Numerical Simulation of an Energy Pile Using Thermo-Hydro-Mechanical Coupling and a Visco-Hypoplastic Model

Xiaolong Ma[1], Gang Qiu[2], Jürgen Grabe[2]
[1]*DB ProjektBau GmbH, Hannover, Germany*
[2]*Institute of Geotechnical Engineering and Construction Management, Hamburg University of Technology Hamburg, Germany*
E-mail: xiaolong.ma@deutschebahn.com

ABSTRACT: Geothermal energy has been proven to be an economical renewable energy source and is applied all over the world. One of the efficient ways to use shallow geothermal energy is the thermal usage of piles. However, as temperature changes and the thermal expansion coefficients of concrete and soils are not the same, the interaction between them will be affected. In this article the thermal-hydro-mechanical (THM) behavior of an energy pile is simulated. The THM-coupling is implemented in the commercial software code Abaqus/Standard. The pore water pressure in the low permeability soils will be considered as they can have a considerable effect on the effective stress. A visco-hypoplastic soil model is used to reproduce the viscous behavior including creep, relaxation and rate dependency of fine grained soils. The calculated temperature development, the pile head settlement as well as the shaft resistance will be compared to results of a field test. Furthermore, a simplified concept will be introduced to understand the behavior of the shaft resistance and strains of energy piles due to mechanical and thermal loads.

KEY WORDS: thermal-hydro-mechanical coupling, energy pile, Abaqus, thermal loading, pore water pressure.

1. INTRODUCTION

Shallow geothermal energy systems use the energy, which is stored to depths up to 400 m in the earth. The relatively constant temperature of the underground to this depth offers the opportunity to heat and to cool buildings in an environmentally sound and cost-effective way. The heat transfer between the ground at depth and the building is usually achieved with either open or closed systems. In Germany, the open system is seldom used due to the possibility of groundwater contamination.

The most popular system is the borehole heat exchanger (closed system). Boreholes must be drilled into soil, which constitutes the largest part of the costs of a geothermal system. Another closed system is thermal-active foundations (Brandl, 2006). The original purpose of these elements is to fulfill the engineering design requirements. The extra costs to use them as soil heat exchangers are relatively low, which makes the geothermal system cost-effective. The energy pile is one of the most frequently used geothermal foundations.

Energy piles are usually designed according to static and dynamic requirements. Therefore, the main task of an energy pile is to withstand the loading from construction. The thermal usage should not reduce the overall bearing capacity of the foundations.

First investigation of the influence of thermal usage on the pile bearing capacity took place in Austria (Peron et al., 1999). In order to ensure the stability of energy piles on a slope, field tests were carried out in the investigation. Further measurements and numerical simulations can be found in Ennigkeit (2002), Laloui et al. (2006) and Bourne-Webb et al. (2009).

In sandy soils, temperature changes result only in thermal expansion, while in cohesive soils the stiffness can also be affected. Thermo-mechanical models to describe the behavior of clay under thermal loading were developed by several authors over the last years. Hueckel and Borsetto (1990) have formulated a thermo-elasto-plastic behavior and implemented it in the Cam-Clay-model. This model was then extended by other authors (Cui, et al., 2000, Graham, 2001, Abuel-Naga, 2007). Laloui and Cekerevac (2003) presented a thermo-plastic model with thermal evolution of the pre-consolidation stress.

In this paper, the authors investigate the behavior of energy pile systems using numerical simulation under considering of the non-uniform temperature change, different thermal expansion coefficients of pile/soil and visco-hypoplasticity. Furthermore, as soil is a porous medium consisting of two or three material phases (solid, air and fluid phases), thermo-hydro-mechanical (THM) coupling is regarded in the simulation.

The THM-coupling is implemented in the commercial software code Abaqus/Standard. The pore water pressure in the low permeability soils is considered as they can have a considerable effect on the effective stress. A visco-hypoplastic soil model without stiffness change due to temperature variation is used to reproduce the viscous behavior including creep, relaxation and rate dependency of fine grained soils. The calculated temperature development, the pile head settlement as well as the shaft resistance is compared to results of a field test, which was carried out at the Lambeth College. Furthermore, a simplified concept is introduced to understand the behavior of the shaft resistance and strains of energy piles due to mechanical and thermal loads.

2. PILE UNDER THERMAL AND STATIC LOADING

Bourne-Webb et al. (2009) have described the behavior of an energy pile under thermal static loading using a simplified concept. In this paper, an extended model of such a system will be introduced. Pile compression will be defined as positive. It is assumed that the axial loading is only carried by the shaft friction and that the pile head and toe can move freely under the thermal load. The shaft friction and pile strain due to static and thermal loading can be described as follows:

- Under solely static loading alone: the loading is carried by shaft friction, Figure 1, SS. The shaft friction and pile strain are positive (SF)
- When the pile is cooled, the pile contracts (positive strain, Figure 1, CS). Under the assumption that the pile head and toe can move freely, the maximum strain occurs in the middle of the pile and decreases to zero to the two ends. In the upper part of the pile, shaft friction is negative and in the lower part is positive (CF).
- When the pile is loaded statically (pressure) and thermally (cooling), both effects will be added (Figure 1, SCS, SCF). The shaft friction in the upper part increases and in the lower part decreases.
- During heating the pile expands (Figure 1, HD, HF).
- The resulting strain and shaft friction due to static (pressure) and thermal (heating) loading are shown in Figure 1, SHS and SHF.

To simulate the behavior of the pile and the surrounding soils under static and thermal loading, the thermo-hydro-mechanical coupling is required. According to the conservation laws (mass conservation, energy conservation, momentum conservation), a physical parameter of an isolated system will remain constant over time. The sum of the sources and all currents through the boundary $\partial\Omega$ is equal the change of the parameter in the system Ω.

3. NUMERICAL SIMULATION

3.1 System description

A numerical simulation of the energy pile test carried out at the Lambeth College will be presented and the results will be compared with the field test. The tested energy pile has a length of 23 m. The pile is 610 mm in diameter over the first 5 meters and 550 mm at greater depth. Three U-loops of heat transfer tubes with a diameter of 32 mm are installed in the pile. The pile is loaded under thermal and static loading. The loading history is listed in Table 1.

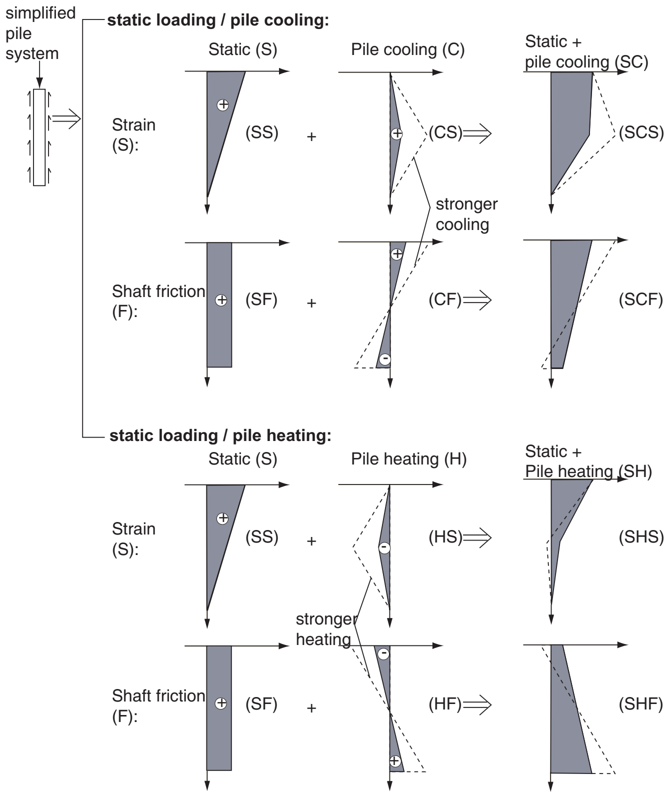

Figure 1 Pile strain and shaft friction due to static and thermal loading

Table 1 Loading history of the energy pile test at the Lambeth College (Bourne-Webb et al. 2009)

Stage	Days	Activity
1	1	1st. static loading of 1800 kN
2	2-3	unloading
3	4-47	2nd. static loading of 1200 kN
4	4-33	1st. pile cooling, inlet temperature -6°C
5	34	1st. pile heating, inlet temperature +40°C
6	35-36	Power failure
7	37-43	Continuation of the 1. Pile heating
8	44	2nd. pile cooling, inlet temperature -6°C
9	45	2nd. pile heating, inlet temperature 40°C
10	46-49	3rd. pile cooling, inlet temperature -6°C
11	48	3rd. static loading of 3600 kN
12	49	unloading

3.2 Model development

The test pile is simulated using the commercial code Abaqus/Standard 6.10 with thermal-hydro-mechanical coupling. The first 4 meters of the soil consists mainly of sand and is simulated using an elastic-ideal plastic material obeying Drucker-Prager yield criterion. A visco-hypoplastic model is used to describe the underlying London Clay. Both oedometer tests and CU tri-axial tests have been carried out by Masin (2004) to determine the soil properties of the London clay. Based on the lab tests, the visco-hypoplastic parameters are determined and shown in Table 2. The numerical single element tests are compared with the results from oedometric and tri-axial tests in Figure 2. The calculated results of an oedometric test and a CU-test using the parameters in Table 2 shows very good agreement with the test data. The pile is simplified to an axis-symmetric model as shown in Figure 3. The system is considered to be quasi-static.

Table 2 Visco-hypoplastic parameters for London Clay

Parameter			Value
Void ratio for p = 100 kPa	e_{100}	[-]	0.941
Compression index after Butterfield, 1979	λ	[-]	0.125
Swelling index after Butterfield, 1979	κ	[-]	0.02
Shape of Redulic surface	β_R	[-]	0.85
Leinenkugel's index of viscosity	I_v	[-]	0.031
Reference creep rate	D_r	[1/s]	$1 \cdot 10^{-7}$
Friction angle	φ_c	[°]	18
Stiffness multiplier	m_T	[-]	2.0
Stiffness multiplier	m_R	[-]	5.0
Stiffness elastic strain range	R	[-]	$1 \cdot 10^{-4}$
Stiffness parameter	β_r	[-]	0.5
Stiffness parameter	χ	[-]	1.0

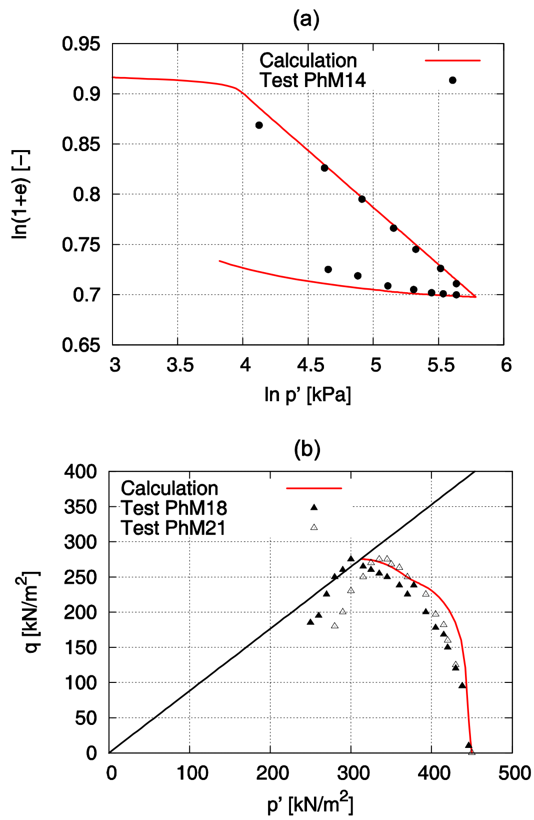

Figure 2 Comparison of the calculated element test of (a) an oedometer test and (b) a CU-test for London clay with test datas from Masin (2004)

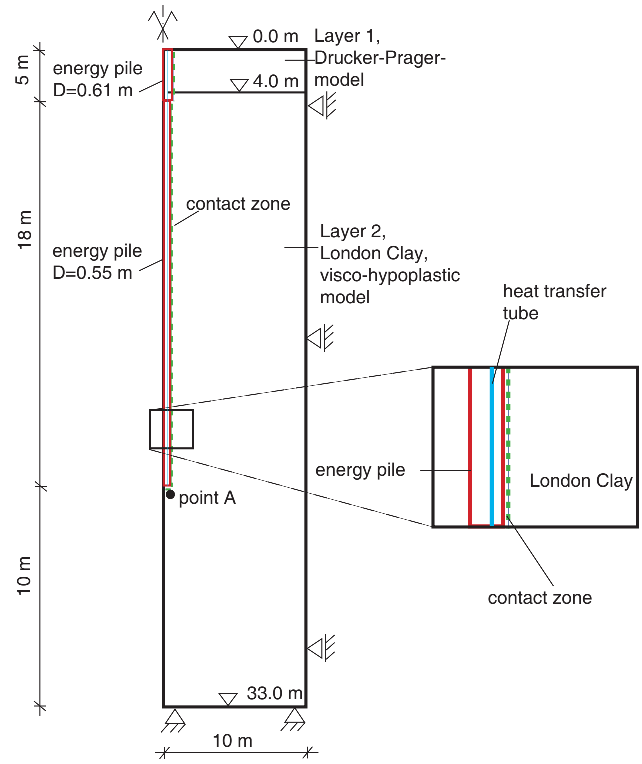

Figure 3 Simplified 2D axis-symmetric FE-model of the energy pile

The interaction between the pile and the soils is simulated using the Abaqus implemented "master-slave" contact formulation. The calculation of the contact stress is carried out using the "penalty" formulation. In the contact area only pressure can be transferred. For the tangential stress τ, the Coulomb theory is used. The wall friction angle δ is equal to the soil friction angle φ'. This assumption is justified by the pile roughness (Reul 2000, Ouyang et al. 2011). The heat transfer in the contact zone is described with the "gap-conductance" principle (Dassault Systèmes, 2010).

The FE-mesh of the energy pile and the soils is shown in Figure 4. The mesh is chosen to become coarser with increasing distance from the pile as loading effects decrease with increasing distance, since the effect of the loading decreases in this direction. The original stress field of the model is determined by the soil weight and the over consolidation ratio (OCR). The relationship of the at-rest earth pressure for normally consolidated soil K_0 (NC) and for over consolidated soil K_0(OC) can be calculated after Mayne and Kulhawy (1982).

3.3 Parameters selected

The pile is simulated using a linear-elastic model. London-Clay has a viscous character and is modeled using a visco-hypoplastic model (Niemunis 2003, Qiu and Grabe 2011). The visco-hypoplastic model is able to reproduce the viscous behavior including creep, relaxation and rate dependency of fine grained soils. The change of stiffness due to temperature variation is jet not implemented in this model and is now in the development. The OCR is taken to be 5 for London Clay after Mayne and Kulhawy (1982). The heat expansion coefficient is assumed to be equal to $1{\cdot}10^{-5}$ m/m/K according to Erbert et al. (1965). The chosen thermal and mechanical parameters are summarized in Table 3.

The temperature of the soil in the energy pile test is sunken to below the freezing point of pore water. It's assumed, that the permeability of frozen soil amounts $1{\cdot}10^{-12}$ m/s. The abrupt decrease of soil permeability by changing the temperature from 1°C to 0°C indicates the freezing process.

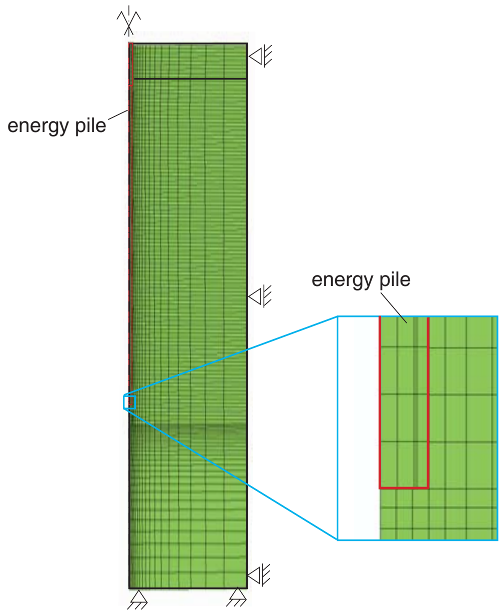

Figure 4 Finite element mesh to investigate the energy pile with the axis-symmetric model

Table 3 Summary of the parameters for pile and soils

Parameter	**Pile**	**Layer 1**	**Layer 2**	**Water**
Young's modulus, E [MPa]	$4{\cdot}10^4$	36	s. Table 2	-
Unit weight (buoyant unit weight), $\gamma(\gamma')$ [kN/m³]	25	18(8)	16 (6)	10
Heat expansion coefficient of soil, α [m/m/K]	$8.5{\cdot}10^{-6}$	$1{\cdot}10^{-5}$	$1{\cdot}10^{-5}$	-0.1°C: $5.1{\cdot}10^{-5}$ 0°C: $5.1{\cdot}10^{-5}$ 1°C: $-1.7{\cdot}10^{-5}$ 4°C: $0.0{\cdot}10^{-5}$ 20°C: $6.9{\cdot}10^{-5}$
Permeability, k [m/s]	-	0°C: $1{\cdot}10^{-12}$ 1°C: $1{\cdot}10^{-4}$	0°C: $1{\cdot}10^{-12}$ 1°C: $1{\cdot}10^{-9}$	-
Heat conductivity, λ [W/(m·K)]	2	2	1.5	-0.1°C: 2.2 0°C: 0.57 10°C: 0.6
Specific heat capacity, c [kJ/(m³·K)]	1800	2300	2300	-0.1°C: 2060 0°C: 4200 10°C: 4200

4. RESULTS

The calculated pile-head displacement throughout test period agrees very well with the observed values (Figure 5). Under the first static loading of 1800 kN the pile head settles about 3.3 mm. After the unloading and reloading to 1200 kN, the displacement is about 2.5 mm. The first pile cooling causes an additional quick settlement of about 1 mm. The settlement increases with time due to the viscous character of the London Clay.

When heated, the pile-head uplifts quickly by about 2 mm. Under the final loading of 3600 kN the pile-head settles by a total amount of about 10.5 mm. The strain development of the pile can be reproduced numerically (Figure 6, left). The shaft friction of the pile is shown in Figure 6 (right). If the pile is cooled, the shaft friction in the upper part of the pile increases, while it decreases in the lower part. During the pile heating, the opposite effect can be observed. In the upper 4 meters, the shaft friction is reduced by such a high amount that negative shaft friction occurs.

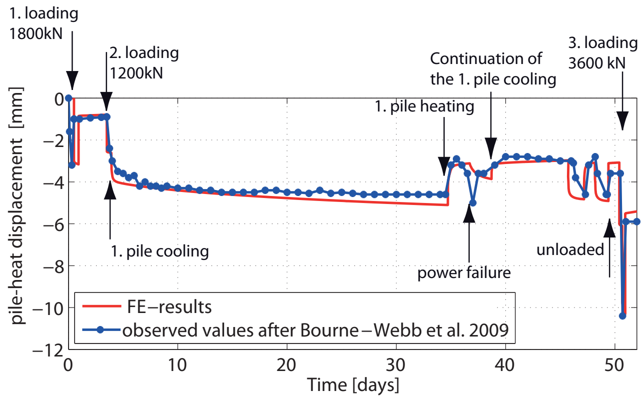

Figure 5 Calculated and measured pile-head displacement under mechanical and thermal loading

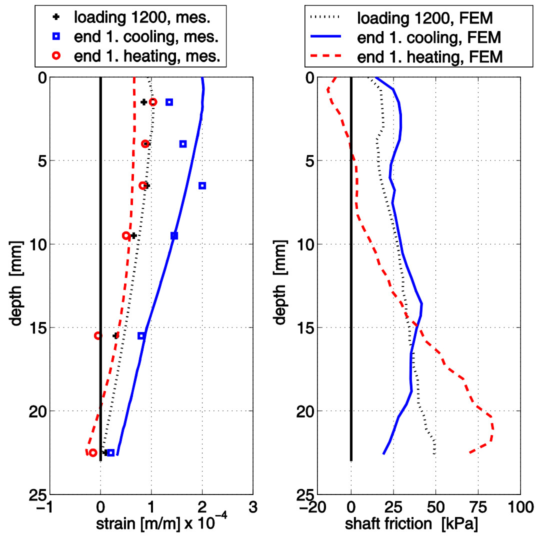

Figure 6 Calculated and measured strain (left) and shaft resistance (right) of the energy pile after reloading to 1200 kN, after the 1st. pile cooling and the 1st. pile heating

Figure 7 shows the calculated change in shaft friction of the pile as a result of the thermal force. Through the applied thermal loading after Bourne-Webb et al. (2009), a change of the shaft friction can be observed up to 40 kPa. The simplified distribution of shaft friction change presented in Figure 1 due to thermal loading agrees with the numerical results.

With the coupled thermo-hydro-mechanical simulation, the pore water pressure, which plays an important role for soils with low permeability (Graham et al. 2001), can be calculated. The calculated time dependent behavior of temperature, pore water pressure and effective vertical stress under static and thermal loads as well as under only static loads at point A (see to Figure 3) are shown in Figure 7.

When the pile is just loaded statically on the 3rd day (2nd Loading), the change of total stress is in the beginning partially carried by the pore water. This causes excess pore water pressures at this point, which decrease over time. As a result, the effective stress in the soils increases over the time. This would be accepted as normal pile behavior.

When the pile is thermally loaded, the pore water pressure and the effective stress change. Directly after activation of the first pile cooling, the pile contracts and the pile toe moves upwards. This causes a quick change of the pile end bearing and an unloading of the surrounding soils. The pore water pressure is reduced by about 90 kPa and reaches the hydrostatic level. It remains almost constant during the pile cooling. The effective stress is increased by 20 kPa due to the pile cooling and increases over the time. The increase can be explained by increasing of the pile-head displacement. With growing pile-head displacement, the soil surrounding the pile toe will be loaded increasingly. This results in a rise of the total stress. Since the increase occurs very slowly, no excess pore water over pressure develops. The increase of the total stress is hence carried by the effective stress of the soils.

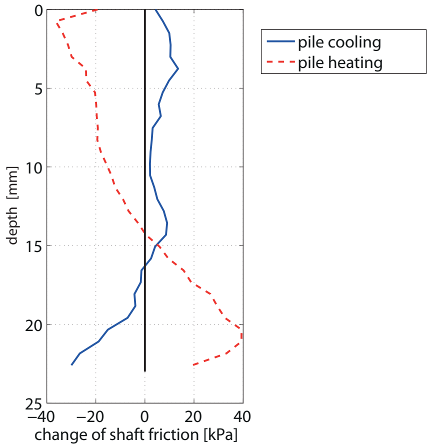

Figure 7 Resulting changes of pile shaft resistance due to thermal loads

When the pile is heated, the pile extends. Pore water pressure at the point A rises immediately by 40 kPa and degrades over the time, while the effective stress increases. The thermal loading of the pile also causes a temperature change in the soil. This change is delayed because of the relative slow heat conduction. The temperature at point A is reduced by up to 3°C during the pile cooling and raised up to 26°C during the pile heating. At the end of the test, the temperature at this point is changed by -12°C. This temperature change causes thermal expansion of the soils. This effect was researched by Ma et al. (2011). The thermal expansion of the soils is very small compared to the pile and can be hardly observed in Figure 8.

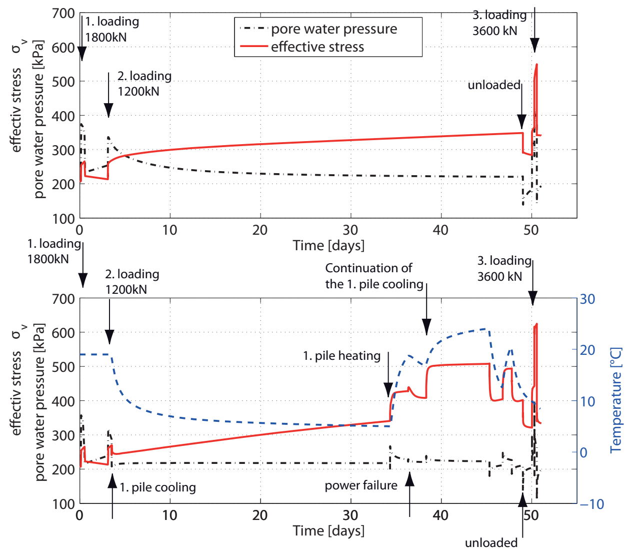

Figure 8 Calculated time dependent behavior of temperature, pore water pressure and effective vertical stress under static and thermal loads (below) as well as under only static loads (above)

5. CONCLUSIONS

With the usage of a visco-hypoplastic soil constitutive and the coupled model it is possible, to simulate the thermo-hydro-mechanical behavior of an energy pile. The calculated pile-head displacement and pile strain agree for the most part with observed values. The thermal activation of the pile causes changes of strain and stress. Under the simulated conditions, the pile shaft friction can be changed by up to 40 kPa.

The behavior of an energy pile under thermal and static loading can be explained by the in this article presented system, which is in accordance with the numerical results. It can be recognized from the simulations that a rapid change of stress in the soil will in the beginning be partially carried by the pore water and over time the stress will be transferred to the granular skeleton. Therefore, it is fundamental to consider pore water pressure to understand the interaction of energy pile and soils.

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