soil stratifications and moisture conditions is undertaken to contribute to existing knowledge in this domain. Furthermore, the effect of groundwater flow is addressed by assessing different groundwater velocities and table depths influence on short- and long-term thermal performance of SBTES system under fixed- and variable-energy supply and demand conditions. Finally, to mitigate the heat loss attributed by groundwater flow, a design aid in the form of a vertical barrier within the SBTES domain is proposed. Additionally, a detailed analysis is performed across varying scales of SBTES domains to offer a suitable range of vertical barrier design components, refining the geometry of vertical barrier to achieve optimal thermal performance.

This chapter highlights the major contributions, important conclusions, and provides recommendations for future research prospects.

6.1 Major contributions and conclusions

Summary of major contributions and conclusions from this work are as follows:

- (i) In the conduction-based study for saturated soil conditions, it was determined that soil thermal conductivity primarily affects the ground average temperature, while specific heat capacity notably impacts the heat stored in the SBTES domain. Lower soil thermal conductivity enhances heat accumulation whereas higher thermal conductivity improves the ability to distribute the heat in the domain. Additionally, soil with lower specific heat capacity contribute to higher ground average temperature, whereas those with higher specific heat capacity offer superior heat stored. Therefore, a medium range of soil thermal conductivity and specific heat capacity is considered favourable. Such conditions ensure a reasonable temperature rise in the storage domain while effectively retaining the stored heat. Furthermore, the findings indicated that widely spaced BHEs promoted efficient thermal dissipation and temperature distribution within a larger thermal volume. On the other hand, closely spaced BHEs are associated with increased heat loss and less efficient thermal performance due to enhanced heat accumulation. These findings suggest that the thermal performance corresponding to ground parameters can significantly vary under different design scenarios and, therefore, require careful evaluation in the SBTES design process.
- (ii) The study conducted in Chapter 3 provides valuable insights into the thermal performance of SBTES systems in unsaturated soil conditions. The findings emphasize the key role of subsurface moisture content in influencing thermo-hydraulic properties, with higher moisture content leading to lower average temperatures within the thermal storage domain. Additionally, it is observed that the seasonal variation in surface pressure can cause hydrodynamic changes, leading to temporal and spatial variations in the thermo-hydraulic properties of soil, particularly at shallow subsurface depths.

Importantly, these effects were observed to have limited significance on the overall temperature rise in the SBTES system. Furthermore, while determining the significance of soil porosity, it is observed that lower porosity levels were found to yield superior thermal performance. In the high-porosity soils, more pronounced hydrodynamic fluctuations are detected in thermo-hydraulic properties, particularly in shallow depths, in response to surface pressure variations. Additionally, the investigation of layered soils demonstrated varying volumetric water contents and thermal conductivities across different soil layers, although these disparities had minimal impact on SBTES performance. The thermal performance of the SBTES system varies modestly when one soil type dominates and has a higher volume fraction than others in the soil stratification. When the different soil types have equal volume fractions, then layering has no impact on SBTES performance.

- (iii) The findings from Chapter 4 have provided crucial insights into the effects of groundwater velocity and groundwater table depth on the short- and long-term performance of SBTES system. It is observed that for a given groundwater table depth under the low velocity condition ($1 \times 10^{-9} \text{ m s}^{-1}$), the thermal performance of the SBTES is same as that of the zero-velocity condition. Further, the results indicate that low and medium groundwater flow velocities do not have a significant influence on the average temperature of the SBTES when the groundwater table is located either 5 m below or at the base of the SBTES domain. However, in the presence of high velocity ($1 \times 10^{-5} \text{ m s}^{-1}$) groundwater flow below the SBTES domain, a notable reduction in average temperature is observed, particularly over the long-term operation. Generally, these groundwater flow conditions are overlooked during the analysis and design of SBTES. This finding highlights the importance of heat loss resulting from high velocity groundwater flow taking place below the SBTES. Therefore, to ensure reliable

performance estimates of SBTES and accurate accounting of potential heat loss, it is crucial to consider these conditions during the analysis and design processes. The findings suggest that the influence of medium-velocity groundwater flow may become evident after the first few years of operation when the entire domain is affected by groundwater flow. However, in cases where the groundwater table is located at the mid-depth of the SBTES domain, the significant influence of medium velocity flow may only become evident during long-term operation. This observation highlights the importance of considering the long-term effects of groundwater flow conditions on SBTES analysis. For the high-velocity ($1 \times 10^{-5} \text{ m s}^{-1}$) groundwater flow conditions, the results showed that such conditions lead to a massive reduction in SBTES thermal performance, particularly when a half or the entire domain is under the influence of groundwater flow. Therefore, sites with such groundwater flow conditions are unsuitable for SBTES installation without proper engineering modifications.

- (iv) In Chapter 5, a novel approach has been introduced to enhance the thermal performance of SBTES system by proposing the installation of a vertical barrier within the SBTES domain. The findings from this study have proved the effectiveness of vertical barriers as a design aid to mitigate the negative impact of groundwater flow on the thermal performance of SBTES systems. The study is systematically progressed to address four key research questions to establish a robust framework. Among different types of vertical barriers, enclosed barrier provided significant thermal performance improvement. Furthermore, while comparing the thermal performance of SBTES systems integrated with hydraulic enclosed barriers and thermo-hydraulic enclosed barriers, it is observed that, over the long-term, the thermo-hydraulic enclosed barrier outperformed the hydraulic enclosed barrier. With the thermo-hydraulic enclosed barrier established as the superior choice, the study progressed to explore its optimal

design geometry to maximize SBTES thermal performance. From a rigorous analysis conducted for small, medium, and large scale, total combined fifty SBTES configuration, the range of values that should be considered when selecting thermo-hydraulic enclosed barrier design components for any SBTES domain has been narrowed down, providing valuable design recommendations for future applications.

6.2 Recommendations for future work

In light of the insights gained from this research and the acknowledged limitations, the potential extensions of the present research work are outlined as follows:

- (i) The approach in present study simplifies the complex heat injection and extraction process by modeling the BHE as a line heat source. The heat injection and extraction process is simulated using a time-varying heat flux applied at the BHEs. To refine the analysis, future research could consider modeling this process as a non-isothermal laminar flow.
- (ii) The current approach does not account for ambient temperature fluctuations or geothermal gradients, maintaining a constant initial ground temperature. Future investigations could incorporate these dynamic factors for a more realistic representation.
- (iii) In the present study, the modeling of thermal effects induced by groundwater flow does not consider the influence of thermal dispersion. Enhancing the present study by accounting for the effects of thermal dispersion would be an advancement.
- (iv) While an initial exploration into the installation of a vertical barrier in the SBTES domain to mitigate groundwater concerns has been undertaken, further investigation could delve into identifying suitable barrier materials and examining their structural integrity.

- (v) In evaluating the performance of SBTES, it has been observed that SBTES systems (operating without a heat pump for direct use) encounter complexities in quantifying their efficiency and effectiveness due to the absence of standardized performance indicators. To tackle this challenge, future studies may concentrate on formulating appropriate dimensionless numbers that encapsulate critical performance factors such as system efficiency, thermal losses, overall system effectiveness, and the ability to meet specific energy demands. These dimensionless numbers should offer a holistic view of SBTES system performance, facilitating comparative analyses across different designs and operational conditions. The development of these performance indicators will not only assist in benchmarking and optimizing current SBTES designs but also pave the way for standardized assessment methodologies.

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