# Computational Mechanics Tools

## Course Simulation Project
## Thermo-activated pile foundation

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# 1 Introduction

Heating, ventilation and air conditioning (HVAC) is a necessity in every building. Whether one is heating, cooling, or ventilating, one needs to have systems in place that will do the job efficiently, effectively, and comfortably. But, there's not one system that will do the job for every facility. As technology develops, green becomes status quo, and people demand healthier, more comfortable places to live, work, and play, one may want to investigate other HVAC options. Traditional HVAC systems have been energy intensive systems that depend heavily on electrical energy. Electricity is mostly generated from fossil fuels - coal, natural gas, and petroleum. As the demand for energy increases, the supply for it is decreasing and depleting rapidly all over the world. Plus, this energy is also responsible for the green house gases that have adverse effect on the environment and are the cause for the global warming that is melting glaciers and causing tsunamis. All this has led to increased environmental awareness and the need to source energy for electricity from alternate sources and renewable sources such as wind, sun, biomass fossils.

The ground absorbs nearly half of the solar energy our planet receives. As a result, the earth remains at a constant, moderate temperature just below its surface all year round. However, air temperature varies greatly from summer to winter, making air source (traditional) heating and cooling least efficient when one needs it the most. Geothermal energy, derived out of the heat of the earth, generally involves low running costs since it saves 80% costs over fossil fuels and no fuel is used to generate the power. In this project, geothermal energy is used in an HVAC system called as geothermal heat pump. A ground source heat pump extracts ground heat in the winter (for heating) and transfers heat back into the ground in the summer (for cooling). Some systems are designed to operate in one mode only, heating or cooling, depending on climate. Since these systems require pipes that go inside the earth, it is possible to integrate these into the foundation of buildings.

Pile foundations are principally used to transfer the loads from a superstructure, through weak, compressible strata or water onto stronger, more compact, less compressible and stiffer soil or rock at depth, increasing the effective size of a foundation and resisting horizontal loads (Tomlinson & Woodward, 2008). They are used in very large buildings, and in situations when the soil under a building is not suitable to prevent excessive settlement. Geothermal piles consist of pile foundations combined with closed-loop ground source heat pump systems. Their purpose is to provide support to the building, as well as acting as a heat source and a heat sink. In this project structural and thermal analysis of such thermally activated pile foundations have been carried out. Upon completion of these analysis, some suggestions have been made to improve the structure in order to maximize the thermal loads that the structure can withstand.

This report has the following chapters. In Chapter 2, the theory and construction of thermally activated pile foundations is provided. Chapter 3 deals with the mathematics of various loads acting on the structure enabling one to compute these loads. Chapter 4 details the modelling for carrying out structural and thermal analysis. In Chapter 5, results and discussion of the analysis are detailed along with conclusions drawn out of the analysis and modifications suggested to improve performance.

# 2 Background

## 2.1 Ground source heat pumps (GSHP)

Ground source heat pump shortly known as GSHP is a cooling or heating system that transfers heat to or from the ground through buried pipes. Although many places experience seasonal temperature extremes from scorching heat in the summer to sub-zero cold in the winter, a few feet below the earth's surface, the ground remains at a relatively constant temperature. The GSHP takes advantage of this fact. Its working mainly depends on the fact that the ground temperature at certain depth, that is about 10 meters, is independent of seasonal temperature changes (see Figure 2.1).

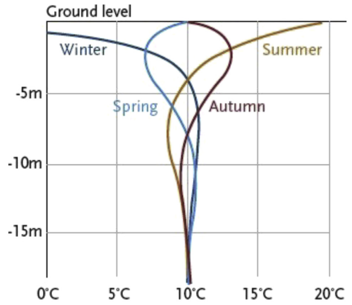


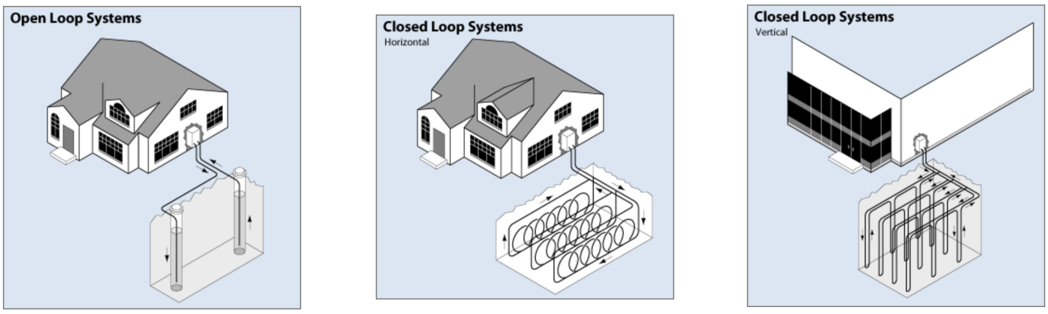
Figure 2.1: Annual ground temperature
(Source: Schiel, K. et al., (2016) [1])

The GSHP systems are widely used because they are considered as both renewable and energy efficient [2]. The main benefits of this system are as follow. The GSHP can provide cooling in summer, as well as heating in winter. They are much cheaper to run than direct electric heating, oil boilers and gas boilers. Unlike burning oil, gas, LPG or biomass, GSHP doesn't produces any carbon emissions. Due to the absence of fuel storage container, this heat pump saves space. This heat pump is safer, as there is no combustion, emission of potentially dangerous gases or requirement for fuels. It requires less maintenance than combustion based heating systems. Along with these advantages, the main drawback of the GSHP is that they are more expensive to install than other source heat pumps because of the need to install a ground heat exchanger. However, this connection to the ground is what enables a GSHP to perform much more efficiently.

Based on the type of arrangement, the GSHP are classified into two:

- Open loop systems
- Closed loop systems
  - Horizontal closed loop systems
  - Vertical closed loop systems

The open loop systems, shown in Figure 2.2a, use well or surface body water as the heat exchange fluid that circulates directly through the GSHP system. Once it has circulated through the system, the water returns to the ground through the well or surface discharge. This option is practical only when there is an adequate supply of relatively clean water. The closed loop system works based on the method where the heat transfer process occurs indirectly between the soil and heat carrier medium flowing through the pipes. This system is further classified into two types based on the direction of looping: horizontal and vertical closed loop system, as shown in Figures 2.2b and 2.2c respectively. Generally, the vertical systems are preferred because they need lower surface area, lower pumping cost as they have shorter pipe lengths and higher in efficiency [3]. As the horizontal loops are present in the surface areas of the ground, it is affected by the shallow ground temperature fluctuations [4]. The closed loop systems require high initial cost compared to open loop systems. However, this is compensated by greater versatility, long-term economic benefits and lower risks in long-term under various ground conditions.



(a) Open loop (b) Horizontal closed loop (c) Verticle closed loop

Figure 2.2: Types of GSHP systems
(Source: U.S department of energy)

## 2.2 Pile foundation

Foundations provide support for structures by transferring their load to layers of soil or rock that have sufficient bearing capacity and suitable settlement characteristics. For different applications, there are a wide range of foundation types. Pile foundation is a type of foundation which is a long cylinder of a strong material such as concrete that is pushed into the ground to act as a steady support for structures built on top of it. Usually, pile foundations are used where the bearing capacity of the surface soils is insufficient to support the imposed loads. These loads are transferred to deeper layers with higher bearing capacity. It is also used in buildings, such as a high rise structures, bridges or water tanks, which have very heavy and concentrated loads. Pile foundations are broadly classified based on their design into:

- End bearing piles
- Friction piles

as shown in Figure 2.3. In the case of end bearing piles, the bottom end of the pile rests on a layer of strong soil or rock. On the other hand, friction piles work on a different principle where the pile transfers the load of the building to the soil across the full height of the pile by friction. That is, the entire surface of the pile works to transfer the forces to the soil. The choice of the pile foundation mainly depends on the location, type of structure, conditions of the ground, sustainability of the material in the environment and of course cost.

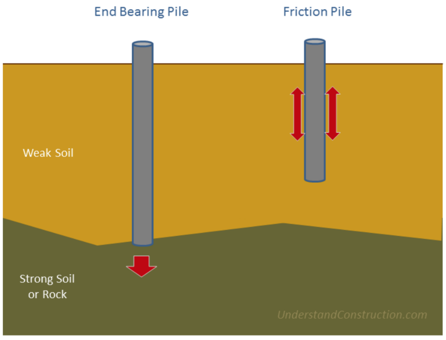


Figure 2.3: Pile foundations
(Source: http://www.understandconstruction.com)

Based on the method of construction, pile foundations can be classifies into three types:

- Driven piles
- Bored piles
- Screw piles

The driven piles are placed into ground by displacing the material around the pile shaft instead of removing it. So, they are also called as displacement piles. Usually, this kind of pile is used in offshore applications which are stable even in the soft squeezing soils. They are easy to adapt and can be used to accommodate compression, tension and lateral loads according to the structure and soil conditions. Whereas, the bored piles are constructed by removing the soil and there by forming a borehole for the concrete pile which is poured in situ. It is also called as the replacement piles as the soil is replaced by the pile. The construction of driven piles leads to heavy vibrations. Whereas, the bored piles has minimal vibration and therefore preferred in the urban areas.

## 2.3 Thermo-activated pile foundation

The thermo-activated pile foundations, shown in figure 2.4 are the combination of the pile foundation and the closed-loop ground source heat pump system. It acts as a support to the building as well as a heat source and sink. This system allows to store unwanted heat to cool the building in summers and allows to warm the building in winters [5].

Figure 2.4: Thermo-activated pile foundation model
(Source: James Weir pile design)

The materials used for the construction of thermo-activated pile foundations in the past studies [6, 7, 8, 9] are:

- Reinforced concrete
- Steel
- Grout (fluid form of concrete used to fill gaps)

Among these materials, reinforced concrete piles are found to be commonly used [10]. Comparatively it possess more advantageous because of its high thermal storage capacity and high heat transfer capability [6, 8]. Whereas, steel immensely assists the heat transfer between the ground and medium due to its lower thermal resistance and higher thermal conductivity [9]. Combination of the above mentioned materials are considered in past studies [10], which includes steel tubes filled with concrete. However, including partially grounded columns reduced the efficiency [11]. So, in general reinforced concrete and steel are preferred over other materials.

The pipe shape and diameter play vital role in the design as they should resist all the applied structural loads. Especially, the pipe shape effects the total efficiency of the system. The commonly used shapes in the past studies [12] are:

- U-shaped pipe
  - Single pipe
  - Doube pipe
  - Triple pipe
- W-shaped pipe

as shown in the Figure 2.5. The experimental and numerical simulation results of [6, 12] showed that the W-shaped loops were more effective then U-shaped loops. However, U-shaped loops were more effective in terms of workability and economic point of view [13].

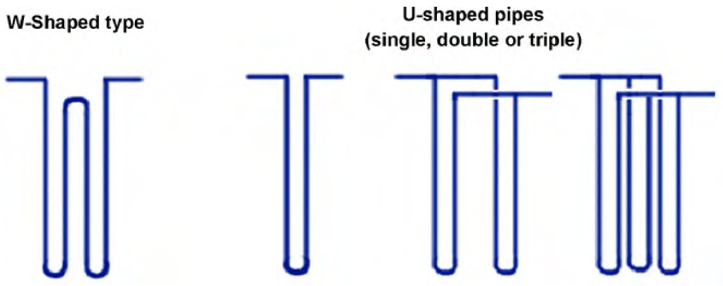


Figure 2.5: Various pipe shapes
(Source: Gao, J. et al., 2008 [12])

The use of thermo-activated pile foundation has environmental, economic and social benefits. However, the construction costs of these systems are critical and moreover the risk of design increases the initial cost of the system. But, these high installation costs are countered by including the system in the structure piles. This technology is widely accepted in all the ground conditions and is not limited to only urban areas. Like in all other systems, there are limitations for this system also. The temperature fluctuations which occur during the year leads to the reduction of the efficiency of the heat pump system. Additionally, the presence of dry sand or grave requires deeper piles and larger area of absorbers which leads to higher cost and reduction of economic benefits. The installation cost depends on the pile length, but this is balanced due to the increase in energy potential with depth.

Usually, this system is present in a buried tube with a bored hole where a fluid, in this case water, can flow. As mentioned earlier, the major disadvantage of ground source heat pump is the high installation cost. A creative solution is to embed the tubes in the foundation piles instead of drilling as this reduces the costs of the GSHP installation. The heat exchanger is co-axial with an inner ring in the pipe and therefore the water flows from surface through the external annulus and comes up along the inner ring of the pipe as shown in the Figure 2.6.

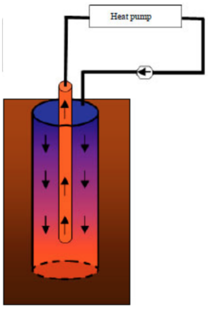
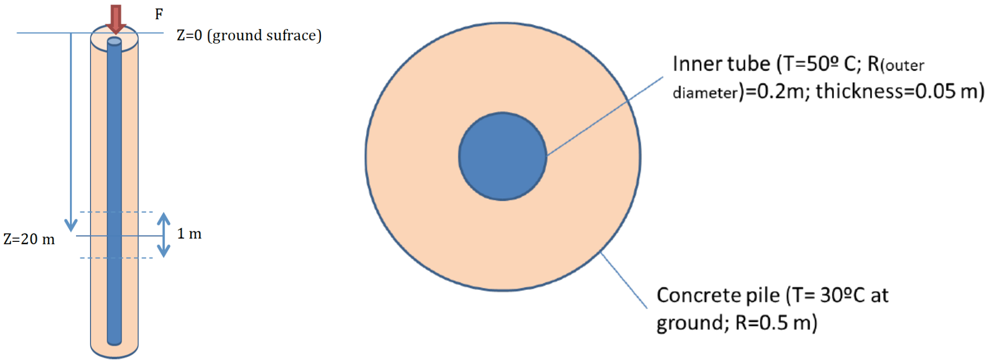


Figure 2.6: Co-axial heat exchanger

In the present work, a 20 $m$ long concrete pile with an outer radius of 0.5 $m$ is considered. Also a steel pipe with outer radius 0.2 $m$ and thickness of 0.05 $m$ is embedded in the pile as shown in Figure 2.7.



(a) (b) At z=20

Figure 2.7: Design of thermopile

The main challenge is to know the performance of the concrete pile and steel pipe under various loads like earth pressure, hydrostatic pressure and structural loads which are catalogued in the next chapter.

# 3 Load calculations of thermo-activated pile foundation

The designed pile foundation should be resistant to the externally applied loads which include:

- Earth pressure
- Hydrostatic pressure
- Structural loads

In this chapter each loading case is detailed and computed for the model described in the previous chapter.

## 3.1 Earth pressure

The lateral pressure exerted by the soil on the system is termed as earth pressure. There are three types of earth pressures that can be exerted on the foundation:

- At-rest earth pressure
- Active earth pressure
- Passive earth pressure

When the foundation is not permitted to move in the ground then the exerted earth pressure is termed as at-rest earth pressure. The active earth pressure occurs when the foundation is allowed to move in the ground. On the other hand, passive earth pressure occurs when the foundation is forced to move towards the ground. In the present case, only at-rest earth pressure is application as the foundation should not be moved in the ground.

The Figure 3.1 shows the details of the ground elements in contact with the pile foundation. There are two types of pressure are exerted on the foundation: first pressure $\sigma'_h$ is due to grains and it is defined as the intergranular stress or effective stress and the second pressure $u$ is due to the water pressure. The pressure due to grains is considered for the current calculation.

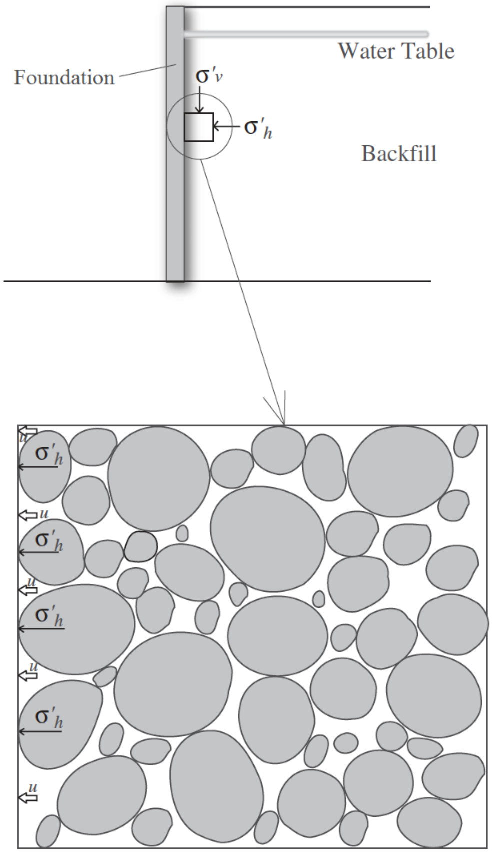


Figure 3.1: Lateral earth pressure

Consider an element in contact with the foundation that is restricted from the lateral movement as shown in the Figure 3.2. The at-rest earth pressure is computed by multiplying the effective vertical stress by the coefficient of lateral earth pressure at rest ($K_0$). This coefficient of lateral earth pressure can be determined experimentally for the ground by restraining the ground from lateral movement and subjecting it to an effective vertical stress $\sigma'_v$. The effective horizontal stress, $\sigma'_h$, exerted on the sides of the foundation and consequently, the coefficient of at-rest lateral earth pressure can be calculated as,

$$K_0 = \frac{\sigma'_h}{\sigma'_v}$$

The Mohr's circel as shown in figure 3.2 represents the stress state in the ground. In the absence of experimental results, the coefficient of at-rest earth pressure can be determined analytically by,

$$K_0 = 1 - \sin\phi'$$

where $\phi'$ is internal friction angle of the soil. In this case, the effective stresses are the same as the total stresses because of the absence of the water. So, the pressure on the walls of the foundation is the effective lateral earth pressure only which can be written as,

$$\sigma'_h = K_0 \sigma'_v$$

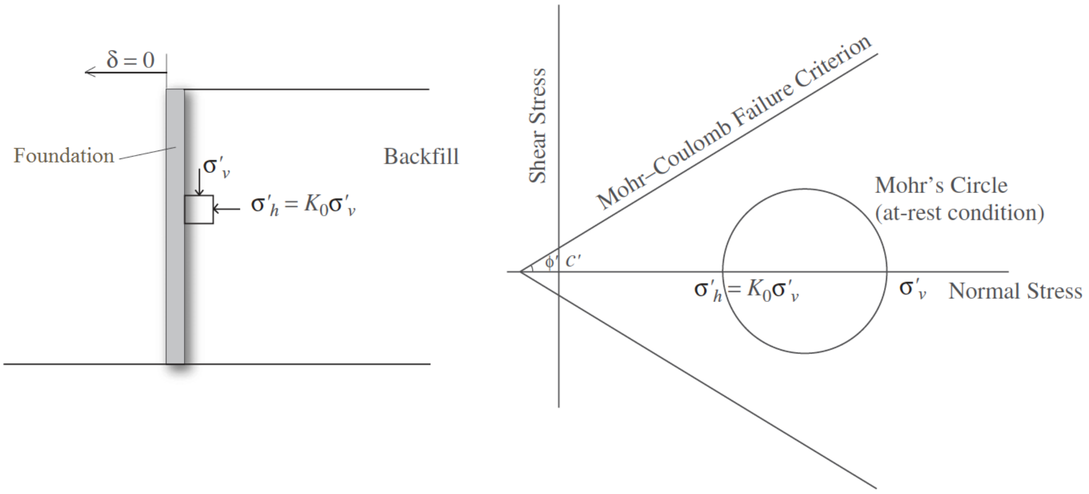


Figure 3.2: At rest lateral earth pressure

Here,

$$\sigma'_v = \gamma Z$$

where $\gamma$ is the unit weight of the ground behind the foundation and $Z$ is the measure depth from the top surface. Combining these two equation, we get

$$\sigma'_h = K_0 \gamma Z$$

This shows that the effective lateral earth pressure increase linearly with the depth. At the top surface, $\sigma'_h = 0$ because of $Z = 0$ and at the bottom, where $Z = H$, $\sigma'_h = K_0\gamma H$.

In this case, the internal friction angle of the ground is given as $30^o$. So, the coefficient of lateral earth pressure $K_0 = 0.5$. As the density of the soil is 2000 kg/m$^3$, the unit weight of the soil is $\gamma = \rho g = 19620$ N/m$^3$. At $Z = 20$ m, the vertical lateral earth pressure is $\sigma'_v = 392400$ N/m$^2$ and effective horizontal stress $\sigma'_h = 196200$ N/m$^2$. Therefore, the net force on the lateral surface is $f'_h = \sigma'_h\, A_{lateral} = \mathbf{616.38}$ kN.

## 3.2 Hydrostatic pressure

The pressure exterted by the water on the system is termed as hydrostatic pressure. The hydrostatic pressure increases with increase in the depth from the surface because of the increasing fluid weight exerting downward force from above. So, the hydrostatic pressure can be written as $f^h = \rho g Z A_s$. For example, if there is an object placed in a fluid within a container then, the deeper the object is placed in the fluid, the more pressure it experiences. This is because the weight of the fluid is above it. The more dense the fluid above it, the more pressure is exerted on the object that is submerged, due to the weight of the fluid.

As there is flow of water in the steel pipe, the hydrostatic pressure on the inner walls of the steel pipe should be considered. In this case, at the depth of 20 m, the hydrostatic pressure acting on the inner surface of the steel pipe is given by $f^h = \mathbf{184.91}$ kN, where $A_s$ is the inner surface area of the steel pipe.

## 3.3 Structural and thermal loads

Strutural load is one of the most important parts of the building construction. These loads can cause stress and deformations that may lead to structural problems and might even lead to failure. Therefore the regulations of the buildings should consider the ability of the building to withstand all the structural loads. In general, the loads are categorised as concentrated, line and distributed loads. The concentrated loads also referred as point or single loads acts over a very small area such as column loads. The line loads are exerted along a line such as a partitions on the floor. The distributed loads are also called as surface loads as they are exerted on the surface area such as weight of floor or roofing materials.

There are different types of structural loads which will vary based on the design, location and material used. The structural loads can also be classified as:

- Dead loads
- Live loads

Dead loads refer to the structure's self weight and usually are constant through out the structure's life. On the other hand, live loads refer to varying loads like traffic loads on bridges. In addition to these, depending on the environmental conditions, the structure loads may also include environmental loads like wind, snow and settlement loads. Almost all the materials can expand or contract with variations in temperature. This can exert significant loads on the structure and should be considered in the process of design. These loads due to the varying temperature are termed as thermal loads.

In the case under consideration for the present study, dead loads are applied as there are no varying structural loads. Dead load due to the structure is equal to **300** kN which acts only on concrete. Whereas, at 20 m, the calculated self weight due to the concrete volume ($V_c$) on the concrete pile is $f_c = \rho g V_c = \mathbf{315.51}$ kN and due to the volume of steel ($V_s$) on the steel pipe is $f_s = \rho g V_s = \mathbf{82.033}$ kN. As there is flow of water under varying temperature in the steel pipe, thermal loads should also be considered.

# 4 Modelling

The analysis of the thermo-activated pile foundation section under study is carried out in Abaqus/CAE. First the parts are created by using the axisymmetric modelling space of the deformable type with shell base feature. The part created is as shown in Figure 4.1. It is possible to consider this model as axisymmetric since all the loads and boundary conditions are symmetric about the axis of revolution of the model. Concrete pile has an inner radius of 0.2 m and an outer radius of 0.5m, while the steel pipe has an outer radius of 0.2 m with a thickness of 0.05 m. The section under consideration is a 1 m high section centred at 20 m below the surface ground.

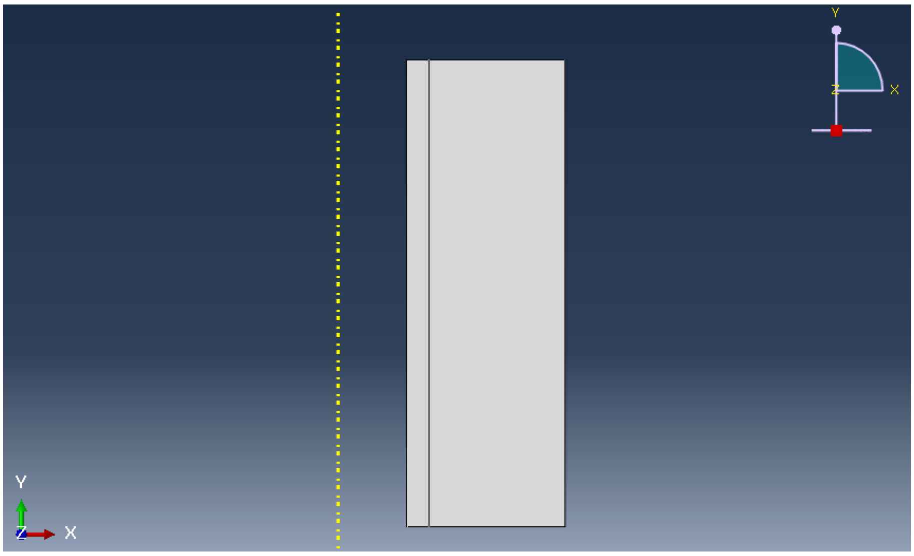


Figure 4.1: The part modelled using Abaqus/CAE

Following this two materials and sections are created, one for concrete and one for steel with their corresponding properties. The sections are assigned to the corresponding parts. Then, an assembly instance is created for the part. After this, a static general step is defined for analysis.

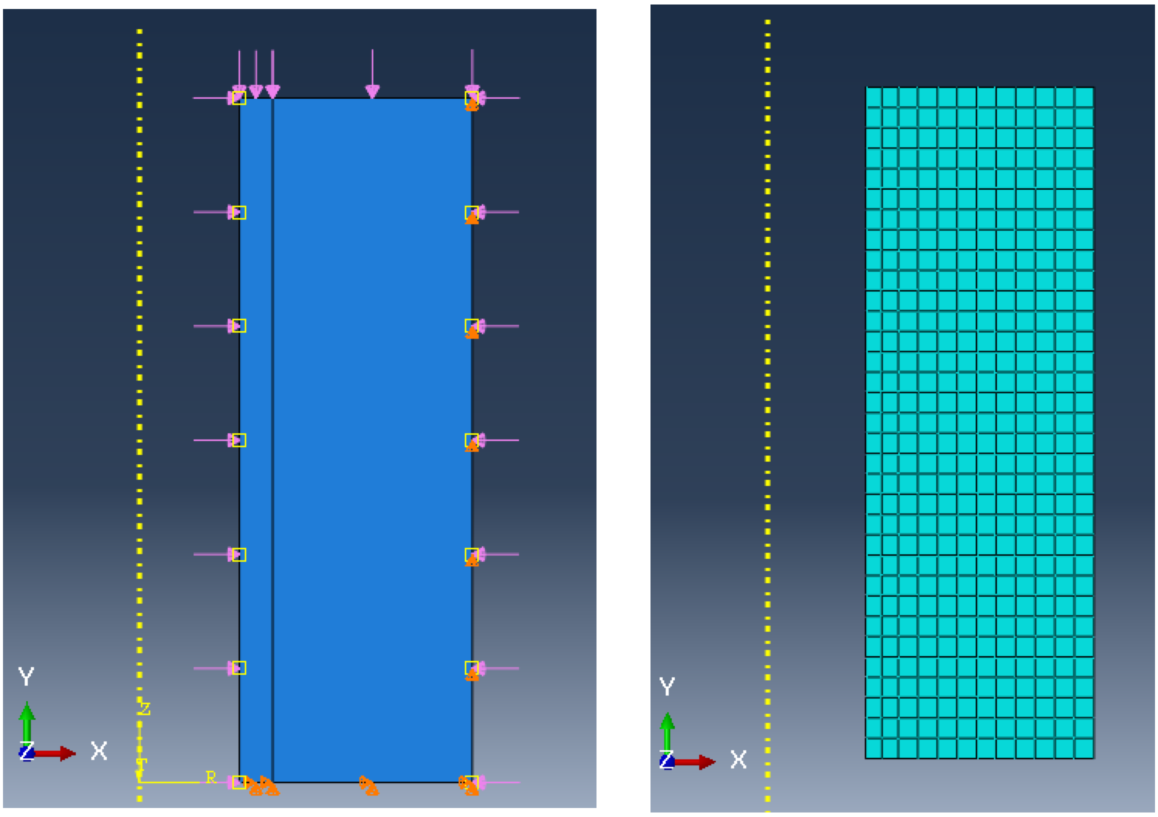
Following this loads and boundary conditions are defined. Under loads, structural loads and earth pressure on concrete are assigned along with self weight and hydrostatic pressure on steel. The boundary conditions assigned are all degrees of freedom fixed on the bottom surface of both concrete and steel, while the lateral surface of concrete is fixed in the $y$-direction. The model with all the applied conditions is shown in Figure 4.2a. Since this is an axisymmetric model, the value of earth pressure, hydrostatic pressure and structural loads including self weights are computed adjusting for the axisymmetry of the model. Since these loads are applied as pressure, their values are taken keeping in mind, the integration along the axis. The values for these that are input into the model are as follow:

(a) Earth pressure = 196200 N/m$^2$,

(b) Hydrostatic pressure = 196200 N/m$^2$,

(c) Self weight of steel = 149201 N/m$^2$ and

(d) Self weight and structural loads on concrete = 932966.28 N/m$^2$



(a) Model with loads and boundary conditions (b) CAX4T mesh for coupled analysis

Figure 4.2: Loads applied and a sample mesh used during the analysis

Finally the parts are meshed before the job is submitted for analysis. For an analysis without including temperature loads, CAX4R linear mesh is used. However, when temperature effects are included corresponding to the couple thermal-displacement step CAX4T mesh with linear elements is used. The CAX4T mesh used for analysis is shown in Figure 4.2b.

A final task was to include material properties that vary with temperature. In this work, concrete with temperature dependent Young's modulus is considered. In order to model such a material using Abaqus/CAE, while defining the elastic material behaviour, the field temperature-dependent data is toggled on and then, Young's modulus corresponding to various temperature is defined.

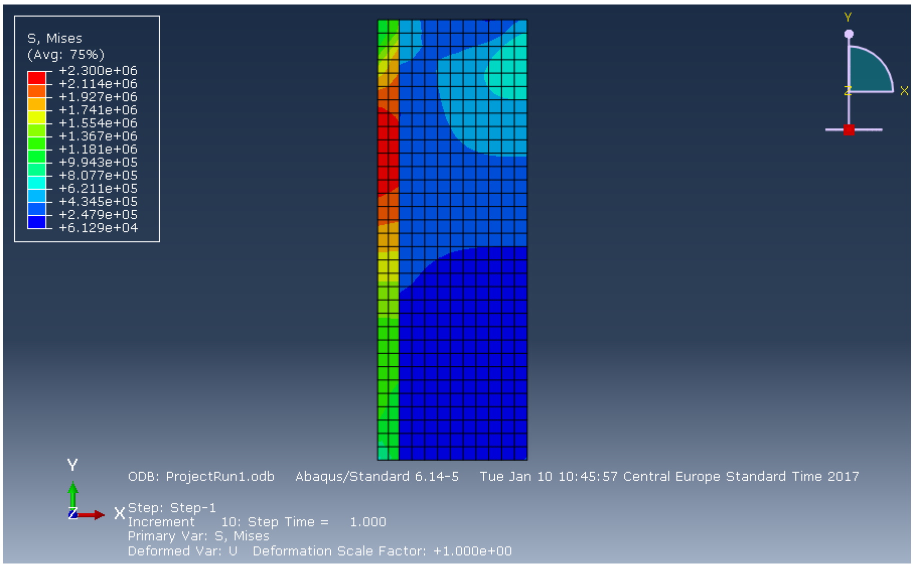
The results obtained upon completion of the analysis of this model are discussed in the following chapter.

# 5 Result, discussion and conclusions

In order to carry out the analysis of the thermo-activated pile foundation, a number of tests are carried out. The results of the various tests performed are summarised in this chapter.

## 5.1 Structural analysis

Initially, the analysis of the structure is carried out without considering the effects of thermal loads. This is done by including a static general step and during this analysis the mesh elements considered are of the type CAX4R. Here the structure is subjected to structural loads, self weight, earth pressure and hydrostatic pressure. Figure 5.1 shows the von-Mises stress distribution in the pile foundation due to these loads.



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Increment     10: Step Time =     1.000
Primary Var: S, Mises
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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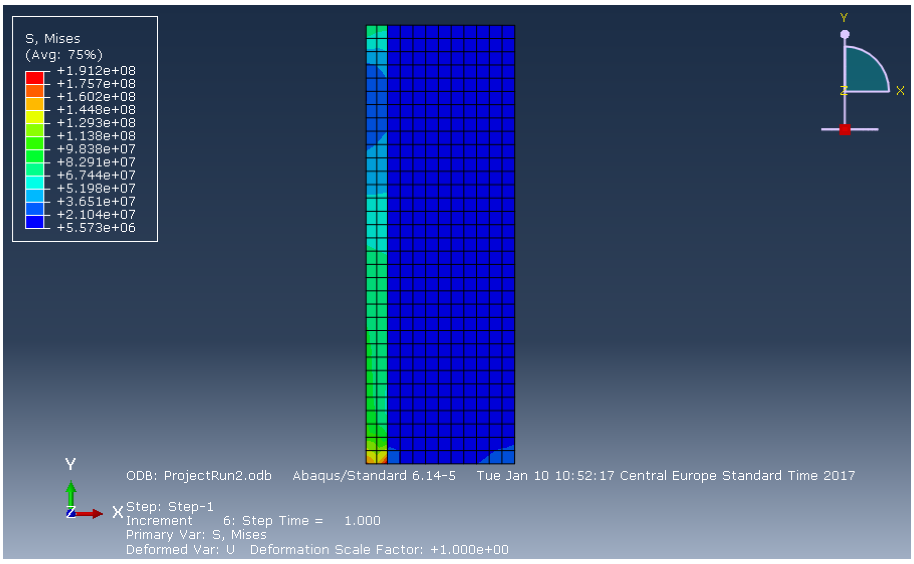
Figure 5.1: Results of the structural analysis of the pile

From the figure it can be seen that in the absence of thermal loads, the stresses that are developed in both steel and concrete are well within the yield point of both these materials.

## 5.2 Coupled structural and thermal analysis

In order to carry out the thermal analysis of this structure coupled with structural analysis, some changes need to be made, First of all, the analysis step is no longer a static general step, but a coupled temperature-displacement step. In order for Abaqus/CAE to be able to handle a addition degree of freedom (DOF) at every node in the form of temperature, the mesh of the part needs to be modified. In the structural analysis whose results are presented in 5.1, the elements used in the mesh were of the type CAX4R, which is a 4-node bilinear axisymmetric quadrilateral, reduced integration, hourglass control. These elements cannot handle temperature as a degree of freedom. Hence the elements are changed to type CAX4T, a 4-node axisymmetric thermally coupled quadrilateral, bilinear displacement and temperature element type mesh, which in addition to handling structural DOFs, can also handle temperature as a DOF.

In this analysis, hot water at 50°C is assumed to be flowing in the steel pipe, thus maintaining the temperature of the inner wall of steel at that temperature, while the outer surface of concrete, which is in contact with ground is at 30°C. Figure 5.2 shows the contour of von-Mises stresses developed in the part due to the structural and thermal loads.



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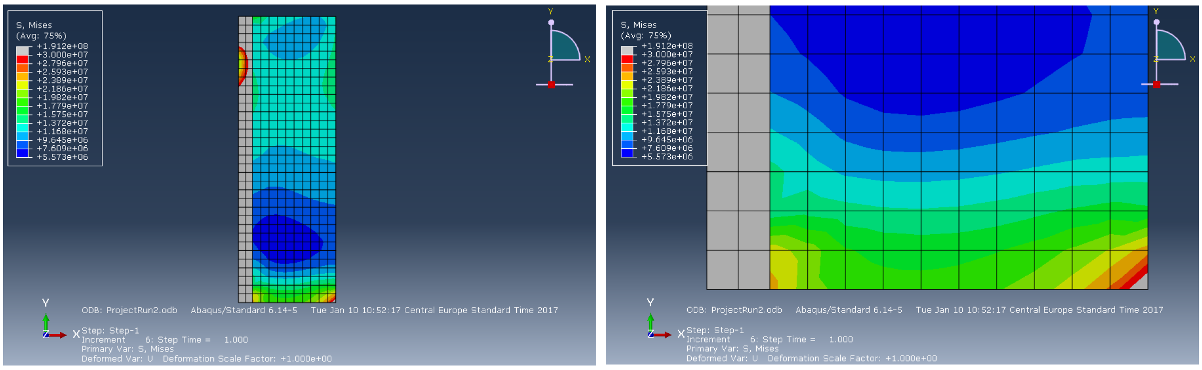
Increment    6: Step Time =    1.000
Primary Var: S, Mises
Deformed Var: U   Deformation Scale Factor: +1.000e+00

Figure 5.2: Results of the coupled thermal and structural analysis of the pile

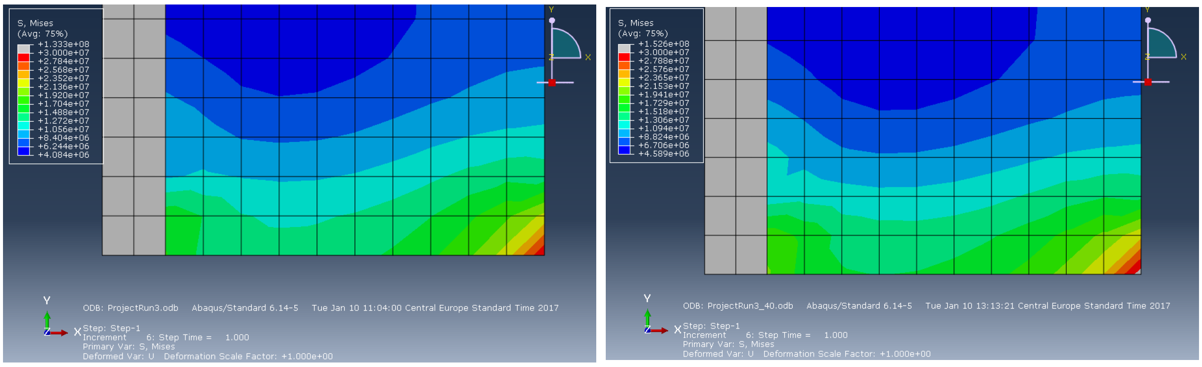
When compared with the case of only structural loads, thermal loads increase the stresses quite a lot. Since the temperature difference of 20°C is quite high, such a temperature difference causes very high stresses to develop in the materials. Assuming that steel yields at a stress of 500 $N/m^2$ and the cubic compressive strength of concrete is 30 $N/m^2$, steel does not yield as the maximum value of stress does not cross 200 $N/m^2$. This is however not the case with concrete. Figure 5.3 shows the results with the upper limit of the band set at the compressive strength of concrete. From Figure 5.3b it can be seen that when the temperature difference is 20°C, stresses in concrete cross its compressive strength and hence this structure cannot withstand such a big temperature difference.

A study was performed to see the temperature difference that concrete can withstand without failing. Figures 5.4a and 5.4b shows the stress distribution in the bottom of the concrete pile when the temperature of water in the steel tube is 35°C and 40°C, respectively.



(a) (b)

Figure 5.3: Result of the coupled thermal and structural analysis focussing on stressing in concrete

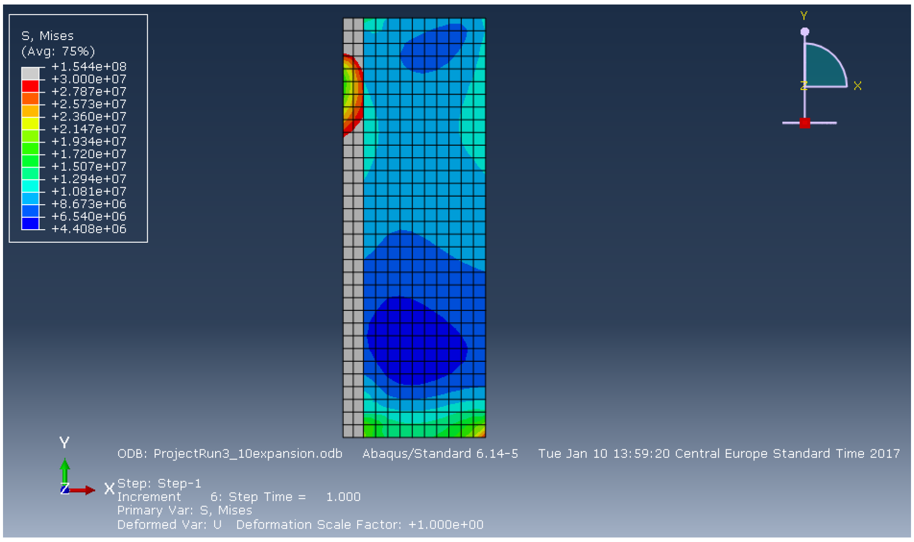


(a) Water temperature = 35°C (b) Water temperature = 40°C

Figure 5.4: Result of the coupled thermal and structural analysis focussing on stressing in concrete while varying temperature of water in steel tube

From these figures it can be seen that the structure can at most withstand a temperature difference of 10°C between the water flowing within the tube and soil temperature. This poses a serious limitation on the performance of the heat pump. Since the aim of this system is to be able to be operate both during summer and winter months, the system should be able to withstand higher temperature differences, and hence higher thermal loads.

One of the tried and tested ways of improving the thermal resistance of concrete is by using concrete made of different aggregates [14]. Concrete with lower coefficient of thermal expansion will develop smaller stresses for a given temperature load and hence will perform better under thermal loading. Figure 5.5 shows the stress field for a case where the temperature difference between water and concrete is 20°C. However, in this case, the thermal expansion coefficient of concrete is considered as $0.9 \times 10^{-5}$, instead of the value prescribed in the problem $(1 \times 10^{-5})$. With a decrease in the thermal expansion coefficient by 10%, the temperature of water that can be withstood by concrete doubles. Though it is a common practice to increase the dimension of structures to increase their load bearing capacity, in this case a better practice would be use concrete made of aggregates that results in lower thermal expansion coefficient and in turn higher resistance to thermal stresses.



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Deformed Var: U   Deformation Scale Factor: +1.000e+00
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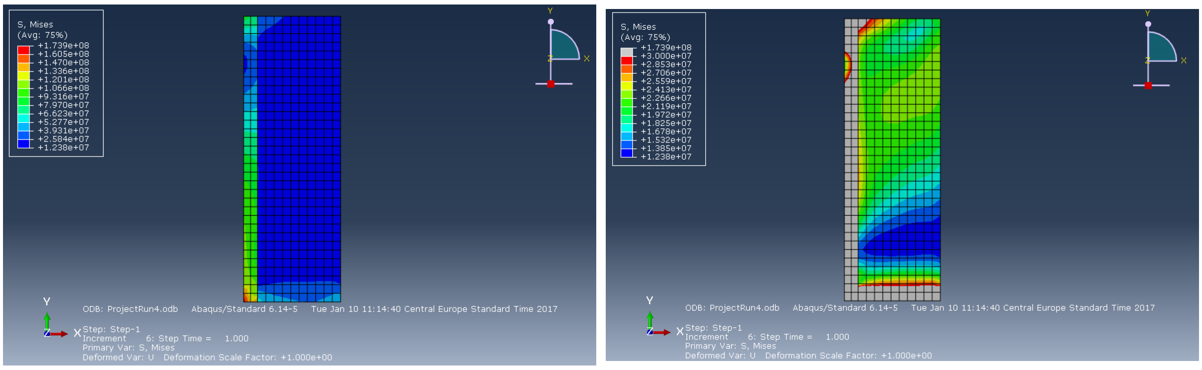
Figure 5.5: Results of the coupled thermal and structural analysis of the pile using concrete with lower thermal expansion coefficient

Finally, a case of more realistic material behaviour is temperature dependent Young's modulus. Since this is a problem where the temperature field of the material varies uniform across the cross section of the material, it would be more practical to consider material properties that vary with temperature. Hence in the final analysis Young's modulus of concrete is assumed to vary with temperature according to the Table 5.1.

| Temperature (°C) | Young's Modulus (MPa) |
|---|---|
| 15 | 27000 |
| 25 | 35000 |
| 35 | 50000 |
| 45 | 70000 |
| 55 | 100000 |

Table 5.1: Temperature dependent material properties of concrete

This is modelled in Abaqus/CAE by modelling a material by toggling on the temperature dependence while defining the elastic properties. The temperature of water flowing in the steel pipe is considered as 50°C, while soil temperature is taken as 30°C. Figure 5.6a shows the stress field in the entire material when the limits automatically set by Abaqus/CAE are considered, while Figure 5.6b shows the stress that are within the compressive strength of concrete. From the figures it can be clearly seen that when temperature dependent material properties are considered, there is a clear evidence of failure in the concrete section. A temperature difference of 20°C is too high for concrete pile to withstand.



(a) (b)

Figure 5.6: Result of the coupled thermal and structural analysis when temperature dependent material properties are considered for concrete

## 5.3 Conclusions and future works

From the work carried out, it can be clearly seen that in case of thermo-activated pile foundations, thermal stresses have major role in deciding the performance of the structure. Though, integrating the ground source heat pumps with the foundation is an innovative technique to save space and installation costs, thorough analysis of the stresses developed due to thermal loads must be performed to ensure the durability of the foundation.

In the case of the specimen tested, it was seen that it cannot withstand thermal loads greater than those generated due to a temperature difference of 10°C between the flowing water and soil. In order to make the system capable of withstanding higher thermal loads, it is necessary to consider piles made of concrete with aggregates that will lower the coefficient of thermal expansion of concrete. It is not advisable to increase the thickness of the concrete pile to make it withstand higher stresses as the transfer of heat between water in the steel pipe and the ground is a conduction phenomenon which will slow down if the thickness of the pile increases. Thus efforts must be put into developing concrete with lower thermal expansion coefficient.

Future works include considering more realistic cases such as including change in material properties with temperature, effect of ground water tables on pile foundations and optimising the geometry of the foundation to increase its resistance to thermal and structural stresses. Also it is worth investing time to study behaviour of the structure when concrete with different aggregates are used in the foundation.

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# A Work distribution

The present work, which included understanding the problem and background, load calculations, modelling and analysis in Abaqus/CAE, overcoming the typical errors and finally report writing, was performed by both the authors together right from beginning of the project till writing this report. References were collected by both, read and discussed before the calculations were performed. The analysis Abaqus/CAE was done together. The task of report writing too was divided evenly with chapter on introduction, modelling and results written by the first author while the chapters on literature review and the part on conclusions were written by the second author.