Escola Tècnica Superior d'Enginyers de Camins, Canals i Ports de Barcelona

CIMNE International Center for Numerical Methods in Engineering

Master in Numerical Methods in Engineering

COMPUTATIONAL MECHANIC TOOLS

Simulation Project

"THERMO-ACTIVATED PILE FOUNDATION"

Team 7

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INTRODUCTION

GSHP

The ground source heat pump (GSHP) is a technology useful to obtain the heat energy from the ground. Under a certain depth (of about 10 meters), due to the solar energy's ground absorption, the soil remains at a constant moderate temperature throughout the whole year. From the course of the shallow soil temperature over the year it becomes apparent the ground energy is an always functioning and constant source of energy.

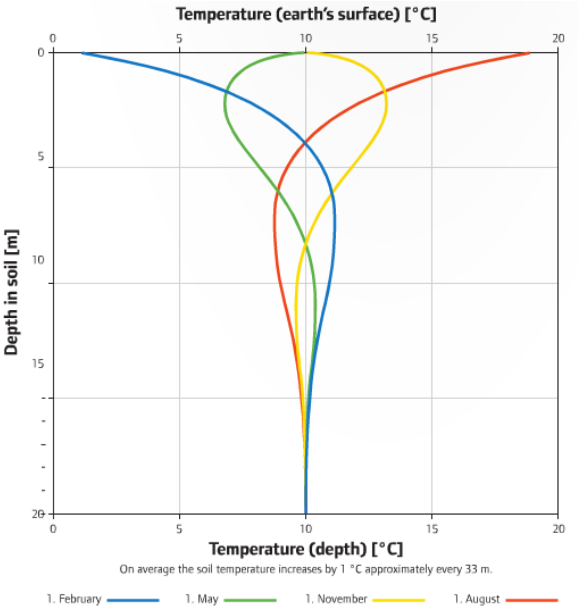

Figure 1: Ground temperature profile.

Ground energy benefits

In order to reduce de energy consumption depending on fossils fuel, governs across Europe, with several legislative initiatives promote the use of renewable energy sources.

Ground energy has various numbers of benefits:

- Ground energy is available endlessly 24 hours a day for cooling and heating
- The usage of ground energy reduce the emission of greenhouse gas
- Ground energy is technically mature (it has been used for heating and cooling for more than 50 years)
- Ground energy can be used in combination with other energy sources.
- Ground energy is economically sustainable because it is independent of external suppliers and change in currency exchange rates.

What is a heat-exchanger?

A Heat-exchanger is a device which is useful in order to facilitate energy transfer between two different medium.

Heat can be defined as the energy which can be transferred from two different systems by temperature difference. Heat always goes form high temperature to low temperature and the heat transfer stops when the temperature of both medium is the same.

Three different ways describes heat transfer: conduction, convection and radiation.

In GHPS is extremely important the heat transfer due to the conduction between the soil and the inner pipe, in order to increase the temperature of the fluid which flow in it.

The conduction can be defined as the energy transfer between particles with high energy to particles with less energy.

System overview

Depending with the environment (climatic condition and soil properties), the surface available or the type of building, different GSHP systems are used. The distinction is made between vertical and horizontal heat exchangers (energy collectors).

Conventional GSHP systems can be sort as:

- Horizontal
    - Horizontal collector
    - Spiral and energy cages
    - Rift collectors

- Vertical
    - Boreholes
    - Energy piles

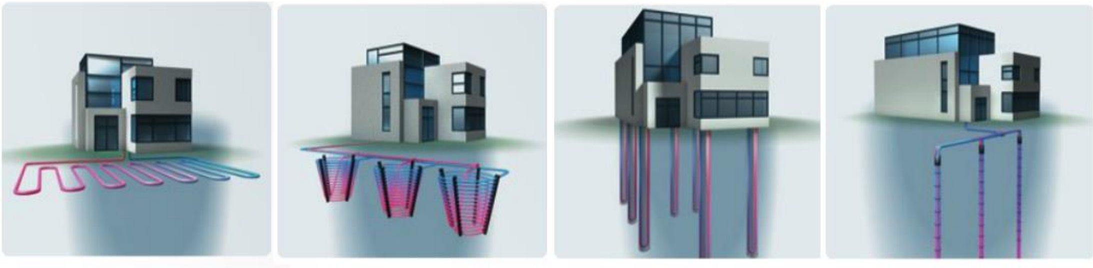

Figure 2: Conventional GSHP systems

The present project is focused only on the energy piles vertical collectors, where the heat exchangers are embed in foundation piles. Individual or several pipe circuits can be installed in U-shape, spiral or mender shape. An innovative design is a coaxial design, which is the case of study of the present project, where tubes are inserted concentrically as inner and outer tube.

Coaxial heater exchanger

A coaxial heater exchanger consists of a minimum of two tubes with different diameter. The outer pipe, which in order to provide a good energy transfer between external medium and the liquid flowing is characterized by a high thermal conductivity material. The inner pipe usually has a high thermal resistance in order to reduce thermal losses resulting from the internal heat exchange.

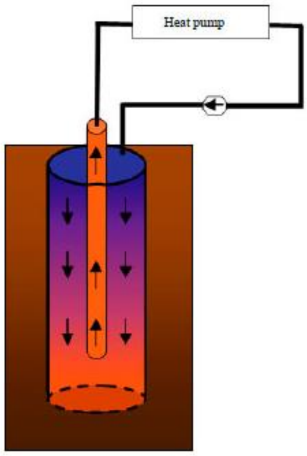

Figure 3: Coaxial heater exchanger

Energy piles

The two basically functions which the energy pile system must performs are transfer the load into the ground and use the ground as an energy source.

Figure 4: Schematic illustration of an energy pile system

This technology offers several benefits like the high impact to the entire energy system for a very-low cost implementation, compared with a solution where drilling is required, and it is an ideal solution for residential and non-residential applications.

CASE OF STUDY

In the co-axial heat exchanger water flows from the surface through the exterior annulus and comes up via the inner ring.

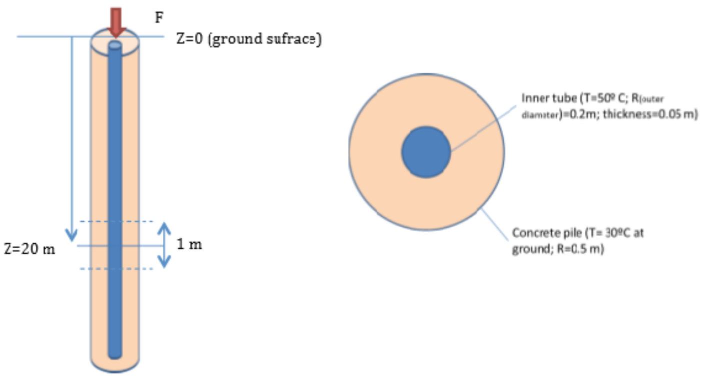

Figure 5: Schematic thermopile and boundary conditions

Material	Young's modulus (MPa)	Density (Kg/m^3)	Poisson's ratio	Thermal expansion coefficient ($°C^{-1}$)	Thermal conductivity (W/m K)	Friction angle
Concrete	27000	2500	0.2	1.0e-5	2	-
Steel	210000	7800	0.3	1.2e-5	50	-
Ground	-	2000	-	-	-	30

Table 1: Material properties.

Outer radius= 50cm
Inner pipe radius (outer side)=20cm
Pipe thickness=5cm

Outer temperature=30°C

In this study will be analyzed:

1. The stress state of the concrete and steel pipe of a slice of 1 meter (centered at a depth of 20 m) due to the ground pressure (surface at z = 0), as shown in Fig. 4, and a vertical load (F) applied at the top of the pile due to the structure loads of 300 KN (applied only to the concrete section). Considering also the weight of the pile above the section of analysis.
2. The increase of stresses in the concrete due to the flow of water at 50◦C inside the pipe.
3. Maximum increase in water temperature that the steel pipe and the concrete can withstand if we consider that steel yields at 500 MPa and the concrete used has 30 MPa of characteristic cubic compressive strength. Propose changes in the structure to increase the admissible water temperature.
4. Study of a new type of concrete whose properties vary with temperature according to Table 1 and its affect the results obtained in 1.

Table 1: Temperature dependent material properties of concrete

Temperature (C)	Young's modulus (MPa)
15	27000
25	35000
35	50000
45	70000
55	100000

METHODOLOGY

The problem is studied by doing numerical simulations using the finite element program Abaqus™ from Dassault Systems.

Type of model

Due to the cylindrical geometry we decided to use a 2D axil-symmetric model.

Some of the benefits of working with a 2D model, compared to a 3D one are:

- Reduce de size of the problem
- Less number and lower dimension of elements
- Faster execution
- Easier post processing

A cross section of the pile was created. Abaqus accounts for the fact that it is really 3D, axisymmetric structure.

Dimension of the model

It was proposed in the statement of the problem to analyse a slice of 1m of length of the pile. The first simulations were carried down using this criteria, but perturbations in temperature and stresses distributions were detected in the area of interest due to extreme boundary conditions. Therefore, finally a model of 3m of length was used to guarantee the remoteness of perturbations.

Finite Element Mesh

The importance of the mesh is crucial in order to get reliable results for any simulation.

Due to the type of the problem, the increase of number of elements in the area where the steel pipe and concrete pile interact is crucial. The reason is that there, there is a great gradient of stresses in a relatively short distance and that the steel section is much thinner that the concrete one.

Even though it is important to have a finer mesh in the interior part of the pile, precise result are not needed far away from the interest slice of 1m neither and a coarser mesh can capture results with sufficient precision.

A triangular elements mesh was used due to the capacity of adapting to the needs of our problem without distorting the geometrical properties of the elements.

The mesh used is composed of triangular linear elements. For the pure mechanical simulations, the axisymmetric stress type of elements were used while when the thermomechanical problem was analyzed displacement-temperature coupled elements were used.

The total number of element used is 10592 with a smallest element length of 1cm as it can be seen in the following figure.

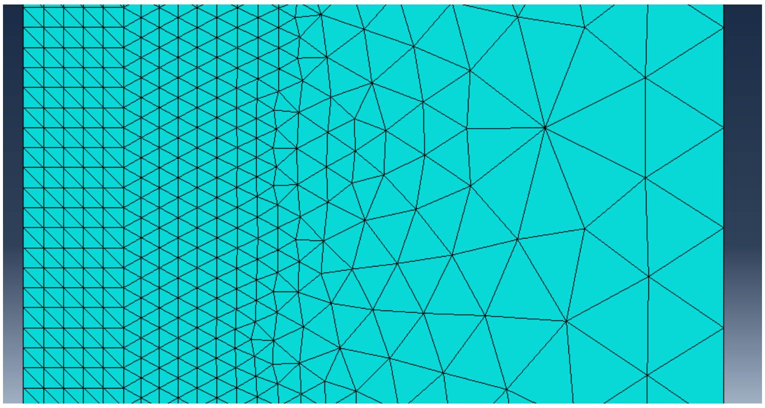

Figure 6: Triangular size element mesh

Boundary conditions

Described in cylindrical coordinates the following mechanical conditions were imposed.

- Bottom part of the pile
  - *Ur, Uz, Uθ*
- Upper part of the pile
  - *Ur, Uθ*

Where *r* is the radial direction, *z* is the vertical direction and *θ* is angle related to the rotation.

In the upper and bottom part of the model, a restriction to the radial displacement was introduced in order to control the effect of load introduction on unreal limits of the structure (the pile continues over and down the model limits).

Loads

In order to obtain a complete study, all the mechanical loads applied had been considered as:

- Structure load = $4.547 \cdot 10^5$ Pa
- Soil pressure (at 18.5m) = $1.814 \cdot 10^5$ Pa
- Soil pressure (at 21.5m) = 2.10810^5 Pa
- Internal water pressure (at 18.5m) = $1.814 \cdot 10^5$ Pa
- Internal water pressure (at 21.5m) = 2.10810^5 Pa
- Concrete self-weight = $5.536 \cdot 10^5$ Pa
- Steel self-weight = $1.415 \cdot 10^6$ Pa

And temperature load at the:

- Inner pipe temperature of 50ºC
- Outer pile temperature of 30ºC
- Bottom and upper pile surface of 30ºC

A detailed description of the calculation of this loads is available in Appendix 1.

Cases modeling aspects

Case 1

- Element type: axisymmetric stress.
- Loads and boundary conditions: mechanical.
- Type of analysis: static, general.

Case 2

Two different simulations were carried out, a steady state and a transient analysis. For both of them:

- Element type: displacement-temperature coupled elements.
- Loads and boundary conditions: mechanical and thermal.
- Type of analysis: displacement-temperature coupled.

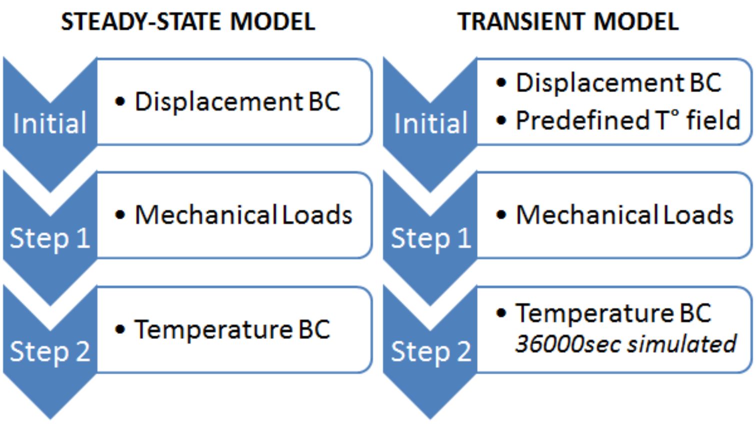

Figure 7: Steps for case 2

Step 2 simulation for the transient mode consisted in a 10hs (factious time) simulation with 3600 steps of 100sec each, starting from a predefined-field temperature for all the model of 30°C.

Case 3

In this case an internal thermal load of 500°C was applied in 100 increasing steps.

- Element type: displacement-temperature coupled elements.
- Loads and boundary conditions: mechanical and thermal.
- Type of analysis: displacement-temperature coupled.

Case 4

The same analysis from case 2 was carried out, but accounting for a concrete material with temperature dependent elasticity module.

- Element type: displacement-temperature coupled elements.
- Loads and boundary conditions: mechanical and thermal.
- Type of analysis: displacement-temperature coupled.

RESULTS

The results shown in this section correspond to a depth of 20m of the pile.

Case1 (Mechanical problem)

The analysis of the stress state due to mechanical loads describes that the highest value of the Von-misses stress, which reaching value of 4.50e6 Pa, are concentrated in the steel pipe. We can appreciate how the stresses decrease abruptly in the contact area between concrete and steel. This is due to the great difference of the elasticity module, making the steel section stiffer and therefore absorbing a greater part of the loads.

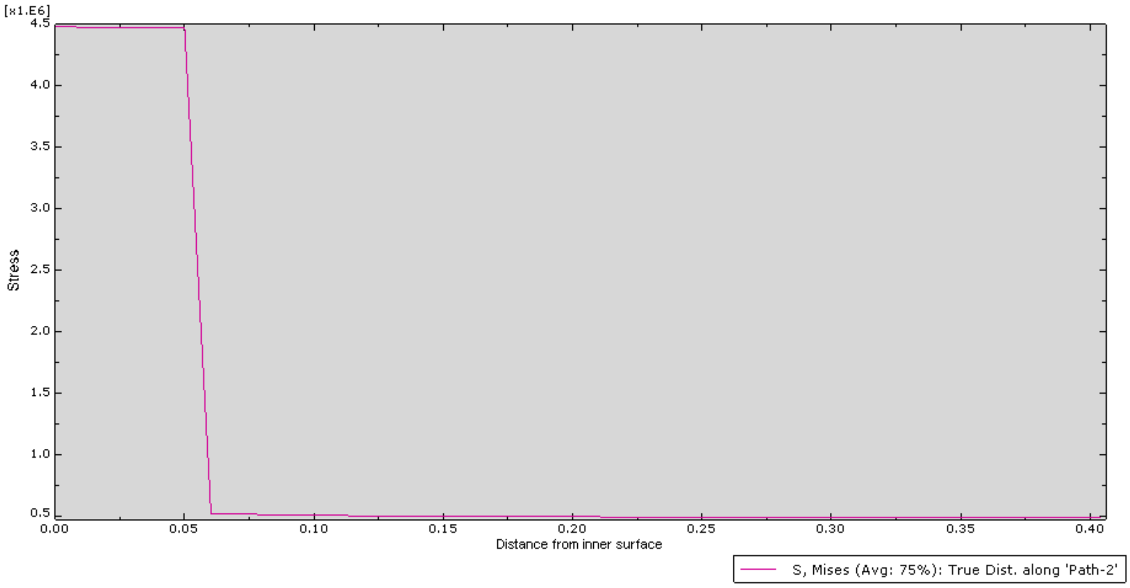

Figure 7: Von-Misses Stress [Pa] = f (radius)

Case 2 (Thermo-mechanical problem)

After adding temperature at the system, the results show the temperature distribution in the whole model and we can see an almost linearity description of the temperature in the concrete pile foundation (figure 8). For both steady-state and transient simulations the same final temperature profile was observed. It can be observed that the steel section has a lower slope due to its high conductivity. Both inner and outer temperature boundary conditions are preserved.

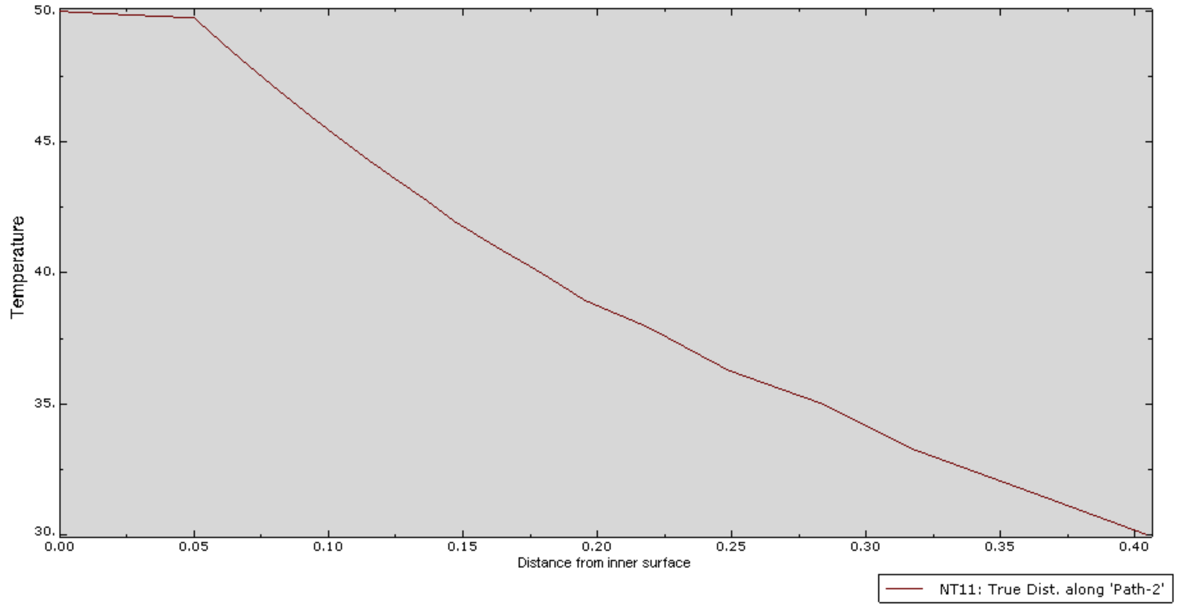

Figure 8: Von-Misses Stress [Pa] = f (radius)

Steady state analysis

The analysis of the stress state due to thermo-mechanical loads describes, also for the case 2, the presence of Von-misses highest value in the steel pipe (figure 9). Due to the temperature the maximum stress value increase to 33.5e6 Pa, compared with the previous mechanical problem. Also an increment of concrete stresses has been recognized due to the heat exchange.

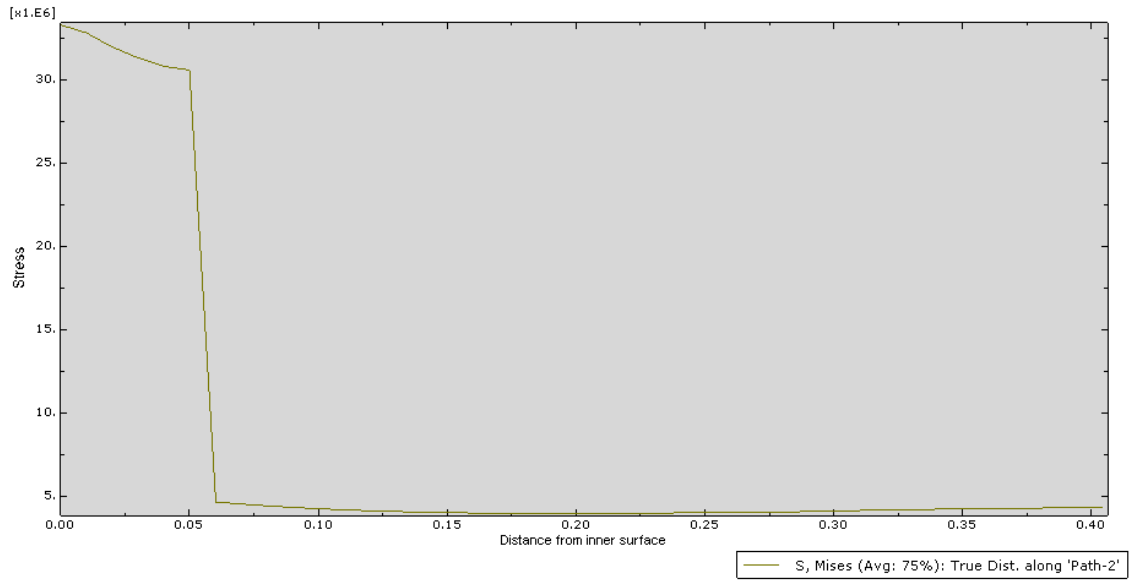

Figure 9: Temperature [°C] = f (radius)

Transient analysis

The transient simulation for the final state describes a similar stress state behavior as the steady state analysis, but with a lower Von-misses stress value, with a maximum of 26.5e6 Pa.

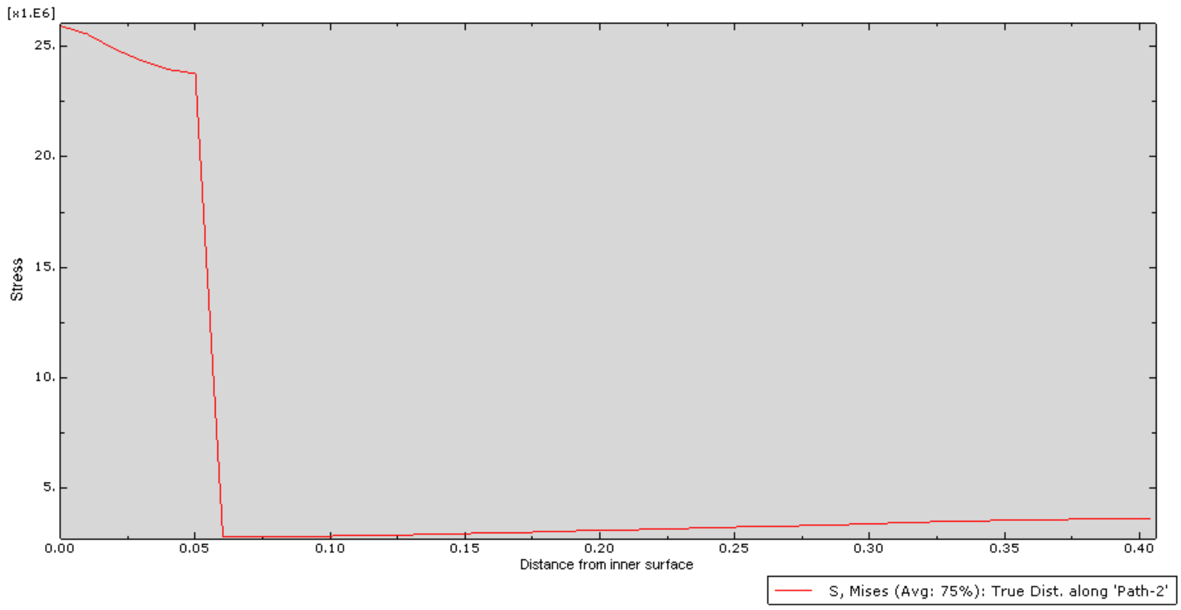

Figure 10:Von-Misses Stress [Pa] = f (radius)

Case 3 (Thermo-Mechanical failure)

As the 500°C internal temperature was introduced gradually, it was possible to identify the failing time for the steel (step 480) and the concrete (step 305). The corresponding internal temperature was calculated as a post-process.

The failure criteria adopted was: 500MPa for the Von Misses stress for the steel pipe and 30MPa compressive normal stress for the concrete pile.

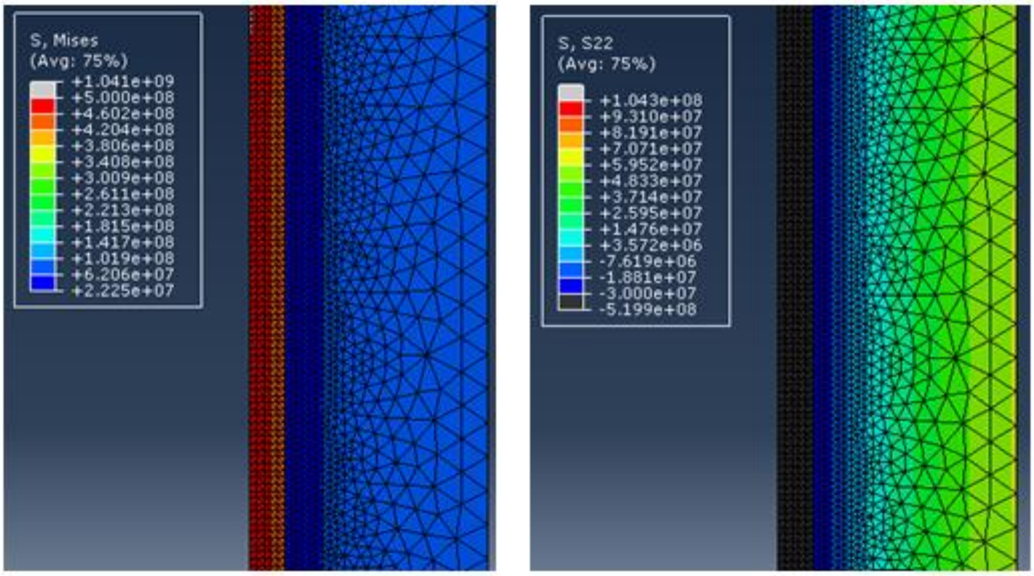

Figure 11: Steel, Von Misses stress failuren(left) and Concrete, normal stress failure (right).

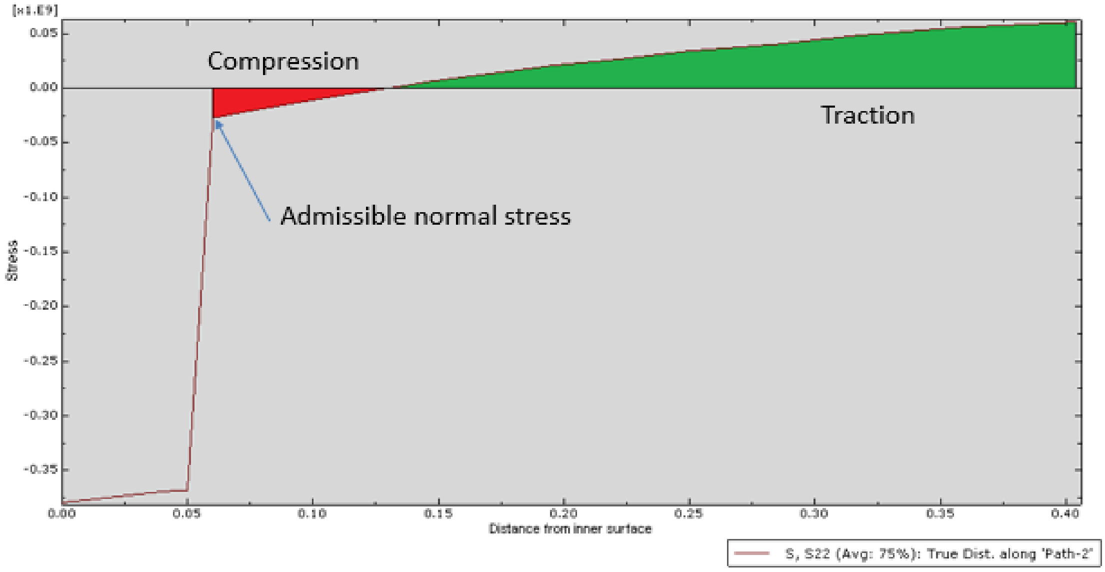

Figure 12: Concrete thermo-mechanical failure

Knowing the temperature evolution of the two failing points (for steel in the internal side and for concrete in the interface) both failing temperatures can be found using (figure 13). From there we can see that the maximum internal temperature bearded by the structure correspond to the concrete failure and takes a value of 315°C.

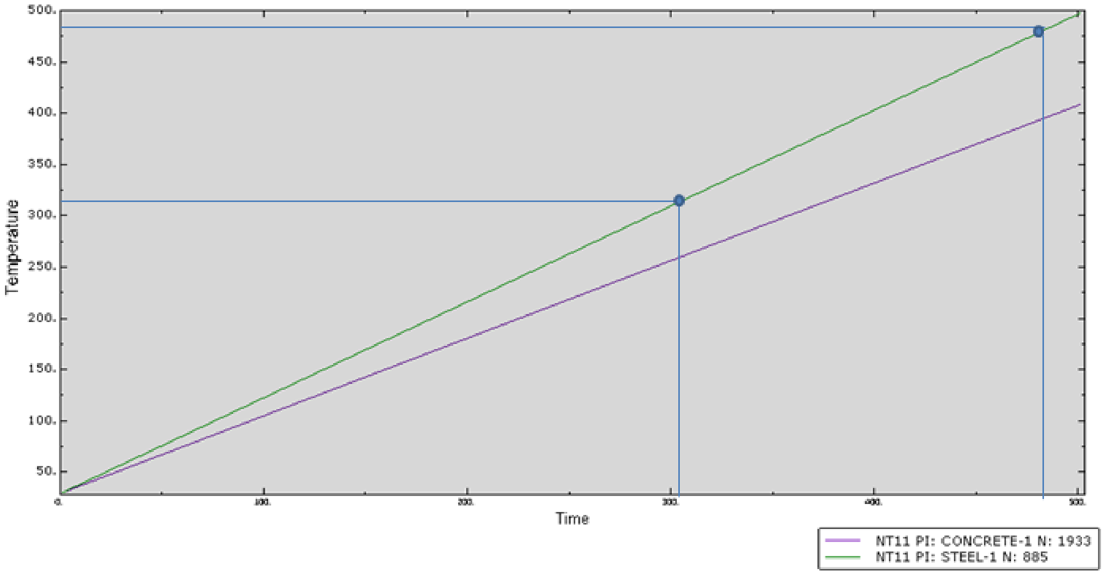

Figure 13: Concrete and steel failure

Proposed changes to accomplish higher temperatures:

- Use of concrete with higher compressive strength.
- Account for the concrete plastification

- Include between the steel pipe and the concrete some material with low thermal conductivity to drop the temperature before it reaches the concrete. Although this thermal insulator would solve the structural problem, it would act against the system's objective: exchange of heat with the media.

Case 4 (New concrete)

Comparing the results of this simulation versus the case 2, it can be observed that the temperature dependent concrete (figure 14) has higher values of von Misses Stresses. The highest stress value for the new concrete is almost 35e6 Pa while in the case 2 simulation was about 30e6 Pa. This behavior can be related with the increasing of Young's module property with temperature increasing.

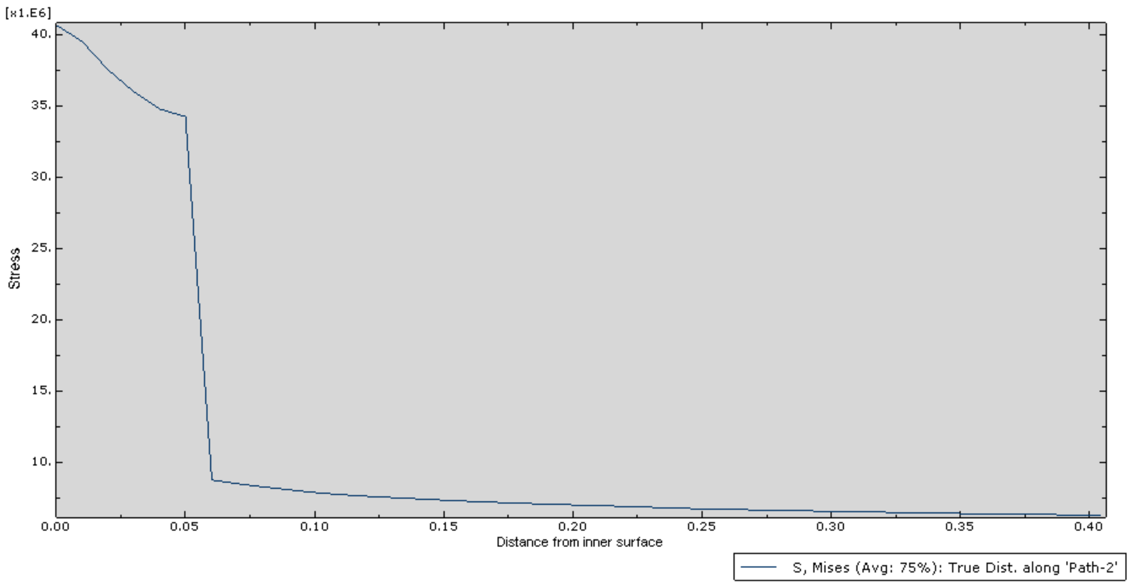

Figure 14: Von-Misses Stress [Pa] = f (radius)

CONCLUSIONS AND FUTURE WORK

From the analysis of the results obtained from the simulations we can say:

- Variations in temperature can provoke great changes in the structure stress state. Therefore is important the study and simulation of its effect when thermal loads are expected.
- Temperature distribution in the model occurs similar as expected in simple heat transmission problems through different material walls.
- Normal stress distribution for the concrete failure has a logical almost linear distribution corresponding to the classical effect of axial loading and bending momentum of beams.

- The incorporation of an increasing elastic modulus as a function of temperature concrete increases the performance of the pile.

For future works some hypothesis improvements for the models are proposed:

- Account for the interaction between the soil and the structure, with some simple model as mohr-coulomb for the first one. It is improbable that the mechanical loads would travel 20m through the pile with the contact to a normal ground without discharging the structure.
- Account for material non-linarites of the concrete.
- Carry out a CFD simulation of the whole pile-soil interaction to analyze the real efficiency of the system and understand better the thermal-interaction.

Finally it is important to remark that this type of analysis should be done by qualified and experienced professionals although the availability of user friendly commercial codes. A strong understanding of structural analysis, material resistance, numerical methods and modeling is fundamental to make simulations representative of reality and take intelligent decisions in consequence.

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- Tomasz Sliwa (2014). Use of Oil Boreholes in the Carpathians in Geo-energetic Systems: Historical and Conceptual Review. Research Journal of Environmental Sciences, 8: 231-242.
- Fully-Coupled Thermo-Mechanical Analysis, http://www.ccg.msm.cam.ac.uk/
- Uponor Energy piles Geo Palix. https://www.uponor.com/solutions-from-uponor

APPENDIX 1 - MECHANICAL LOAD CALCULATION

Load calculations

A model of 3m height pile is done to avoid perturbations due to boundary conditions in the middle section of it (20m deep).

$z_{ground} := 0\text{m}$	*ground level*
$z_{bot} := 21.5\text{m}$	*bottom level of the pile model*
$z_{top} := 18.5\text{m}$	*top level of the pile model*
$L_{pile} := z_{bot} - z_{top} = 3\,\text{m}$	*pile model lenght*

Self weight of the model is taken into account by applying gravity $g = 9.807\dfrac{\text{m}}{\text{s}^2}$

- Gravity
- Concrete Self-weight

$\delta_c := 2500\dfrac{\text{kg}}{\text{m}^3}$	*concrete density*
$\boxed{p_{csw} := \delta_c \cdot g \cdot z_{top} = 4.536\times 10^5\,\text{Pa}}$	*top distributed load over the concrete due to its weight*

- Steel Self-weight

$\delta_s := 7800\dfrac{\text{kg}}{\text{m}^3}$	*concrete density*
$\boxed{p_{ssw} := \delta_s \cdot g \cdot z_{top} = 1.415\times 10^6\,\text{Pa}}$	*top distributed load over the steel due to its weight*

- Structure load

$P := 300\text{kN}$	*axial load from the building structure acting on the pile*
$r_{ec} := 0.5\text{m}$	*external radius of the concrete pile*
$r_{ic} := 0.2\text{m}$	*internal radius of the concrete pile*
$A_c := \pi\cdot\left(r_{ec}^{\ 2} - r_{ic}^{\ 2}\right) = 0.66\,\text{m}^2$	*area of the concrete section*
$\boxed{p_{sl} := \dfrac{P}{A_c} = 4.547\times 10^5\,\text{Pa}}$	*top distributed load due to the structure*

- Ground pressure

$\delta_g := 2000\,\frac{kg}{m^3}$ *ground density*

$\psi := 30°$ *ground friction angle*

$K_0 := 1 - \sin(\psi) = 0.5$ *ground lateral pressure coefficient*

$p_g := K_0 \cdot \delta_g \cdot g = 9.807 \times 10^3 \cdot \frac{Pa}{m}$ *ground pressure (depends on z)*

$\boxed{p_{g\_top} := p_g \cdot z_{top} = 1.814 \times 10^5\,Pa}$ *ground pressure at top of the model*

$\boxed{p_{g\_bot} := p_g \cdot z_{bot} = 2.108 \times 10^5\,Pa}$ *ground pressure at bottom of the model*

- Internal water pressure

$\delta_w := 1000\,\frac{kg}{m^3}$ *water density*

$p_w := \delta_w \cdot g = 9.807 \times 10^3 \cdot \frac{Pa}{m}$ *water pressure (depends on z)*

$\boxed{p_{w\_top} := p_w \cdot z_{top} = 1.814 \times 10^5\,Pa}$ *ground pressure at top of the model*

$\boxed{p_{w\_bot} := p_w \cdot z_{bot} = 2.108 \times 10^5\,Pa}$ *ground pressure at bottom of the model*

APPENDIX 2 – TEAM WORK DISTRIBUTION

Christian Rossi:

- GHSP State of art research
- 3D and Axisymmetric geometry modeling
- Mechanical boundary conditions
- Mechanical loading and simulation
- General result output
- Report preparation
- Correspondence with professor

Lisandro Roldan:

- Loads values calculations
- Meshing
- Thermal boundary conditions
- Thermal loading and simulation
- Results interpretation
- Slide preparation