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KARAKTERISTIK FISIK DAN MEKANIK DARI PONDASI GEOTHERMAL

TESIS

M E SURYATRIYASTUTI
0806423721

FAKULTAS TEKNIK
PROGRAM TEKNIK SIPIL
DEPOK
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PHYSICAL AND MECHANICAL BEHAVIOR OF ENERGY PILES

THESIS

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diajukan sebagai salah satu syarat untuk memperoleh gelar Master

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0806423721

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KEKHUSUSAN STRUKTUR
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THESIS

is submitted as requirement to obtain Master Degree

M E SURYATRIYASTUTI
0806423721

FACULTY OF ENGINEERING
CIVIL ENGINEERING DEPARTMENT
SPECIALITY STRUCTURE
DEPOK
JULY 2010

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NPM	**: 080642372**
Tanda tangan	**:**
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Student Number : 080642372

Signature :

Date : July, 10th 2010

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Tesis ini diajukan oleh	:
Nama	: M E Suryatriyastuti
NPM	: 0806423721
Program Studi	: Civil Engineering
Judul Tesis	: Karakteristik Fisik dan Mekanik dari Pondasi Geothermal

Telah berhasil dipertahankan di hadapan Dewan Penguji dan diterima sebagai bagian persyaratan yang diperlukan untuk memperoleh gelar Magister Teknik Sipil pada Program Studi Teknik Sipil Fakultas Teknik, Universitas Indonesia.

DEWAN PENGUJI

Pembimbing	: Dr Hussein MROUEH	( )
Pembimbing	: Dr Sébastien BURLON	( )
Penguji	: Prof Issam SHAHROUR	( )
Penguji	: Prof Erick CARLIER	( )

Ditetapkan di : Villeneuve d'Ascq, France
Tanggal : July, 10th 2010

APPROVAL

This thesis is submitted by :
Name : M E Suryatriyastuti
Student Number : 0806423721
Department : Civil Engineering
Thesis Title : Physical and Mechanical Behavior of Energy Piles

has been successfully defended in front of Committee of Jury and is accepted to fulfill one of requirement needed to obtain Master Degree in Civil Engineering Department, Faculty of Engineering, University of Indonesia.

COMMITTEE OF JURY

Advisor : Dr Hussein MROUEH ( )

Advisor : Dr Sébastien BURLON ( )

Jury : Prof Issam SHAHROUR ( )

Jury : Prof Erick CARLIER ( )

Assigned at : Villeneuve d'Ascq, France
Date : July, 10th 2010

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ABSTRAK

Nama : M E Suryatriyastuti
Program Studi : Teknik Sipil
Judul Tesis : Karakteristik Fisik dan Mekanik dari Pondasi Geothermal

Sebuah teknologi baru bernama pondasi geothermal, integrasi dari pipa penukar panas dengan pondasi tiang beton, adalah sebuah solusi inovatif untuk sistem pemanas bangunan yang mendukung pembangunan energi berkelanjutan. Pondasi geothermal menggunakan energy geothermal dangkal secara langsung dari tanah dan bekerja dengan prinsip energi transfer untuk memproduksi panas yang dibutuhkan oleh bangunan. Pondasi ini bertujuan untuk menghangatkan bangunan selama musim dingin dan mengembalikan energy panas ke dalam tanah selama musim panas. Tesis ini menyajikan studi literatur mengenai mekanisme kompleksitas transfer panas yang terdiri dari kopling termo-hidro-mekanis kemudian menjabarkannya dalam penurunan persamaan konservasi energi. Permasalahan timbul dalam sistem pengoperasian pondasi geothermal yang berbeda setiap musimnya, pondasi geothermal ini dibebani oleh kontraksi termal dan dilatasi termal secara bergantian sehingga mengancam kekuatan mekanis struktur pondasi tersebut, terutama di bagian *interface* tanah-pondasi. Untuk mengamati perngaruh difusi termal pada kekuatan mekanis pondasi, simulasi numerik pada satu pondasi geothermal di tanah homogen dilakukan dengan menggunakan *finite difference code*. Batasan studi ini terletak pada pengamatan area difusi termal dalam tanah dan pengaruh dilatasi termal pada pondasi dalam pembebanan termal monoton. Hasil studi diperoleh bahwa area difusi termal yang terpengaruhi mencapai luas 30xdiameter tiang pondasi dan bahwa pembebanan termal monoton hanya memberikan ±1 kPa tegangan termal. Kekuatan mekanis pondas geothermal menjadi suatu permasalahan besar ketika pondasi ini dibebani oleh pembebanan termal siklis sesuai musim.

Kata kunci:
Pondasi geothermal, transfer panas, kopling termo-hidro-mekanis, dilatasi termal, pembebanan termal monoton

ABSTRACT

Name : M E Suryatriyastuti
Department : Civil Engineering
Thesis Title : Physical and Mechanical Behavior of Energy Piles

A new technology called energy piles, an integration of heat exchanger pipes with concrete piles foundations, is an innovative solution of thermal building system to support energy sustainability development. Energy piles use direct shallow geothermal energy in soil as their heat source and work with the heat transfer principle in order to produce potential heat energy for the building. They intend to warm the building during winter season and to recharge the thermal energy of soil during summer season. This paper reviews literally complex heat transfer mechanism of system that consists of thermo-hydro-mechanics coupling and divides them into different energy conservations. Nevertheless, due to their seasonal operation time, energy piles are subjected by thermal contraction and dilatation alternately which threaten their mechanical durability, especially at interface soil-pile. Numerical model of a single energy pile in homogenous soil is conducted in this study by using finite difference code. It aims to observe the thermal influence on mechanics behaviour of energy pile. The main observations in this study are limited on the area of thermal diffusions in soil and thermal dilatations effect under monotonic thermal loading. The result shows that area diffusion influenced is about 30xdiameter of pile and monotonic thermal loading just gives ±1 kPa thermal dilatation stress. Behavior of energy piles is threatened under cyclic thermal loading in their seasonal operation time.

Key words :
Energy piles, heat transfer, thermo-hydro-mechanic coupling, thermal dilatation, monotonic thermal loading

RESUME

Nom Prénom : Suryatriyastuti, Maria Elizabeth
Département : Génie Civil
Titre : Comportement Physique et Mécanique des Pieux Energétiques

Pieux énergétiques, une intégration des tuyaux de l'échangeur de chaleur avec les fondations des pieux en béton, est une solution innovante de système thermique du bâtiment pour soutenir le développement durable. Pieux énergétiques utilisent l'énergie géothermique peu profonde directement dans le sol comme une source de chaleur et travaillent avec le transfert de chaleur afin de produire l'énergie thermique potentielle pour le bâtiment. Ils ont l'intention de se réchauffer le bâtiment pendant l'hiver et de recharger l'énergie thermique du sol pendant l'été. Ce document passe en revue littéralement le mécanisme de transfert de chaleur qui se compose par un couplage thermo-hydro-mécanique et le dérive en équation de la conservation d'énergie. Néanmoins, en raison de leur système saisonnier, pieux énergétiques sont soumis par la contraction et la dilatation thermique en alternance qui menacent leur durabilité mécanique, surtout à l'interface sol-pieu. Un modèle numérique d'un pieu dans le sol homogène est mené dans cette étude en utilisant le code aux différences finies. Il vise à observer l'influence thermique sur le comportement mécanique des pieux énergétiques. Les principales observations de cette étude sont limitées sur la zone des diffusions thermiques dans le sol et l'effet thermique des dilatations thermiques sous chargement thermique monotone. Le résultat montre que la zone influencée par la diffusion est d'environ 30xdiamètre du pieu et le chargement thermique monotone donne le stress thermique ±1 kPa. Comportement des pieux énergétiques est menacée sous chargement thermique cyclique pendant leur temps d'opération saisonnier.

Mots clés :
Pieux énergétiques, transfert de chaleur, couplage thermo-hydro-mécanique, dilatation thermique, chargement thermique monotone

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NOMENCLATURE

α	thermal expansion coefficient	
β	compressibility coefficient	
ε	strain / deformation	
η	tortuosity coefficient	
θ	water content	
λ	thermal conductivity	(W/m °C)
ρ	density	(kg/m^3)
σ	stress / tension	(Pa)
τ	shear stress	(Pa)
ϕ	friction angle	(rad)
ψ	suction head	(m)
ω	radial frequency	(rad/s)
a	air content	
c	specific heat extraction	(J/kg °C)
c	cohesion	
d	damping depth	(m)
f_s	volume fraction of solid	
g	gravity	(m/s^2)
h	heat transfer coefficient	
p	pore pressure	(Pa)
n	porosity factor	
$\vec{q}$	heat flux	(W/m)
u	displacement	(m)
$\vec{v}$	flow velocity	(m/s)
A	surface area	(m^2)
A_0	amplitude	(m)
E	Young's modulus	(Pa)
C	elastic tensor modulus	(Pa)
C_v	heat capacity	(J/m^3 °C)
D_T	thermal diffusivity	(m^2/s)

D_θ	isothermal diffusivity	(m^2/s)
D_{atm}	molecular diffusivity	(m^2/s)
F	force	(N)
I	momentum	(kg/m)
K	hydraulic conductivity	(m/s)
L_v	latent heat	(J/kg)
M	mass	(kg)
$\dot{Q}$	energy	(W)
T	temperature	(°C)

CHAPTER 1
INTRODUCTION

1.1 Background

In a move to reduce the effects of global warming and due to fact of fossil fuels' depletions, an innovative building using renewable energy needs to be developed. Hydropower energy, shallow and deep geothermal energy, solar thermal energy, and wind energy are the promising alternatives to be integrated in environmentally friendly building technology.

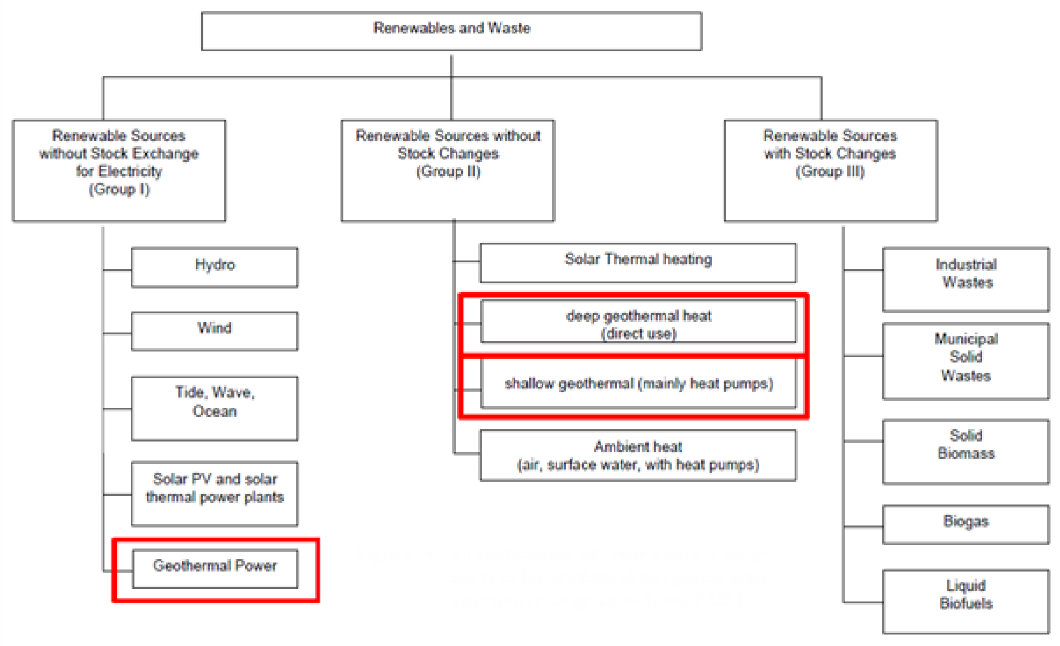


Figure 1.1 Classification of Renewable Energies (Antics, M., and Sanner, B., 2007)

Geothermal Energy is energy stored in the form of heat beneath the surface of the solid earth, where its temperature increases with soil depth. In France, the average soil temperature is about 10 – 14°C, and its geothermal gradient increases 4°C / 100 m depth (BRGM). Sub-surface or shallow geothermal energy represents a great potential of directly usable energy, especially in connection with the ground-source/coupled heat pump (GSHP/GCHP) systems, which can achieve energy-efficient space cooling and heating systems for public, residential buildings and even large architectural complexes. This system is known as ground heat exchanger system, where energy is extracted from the soil through using the ground as a heat source in heating and a heat sink in cooling mode operation.

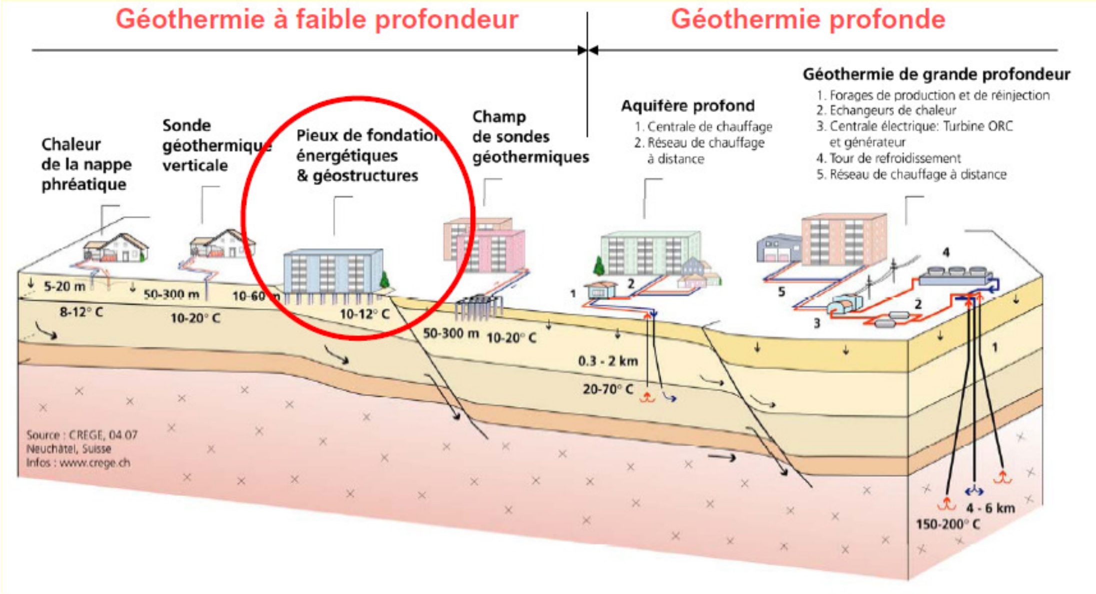


Figure 1.2 Utilization of shallow and deep geothermal energy

Conventional ground heat exchangers consist of two methods, the first is the open loop systems, where the ground water is used as a heat carrier and pumped directly from an aquifer to the heat pump, then the waste heat water is returned to the same aquifer or another well. This system is simpler but hardly used because of operational problems such as clogging or bio-fouling in the wells and heat exchangers components.

The second is the closed loop systems, where the absorber pipes (U-shaped of plastic tubes) inserted into a borehole which is laid either horizontally or vertically, and a heat carrier medium is circulated through the plastic pipes transporting heat from the ground to the heat pump. This system is also called as borehole heat exchanger (BHE) system. The heat transfer from the surrounding soil/rock to the heat carrier fluid takes place via the absorber pipes and the groundwater or material that fills the borehole. Due to its high cost of drilling and its need of additional land, the closed loop systems have been integrated to the structural foundations systems.

Foundation systems which have both functions as structural elements and heat exchanger elements are called as energy foundations. They have been developed increasingly since the beginning of the 1980s in Austria and Switzerland, at first from base slabs, then from piles (1984) and diaphragm walls (1996) (Brandl, 2006). The systems contains of closed coils of plastic piping through which a heat carrier fluid is pumped that exchanges energy from a building with the ground. The essential difference with conventional borehole heat exchanger is that the earth-contact concrete elements that serve as heat exchangers are already required for structural reasons and need not be constructed separately; therefore they have a double function. Furthermore, concrete as a heat transfer medium in energy foundations has a higher thermal conductivity than soil. This innovative method is significantly more cost-effective than conventional systems, and it is environmental friendly because it uses clean and renewable energy.

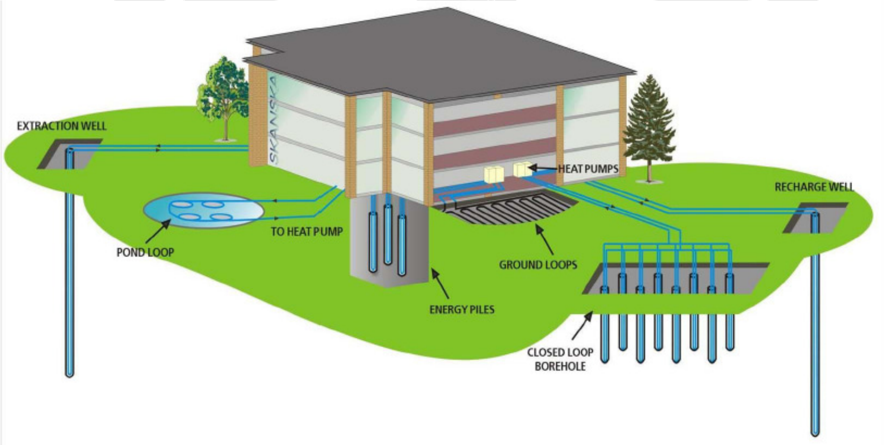


Figure 1.3 Ground Heat Exchanger System for building

Certain studies and applications have been developed: Main Tower in Frankfurt-Germany (1999), Keble College in Oxford-UK (2001), Dock Midfield Zurich Terminal Airport-Switzerland (2003), Lainzer Tunnel Vienna-Austria (2004), etc. Despite the fact that this technology has already been used quite often, the questions of the sustainability and durability of system haven't been specifically investigated until now. First of all is the influence of groundwater flows and the fluctuation seasonal ground temperature on the physical heat transfer process in soils, secondly is the thermal effect on the mechanical behaviour of soils and concrete piles. Those questions are based on the thermo-hydro-mechanical coupling effects which occur in the systems. Therefore, by this paper we will try to develop resolved ideas in order to apply this system in France.

1.2 Objective

This paper is submitted to accomplish the Master Degree of the author, in objective:

1. To introduce the energy foundations technology systems to France and to induce the development of the innovative environmentally friendly building as an accomplishment of renewable energy policy of France
2. To inform the work of previous researches and their solutions, in order to be able to develop ideas to solve the remaining questions
3. To find out and well understand each phase of physical heat transfer process in the system and to simulate a simple numerical model in applying thermo-hydro-mechanic coupling equations

1.3 Planning

I. INTRODUCTION

This chapter discusses about the importance of geothermal energy and its application, and the objective and planning of this research

II. DEVELOPMENT OF ENERGY FOUNDATIONS

This chapter discusses about the system of application of energy foundations (energy piles, energy diaphragm walls, energy tunnels, etc) in 6 countries

III. DESIGN OF ENERGY PILES

This chapter discusses about the determination of each parameter, variables, and step by step for the application of energy piles

IV. MATHEMATICAL MODEL (ANALYTICAL APPROACH)

This chapter discusses about the process of energy transfer and mathematical model of heat transfer in energy piles, which influence its mechanical and hydrological behaviour.

V. NUMERICAL MODEL

This chapter shows the result about simple modelling of heat transfer process in energy piles system with the finite element software FLAC 3D

VI. CONCLUSION

This chapter summarizes the entire chapters and suggest the recent topic to be developed in next research.

CHAPTER 2
DEVELOPMENT OF ENERGY FOUNDATIONS

The system of energy foundations is based on ground source/coupled heat pumps technology. This technology isn't new, as Lord Kelvin developed the concept in 1852, which was then modified by Robert Webber in the 1940s. Energy foundations itself have been developed recently in the world since early 1980s in Austria and Switzerland. In this chapter we will discuss the system general and history application of energy foundations over the world.

2.1 Energy Foundations System

Energy foundations systems contain of three circuit energy transfer. The primary circuit is the shallow geothermal energy, which is naturally placed in soils at shallow depth 10-60 m. The climatic temperature change over the seasons is reduced to a steady temperature at 6-10 m depth (Williams, G.P., and Gold, L.W., 1977). Thus, variation of temperature in the first 5 m depth should be taken in consideration on heat transfer phenomena. Heat transfer of soils depends on its thermal properties and thermal capacity which vary by its depth and its composition minerals. Generally, we take a thermal response test to determine natural ground temperature and heat capacity of soil. On the other side, we can calculate heat capacity of soils theoretically by its composition.

The second circuit contains of closed pipe work in earth-contact concrete elements (piles, barrettes, diaphragm walls, columns, base slabs, etc.) through which a heat carrier fluid is pumped to exchange energy from the building to the ground. The heat carrier fluid is a heat transfer medium: either water, water with antifreeze (glycol) or a saline solution. Glycol–water mixtures have proved as the most suitable, containing also additives to prevent corrosion in the header block of valves of the heat pump. Once it's been casted, the piping systems within the underground-contact concrete elements are individually joined to a header and manifold block. They are joined by connecting pipes which, in the case of energy foundations, are normally laid within the blinding beneath the base slab.

The third circuit is a closed fluid-based building heating or cooling network (secondary pipe work) embedded in the floors and walls of the structure or in bridge decks, road structures, platforms etc.

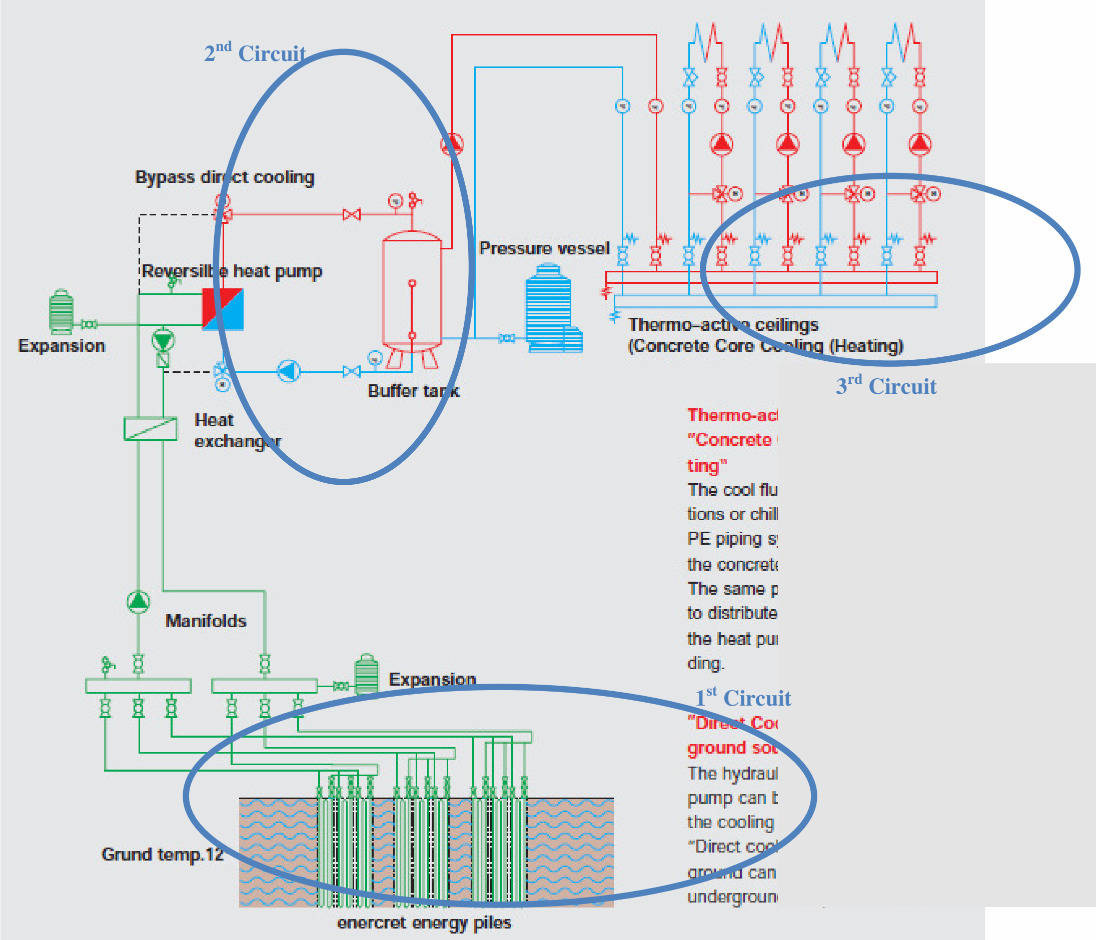


Figure 2.1 Scheme of Energy Foundations System

Commonly, second and third circuits are connected via a heat pump that increases the temperature level, typically from 10 – 158°C to a level between 258 – 358°C. The requirement for this process is a low application of electrical energy for raising the originally non-usable heat resources to a higher-usable temperature. The principle of a heat pump is similar to that of a reverse refrigerator. In the case of heat pump, however, both the heat absorption in the evaporator and the heat emission in the condenser occur at a higher temperature, whereby the heating and not the cooling effect is utilized.

The coefficient of performance, COP, of heat pump is a device parameter and is defined by:

$$COP = \frac{energy\ output\ after\ heat\ pump\ (kW)}{energy\ input\ for\ operation\ (kW)}$$

The efficiency of heat pump is strongly influenced by the difference between extracted and actually used temperature. A high user temperature (inflow temperature to the heating system of the second circuit) and a low extraction temperature (due to too low a return-flow temperature) in the heat exchanger (primary circuit) reduce its efficiency. For economic reasons a value of COP > 4 should be achieved. Therefore the usable temperature in the second circuit should not exceed 35 – 458°C, and the extraction temperature in the absorber pipes should not fall below 0 – 58°C. Consequently, this technology tends to be limited to low temperature heating (and cooling).

The seasonal performance factor (SPF) of a thermo-active system with a heat pump is the ratio of the usable energy output of the system to the energy input required to obtain it. Therefore SPF includes not only the heat pump but also the other energy-consuming elements (e.g. circulation pumps). At present, values of SPF = 3.8 – 4.3 are achieved with standard electric heat pumps; special devices with direct vaporization increase SPF by 10 – 15%.

$$SPF = \frac{usable\ energy\ output\ of\ the\ energy\ system\ (kWh)}{energy\ input\ of\ the\ energy\ system\ (kWh)}$$

If only heating or only cooling is performed, high permeability ground and groundwater with a high hydraulic gradient are of advantage. However, the most economical and environmentally friendly is a seasonal operation with an energy balance throughout the year, hence heating in winter (i.e. heat extraction from the ground) and cooling in summer (i.e. heat sinking/recharging into the ground). In this case low-permeability ground and groundwater with only low hydraulic gradients are favourable. Dry soil makes deeper piles and a larger area of the heat exchanger necessary.

Depend on soil properties and the installation depth of the absorbers, 1 kW heating needs roughly between 20 m^2 (saturated soil) and 50 m^2 (dry sand) of the surface of concrete structures in contact with soil or groundwater. There is no limitation to the depth of piles or diaphragm walls as far as the installation of energy absorber systems is concerned. The energy potential increases with depth, hence deeper foundations are advantageous. The economically minimum length of piles, barrettes or diaphragm wall panels is about 6 m.

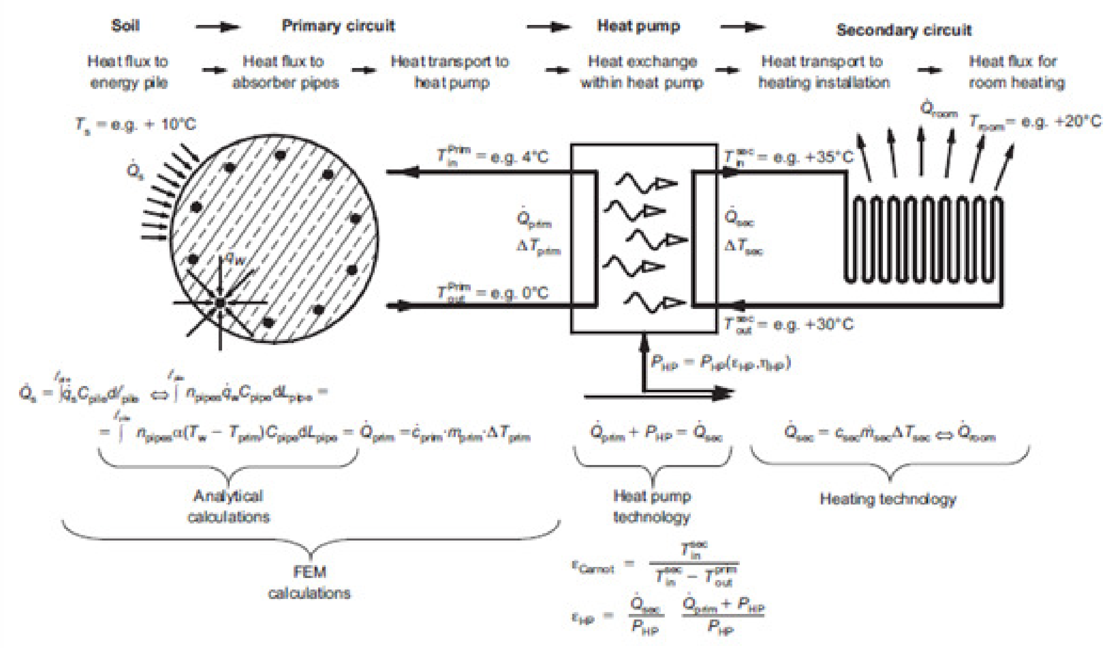


Figure 2.2 Heat flux transport in three circuits

2.2 Application over the world

2.2.1 Main Tower Frankfurt – Germany – 1999 (Quick, H., et al., 2005)

The building reaches a height of 200 m. The building is founded on a combined pile-raft foundation. The thickness of the raft within the tower is between 3 to 3.8 m. A total of 112 piles with diameter of 1.5 m were installed. The length of the piles varies from 20 m to 30 m.

The ground encountered consists of quaternary sands down to 10 m below the surface. To ensure an economic design of the Main Tower, an innovative idea has been applied. Apart from their static function the piles of the foundations and partly of the retaining wall are used for the environmental-friendly heating and cooling of the building. For this, the piles were additionally installed with heat exchanger tubes, so that the piles work as heat exchanging elements to create a closed system. Energy is transferred to the ground from the exterior (outside air) and stored until it is needed

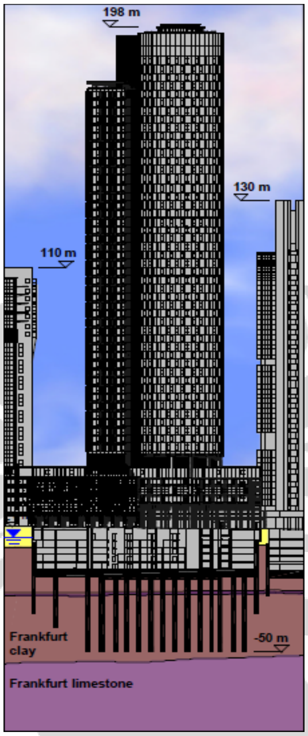


Figure 2.3 Frankfurt am Main

The energy piles can load and unload the seasonal storage. In winter energy can be withdrawn, thus a cooling of the ground arises. In summer the cooled down ground can be used for cooling the building through the ceilings. For this, a very low groundwater velocity is essential. The monitoring shows that the foundation piles of the Main Tower carry approx. 37% of the total load of the building whereas the piles of the retaining wall carry approx. 26%.

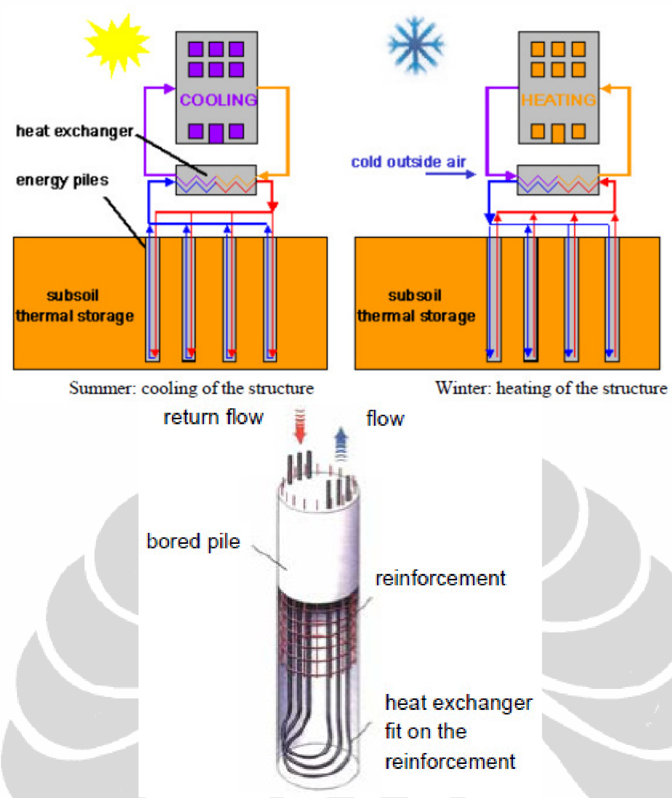


Figure 2.4 Seasonal Storage of Energy Piles

2.2.2 Office Residential Building, Hokkaido – Japan – 2000 (Hamada, Y., et al., 2007)

The building is located in Sapporo, of which the construction was completed in December 2000. Designed as a house combined with an office, the building is two-storey with a semi basement. The standard floor is 10.4 m x 8.135 m, with the building area and total floor area being 92.70 and 247.53 m^2, respectively. The conceptual diagram of heating operation is shown in Figure 2.6. Since it is a reinforced concrete building, where the heat capacity is high, the energy piles below the building are used for air-conditioning, in which warm/cool water is obtained and delivered through pipes laid in the floors and ceilings. In addition, it features a large glazing on the eastern side.

Building specifications and introduction methods	
Building specifications	
Location	Hokkaido, Japan
Structure	Reinforced concrete
Number of floors	One semibasement, two-storied
Area	Total floor area 247.53 m^2 Building area 92.70 m^2
Introduction methods	
Passive strategies	Outside thermal insulation Utilization of building frame's thermal capacity Passive solar utilization Solar shading and outdoor air cooling during summer
Active strategies	Energy pile system for air conditioning Heat pump using non-CFC refrigerant Low-temperature radiant heating and direct cooling by underground thermal system

Figure 2.5 External Facade of Building

Ground Source Heat Pump (GSHP) is used as the heating method, and a total of 26 concrete friction piles (outer diameter 302 mm, inner diameter 232 mm) are used as underground heat exchangers at a depth 9 meters. Piping is performed in the hollow portions of the pipes, in which antifreeze solution (propylene glycol solution 40%) is circulated as the heating medium, and mortar is used to fill in the voids.

Surface temperature measurement sensors (thermocouple) were installed at a total of five locations in 9 meters under ground. In addition to friction pile external surface temperatures (five points), measurements taken include outdoor air temperatures, indoor temperatures/humidity (four points), supplying/returning temperatures of the antifreeze solution on the ground side and hot water on the building side, flow rate of heat medium circulation and power consumption of the heat pump, circulation pump, auxiliary heater and control unit. Measurements were performed at 10-min intervals.

In designing internal pile specifications, performance tests were conducted on three kinds of heat exchangers pipes: U-shaped, double U-shaped, and indirect double-pipe. As a result, the U-shaped pipe type was employed from the viewpoint of economic efficiency and workability. Results of heating operation conducted from mid-December 2000 to late-April 2001 were clarified. During this period, the average fluid return temperature on the ground side and friction pile surface temperature were 2.4 and 6.7°C. Indoor temperatures ranged between 20 and 26.8°C. In addition, the coefficient of performance was relatively high at 3.9. The seasonal amount of heat supplied was approximately 66 GJ, accounting for approximately 90% of the predicted value. The system coefficient of performance that has taken power consumption in the conveyance and control systems into consideration was 3.2, while the primary energy reduction rate during the heating period relative to the conventional method was 23.2%.

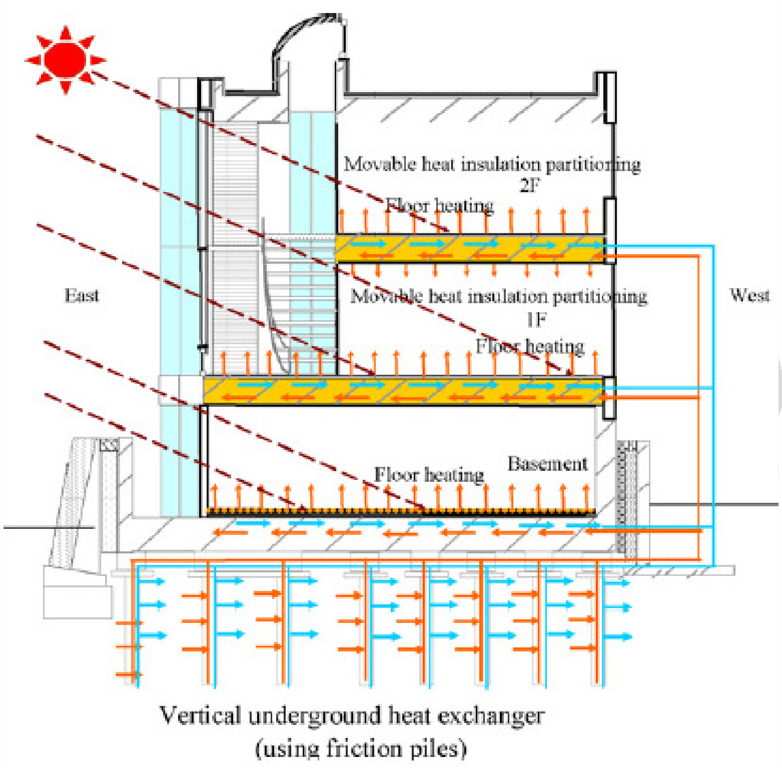


Figure 2.6 Heating/Cooling Integration System with Solar Panel

2.2.3 Keble College, Oxford – UK – 2001 (Amis, 2009; Brandl, 2006)

Over the last six years, there has been a significant increase in the use of energy piles as part of Ground Sourced Heat Pump systems being used to heat and cool the buildings which they support. Incorporating pipe loops in the piles allow the geothermal energy to be transferred via heat pumps for use in the building as required. This method of heating and cooling provides an excellent means of reducing CO_2 emissions and can greatly assist in meeting renewable energy targets now required in the United Kingdom as part of building regulation. Where piled foundations are required, it seems obvious to utilise the piles with their good thermal conductivity properties to capture the latent geothermal energy in the ground, for use in the heating and cooling of the building. Energy piles provide not only a renewable energy source but also a cost effective engineering solution when compared to other geothermal methods.

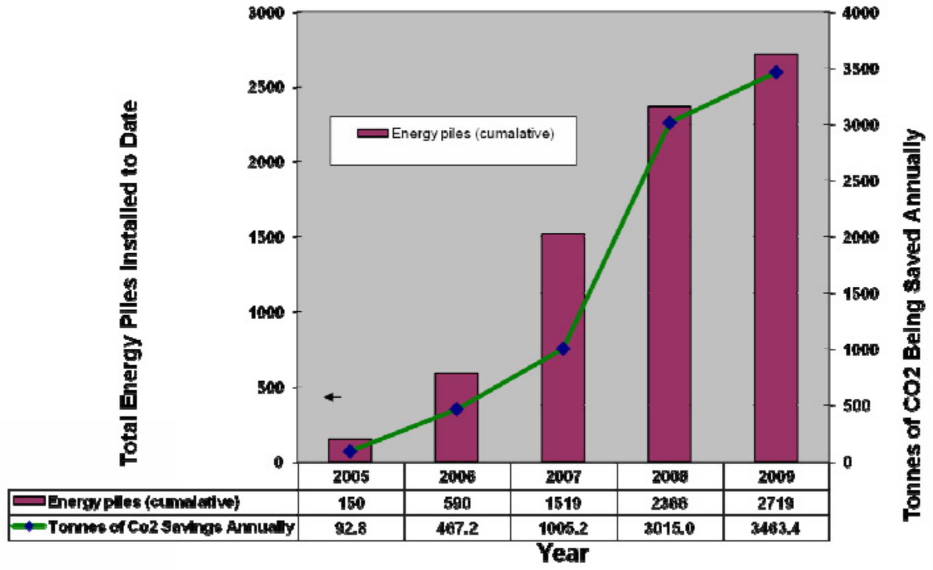


Figure 2.7 Statistic of Energy Piles Application in UK

The first energy pile project in the United Kingdom started in 2001 was installed by Cementation SKANSA by using Austrian geothermal piling designer (Enercret, Negelebeau). It was a new building for Keble College at Oxford University, a six-storey structure including a basement up to 7 m below existing ground level, providing a new lecture theatre, teaching rooms and study bedrooms.

The soil profile can be roughly summarised as follows: made ground (3 m), firm alluvial clay (1 m), medium dense Thames river deposits (3.5 m), and very stiff to hard Oxford clay (below). There is a perched groundwater table in the upper part of the river deposits.

According to figure 2.8, 90 energy piles were built to support the foundations system of the building. For the retaining wall section, 15 hard piles D 750 mm L 12.5 m were installed in areas of higher ground retention, and also 14 hard piles D 600 mm L 7.5 m in areas of lower ground retention. In order to take the structural load, 61 bearing piles D 450 mm L 5 m installed within the basement. The system used absorber pipes PE-HD diameter 20 mm, with 41 loops of piping, where each loops approx 150 m long, thus the total length amounts to 6.150 m.

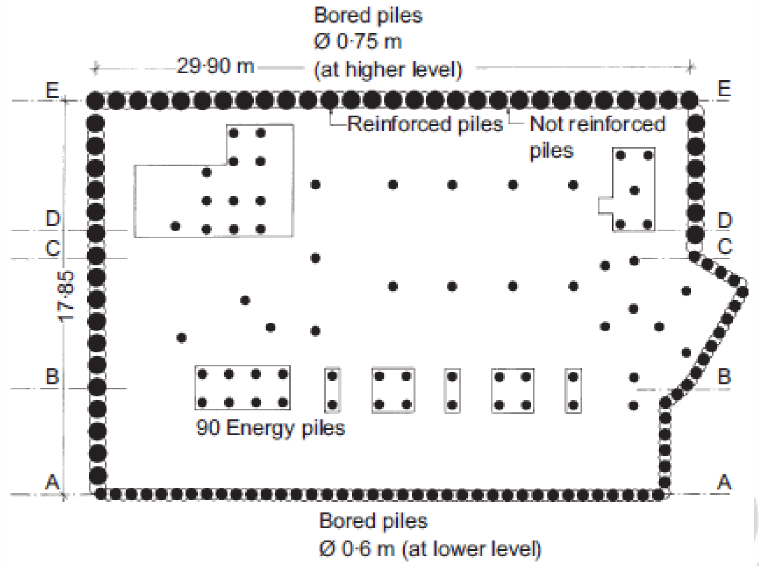


Figure 2.8 Energy Piles for foundation and pit retaining wall at Keble College, Oxford

An innovative chilled slab system consists of plastic pipes spaced at regular intervals cast into the concrete slab. The mass of the exposed concrete can absorb large amounts of thermal energy and either absorb or radiate heat to rooms to maintain thermal stability. Additional cooling to the theatre is provided via a displacement ventilation system when necessary. The building as a whole is thermally coupled to the earth via water circulating through the foundation pilings, thereby minimising heating and cooling energy requirements. The heating load of the building is 85 kW and the cooling load 65 kW, fully covered by this geothermal system. The annual heating load is 74MWh, where the annual cooling load is 55MWh.

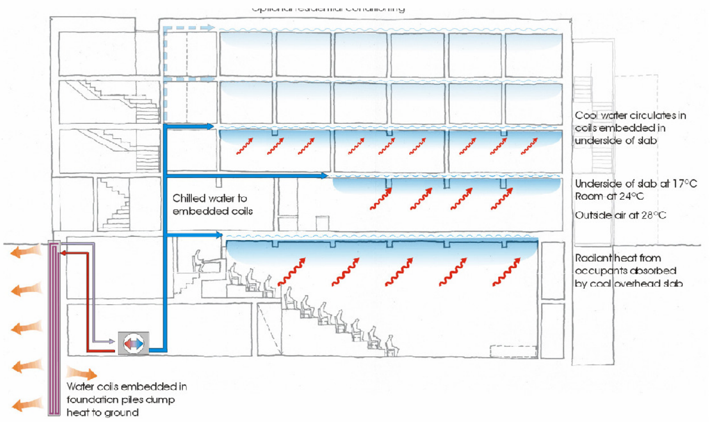


Figure 2.9 Heating/Cooling Integration System at Keble College, Oxford

2.2.4 Zurich Airport – Switzerland – 2003 (Pahud, D., and Hubbuch, M., 2007)

The Dock Midfield is the new terminal E of the Zürich Airport, designed for 26 planes and has a 500 m long – 30 m wide. Due to its instable upper ground soil layer, the foundation was constructed on 441 piles in 30 m depth and 0.9-1.5 m diameter. About 310 of those piles function as energy piles, equipped with 5 U-pipe which contain a water-glycol-mixture solution, embedded on the steel reinforcement, in order to exchange heat with the surrounding soil. This heat exchange is being used in conjunction with the ground water saturated soil as a seasonal storage.

Figure 2.10 The Dock Midfield Zürich Airport

During the summer, internal waste heat is collected through a heat exchange and ventilation system, and then being stored in the soil via the energy piles. The necessary cooling that is required for the heat exchange can be provided almost entirely by the energy piles. In winter, the heating can be covered by internal waste heat and heat from the soil storage. A heat pump is used as part of this process. In total, more than half of the cooling and heating demand can be covered by this system.

The heat pump coupled to the piles has been sized so that the fluid temperature in the pile circuit never drops below 0°C, both for short term or long term system operation. The temperature of soil is 10°C with no flow is expected. It delivers a heating power of 630 kW at the temperature conditions. Peak power loads are met with district heating demand, which was established to 2720 MWh/year, should be recovered by the heat pump. The cooling requirements are met by a cooling distribution network coupled to the pile system and the building ventilation system with conventional cooling machines. Cooling energy covered by the pile system is either made by geo-cooling or for heating purposes, if the heat pump is in operation. The return fluid temperature in the cooling distribution is expected to be 21°C. If geo-cooling is not sufficient to meet the cooling demand, the heat pump is used as a cooling machine. Its waste heat is dumped in cooling towers placed on the roof of the building.

2.2.5 Lainzer Tunnel, Vienna – Austria – 2004 (Brandl, 2006)

Austria is one of the pioneer countries in energy foundations applications. They started from base slabs heating system, energy piles, energy diaphragm wall, and the latest innovation is energy tunnel.

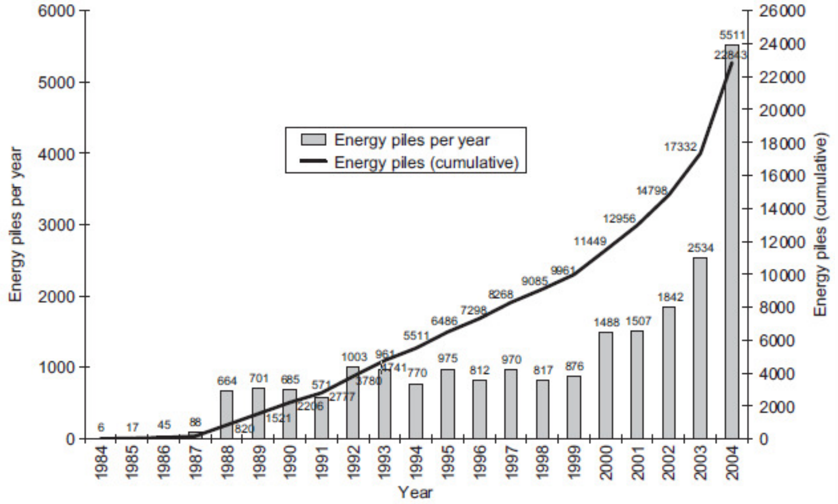


Figure 2.11 Statistic of Energy Piles Application in Austria

To upgrade the railway line between Vienna and Western Europe for four-track operation, a tunnel through the northern Vienna woods is being built. The core section of Lainzer Tunnel is 12.8 km long, which partly also serves as large energy-absorbing tube. A tunnel activates a significantly larger quantity of usable geothermal heat than deep foundations. The energy can be used for heating and/or cooling of railway stations, administration and residential buildings, and for keeping platforms, bridges, passages etc. free from ice in winter.

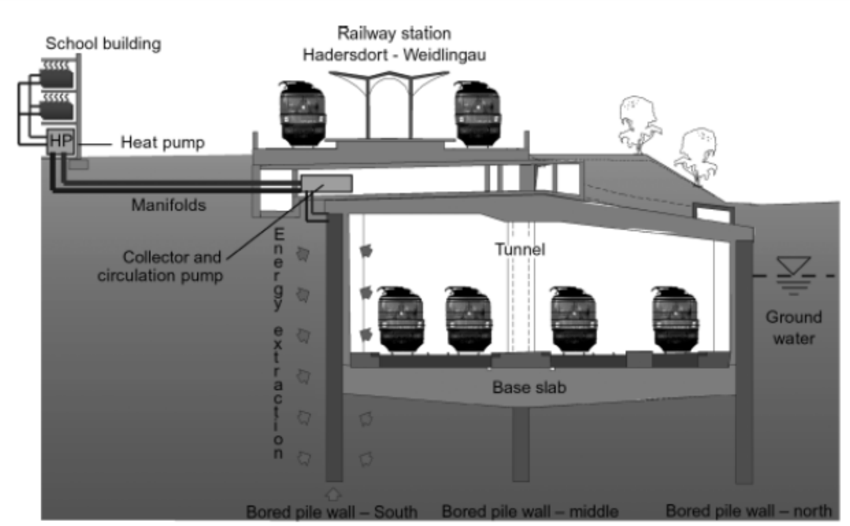


Figure 2.12 Cross Section of LT24: Hadersdorf–Weidlingau, Lainzer Tunnel

The Lainzer Tunnel has been constructed in several sections and by different methods:

(a) Cut and cover Method in section LT24. The primary side wall lining of the tunnel consists of bored piles, whereby each third pile is used as an energy pile, thus the energy plant LT24: Hadersdorf–Weidlingau comprises 59 bored piles with a diameter of 1.2 m and an average pile length of about 17.1 m. The intermittent pile wall exhibits jet-grouting columns between the piles. Pile excavation was supported by casings using rotating equipment. The energy piles are equipped with absorber pipes connected to collector/distributors, which are located at a central point of the tunnel. The pipes leading from the piles to the collector/distributors are placed alongside the cover of the tunnel. The connecting pipes lead into a collector/distributor room that is easily accessible on top of the cut and cover tunnel. The manometers allow a detailed water tightness check of all absorber pipes. A manifold with a diameter of 150 mm connects the collector/distributors with heat pumps in an adjacent school in order to heat the building.

Because of this scientific background, the plant is intensively instrumented with measurement devices. Six energy piles are fitted with 18 temperature gauges at different levels; additionally, one pile is fitted with combined strain–temperature gauges at five levels for measuring strains and temperature. The aim of this measuring system is to investigate the effects of temperature changes within an energy pile on its bearing capacity and the temperature fluctuation in the energy piles during operation. Moreover, heat carrier fluid passage, total extracted heat, and temperatures in the manifold are monitored. The groundwater temperature surrounding the energy plant is also registered (at different distances).

(b) New Austrian Tunnelling Method (NATM), with a primary support of reinforced concrete, rock bolts and anchors, and a secondary lining of reinforced concrete.

The NATM method for heat extraction/storage requires special absorber elements. The construction sequences make the installation of continuous absorber pipes in the longitudinal direction rather complicated. In principle, three structural elements can be used for thermal energy extraction/storage:

- energy anchors or nails that thermally activate the surrounding soil or rock
- energy geo-synthetics that make use of the ground around the tunnel circumference, mainly non-woven geo-textiles and geo-composites, but also some geo-membranes
- thermo-active secondary lining (inner reinforced concrete).

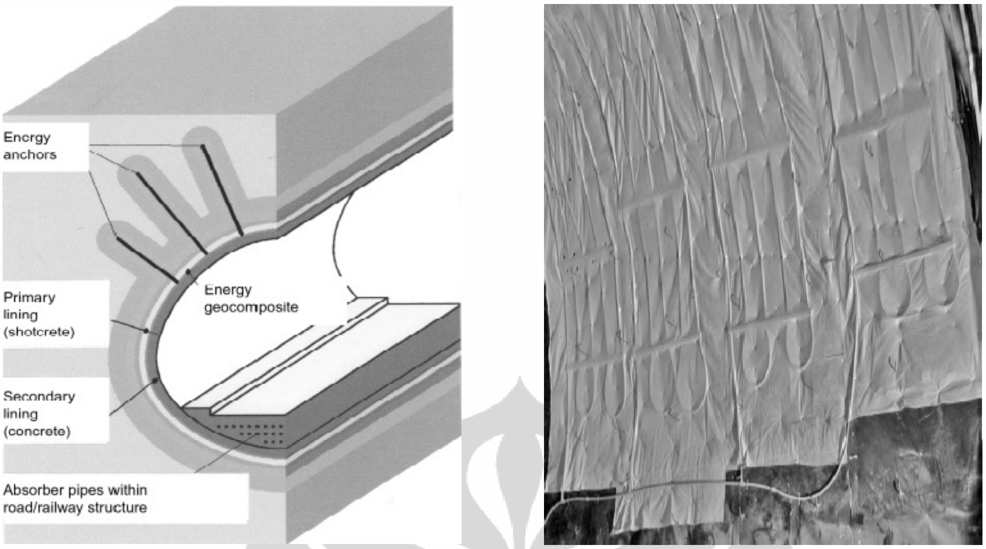


Figure 2.13 (a) Cross Section of Energy Tunnel with NATM Method (b) Energy geo-textile

The operation of the energy plant started in February 2004, and during the first testing phase, initial data were obtained that could be used to optimise the absorber system. About 40 MWh of heating energy could be extracted from the energy piles during the first six weeks of operation. The temperature induced deformations are significantly smaller than those caused by earth pressure, and the natural fluctuation of the tunnel temperature has a greater influence than the temperature changes due to energy extraction/storage in the energy piles. The energy operation causes a stronger cooling or heating of the piles, but this occurs uniformly, and hence causes a volumetric deformation without constraints, and therefore no additional load on the structure.

2.2.6 District Building, Shanghai – China – 2006 (Gao, J., et al., 2008)

A case study is presented to assess the geothermal energy for a district heating and cooling system in Shanghai, China. This study reports the numerical and experimental assessment of thermal performance of the vertical energy piles. First, the experimental setup and numerical method are introduced in three-dimensional numerical simulations; coupling heat convection and conduction through water in pipeline, concrete pile and soil; are performed to determine the most efficient type of pile-foundation heat exchangers. Experimental data are used to validate the numerical results. Second, numerical method is further applied to investigate five-year variations of the ground temperatures. The potential of geothermal energy and the operating performance of ground heat exchanger selected are analyzed using the modified energy output based on the practical ground temperatures in operation.

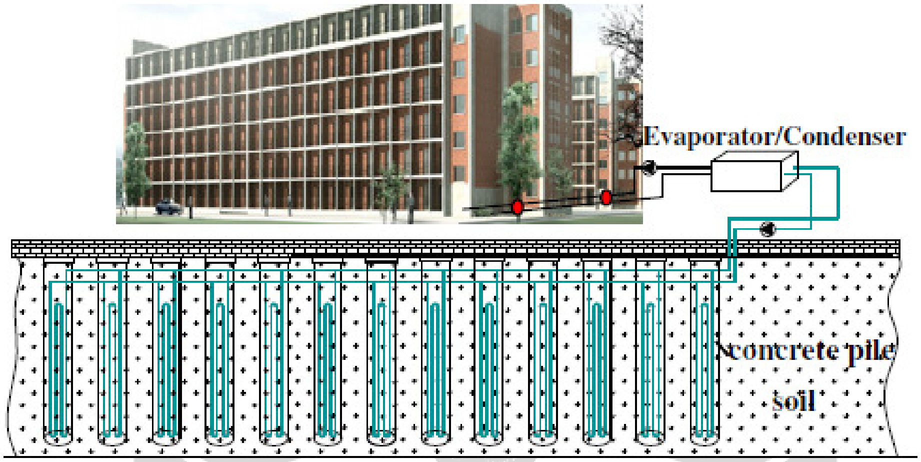


Figure 2.14 Conceptual diagram of heating operation

The building is completed in 2006, based on which a group of 5500 cast in-situ concrete pile foundations in a land parcel of 100 m x 1000 m, was used as energy piles. These energy piles will be operated in a GCHP system and are designed to take about 30% thermal load of the district heating and cooling system. The cast-in situ concrete bearing piles are used as pile-foundation heat exchangers with diameter 600 mm and length 25 m. The thermal medium is water, which flows in the high-density polyethylene (HDPE) pipes cased in the piles, with two different types: U-shaped pipe and W-shaped pipe.

Table 2.1 Specification of Material

Material	Thermal conductivity (W/m K)	Density (kg/m^3)	Heat capacity (J/kg K)
Soil (sandy silt)	1.3	1847	1200
Concrete	1.628	2500	837
HDPE	0.42	1100	1465

According to the climate data of Shanghai, space cooling season is designed from May to September and space heating season from December to next February. Depth of frozen earth in Shanghai is about 8 cm and soil temperature under 5 m depth stays almost constant in 18.2°C. Groundwater velocity in the soil is ranged from 3.65 m to 10.95 m/year so the effect of groundwater advection is neglected. Numerical study on the solid-fluid conjugated heat transfer encountered in the ground pile-foundation heat exchangers takes into consideration the mass, momentum, turbulence and energy conservation of water flow, and the energy conservation of soil and concrete pile. Performance test on heat transfer are conducted in situ, doesn't require constant heat flux but constant inlet temperature. Significantly, larger amount of thermal load can be achieved in shorter period of time because it produces larger heat exchange by its high inlet temperature. As a result, good agreement between the numerical and experimental results is achieved. Comparatively, numerical method provides more detailed information, which in some cases can be a good alternative of the experimental method on the premise of being well verified and validated.

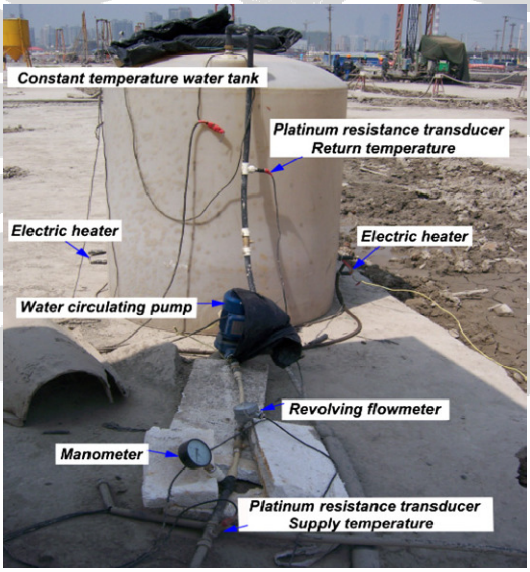


Figure 2.15 In-situ Thermal Performance Test Equipments

CHAPTER 3
DESIGN OF ENERGY PILES

The system of energy foundations requires necessarily heat transfer process from ground-source (geothermal source) in the soil, to the concrete piles, through a U-pipe plastic, along the heat pumps, in order to supply the demand heat for the building. In this chapter, we try to divide separately each energy transfer process which occurs in system to well establish the model application.

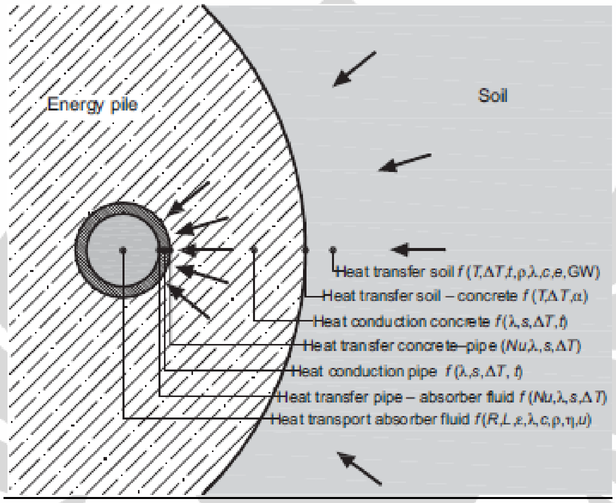


Figure 3.1 Heat Transfer of Energy Piles

3.1 Types of Energy Transfer

Before we continue to study the energy piles, we begin with the basic physics of energy transfer. There are three principal of energy transfer (Hillel, 2004) :

1) *Conduction* is the propagation of heat within a body by internal molecular motion due to a temperature gradient. Because temperature is an expression of the kinetic energy of a body's molecules, the existence of a temperature difference within a body will normally cause the transfer of kinetic energy by the collisions of rapidly moving molecules from the warmer region of the body to their neighbours in the colder region. The process of heat conduction is thus analogous to diffusion; and in the same way that diffusion tends in time to equilibrate a mixture's composition throughout, heat conduction tends to equilibrate a body's internal temperature.

2) *Convection* is the movement of a heat-carrying mass of a molecule within fluids i.e. liquids and gases). It cannot take place in solids, since neither bulk current flows nor significant diffusion can take place in solids. Convection refers to heat convection in which heat is the entity of interest being advected (carried) and diffused (dispersed). There are two major types of heat convection :

   - Heat is carried passively by a fluid motion which would occur anyway without the heating process. This heat transfer process is often termed *forced convection* or occasionally *heat advection*.
   - Heat itself causes the fluid motion (via expansion and buoyancy force), while at the same time also causing heat to be transported by this bulk motion of the fluid. This process is called *natural convection,* or *free convection*. With natural convection, heat transport (and related transport of other substances in the fluid due to it) is generally more complicated.

3) *Radiation* is the emission of electromagnetic waves energy from all bodies above 0°K.

The difference between these three types is that convective heat transfer is a mechanism of heat transfer occurring because of bulk motion (observable movement) of fluids. This can be contrasted with conductive heat transfer, which is the transfer of energy by vibrations at a molecular level through a solid or fluid, and radiative heat transfer, the transfer of energy through electromagnetic waves.

3.2 Method of Application

Heat transfer process in energy piles system gives some physics implications to the behaviour of soils and mechanics implications to the interaction of structure concrete piles and soils. In soils, heat transfer depends on its physical thermal properties, where soil's thermal properties depend on groundwater flows and saturation degree; hence it's a hydro-thermal transfer process. Besides, heat transfer from soil to concrete in pile's interface is a thermo-mechanical process, where its thermal load gives thermal dilatation, in which causes i) an additional stress, ii) a lateral friction in interface, and iii) a head uplift displacement (Laloui, L., Nuth, M., and Vulliet, L., 2006).

This complex system needs a fully-consideration design, both in numerical approach and experimental approach to validate the design. Before that, we have to determine all parameters and variables to create an energy piles system, including their energy transfer in thermal-mechanical-and hydraulic transfer. As a summary of history application of energy piles over the world, we propose a method of design planning and application of this system:

1. Preliminary Test : Geological Soil Investigation and Thermal Response Test
   to determine the geology, hydrogeology, mechanical, and thermal properties of soil
2. Design Mathematical Model (Analytical Approach)
   based on the parameters obtained in preliminary test, divided by 2 basic parameters groundwater velocity and saturation degree
3. Numerical Approach of Thermo-Hydro-Mechanical Model
   by using finite element model in applying thermo-hydro-mechanic coupling
4. Validation Model : Thermal Performance Test by Experimental Approach
   to validate the design and its visibility, the experimental test should be done simultaneously to compare the result of numerical and experimental

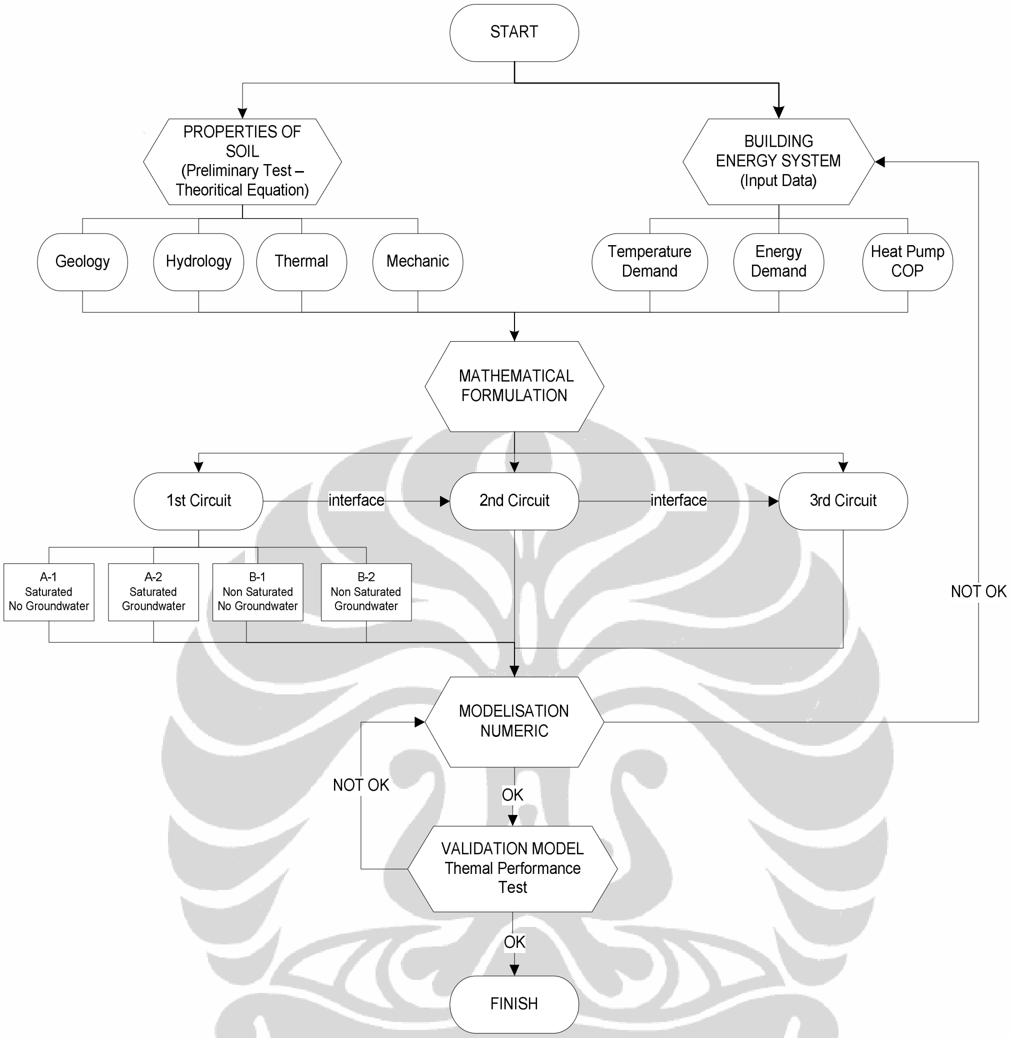


Figure 3.2 Flow chart design application of energy piles

Below we note in table the parameters and variables required to design energy piles system, both by preliminary test, theoretical equation and by input data.

Table 3.1 Parameters and Variables Required

No	System		Parameter				obtained by		
	Layer	Transfer Energy				symbol	in-situ test	theoretical coefficient/equation	input design
1	CIRCUIT 1 : SOIL	heat transfer : a.conduction only b.conduction + convection	Geology	SOIL LAYERING!			x		
				density		ρ	x		
				water content		θ	x		
				porosity		n	x		
				degree of saturation		Sr	x		
				void ratio		e	x		
				permeability/hydraulic conductivity		K	x		
			Hydrology	ground water table	depth		x		
					seasonal fluctuation		x		
				ground water	flow direction		x		
					velocity (Darcy)	$\vec{v}_{gr.w}$		x	
			Thermal	in situ ground temperature		T	x		
				thermal conductivity		λ		x	
				heat capacity		C_v		x	
				thermal gradient		ΔT	x		
			Mechanic	shaft friction		q_s	x		
				tip capacity		q_p	x		
				poison ratio		υ		x	
				young modulus		E		x	
				shear modulus		G		x	
				friction angle		ϕ	x		
				cohesion		c	x		
2	INTERFACE 1	heat transfer	heat transfer coefficient			h		x	
3	CIRCUIT 2 : CONCRETE	heat conduction	Geometry	dimension	diameter	d			x
					length	L			x

				Reinforcement	diameter	d			x
					spacing position	s			x
			Thermal	heat conductivity		λ		x	
				specific heat capacity		C_v		x	
				specific heat extraction		c		x	
4	INTERFACE 2	heat transfer		heat transfer coefficient		h		x	
5	CIRCUIT 2 : PIPE	heat conduction	Geometry	type					x
				dimension	inner diameter	d_i			x
					outer diameter	d_o			x
					length	L			x
				spacing position		s			x
			Thermal	heat conductivity		λ			x
				specific heat extraction		c			x
6	INTERFACE 3	heat transfer		heat transfer coefficient		h		x	
7	CIRCUIT 2 : FLUIDE	heat convection	Thermal	temperature (input heat pump)		T			x
				velocity		$\vec{v}$			x
8	HEAT PUMP	heat exchange	Energy	annual hours operation					x
				COP					x
9	CIRCUIT 3 : BUILDING	heating/cooling system	Thermal	temperature (output heat pump)		T			x
			Energy	system energy	heating/cooling only				x
					both heating cooling				x
				monthly demand		$\dot{Q}$			x
				peak demand		$\dot{Q}$			x

CHAPTER 4
MATHEMATICAL MODEL (ANALYTICAL APPROACH)

The heat transfer between a building and the surrounding soil is complicated by many unknowns, such as the soil's physical properties and complex physical processes, many of which involve moisture considerations. For example, heat is transferred by thermal conduction and moisture flow transfer; the thermal properties of soil are strong functions of water content; and moisture phase change includes latent heat effects and changes in the soil's thermal and hydraulic properties (Deru, M.A., and Kirkpatrick, A.T., 2001).

Therefore, modelling the energy piles require a coupled system of thermo-hydro-mechanical (THM) because each other correlated and influenced simultaneously: heat transfer process causes the hydrology flow (moisture transfer) in soil, and those change the mechanic behaviour of soil and concrete themselves. Soil and concrete are porous medium, consist of three elements: solid, liquid, and air, thus the main idea for modelling the energy piles system is the thermo-hydro-mechanical model in porous medium.

1. The Hydraulic Process

   There is a natural hydraulic process in soil with its groundwater flow, named moisture transfer under both moisture (water content) gradient and temperature gradient. Moisture transfer based on mass conservation's formula can be separated in two phase of groundwater: liquid phase and vapour phase. According to the study of Hadley and Eisenstadt (1955), moisture transfer under temperature gradients is negligibly small both in very wet medium and in very dry medium. It means that the influence of temperature in groundwater flows only exists in partly saturated soil.

2. The Thermal Process

   Heat transfer in soil occurs by conduction through the soil grains, liquid, and gases; latent heat transfer through evaporation-condensation cycles; sensible heat transfer by vapour and liquid diffusion and convection; and radiation in the gas-filled pores (de Vries, 1975). Conduction through the solid soil particles is the dominant mode of heat transfer under most circumstances. The presence of moisture in the soil provides additional transport mechanisms. In this case, we neglected the type of transfer by radiation solar. The heat transfer governed in equation of energy conservation.

3. The Mechanic Process

   Due to the hydraulic and thermal process in porous medium, they affect an addition in pore water pressure and effective stress. We have to consider the thermal stress, pore pressure, beside the elastic stress itself, which formed in equilibrium momentum conservation.

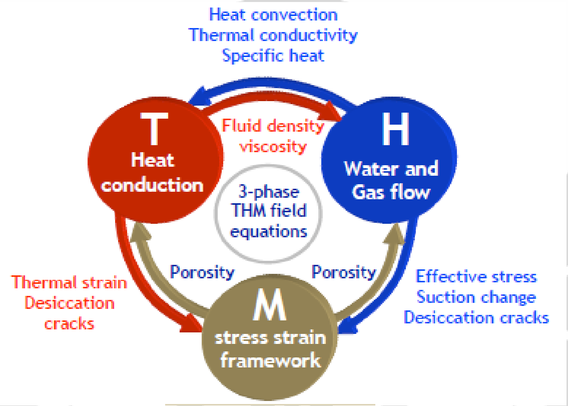


Figure 4.1 Thermo Hydro Mechanic Coupled of Energy Piles (Peron, 2010)

4.1 Soil System (1^{st} Circuit)

4.1.1 Thermal Properties

Soil thermal properties largely depend on the volume fraction of water ($f_w = \theta$), solids (f_s), and air ($f_a = a$) in the soil (Ochsner, T.E., Horton, R., and Ren, T., 2001). In many natural settings θ, f_s, and a vary greatly over time and space. The soil thermal properties: ground temperature (T), heat capacity (C_v), thermal conductivity (λ), and thermal diffusivity (D_T) are important in many agricultural, engineering, and meteorological applications. Those properties govern the amount of heat flux in soil.

4.1.1.1 Ground Temperature

Temperature of soil is a function of depth and time, which fluctuates annually and daily affected by variations in air temperature and solar radiation. Generally, the fluctuation of soil temperature becomes constant at depth superior of 5-6 m; contrary in time variation, it forms a sinusoidal function.

The annual variation of daily average soil temperature at different depths is described with the following sinusoidal function (Hillel, 2004) :

$$T(z,t) = T_{ave} + A_o e^{-\frac{z}{d}} \left[sin \left(\omega t - \frac{z}{d} \right) \right]$$

where :

T_{ave} = average soil temperature

A_o = maximum annual amplitude

z = depth in which temperature is investigated

d = damping depth of annual fluctuation

ω = annual radial frequency $\left(\frac{2\pi}{365}\right)$

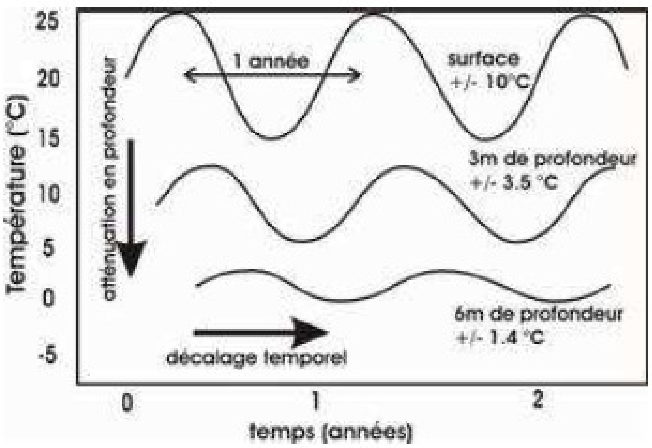


Figure 4.2 Annual variation of soil temperature in different depth in France (Guillou-Frottier, 2004)

4.1.1.2 Heat Capacity

A soil's volumetric heat capacity C_v is defined as the change of a unit volume's heat content per unit change in temperature. C_v depends on the composition of the soil's solid phase (mineral and organic components), on bulk density, and on soil wetness. The value of C_v can be estimated by summing the heat capacities of the various constituents, weighted according to their volume fractions, as given by de Vries (1975) :

$$C_v = \Sigma\left(f_s C_s + f_f C_f + f_a C_a\right) = \Sigma\left(f_s C_s + \theta C_f + a C_a\right)$$

The C value for water, air, and each component of the solid phase is the product of the particular density (ρ) and the specific heat per unit mass(c), written by $C = \rho c$. Generally we assume that soil is biphasic porous medium where the air content is neglected. If n = porosity factor of porous medium, therefore:

$$c_{soil} = (1 - n)c_s + nc_f$$

$$C_v = (1 - n)\rho_s c_s + n\rho_f c_f$$

4.1.1.3 Thermal Conductivity

Thermal conductivity λ is defined as the quantity of heat transferred through a unit area of the conducting body in unit time under a unit temperature gradient. Soil's thermal conductivity depends on its mineral composition and organic matter content as well as on the volume fractions of water and air. The thermal conductivity of air is very much smaller than that of water or solid matter; hence a high air content (or low water content) corresponds to a low thermal conductivity. Moreover, since the proportions of water and air vary continuously and soil composition is seldom uniform in depth, λ is generally a function of time as well as of depth. Unlike heat capacity, thermal conductivity is sensitive not only to the mineral composition of a soil but also to the sizes, shapes, and arrangements of soil particles.

The following form for partly saturated soil was used by van Bavel and Hillel (1975, 1976):

$$\lambda_{soil} = \frac{\theta\lambda_f + k_s f_s \lambda_s + k_a a \lambda_a}{\theta + k_s f_s + k_a a}$$

where k_w, k_a, and k_s are the specific thermal conductivities of the soil constituents (water, air, and an average value for the solids, respectively).

Another approach in biphasic porous medium with porosity n, the soil's thermal conductivity is formed by:

$$\lambda_{soil} = (1 - n)\lambda_s + n\lambda_f$$

4.1.1.4 Thermal Diffusivity

The thermal diffusivity D_T, instead of the conductivity λ, is sometimes desired (Horton, 2002). It can be defined as the change in temperature produced in a unit volume by the quantity of heat flowing through the volume in unit time under a unit temperature gradient. An alternative definition, the thermal diffusivity is the ratio of the conductivity to the product of the specific heat and density

$$D_T = \frac{\lambda}{\rho c_{soil}} = \frac{\lambda}{C_v}$$

4.1.2 Hydrology Properties

Groundwater flows in soils depend on water content (moisture) and temperature gradients, which require a predetermination of thermal and isothermal diffusivity. The water content gradient is generally less that those of temperature; even with the maximum temperature gradient, the flux due to water content gradient is more important that those due to temperature gradient. The thermally induced groundwater flows as the moisture flux through soils which arise solely due to a temperature gradient are rather small to zero in saturated soils, where in partly saturated soils can be large. A widely used theory for coupled heat and moisture flow through soils was developed by Philip and de Vries (1957) for both liquid and vapour phase flows.

4.1.2.1 Groundwater flows in Liquid phase

Liquid transfer is governed by Darcy's law which can be summarized:

$$\vec{v}_{liq} = -D_{\theta,liq} grad\theta - D_{T,liq} gradT - Ki$$

where :

$D_{\theta,liq} = K\frac{\partial\psi}{\partial\theta}$ = isothermal liquid diffusivity

$D_{T,liq} = K\frac{\psi}{\sigma}\frac{\partial\sigma}{\partial T}$ = thermal liquid diffusivity

K = hydraulic conductivity

i = unit vector in vertical direction

ψ = suction head

σ = surface tension

As a complete equation, we can write the liquid flows as:

$$\vec{v}_{liq} = -K\frac{\partial\psi}{\partial\theta}grad\theta - K\frac{\psi}{\sigma}\frac{\partial\sigma}{\partial T}gradT - Ki$$

4.1.2.2 Groundwater flows in Vapour phase

Movement in vapour phase is a process of the diffusion of water vapour in the air-filled pores which can be approximated by modifying the Fick's law of diffusion:

$$\vec{v}_{vap} = -D_{T,vap}gradT - D_{\theta,vap}grad\theta$$

where :

$$D_{T,vap} = \eta a(1-Sr)\frac{D_{atm}}{\rho_w}\frac{d\rho_{vap}}{dT} = \eta a(1-Sr)\frac{D_{atm}}{\rho_w}\frac{M}{RT}\frac{dp_{vap}}{dT}$$

$$D_{\theta,vap} = \eta a(1-Sr)\frac{D_{atm}}{\rho_w}\frac{g\rho_{vap}}{RT}\frac{d\psi}{d\theta}$$

$$D_{atm} = 2290\left[1+\frac{T}{273}\right]^{1,75}$$

$D_{T,vap}$ = thermal vapor diffusivity

$D_{\theta,vap}$ = isothermal vapor diffusivity

D_{atm} = molecular vapor diffusivity

η = tortuosity factor

In a complete formula, the vapour flows is:

$$\vec{v}_{vap} = -\eta a(1-Sr)\frac{D_{atm}}{\rho_w}\left[\frac{d\rho_{vap}}{dT}gradT + \frac{g\rho_{vap}}{RT}\frac{d\psi}{d\theta}grad\theta\right]$$

4.1.2.3 Total Groundwater flows

The total groundwater flows are the sum of groundwater in liquid and vapour flows. The two liquid diffusivities tend to be the most important ones at high moisture contents, whilst the two vapour diffusivities are dominant at low moisture contents (Philip, J.R., and de Vries, D.A, 1957).

A. Saturated Soils

In saturated soils with high moisture content, there is only the liquid flow and the flows transfer under temperature gradient is neglected, thus:

$$\vec{v}_{gr.water} = -D_{\theta,liq}\, grad\,\theta - Ki = -K\frac{\partial\psi}{\partial\theta}grad\,\theta - Ki = -K\,grad\,p$$

B. Non-Saturated Soils

In partly saturated soils with low moisture content, both liquid and vapour flows are considered; and approximately in non-saturated soils, vapour flows under moisture gradient leads the formulation:

$$\vec{v}_{gr.water} = -D_\theta \; grad\;\theta - D_T gradT - Ki \cong -D_{\theta,vap}\; grad\;\theta$$

where $D_\theta = D_{\theta,liq} + D_{\theta,vap}$ and $D_T = D_{T,liq} + D_{T,vap}$

4.1.3 Thermo-Hydro-Mechanical Mathematical Model

There are three basic parameters which govern the coupled of THM in soils, which are: temperature, pore water pressure, and solid deformation. The mathematical formulation is basically driven by the thermodynamics principle in continuum mechanics.

4.1.3.1 Mass Conservation → Hydraulic Process

A porous medium in domain Ω has a mass quantity by unit volume as below:

$$M = \int_V \rho \, dV$$

This mass should be conserved in domain Ω without movement, thus the variation of mass in time should be zero.

$$\frac{dM}{dt} = \frac{\partial \rho}{\partial t} + div(\rho \vec{v})$$

For porous medium biphasic solid-fluid with the porosity n, the equation of mass conservation becomes:

$$\frac{n}{\rho_f}\frac{\partial \rho_f}{\partial t} + \frac{(1-n)}{\rho_s}\frac{\partial \rho_s}{\partial t} + div\big(n\vec{v}_f\big) + div\big((1-n)\vec{v}_s\big) = 0$$

Knowing that the density is a function of temperature and mechanical deformation, for x = phase of porous medium (solid or fluid), the density is $\rho_x(\varepsilon_x, T)$; hence the variation of density in time takes account both of temperature and mechanical deformation.

$$\frac{1}{\rho_x}\frac{\partial \rho_x}{\partial t} = \frac{1}{\rho_x}\left[\frac{\partial \rho_x}{\partial \varepsilon_x} : \frac{\partial \varepsilon_x}{\partial t} + \frac{\partial \rho_x}{\partial T} : \frac{\partial T}{\partial t}\right]$$

For the following equation, we consider two coefficients to be used:

a) Hydro-Thermal coupled as variation of density in temperature

$\frac{\partial \rho_x}{\partial T} = -\rho_x \alpha_x$; α_x = coefficient of thermal expansion

b) Hydro-Mechanic coupled as variation of density in mechanical deformation corresponds to variation of pore pressure in time

$\frac{\partial \rho_x}{\partial \varepsilon_x} : \frac{\partial \varepsilon_x}{\partial t} = \rho_x \beta_x \frac{\partial p}{\partial t}$; β_x = coefficient of compressibility

Then, the variation of density in time is summarized as:

$$\frac{1}{\rho_x} \frac{\partial \rho_x}{\partial t} = \beta_x \frac{\partial p}{\partial t} - \alpha_x \frac{\partial T}{\partial t}$$

We introduce the relative velocity of solid-fluid in porous medium, as a function of:

$$\vec{v}_{rf} = n\left(\vec{v}_f - \vec{v}_s\right)$$

where the relative velocity $\vec{v}_{rf}$ in porous medium soil is equal with the groundwater velocity, which in saturated soils can be replaced directly by the Darcy's equation :

$$\vec{v}_{rf} = n\left(\vec{v}_f - \vec{v}_s\right) = -K\, grad\, p$$

With the known coefficients, the final equation of mass conservation in saturated soils is:

$$\frac{n}{\rho_f} \frac{\partial \rho_f}{\partial t} + \frac{(1-n)}{\rho_s} \frac{\partial \rho_s}{\partial t} + div\left(n \vec{v}_f\right) + div\left((1-n)\vec{v}_s\right) = 0$$

$$\left[n\beta_f + (1-n)\beta_s\right] \frac{\partial p}{\partial t} - \left[n\alpha_f + (1-n)\alpha_s\right] \frac{\partial T}{\partial t} + div\, \vec{v}_{rf} + div\, \vec{v}_s = 0$$

$$\left[n\beta_f + (1-n)\beta_s\right] \frac{\partial p}{\partial t} - \left[n\alpha_f + (1-n)\alpha_s\right] \frac{\partial T}{\partial t} + div\, \vec{v}_s - div\, (K\, grad\, p) = 0$$

4.1.3.2 Energy Conservation → Thermal Process

Energy conservation in soils governed by thermodynamics law:

a) 1st law of thermodynamics to determine heat conduction in steady state condition by Fourier's law

$\vec{q} = -\lambda\, grad\, T$

b) 2nd law of thermodynamics to calculate thermal energy conservation in non steady state condition by modifying Fick's law

$$\rho c \frac{dT}{dt} + div\, \vec{q} = 0$$

$$\rho c \left[\frac{\partial T}{\partial t} + \vec{v}\, grad\, T\right] = -div\, \vec{q}$$

$$C_v \frac{\partial T}{\partial t} + \rho c \vec{v}\, grad\, T = div\, (\lambda\, grad\, T)$$

The following equation governs the energy conservation in soils as biphasic porous medium:

$$\left[(1-n)\rho_s c_s + n\rho_f c_f\right]\frac{\partial T}{\partial t} + \left[(1-n)\rho_s c_s \vec{v}_s + n\rho_f c_f \vec{v}_f\right] grad$$
$$= div\left[\left\{(1-n)\lambda_s + n\lambda_f\right\} grad\, T\right]$$

where the value of $\left[(1-n)\rho_s c_s \vec{v}_s + n\rho_f c_f \vec{v}_f\right] = n\rho_f c_f \vec{v}_{rf} + \rho_s c_s \vec{v}_s \cong \rho_f c_f \vec{v}_{rf}$

Therefore, the final equation of conservation energy in saturated soils where the liquid flows is dominant:

$$C_v \frac{\partial T}{\partial t} + \rho_f c_f \vec{v}_{liq}\, grad\, T = div\, [\lambda\, grad\, T]$$

$$C_v \frac{\partial T}{\partial t} - \rho_f c_f K\, grad\, p\, grad\, T = div\, [\lambda\, grad\, T]$$

According to the equation above, the flux of convection heat transfer can be determined as:

$$\vec{q} = \rho_f c_f (T - T_0)\vec{v}_{liq} = -\rho_f c_f (T - T_0)(K\, grad\, p)$$

In non-saturated soils when evaporation may occur, we have to consider the value of vapour flow. Hillel (2004) formed energy conservation by taking the latent heat L_v transfer:

$$C_v \frac{\partial T}{\partial t} = div\, [\lambda\, grad\, T] - L_v\, div\, \left[D_{\theta,vap}\, grad\, \theta\right]$$

The flux of evaporation heat transfer according to the vapour flows is:

$$\vec{q} = L_v \vec{v}_{vap} = L_v\left(D_{\theta,vap}\, grad\, \theta\right)$$

4.1.3.3 Momentum Conservation → Mechanical Process

The amount of momentum of a porous medium in domain Ω by unit volume is:

$$I = \int_V \rho \vec{v}\, dV$$

For steady state condition in momentum conservation, the variation of momentum in time should be zero as the following equation:

$$\frac{dI}{dt} = div\ \sigma + \rho g = 0$$

While we investigate the saturated soils, the formulation becomes:

$$div\ \sigma_{TOT} + \rho_{sat} g = 0$$

$$\sigma_{TOT} = \sigma_{eff} - p = (C\colon \varepsilon^e) - p$$

By applying the term of total stress, the final momentum conservation's formula is:

$$div\ (C\colon \varepsilon^e) - grad\ p + \rho_{sat} g = 0$$

4.1.4 Formulation Model

The heat transfer process in soil depends on 2 basic parameters: saturation degree and groundwater velocity. As conclusion of part 4.1.3, we define the mathematical equations for each possible condition.

Table 4.1 Division of Problem Heat Transfer in Soil

		SATURATED		NON SATURATED	
		no groundwater velocity	with groundwater velocity	no groundwater velocity	with groundwater velocity
		A-1	**A-2**	**B-1**	**B-2**
Heat Transfer					
	in solid Conduction	v	v	v	v
	In liquid Convection	x	v	x	v
	in vapour Latent	x	x	v	v

Table 4.2 Formulation of Heat Transfer in Soil

A-1	$C_v \frac{\partial T}{\partial t} = div\ [\lambda\ grad\ T]$
A-2	$C_v \frac{\partial T}{\partial t} - \rho_f c_f K\ grad\ p\ grad\ T = div\ [\lambda\ grad\ T]$

B-1	$C_v \frac{\partial T}{\partial t} = div\ [\lambda\ grad\ T] - L_v\ div\ \left[D_{\theta,vap}\ grad\ \theta\right]$
B-2	$C_v \frac{\partial T}{\partial t} - \rho_f c_f K\ grad\ p\ grad\ T = div\ [\lambda\ grad\ T] - L_v\ div\ \left[D_{\theta,vap}\ grad\ \theta\right]$

4.2 Interface Soil – Pile System (2nd Circuit)

At the interface soil – piles, the continuity of system have to be established by 3 conditions:

a) *Continuity of Stress*

$$\sigma_{soil} + \sigma_{pile} = 0$$

b) *Continuity of displacement*

$$\vec{u}_{soil} + \vec{u}_{pile} = 0$$

c) *Continuity of heat flux*

$$\vec{q}_{soil} + \vec{q}_{pile} = 0$$

By introducing the heat transfer coefficient h, Brandl (2006) state that:

$$h = \frac{\vec{q}_{pile}}{T_{soil} - T_{pile}} = -\frac{\lambda\ grad\ T}{\Delta T}$$

If the foundation system is a group piles, then the continuity heat transfer is:

$$\vec{q}_{soil} C_{soil} = n\vec{q}_{pile} C_{pile} = nh\left(T_{soil} - T_{pile}\right) C_{pile}$$

On the other hand of continuity system, the heat transfer process induces thermal dilatation of the concrete pile, which influences its mechanical behaviour. From the thermo-elasticity equation, the thermal dilatation value is:

$$\varepsilon^{th} = \alpha \Delta T$$

The total deformation of structure including elastic deformation and thermal dilatation:

$$\varepsilon = \varepsilon^{e} + \varepsilon^{th}$$

The elastic stress is a linear product of elasticity modulus and elastic deformation:

$$\sigma = E\varepsilon^{e} = E(\varepsilon - \varepsilon^{th})$$

where the thermal stress itself is:

$$\sigma^{th} = E\varepsilon^{th}$$

The recent study of Laloui (2006) remarked that the heat transfer process in the energy piles system cause:

a) pile uplift due to thermal dilatation of pile
b) additional stress related to thermal stress
c) lateral friction by the change of vertical stress $\tau = \sigma_v \tan\phi + c$

4.3 Building Thermal System (3rd Circuit)

The demand of heating/cooling building has to be designed firstly as a crucial parameter. It's used to design the input energy of heat pump as the fluid temperature, and to design how many pipes and piles to be created to support the building mechanical & thermal loading.

For $\dot{Q}_2$ = demand heat of building (3rd circuit) = output energy of heat pump, and $\dot{Q}_1$ = input energy of heat pump (2nd circuit); the energy equation which occurs in the heat pump is:

$$\dot{Q}_2 = \dot{Q}_1 + P_{HP}$$

$$\dot{Q}_2 = \dot{Q}_1 + \frac{\dot{Q}_2}{COP}$$

$$\dot{Q}_2\left[1 - \frac{1}{COP}\right] = \dot{Q}_1$$

The continuity system should have an input energy of heat pump (2nd circuit) equals to the output energy of heat source (1st circuit).

$$\dot{Q}_1 = \dot{Q}_{soil}$$

$$\int (n\vec{q}C\,dl)_{pile} = \int (\vec{q}C\,dl)_{soil}$$

$$\int nh\left(T_{soil} - T_{pile}\right)C_{pile}\,dl_{pile} = \int (\vec{q}C\,dl)_{soil}$$

CHAPTER 5
NUMERICAL MODEL

5.1 Definition Model

A simple modelling to examine how the heat diffuses in the energy piles system will present here by utilising finite element analysis program FLAC3D. The objective of this modelling is to determine whether FLAC 3D is sufficient enough to calculate thermo-hydro-mechanic coupled in time loading analysis until it reach steady state condition.

Due to the short time of this internship research, we limit the model in following conditions:

- no groundwater flows in the soils
- temperature of pile is constant
- no seasonal temperature loading
- pile head is free of constrain
- no mechanical loading
- thermo-elastic condition

A concrete pile with diameter 60 cm and length 10 m is located in the centre of soil area with radius horizontal 20 m. Average ground temperature that we use in calculation is 14°C . During the period of winter, the system works in heating system, heat is extracted from soil to building by fixing the concrete pile in 4°C. Contrary, in the period of summer, the system works in cooling system, heat is injected to soil from building by fixing the concrete pile in 22°C. This model assumes that temperature in concrete pile is homogeneous in one period of season. We neglected the seasonal temperature loading and don't compute the diffusion in concrete itself. Each model is loaded by heating and cooling cyclic time for one season period, started by 1s, 100 s, 500 s, 1000 s, 2500 s, 1 hour, 1 day, 3 days, 7 days, 15 days, 1 month, 3 months, and 6 months.

Table 5.1 Properties of Model

		SOIL	CONCRETE
Thermal conductivity	W/m^2	1.5	1.8
Specific heat extraction	J/kg °C	800	880
Bulk modulus	MPa	20	20000
Shear modulus	MPa	7.5	7500
Density	Pa	1950	2500

5.2 Constant Ground Temperature

The first analysis in constant ground temperature, soil temperature is initialized at 14°C. The depth of soil varies by the ratio of length of pile. This variation allows to determine the distance of temperature diffusion's zone until reach steady state condition. After analyzing the distance of diffusion's zone, we choose one proper model to examine the mechanical behaviour of pile: thermal dilatation, elastic stress and strain.

5.2.1 Zone of Diffusion

To define the proper distance of temperature diffusion, we compare 4 types of model based on variation of ratio length of pile (L) vs. depth of soil (H) as follows:

#1. Ratio 5 : 8, L 10 m H 16 m

#2. Ratio 1 : 2, L 10 m H 20 m

#3. Ratio 1 : 3, L 10 m H 30 m

#4. Ratio 1 : 4, L 10 m H 40 m

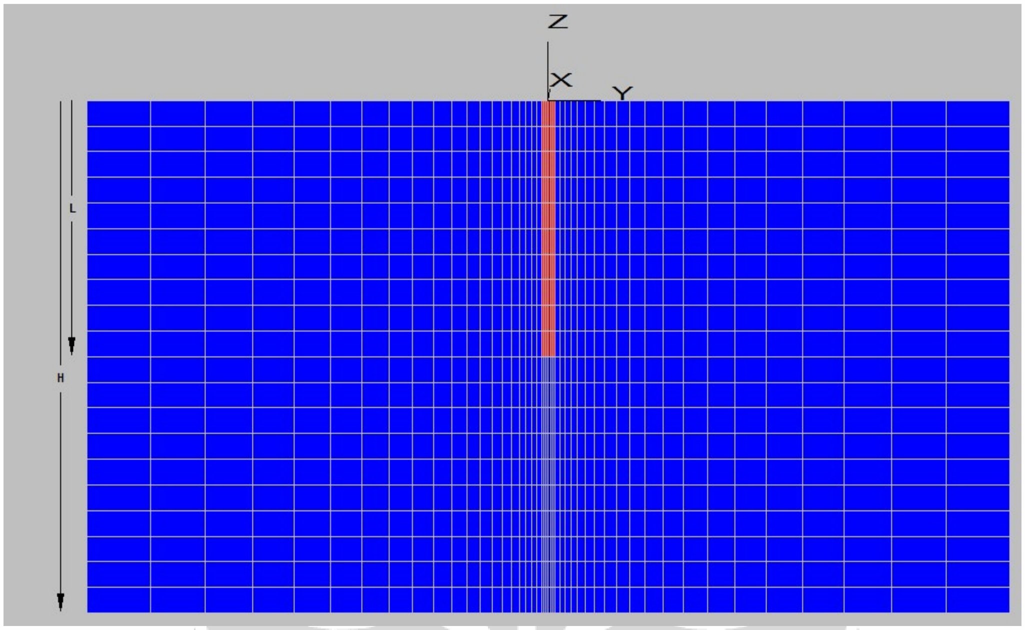


Figure 5.1 Model Cross Section in 2D

When thermal load is applied in time cycle, the diffusion varies in space and time. We present here the result graphic of vertical temperature diffusion in each type of model. According to those, temperature has already reached a steady state condition at depth 20 m; hence we choose the model #3 with the ratio L : H = 1 : 3 as the appropriate model.

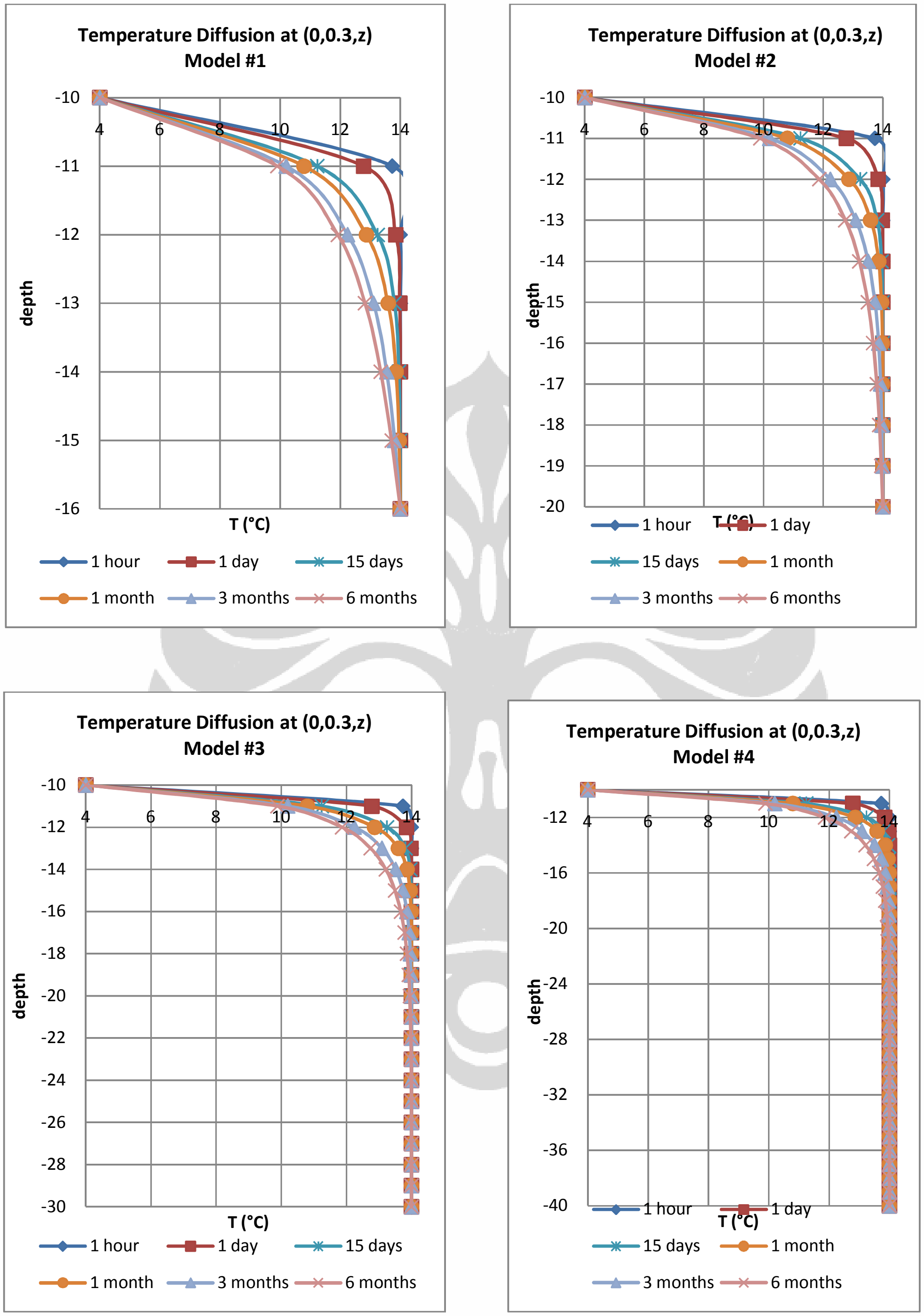


Figure 5.2 Vertical temperature diffusion in Heating System

The time analysis shows that the longer time of heating/cooling, the more smooth and balanced diffusion in vertical depth, which corresponds to larger temperature different between 4 types in reaching their steady state condition.

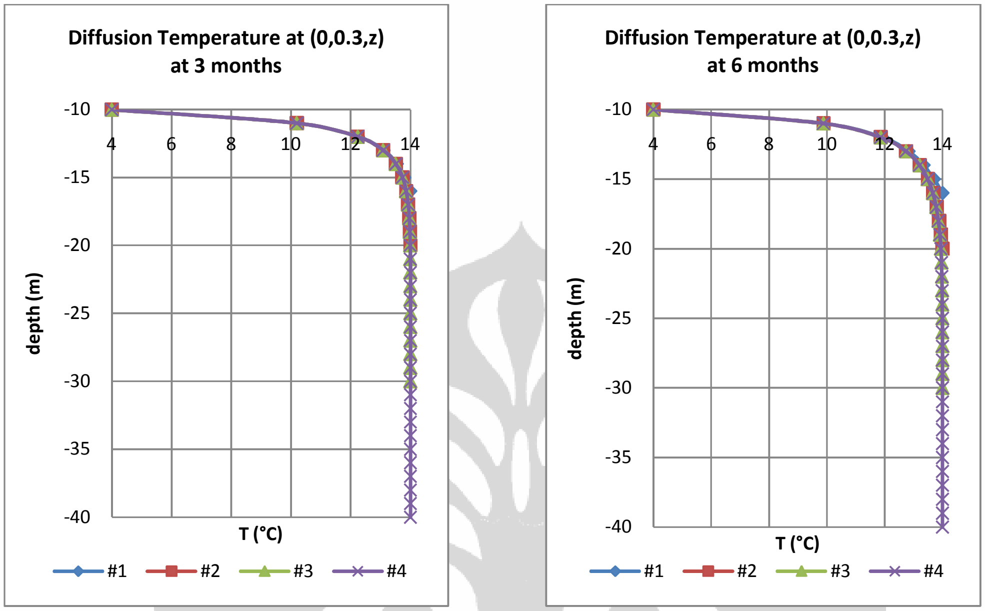


Figure 5.3 Comparison of vertical temperature diffusion in 3 and 6 months

The diffusion in horizontal area is the same in 4 types because no variation of radius horizontal of soils. The result shows that radius 20 m is sufficient enough to the model because the temperature has already reached its steady temperature in radius 12-16 m.

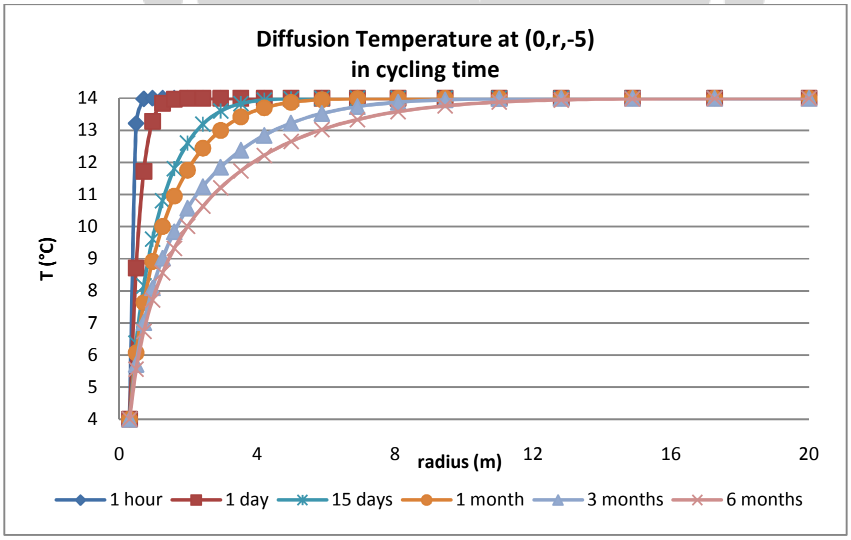


Figure 5.4 Horizontal temperature diffusion in Heating System

5.2.2 Mechanic Behaviour

By the zone diffusion analysis, the model #3 is chosen as our proper model. The further step is examining the mechanical behaviour of pile concrete and taking comparison in heating and cooling system.

5.2.2.1 Pile Uplift

The effect of thermal loading in pile uplift has just increased after 100000 seconds; or correlated to our loading cycle, its influence appeared after 1 day heating/cooling time. The maximum pile uplift in 6 months heating is -0.736 mm, and in 6 months cooling is 0.588 mm. These small displacements consist of only thermal loading, there's no mechanical loading applied in the pile.

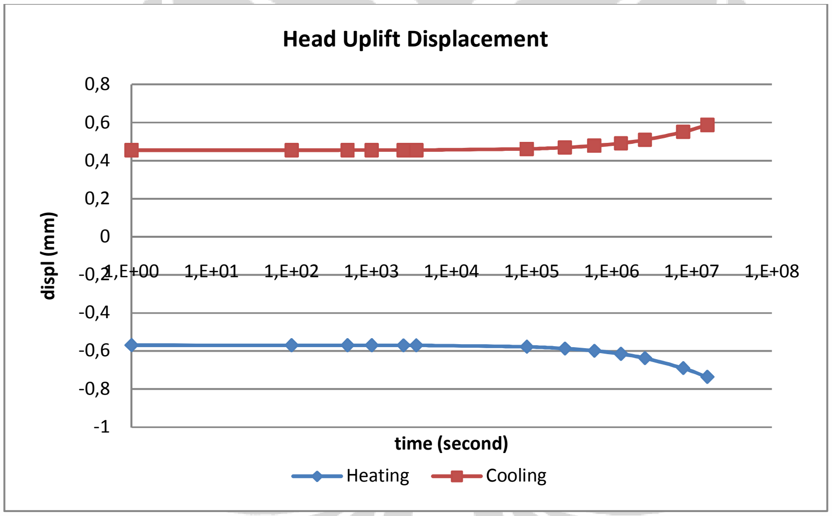


Figure 5.5 Comparison of vertical temperature diffusion in 3 and 6 months

5.2.2.2 Surface Contour Displacement

By the increment of time cycle, z-displacement at soil surface raises. Displacement at soil surface form a settlement contour, where since radius 16 m z-displacement has already in steady condition with no displacement.

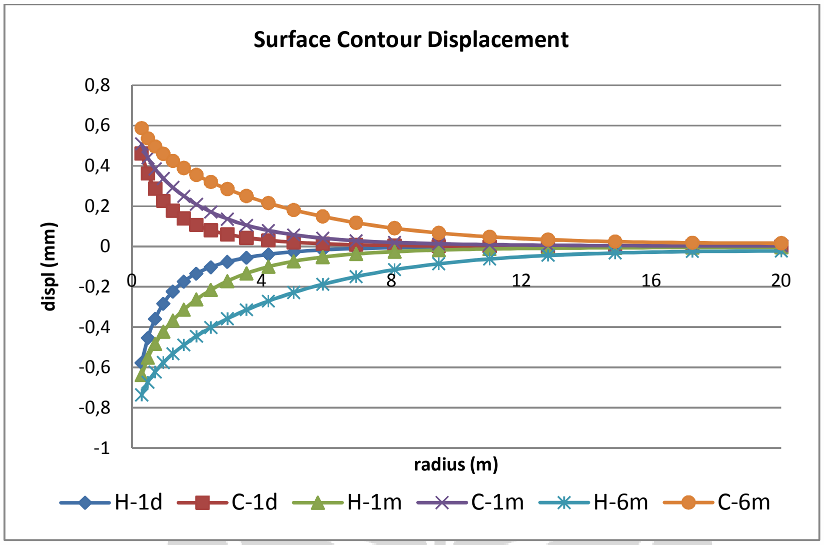


Figure 5.6 Comparison of vertical temperature diffusion in 3 and 6 months

5.2.2.3 Global System : Pile Strain – Stress Relationship

The law of elasticity state that elastic stress of structure is linearly proportional to its strain by a constant factor, named elastic modulus or Young’s modulus. Young's modulus is a measure of the stiffness of an isotropic elastic material, which in this model is specified as 20000 MPa as young’s modulus of concrete.

$$\sigma = E\varepsilon$$

In continuum mechanics, stress is a measure of the average force per unit area of a surface within a deformable body on which internal forces act. Strain or often described as deformation is a change in the shape or size of an object due to an applied force.

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta u/L}$$

By the FLAC 3D analysis, we’ve got directly the vertical pile displacement. Formulating on elastic condition as those equations above, we find the strain, vertical stress and normal force of pile in global system.

Table 5.2 Global Pile Displacement-Stress-Strain-Normal Force in Heating System

Time (s)	Z Disp (mm)	Strain	Vertical Stress (MPa)	Normal Force (kN)
1	-0.96156	-0.000096156	-1.92312	-543.7493698
100	-0.96158	-0.000096158	-1.92316	-543.7606795
500	-0.96155	-0.000096155	-1.92310	-543.7437149
1000	-0.96159	-0.000096159	-1.92318	-543.7663344
2500	-0.96164	-0.000096164	-1.92328	-543.7946087
3600	-0.96170	-0.000096170	-1.92340	-543.8285379
86400	-0.96331	-0.000096331	-1.92662	-544.7389714
259200	-0.96491	-0.000096491	-1.92982	-545.6437501
604800	-0.96673	-0.000096673	-1.93346	-546.6729359
1296000	-0.96888	-0.000096888	-1.93776	-547.8887322
2592000	-0.97126	-0.000097126	-1.94252	-549.2345905
7776000	-0.97550	-0.000097550	-1.95100	-551.6322540
15552000	-0.97825	-0.000097825	-1.95650	-553.1873424

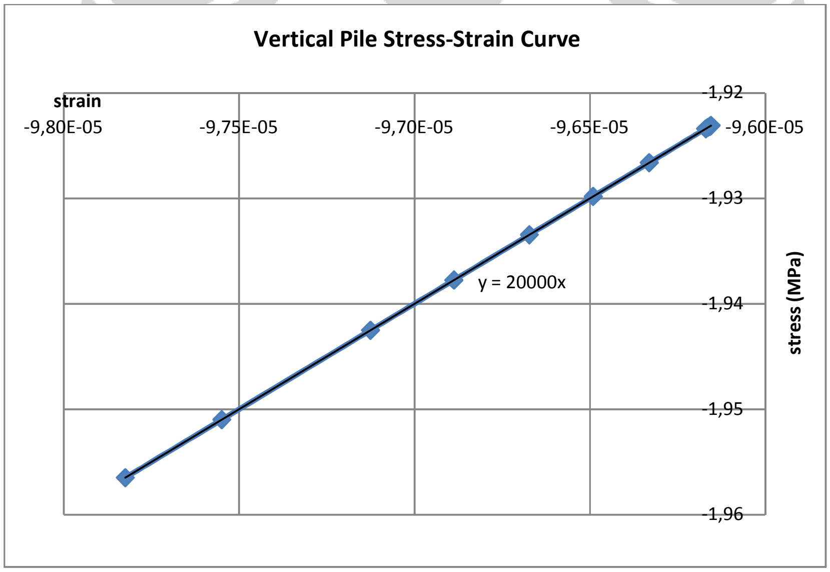


Figure 5.7 Vertical Pile Stress-Strain in Heating System

Table 5.3 Global Pile Displacement-Stress-Strain-Normal Force in Cooling System

Time (s)	Z Disp (mm)	Strain	Vertical Stress (MPa)	Normal Force (kN)
1	0.76923	0.000076923	1.53846	434.9893170
100	0.76923	0.000076923	1.53846	434.9893170
500	0.76925	0.000076925	1.53850	435.0006268
1000	0.76924	0.000076924	1.53848	434.9949719
2500	0.76930	0.000076930	1.53860	435.0289011
3600	0.76931	0.000076931	1.53862	435.0345560
86400	0.77062	0.000077062	1.54124	435.7753435
259200	0.77190	0.000077190	1.54380	436.4991665
604800	0.77335	0.000077335	1.54670	437.3191222
1296000	0.77509	0.000077509	1.55018	438.3030690
2592000	0.77698	0.000077698	1.55396	439.3718388
7776000	0.78038	0.000078038	1.56076	441.2944935
15552000	0.78255	0.000078255	1.56510	442.5215996

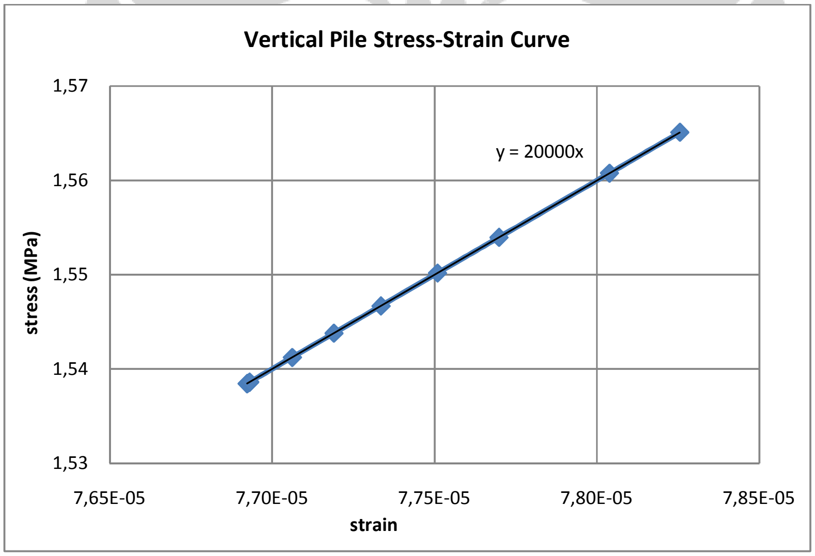


Figure 5.8 Vertical Pile Stress-Strain in Cooling System

5.2.2.4 Local System : Pile Vertical Stress Relationship

Another approach by thermo-elasticity equation is used to see the mechanical, thermal and elastic stress in each depth. The known data by FLAC 3D analysis is the sum of stress zone in each pile's depth. By default, FLAC 3D gives initial stress and elastic stress after thermal loading, where the different between those stresses is the thermal stress.

Table 5.4 Intial Stress Zone of Pile (Local System)

depth	Initial Stress (MPa)
-1	-0.47485
-2	-1.26248
-3	-2.07865
-4	-2.8238
-5	-3.44594
-6	-3.89403
-7	-4.11462
-8	-4.04031
-9	-3.58352
-10	-2.5566

Table 5.5 Mechanical Stress Zone (MPa) of Pile in Heating System

depth	1	100	500	1000	2500	3600	86400	259200	604800	1296000	2592000	7776000	15552000
-1	-0.4519	-0.45193	-0.45192	-0.45197	-0.45205	-0.45212	-0.45451	-0.45621	-0.45776	-0.45929	-0.46074	-0.46308	-0.46449
-2	-1.21082	-1.21086	-1.21085	-1.21092	-1.21105	-1.2111	-1.21484	-1.21811	-1.22147	-1.22502	-1.22854	-1.23431	-1.23782
-3	-2.0038	-2.00382	-2.0038	-2.00388	-2.00402	-2.00411	-2.00803	-2.01191	-2.01622	-2.02109	-2.02621	-2.03491	-2.04026
-4	-2.73241	-2.73244	-2.73239	-2.73247	-2.73259	-2.73272	-2.73658	-2.74062	-2.74528	-2.75081	-2.75686	-2.76751	-2.77421
-5	-3.34433	-3.34437	-3.34433	-3.34439	-3.3445	-3.34461	-3.34831	-3.35231	-3.35699	-3.36274	-3.3692	-3.38089	-3.38831
-6	-3.7884	-3.78841	-3.78839	-3.78846	-3.78861	-3.78869	-3.79213	-3.79597	-3.80052	-3.80613	-3.81258	-3.82438	-3.83204
-7	-4.01128	-4.01132	-4.01129	-4.01135	-4.01146	-4.01156	-4.01473	-4.0183	-4.02253	-4.02777	-4.03383	-4.04501	-4.0523
-8	-3.94597	-3.94601	-3.94595	-3.94601	-3.94611	-3.94624	-3.94908	-3.9523	-3.95604	-3.96068	-3.96597	-3.97574	-3.98219
-9	-3.50566	-3.50564	-3.50565	-3.50567	-3.50576	-3.50584	-3.50837	-3.51112	-3.51416	-3.51784	-3.52195	-3.52962	-3.53475
-10	-2.50553	-2.50552	-2.50554	-2.50554	-2.50564	-2.50571	-2.50778	-2.50967	-2.51159	-2.5138	-2.51631	-2.52099	-2.52419

Table 5.6 Mechanical Stress Zone (MPa) of Pile in Cooling System

depth	1	100	500	1000	2500	3600	86400	259200	604800	1296000	2592000	7776000	15552000
-1	-0.49321	-0.49321	-0.49317	-0.49317	-0.49308	-0.49303	-0.49112	-0.48978	-0.48857	-0.48733	-0.48615	-0.48428	-0.48312
-2	-1.30382	-1.30381	-1.30375	-1.30377	-1.30363	-1.30357	-1.30058	-1.29799	-1.29534	-1.2925	-1.28965	-1.28503	-1.28222
-3	-2.13856	-2.13857	-2.1385	-2.13852	-2.13836	-2.13833	-2.13514	-2.13205	-2.12865	-2.12475	-2.12065	-2.11367	-2.1094
-4	-2.89696	-2.89694	-2.8969	-2.8969	-2.89674	-2.89673	-2.89357	-2.89037	-2.88667	-2.88224	-2.8774	-2.86886	-2.86354
-5	-3.52726	-3.52726	-3.52723	-3.52722	-3.5271	-3.52709	-3.52403	-3.52089	-3.51714	-3.51254	-3.50739	-3.49803	-3.49211
-6	-3.97854	-3.97855	-3.97854	-3.97853	-3.97841	-3.97838	-3.97553	-3.97253	-3.96893	-3.96437	-3.95924	-3.94977	-3.94369
-7	-4.19731	-4.19731	-4.1973	-4.19728	-4.1972	-4.19715	-4.19454	-4.19174	-4.18835	-4.18411	-4.17929	-4.17034	-4.16451
-8	-4.11581	-4.11578	-4.11578	-4.11577	-4.1157	-4.11566	-4.11332	-4.11079	-4.10775	-4.10407	-4.0998	-4.09199	-4.08685
-9	-3.64587	-3.64584	-3.64583	-3.64583	-3.64576	-3.64573	-3.64366	-3.64151	-3.63902	-3.6361	-3.63277	-3.62668	-3.6226
-10	-2.5975	-2.59747	-2.59747	-2.59747	-2.5974	-2.59738	-2.59568	-2.59421	-2.59263	-2.59084	-2.58886	-2.58514	-2.58258

When we investigate the elastic stress locally depth by depth, we've got a hyperbolic stress curve. The stress increases in depth and reach its peak in depth -7 m then decreases until the base pile. In reverse, the thermal stress less varies in depth, it's almost constant. The amount of thermal stress is very small which gives slightly different in initial and elastic stress.

In heating system, the thermal stress is positive due to dilatation of pile, but it gives a reduction of initial stress to elastic stress. In cooling system, the thermal stress is negative who gives additional value of initial stress. The longer time of thermal loading, the smaller thermal stress obtained; hence the elastic stress of the longest thermal loading (6 months) has just ±10 kPa different to the initial stress due to its equilibrium diffusion.

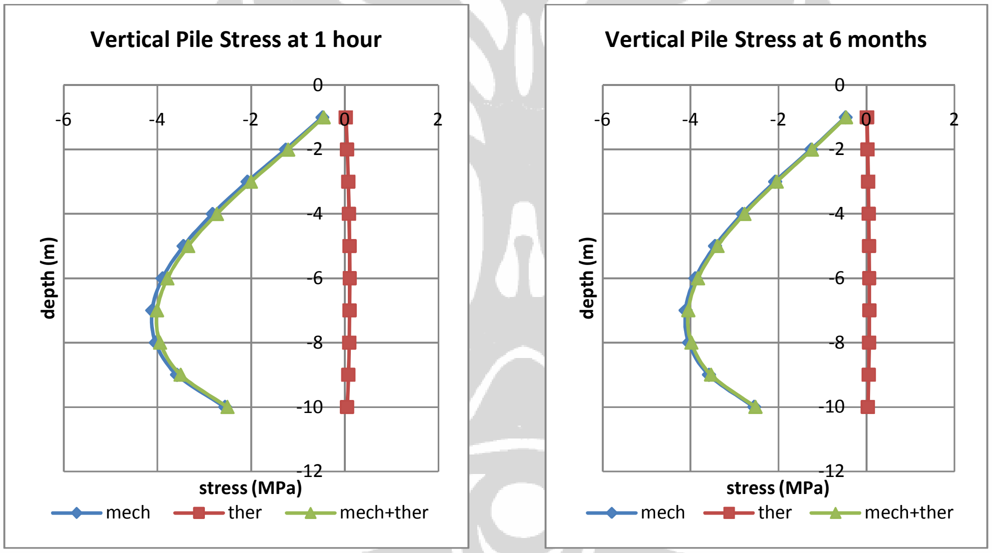


Figure 5.9 Vertical Pile Stress by depth (a) at 1 hour heating (b) at 6 months heating

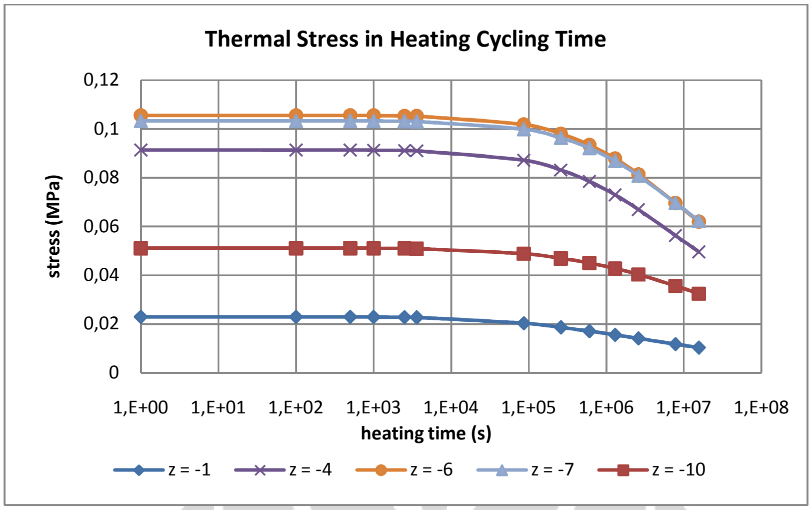


Figure 5.10 Thermal Stress Diffusion in certain depth at Heating System

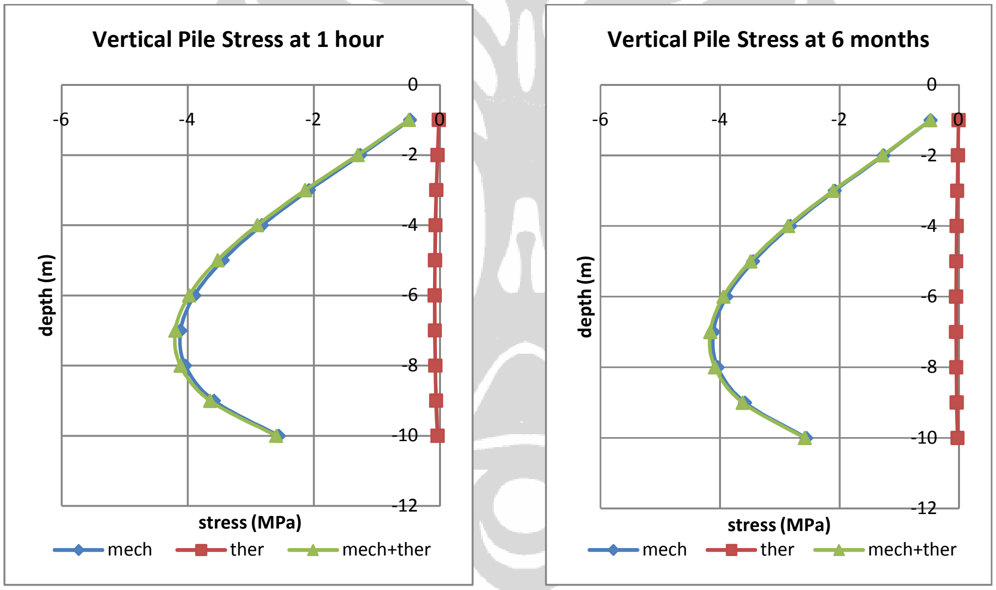


Figure 5.11 Vertical Pile Stress by depth (a) at 1 hour cooling (b) at 6 months cooling

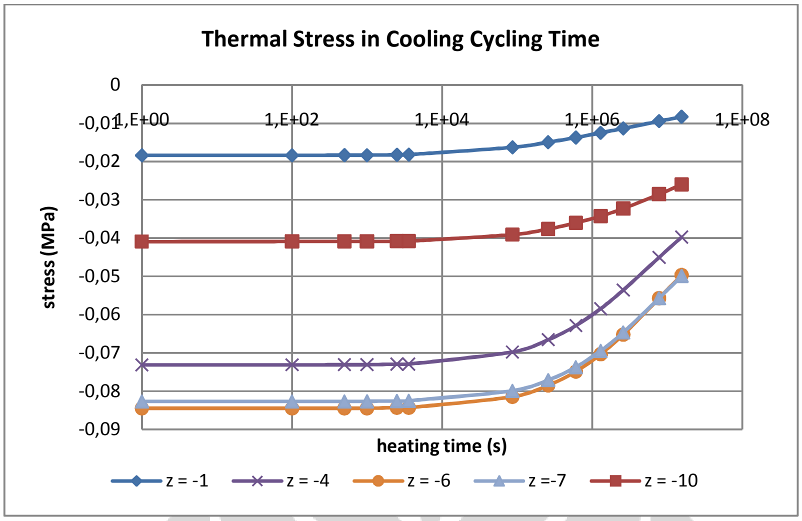


Figure 5.12 Thermal Stress Diffusion in certain depth at Cooling System

5.3 Fluctuation Ground Temperature with Depth

Ground temperature is a function of depth and time. Surface temperature depends on air temperature and solar radiation which affects the fluctuation of ground temperature until 5-6 m below surface. Its variation changes the initial temperature and the diffusion to reach its steady state conditions.

Surface ground temperature is initialized at -10°C related to surface temperature in winter. Between the depth 0 – 5 m below the surface, temperature varies by a function $T = -10 + 4.8z$; and becomes constant at 14°C until soil's base at 40 m.

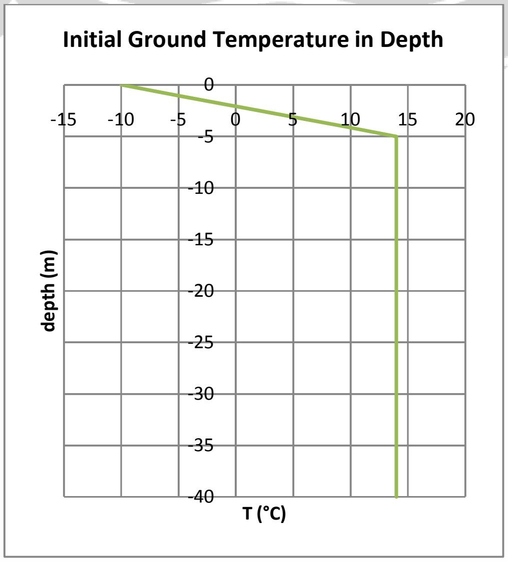


Figure 5.13 Initial Fluctuation Ground Temperature in Depth

The problem is how to define the frontier limit temperature in order to get steady state diffusion. Hence, we make 3 models with different frontier limit temperature at radius soil ±20 m :

#1. boundary limit temperature is the same like initial temperature

#2. boundary limit temperature stays constant at average ground temperature 14°C

#3. no boundary limit temperature at frontier

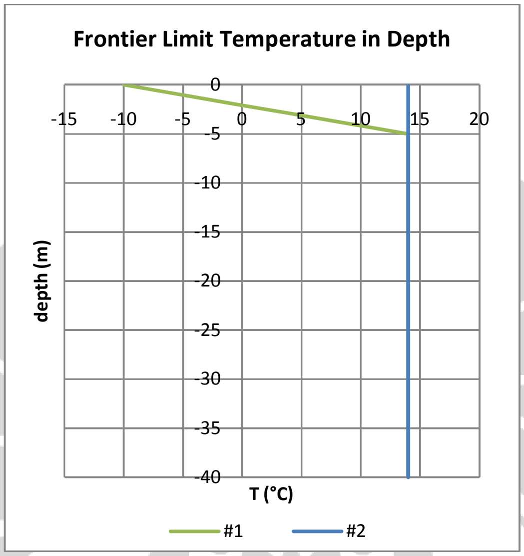
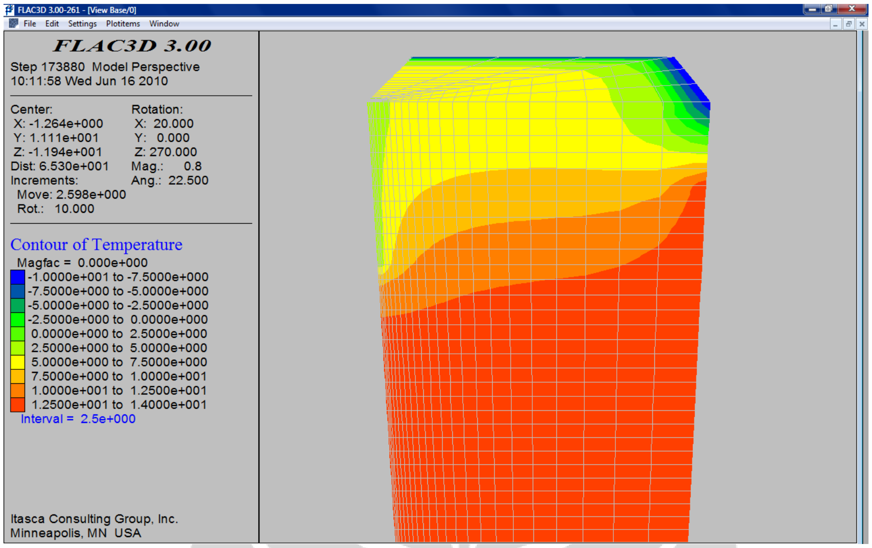


Figure 5.14 Different Model of Frontier Limit Temperature at radius 20 m

Model #1 defines temperature at frontier is like temperature initial. The result shows a wrong definition of limit condition that the diffusion doesn't reach steady state temperature diffusion as we can see in these following figures. Figure 5.16 for temperature diffusion at surface, it looks like temperature has already steady since radius 8 m, but due to frontier limit temperature, temperature will always back to -10°C as defined limit temperature.



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Center:
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Y: 1.111e+001
Z: -1.194e+001
Dist: 6.530e+001
Increments:
Move: 2.598e+000
Rot.: 10.000

Rotation:
X: 20.000
Y: 0.000
Z: 270.000
Mag.: 0.8
Ang.: 22.500

Contour of Temperature
Magfac = 0.000e+000
🟦 -1.0000e+001 to -7.5000e+000
🟦 -7.5000e+000 to -5.0000e+000
🟩 -5.0000e+000 to -2.5000e+000
🟩 -2.5000e+000 to 0.0000e+000
🟩 0.0000e+000 to 2.5000e+000
🟩 2.5000e+000 to 5.0000e+000
🟨 5.0000e+000 to 7.5000e+000
🟧 7.5000e+000 to 1.0000e+001
🟧 1.0000e+001 to 1.2500e+001
🟥 1.2500e+001 to 1.4000e+001
Interval = 2.5e+000

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Figure 5.15 Horizontal Zone Diffusion Model #1

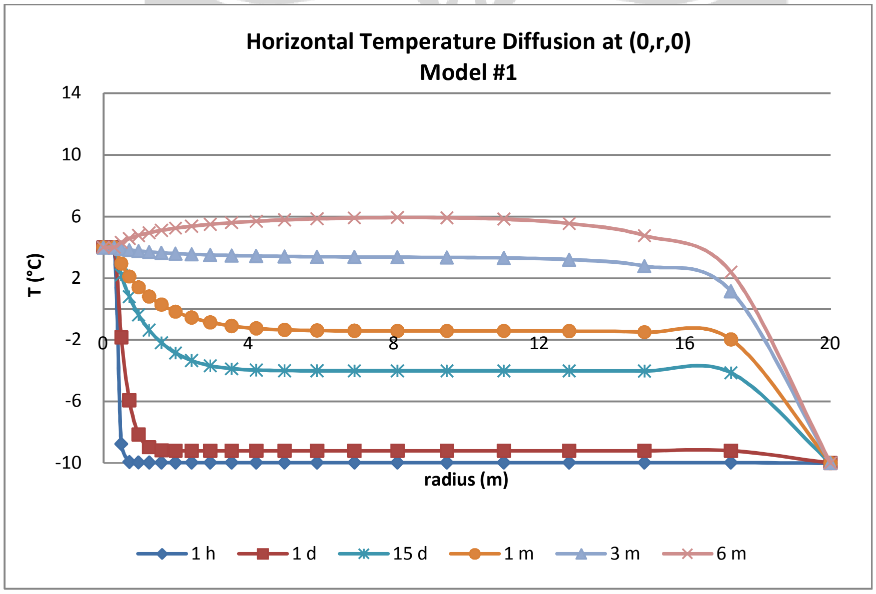
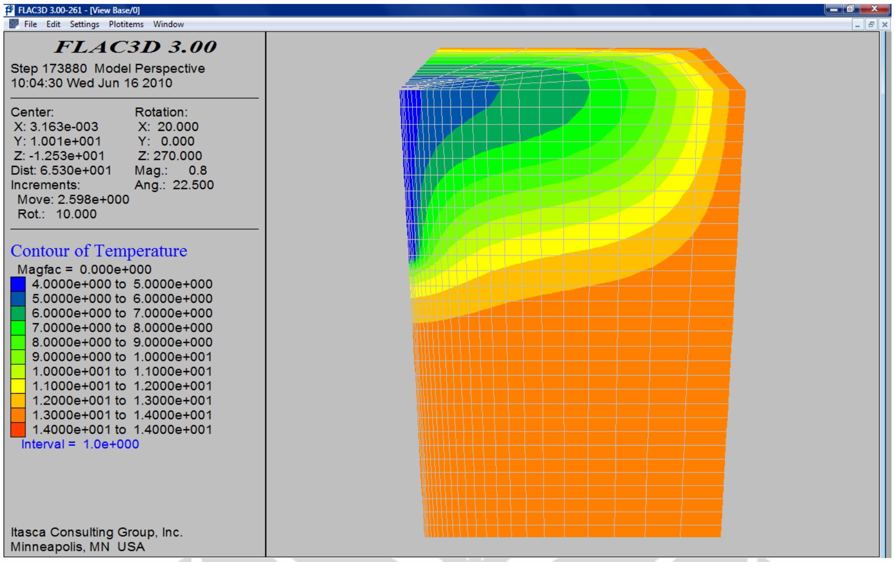


Figure 5.16 Horizontal Temperature Diffusion at Surface for Model #1

Model #2 defines temperature at frontier is generalized at 14°C. The result respectively shows the same like Model #1 that in any value of temperature obtained in diffusion process, it should reach back 14°C at frontier, thus it never reach steady state condition.



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10:04:30 Wed Jun 16 2010

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Y: 1.001e+001
Z: -1.253e+001
Dist: 6.530e+001
Increments:
Move: 2.598e+000
Rot.: 10.000

Rotation:
X: 20.000
Y: 0.000
Z: 270.000
Mag.: 0.8
Ang.: 22.500

Contour of Temperature
Magfac = 0.000e+000
4.0000e+000 to 5.0000e+000
5.0000e+000 to 6.0000e+000
6.0000e+000 to 7.0000e+000
7.0000e+000 to 8.0000e+000
8.0000e+000 to 9.0000e+000
9.0000e+000 to 1.0000e+001
1.0000e+001 to 1.1000e+001
1.1000e+001 to 1.2000e+001
1.2000e+001 to 1.3000e+001
1.3000e+001 to 1.4000e+001
1.4000e+001 to 1.4000e+001
Interval = 1.0e+000

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Figure 5.17 Horizontal Zone Diffusion Model #2

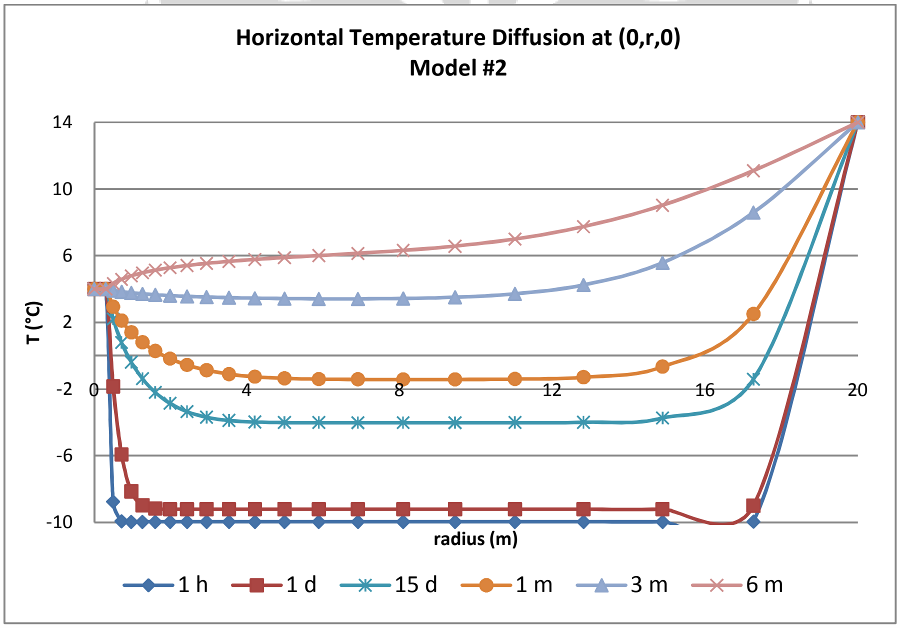
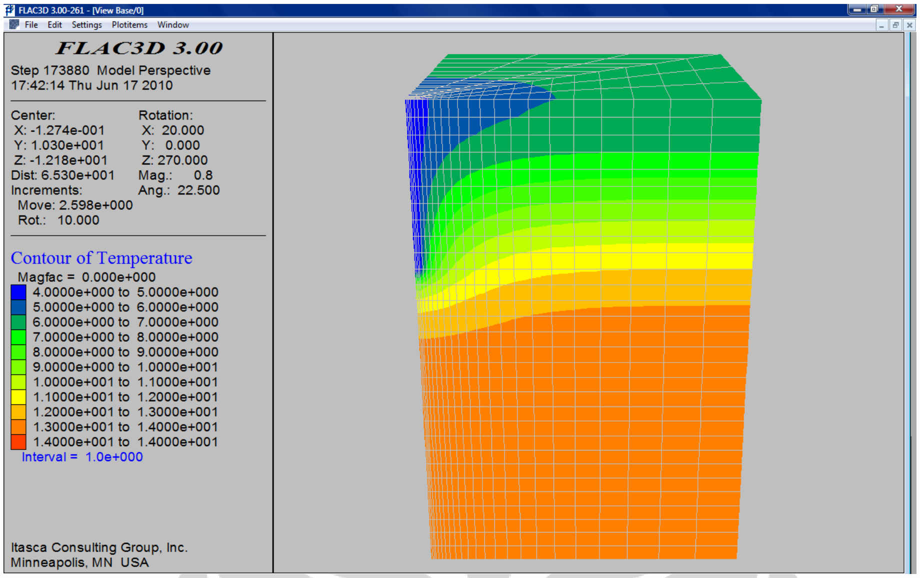


Figure 5.18 Horizontal Temperature Diffusion at Surface for Model #2

If we look carefully on the results of model #1 and #2, we find that about radius 8 m, temperature diffusion has already stable. Hence it shouldn't have defined frontier limit temperature in order to make temperature diffuses steadily. Result of Model #3 shows the best definition of frontier limit temperature, but we must add definition of frontier flux condition.



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17:42:14 Thu Jun 17 2010

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 Y: 1.030e+001          Y:   0.000
 Z: -1.218e+001         Z: 270.000
Dist: 6.530e+001       Mag.:     0.8
Increments:            Ang.:  22.500
  Move: 2.598e+000
  Rot.:   10.000

Contour of Temperature
  Magfac =  0.000e+000
🟦 4.0000e+000 to  5.0000e+000
🟦 5.0000e+000 to  6.0000e+000
🟩 6.0000e+000 to  7.0000e+000
🟩 7.0000e+000 to  8.0000e+000
🟩 8.0000e+000 to  9.0000e+000
🟩 9.0000e+000 to  1.0000e+001
🟨 1.0000e+001 to  1.1000e+001
🟨 1.1000e+001 to  1.2000e+001
🟧 1.2000e+001 to  1.3000e+001
🟧 1.3000e+001 to  1.4000e+001
🟥 1.4000e+001 to  1.4000e+001
   Interval =  1.0e+000

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Figure 5.19 Horizontal Zone Diffusion Model #3

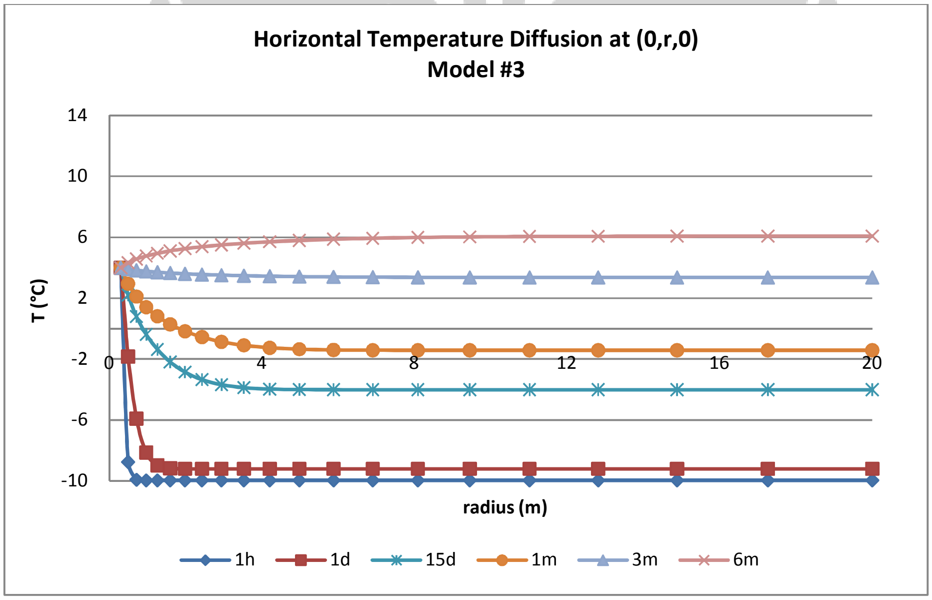

Figure 5.20 Horizontal Temperature Diffusion at Surface for Model #3

CHAPTER 6
CONCLUSION

Energy piles are bi-function foundations which support the load of structure and serve thermal energy to the building as heat exchangers. The questions of sustainability geothermal energy and durability of structural piles have recently been studying. Influence of groundwater flows and fluctuation seasonal ground temperature on heat transfer process in soils, thermal dilatation's effect on mechanical behaviour of soil and concrete pile; are those which should be resolved by engineers to make an innovative environmentally friendly building.

The energy piles in only heating or cooling system, like those who are needed by tropical or glacial countries, need high-permeability of groundwater flows. This system tends to not reach balance energy, thus it needs integration with solar panel system for its sustainability. The most economical and environmentally friendly is a seasonal operation with an energy balance throughout the year, heating in winter and cooling in summer. In this case low-permeability groundwater flows are favourable.

Energy piles have three basic circuits: soils, concrete piles, and building thermal installation system. Designing energy piles system should consider two soils parameters: degree of saturation and groundwater flows. Heat transfer equations in soils divided by those parameters, for saturated soils without groundwater flows which only has conduction heat transfer, saturated soils with groundwater flows influenced by conduction and convection, non-saturated soils without groundwater flows should take latent heat transfer in consideration besides conduction, and the last one is non-saturated soils with groundwater flows which is the most complex system with conduction, convection, and latent heat transfer. The most important is the continuity energy in each circuit, for which the heat transfer in interface is successfully transmitted.

Numerical model have been done in this research to define the proper distance of temperature diffusion with and without fluctuation of ground temperature in depth, and to examine the mechanical behaviour of energy piles. The model with ratio concrete pile's length vs. soil's depth 1:3 is chosen as the proper one. The model is loaded by constant heat in 1 season cycle without seasonal temperature loading.

In heating system, the pile is in contraction, which makes a down settlement of soil surface. Contraction causes negative both vertical & radial displacements and give positive thermal stresses. Therefore the total elastic stresses, including mechanical and thermal stresses, decrease. Inversion result has obtained in cooling system: the pile is in dilatation, uplift settlement of soil surface, positive vertical & radial displacements, thermal stresses become negative thus make total elastic stresses increase.

For the next work, seasonal temperature loading should be applied in numerical model to see how resistance the pile is due to balancing seasonal operating system. The seasonal surface temperature might create effect of frozen soils which definitely affect heat transfer process. Furthermore, existence of groundwater flows which change the diffusion process in soils have to be simulated. Lots of homework should be solved in energy piles application, and it requires an interdisciplinary design by geotechnical, structural, architect, electrical, mechanical, and environmental engineer.

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