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# Experimental Analysis of Thermo-Mechanical Effects on Geothermal Piles

## Analiză experimentală a efectelor termo-mecanice asupra piloților geotermici

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**Abstract.** The growing global population necessitates sustainable energy solutions to meet escalating energy demands. Geothermal energy, abundant and continuous, ranks as a leading alternative after solar energy. Integrating geothermal energy into building systems requires specialized structures. For shallow geothermal applications, thermo-active piles offer a cost-effective and efficient solution regarding both investment and operational expenses. Distinct from traditional piles, these energy piles enable thermal exchange between the pile and surrounding soil, supporting building heating, cooling, and hot water needs. Their design mandates a coupled thermo-hydro-mechanical analysis. This study presents a numerical model of a field-scale energy pile experiment conducted in Houston, Texas, validated through stress and temperature data collected during the experiment.

**Key-words:** geothermal piles, experiment, solar energy

## 1 Case study on the numerical modelling of energy piles

**Energy piles** combine structural foundations with geothermal heating and cooling systems, using the ground as a renewable energy source. This dual-function system has gained attention in sustainable building design due to its environmental and economic benefits. Numerical modelling helps predict their thermal and mechanical performance under various operating and environmental conditions.

The global population is experiencing a rapid increase, with current estimates nearing 8 billion and projections indicating a rise to approximately 9.8 billion by 2050

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[1].This demographic trend has led to a significant escalation in global energy demand. Presently, nearly 60% of this demand is met through the consumption of fossil fuels [2].

The reliance on fossil fuels presents two critical challenges: the intensification of environmental degradation due to greenhouse gas emissions, and the inherent non-renewability of these resources. In response to these issues, geothermal energy has emerged as a viable alternative. Defined as the thermal energy stored within the Earth's crust, geothermal energy ranks as the second most abundant renewable resource globally, following solar energy.

One of the key advantages of geothermal energy lies in its uninterrupted availability, independent of atmospheric conditions, thereby ensuring a consistent and reliable energy supply [3].Due to its sustainability and minimal environmental impact, geothermal energy has garnered increasing interest as a clean energy solution.

Among the various technologies employed to harness shallow geothermal resources, thermo-active piles , commonly referred to as energy piles,) have gained prominence [4] .These structural elements differ from conventional piles by integrating pipe systems that enable heat exchange between the subsurface and the built environment. The temperature of the fluid circulating within these pipes is modulated via a heat pump, allowing for the delivery of thermal energy throughout the structure to satisfy heating, cooling, and domestic hot water requirements.

Extensive research has been conducted to investigate the thermal performance of energy piles under load. Their response to thermal loading has been documented through field experiments [5], [6], [7] ,and subsequently validated using numerical simulations [8], [9].

In the present study, a comprehensive numerical model was developed to simulate the behavior of an energy pile tested at field scale in Houston, Texas. The model was validated using stress and temperature measurements obtained from the experiment, thereby providing a reliable framework for further investigations into the thermo-mechanical performance of energy piles.

## 2 Field experiment

### 2.1 Energy Pile Characteristics

An in-situ energy pile test was carried out in Houston, Texas [7]. The pile, constructed using the Augered Cast-In Place (ACIP) method, has a diameter of 45.7 cm and a total length of 15.24 m. To monitor the pile's mechanical behavior, vibrating wire strain gauges were installed at five different depths along the reinforcement cage (Figure 1).

The pile incorporates high-density polyethylene (HDPE) pipes to facilitate heat exchange between the ground and the structure. These pipes have a diameter of 25.4 mm and a wall thickness of 3.2 mm. A single U-shaped pipe configuration is positioned centrally within the pile. The heat transfer fluid circulating within the pipe is composed of 80% water and 20% antifreeze. During testing, the fluid circulated at a constant flow rate of 0.88 m/s. The thermal conductivity of the pipe material is 0.42 W/m/°C.

The energy pile has a modulus of elasticity of 36 GPa and a linear thermal expansion coefficient of $1.29 \times 10^{-5}$ $\mu\varepsilon/°C$. The instrumentation was placed at depths of -2.7 m, -5.7 m, -8.7 m, -11.6 m, and -14.5 m, respectively.

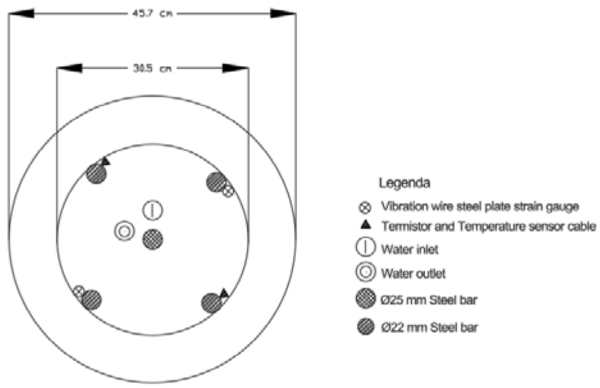


Figure 2-1 Energy Pile instrumentation

### 2.2 Soil properties

Based on the findings from the geotechnical investigations conducted at the site, the subsurface profile consists of a clay layer extending to a depth of 9.8 meters, beneath which a sand stratum is located. The groundwater table was identified at a depth of 3.7 meters below the surface. The geotechnical parameters utilized in the numerical analysis are presented in Table 1.

*Table 1*

*Soil parameter*

| Ground layer | Terzaghi ( Mpa ) | Poisson | Kohezyon (kPa) | Internal friction angle (˚) |
|---|---|---|---|---|
| Clay | 45 | 0.495 | 114 | 0 |
| Sand | 75 | 0.3 | 5 | 43 |

### 2.3 Purpose of the Experiment

As part of this study, the energy pile was subjected to a static load test in the field, and its vertical load capacity was determined to be 2558 kN. After the static load was removed, cyclic thermal loading was applied. This thermal loading consisted of five thermal cycles and lasted for a total of six weeks. The temperature of the fluid circulated through the pipes inside the pile is shown in Figure 2.

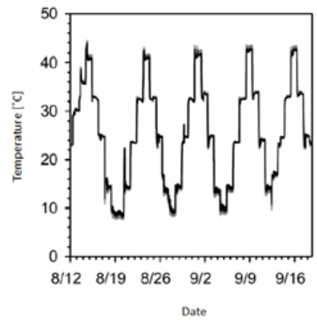


*Figure 2-2 Thermal loading cycles*

## 3 Physico-Mathematical Models for the Simulation of Transfer Processes in Geothermal Piles

Analytical solutions are widely used due to their simplicity and computational efficiency. Most analytical approaches for analyzing geothermal heat pump systems assume conduction-dominated systems (neglecting the natural flow of groundwater) and are based on the infinite line source theory or the cylindrical source theory

$$\frac{T_r - T_e}{T_i - T_e} = \sum_{n=1}^{\infty} \frac{2 J_1(\varepsilon_n)}{\varepsilon_n \left[J_0^2(\varepsilon_n) + J_1^2(\varepsilon_n)\right]} J_0\left(\frac{r}{R}\varepsilon_n\right) exp(-\varepsilon_n^2 Fo) \qquad 3\text{-}1$$

These models are particularly applied for in-situ evaluation of geothermal systems using the Thermal Response Test (TRT), which typically lasts between 12 and 60 hours. However, they are less suitable for long-term analysis, as the effects usually become significant after approximately 1.6 years of operation, depending on the hydrogeological and operational conditions of the geothermal system. The temperature response in an infinite line source model (without groundwater flow) cannot reach steady-state conditions, and the thermal anomaly will increase indefinitely with operating time. Therefore, by using software such as COMSOL, long-term simulations can be performed, allowing for the analysis of axial effects and groundwater flow influence on the temperature distribution along the walls of geothermal foundation structures.

### 3.1 Model "Infinite Line Source" (ILS) *Reg* [10].

The Infinite Line Source (ILS) model is a direct application of Lord Kelvin's heat source approach [11] to ground heat exchangers. This model is based on the idea that any line can be considered as a series of closely spaced point sources. It begins by calculating the temperature change at a specific location within an infinite homogeneous medium using the point heat source formula, and then, through integration, it accounts for the effects of the other point sources at the target location (Figure 3-1).

The following general assumptions were made for the derivation of this model:

1. The soil is considered a homogeneous medium, and its thermophysical properties are assumed to remain constant with temperature
2. The medium has a uniform initial temperature
3. The heating rate per unit length is constant from the start until the end of the thermal loading

The infinite line heat source model is the analytical solution of the conductive heat transfer equation in a homogeneous and isotropic medium, expressed in radial coordinates according to [12] [13]

$$\frac{\delta^2 T}{\delta r^2} + \frac{1}{r} \times \frac{\delta T}{\delta r} = \frac{\rho c_p}{k} \times \frac{\delta T}{\delta t} \quad (3.1)$$

unde,
$T$ : temperatura mediului,
$r$ : distanta radiala de la sursa de caldura,
$\rho$ : densitatea mediului,
$cp$ : caldura specifica a mediului
k : conductivitatea termica a mediului,
t : timpul.

To solve the equation, it is assumed that the system is initially at a constant temperature ($T(r, t=0) = T_0$), and that the boundaries located at an infinite distance from the heat source ($r=\infty$) always remain at a constant temperature ($T(r=\infty, t) = T_0$). The surrounding medium is considered homogeneous and isotropic

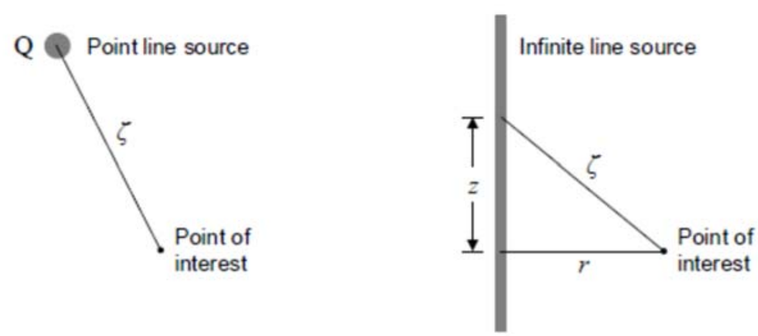


*Figure 3-1Point Line Source" and "Infinite Line Source" models according to [10]*

Ingersoll and Plass (1948) [14] demonstrated that the temperature change at time *t* and at a distance ζ from a point heat source emitting a constant heat rate *q* can be calculated as follows:

$$\Delta T(t) = \left(\frac{q\alpha}{k}\right)\left(\frac{1}{2\sqrt{\pi\alpha t}}\right)^3 exp\left(-\frac{\zeta^2}{4\alpha t}\right) \quad (3.2)$$

The following integral is then used to estimate the temperature change caused by an infinite linear heat source. Again, the linear source is represented by adjacent points, for each of which the distance to the location of interest is 2ζ=r+z, as illustrated in (Figure 3-1)

$$\Delta T = \int_{-\infty}^{+\infty} \left(\frac{q\alpha}{k}\right)\left(\frac{1}{2\sqrt{\alpha\pi t}}\right)^3 e^{-(r^2+z^2)/4\alpha r} dz = \frac{q}{4\pi kt} e^{\frac{-r^2}{4\alpha t}} \quad (3.3)$$

Since the heat source continuously emits from time 0 to t, the temperature change at the point of interest can be estimated as:

$$\Delta T = \frac{q}{4\pi k} \int_0^t \frac{e^{\frac{-r^2}{4\alpha t}}}{t} dt \quad (3.4)$$

Assuming an infinite linear heat source located at r=0r = 0r=0 and represented by a constant heat flux per unit length, and given the prescribed initial and boundary conditions, the solution to equation (3.5) can be expressed as the following temperature increment ΔT(r,t)=T(r,t)−T0, which depends on the distance r from the source and time t

$$\Delta t(r,t) = -\frac{q}{4\pi k} Ei\left(-\frac{r^2}{4\alpha t}\right) \quad (3.5)$$

where,

*Ei(u)*:exponential intergral,

q: heat flux injected per unit length of the borehole

The exponential integral in equation (3.6) can be derived as the following Taylor series expansion [15].

$$E_i(u) = \gamma + ln(u) + \sum_{i=1}^{\infty} \frac{u^t}{i \cdot i!} \quad (3.6)$$

γ is the Euler–Mascheroni constant (γ = 0.57721…).

For large values of $t/r^2$, Ei(u) can be approximated as:

$$\Delta T(r_b, t) = \frac{q}{4\pi k}\left[ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right] \quad (3.7)$$

The relationship between the measured average fluid temperature ($T_f$) during a thermal response test and the temperature at the borehole wall is:

$$T_f(t) = T_0 + qR_b + \frac{q}{4\pi k}\left[ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right] \quad (3.8)$$

where,

$T_0$: initial (undisturbed) ground temperature,

$R_b$: borehole thermal resistance.

The slope of the curve gives:

Equation (3.9) can be expressed in the form

$T_f(t)$ = m·ln(t) + n,

In order to determine the thermal conductivity of the ground. In this way, by using the slope of the evolution of the average fluid temperature with respect to the natural logarithm of time, the thermal conductivity can be evaluated. The slope of the curve gives:

$$m = \frac{q}{4\pi k} \quad (3.9)$$

The thermal conductivity of the ground can be evaluated using this slope, according to the following relation:

$$k = \frac{q}{4\pi m} \quad (3.10)$$

The ILS model does not account for the finite length of typical heat exchangers. The finite length causes an edge effect, which results in a reduction of the temperature change at the ends of the line. This axial effect becomes significant at approximately t≈H^2/180αt for a single line source, where H is the length of the heat exchanger. This limiting time is even shorter if there is interaction between multiple line sources [16].

Representing the heat exchanger as a linear heat source does not provide accurate results for short time periods and in the case of vertical heat exchangers with large diameters, such as thermal piles (which also function as heat exchangers).

### 3.2 Standard Finite Line Source Model (FLS) [17]

Traditionally, heat transfer in the porous soil medium without groundwater flow is described by the heat conduction equation as follows [17] :

$$\rho c \frac{\delta T}{\delta t} - \nabla * (\lambda \nabla T) = 0 \quad (3.11)$$

where:

- ρ is the density of the soil [kg/m³],
- c is the specific heat capacity of the soil [J/kg·K],
- T is the temperature [°C or K],
- t is time [s],
- k is the thermal conductivity of the soil [W/m·K],
- Q is the internal heat source term [W/m³].

$$\rho c = n\rho_w c_w + (1-n)\rho_s c_s \quad (3.12)$$

$\lambda$ – Thermal conductivity [W/m·K]
$\rho c$ – Volumetric heat capacity of the porous medium
$\rho_s c_s$ – Weighted average of the solids in the aquifer medium
$\rho_w c_w$ – Weighted average of the water in the aquifer medium

The solution of the partial differential equation for heat transfer from a source in a porous medium with an initial uniform temperature $T_0$ is given by the relation:

$$\Delta T(x,y,z,t) = \frac{Q}{4\pi\lambda r} erfc\left[\frac{r}{\sqrt{4at}}\right] \quad (3.13)$$

The temperature difference in the borehole, ΔT=T0−T, where T0 is the initial uniform temperature and T is the local temperature, is related to the heat Q extracted or injected from the borehole. The thermal diffusivity is defined as ($a=\frac{\lambda}{\rho c}$), where λ is the thermal conductivity and ρc is the volumetric heat capacity of the porous medium. The distance $r = \sqrt{x^2 + y^2 + (z - z')^2}$ to the heat source, located along the z-axis at coordinates (0,0,z′)

The Finite Line Source (FLS) model can be expressed as follows (H.Y. Zeng, N.R. Diao, Z.H. Fang, 2002): [18], [19].

$$\Delta T_{FLS}(x,y,z,t)=\frac{q_L}{4\pi\lambda}\left[\int_0^H \frac{1}{r} erfc\frac{1}{\sqrt{4at}}dz' - \int_{-H}^0 \frac{1}{r} erfc\frac{r}{\sqrt{4at}}dz'\right] \quad (3.14)$$

## 4 Numerical Model

### 4.1 Standard Finite element numerical model

A three-dimensional numerical model of the energy pile was developed using COMSOL Multiphysics software (refer to Figure 3). The dimensions of the numerical model are 50 m x 50 m x 40 m. The boundary conditions of the model are such that the edges are constrained with sliding supports in the vertical direction, while the base of the model is anchored. Thermal boundary conditions were applied by thermally isolating the model boundaries, with the exception of the upper surface. The initial temperature of the pile and surrounding soil was set to 21.6°C, as determined from field measurements. For the clay and sand soils, the Mohr-Coulomb material model was employed, while a linear elastic material model was used for the thermal pile. The first of the five thermal cycles, as illustrated in Figure 2, was applied to the numerical model for thermal loading. The initial stress conditions are representative of the geostatic state.

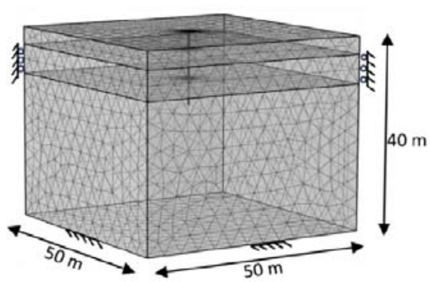


*Figure 4-1 Numerical model and boundary conditions*

## 5 Comparison of the field experiment and numerical model results

In the field experiment, the temperatures measured along the pile and the values calculated by the numerical model are presented for the first three days in Figure 4. Temperature and strain measurements along the pile were made using vibration wire strain gauge sensors, as shown in Figure 1. All values presented in the graphs are the averages of the readings obtained from these two sensors. There are positional differences in the pipe and sensor placements in the field due to manufacturing variations. The distance of the sensors from the center varies between 11.7 cm and 12.9 cm. Therefore, the numerical model results are provided for this range. The D1 and D2 values shown in Figure 4 represent the analysis results at distances of 11.7 cm and 12.9 cm from the center of the pile, respectively. As seen in Figure 4, the temperature values measured in the field and those calculated by the finite element numerical model are in good agreement.

The stresses generated by thermal loading are presented in Figure 5. The stress value obtained from the sensor located at a depth of approximately 8.7 m is higher than the value obtained from the numerical model. Apart from this exception, the stresses measured in the field are in good agreement with the values calculated by the numerical model.

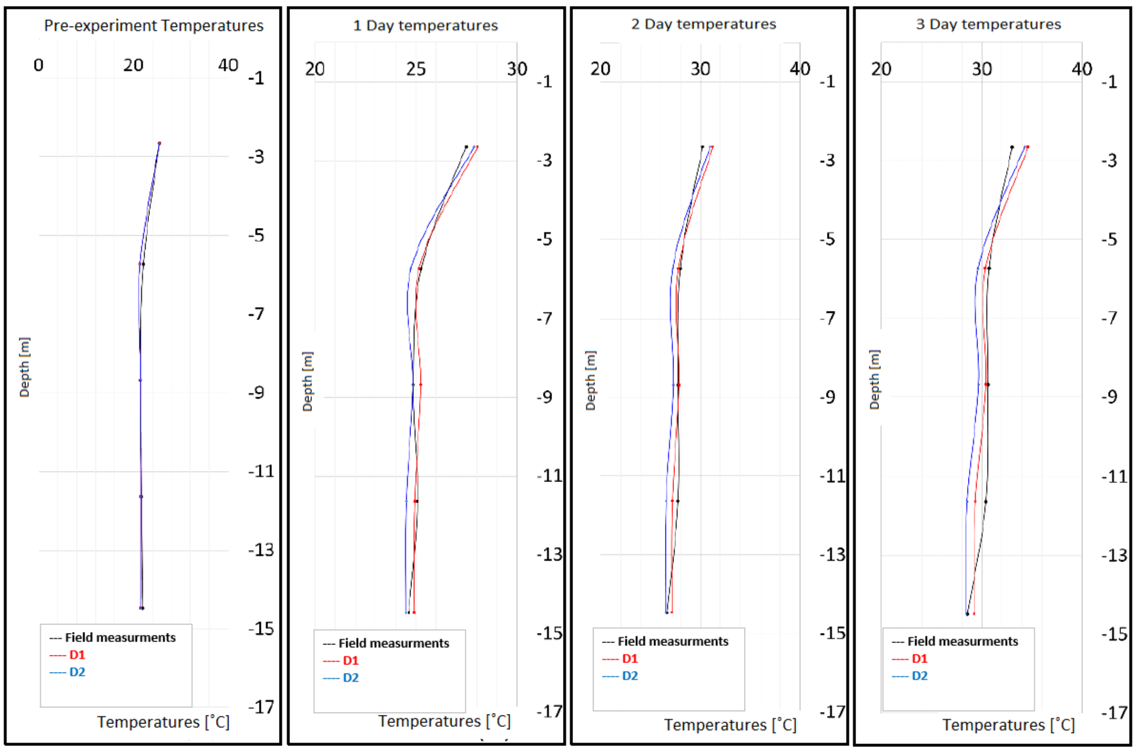


*Figure 5-1 Measured and Calculated Temperatures Along the Pile Before and During Thermal Loading*

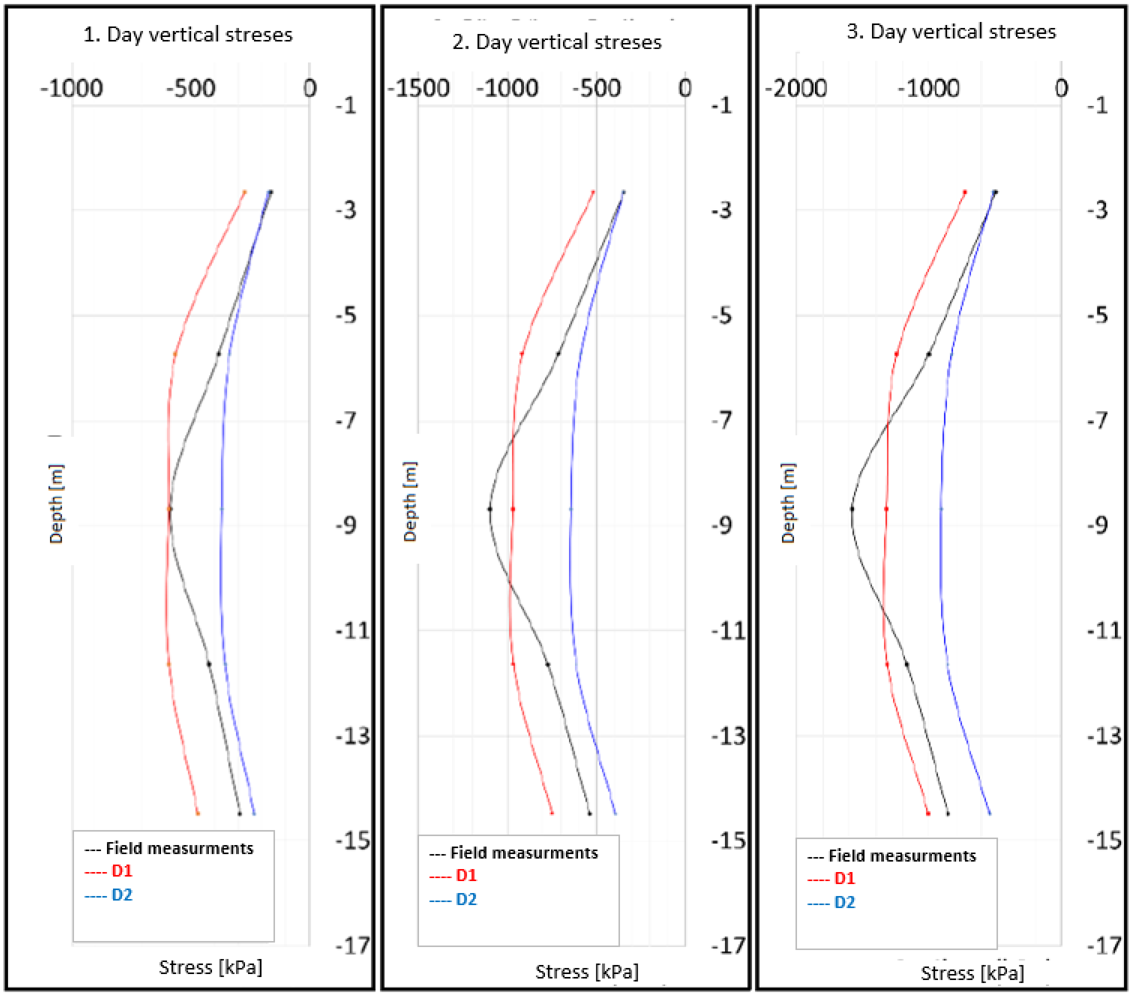


*Figure 5-2 Measured and calculated temperatures along the pile during thermal loading*

## 6 Conclusions

As a result of the numerical analyses conducted, the thermomechanical behavior of the pile under thermal effects was investigated. The temperatures and stresses measured along the pile in the field were compared with the results of the numerical model. The thermal fluid circulated through the pipes within the pile led to an increase in the pile's temperature. The temperature increases measured in the field were consistent with those calculated by the finite element numerical model. The temperature rise within the pile caused thermal expansion, which, depending on the boundary conditions of the pile, induced additional axial stresses along its length. Except for the sensor located at a depth of 8.7 m, the stress increases measured in the field due to thermal expansion were in agreement with those obtained from the numerical model. The discrepancy at this depth can be attributed to a change in sensor positioning during pile installation in the field

Important Considerations in the Numerical Modeling of Energy Piles: There are several important factors that must be taken into account when numerically modeling energy piles. The first is the definition of thermal boundary conditions, which must ensure that the surface temperatures of both the pile and the surrounding soil are consistent with those obtained from field experiments. Secondly, the positioning and installation of sensors in the field-tested pile is critical. Sensors should be placed on the reinforcement in such a way that their positions are not affected by external influences or the construction process. A third important consideration, particularly in water-saturated soils, is the need to account for the thermal properties of water, as it significantly influences heat transfer behavior.

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