Energy Pile Simulation – an Application of THM-Modeling

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Abstract: Energy piles, i.e. heat exchangers located within the foundation piles of buildings, are used for heating or cooling purposes. Although the absolute values of deformations and temperature gradients are low or moderate, the entire setting may be influenced by thermo-hydro-mechanical couplings. The fluctuating thermal regime may affect the deformation due to mechanical loading. Groundwater flow changes the temperature distribution around the piles and due to pore pressure may also have an effect on the mechanical state of the sub-surface material. We show, that such process interactions can be investigated by a coupled numerical approach.

Keywords: Energy pile, THM, solid mechanics, poroelastics, coupled modeling

1. Introduction

Geothermal energy is a renewable, locally available, low-carbon energy (Ashby *et al.* 2012). In comparison to other alternative energies geothermics is independent of season, weather and climate and thus is available permanently. Depending on the depth below the surface, where the installation is placed, one may distinguish between near-surface and deep utilization of geothermal energy. Shallow, near surface systems usually do not reach depth of more than 100 m, while deep geothermal systems utilize reservoirs in several 1000 m depth. Shallow geothermics can be used for heating and cooling, and for both heating and cooling (Stauffer *et al.* 2013, Laloui & di Donna 2013).

Technically one may distinguish between open and closed systems. In closed systems, borehole heat exchangers for example, a fluid is circulating in closed pipe systems, and only conductive heat transfer from the ground is utilized. Most typical is the borehole heat exchanger (BHE) (Holzbecher & Räuschel 2014). In contrast open systems use the heat of the subsurface water directly.

Here we deal with an energy pile installation, which, among others, is one technology for shallow near-surface closed loop geothermics (Laloui *et al.* 2006, Ma *et al.* 2011, Bourne-Webb *et al.* 2012, Amatya *et al.* 2012, Dupray *et al.* 2014). A heat exchanger, that can be of different geometric design, is included in or adjusted to the foundation of a building, most often to a pile. Figure 1 shows an example with a single U-pipe. Usually several of such piles are combined to a system.

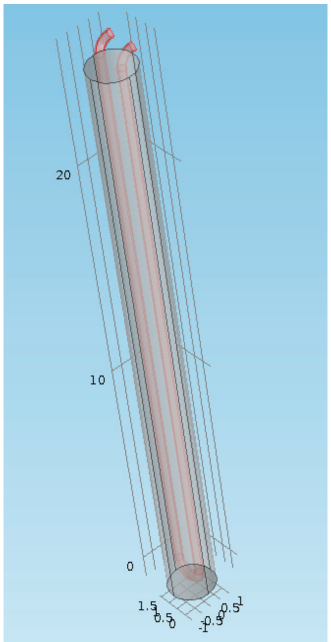

Figure 1: An example of a single energy pile; concrete (gray) and heat exchanger pipe (red), single U-turn type

According to Laloui *et al.* (2006) the advantages of energy piles lie in the reduction of 50% CO2 for new buildings due to (a), of primary energy consumption (b), and of transport energy.

We present a modelling approach in which thermal, hydraulic and mechanical processes are coupled. Pore pressure is a variable, which determines both hydraulics and poroelastics. The hydraulic regime has an influence on heat transport processes. Vice versa the temperature distribution affects hydraulics via fluid density and viscosity and affects the mechanics due to thermal expansion or contraction. Various possibly relevant couplings are studied in the following.

2. Differential Equations and Couplings

In the model we treat the geomechanical, the thermal and the hydraulic regimes within the pile and the adjacent ground. We describe the differential equations for the single processes first and introduce the coupling terms thereafter.

The stress regime within the pile and in the ground and the corresponding deformations are described by the mechanical equations

$$-\nabla\cdot\boldsymbol{\sigma}=\mathbf{F}_V \tag{1}$$

$$\boldsymbol{\sigma}-\boldsymbol{\sigma}_0=\mathbf{C}:\left(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}_0\right) \tag{2}$$

which is a system of differential equations in which the elements of the deformation vector $\mathbf{u}$ are the dependent variables. Further variables are: stress tensor $\boldsymbol{\sigma}$, volume force vector $\mathbf{F}_V$ and stiffness tensor $\mathbf{C}$. The strain tensor $\boldsymbol{\varepsilon}$ is defined by

$$\boldsymbol{\varepsilon}=\tfrac{1}{2}\left(\left(\nabla\mathbf{u}\right)^T+\nabla\mathbf{u}\right) \tag{3}$$

Equation (2) describes the stress-strain relationship in general. In the application below we deal with elastic media only. Subscript 0 denotes initial or reference values.

The thermal regime is described by the equation for heat conduction:

$$\left(\rho C\right)\frac{\partial T}{\partial t}=-\nabla\cdot k_T\nabla T \tag{4}$$

which is a differential equation for temperature T as dependent variable. Other parameters and variables are: specific heat capacity of the fluid-solid system (ρC), and its thermal conductivity k_T. Equation (4) is derived from the energy conservation principle.

The temperature distribution in the subsurface leads to thermal expansion or contraction, depending on the direction of temperature change. In the mathematical description this is taken into account by an extension of the strain tensor. Thus equation (2) has to be modified to:

$$\boldsymbol{\sigma}-\boldsymbol{\sigma}_0=\mathbf{C}:\left(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}_0-{}^{\beta}\!/_{3}\left(T-T_0\right)\mathbf{I}\right) \tag{5}$$

$\mathbf{I}$ denotes the unit matrix. The coupling with the temperature model is given by the thermal expansion coefficient β. The deformation of the model region has an effect on the thermal regime vice versa.

The hydraulic conditions within the ground are described by:

$$\rho S\frac{\partial p}{\partial t}+\nabla\cdot\left(\rho\mathbf{q}\right)=Q \tag{6}$$

$$\mathbf{q}=-\frac{k}{\mu}\nabla(p-\rho gz) \tag{7}$$

Equation (6) is a differential equation for hydraulic pressure p as dependent variable. Other variables and parameters are: Darcy velocity vector $\mathbf{q}$, fluid density ρ, permeability k, fluid dynamic viscosity μ, acceleration due to gravity g, storage parameter S, and fluid source/sink-term Q. Equation (7) is Darcy's Law and equation (6) is a formulation of the mass balance.

The pore pressure also affects the mechanical state of the system. In the mathematical description this is taken into account by another extension in the stress-strain equations (2) and (5) resp.:

$$\boldsymbol{\sigma}-\boldsymbol{\sigma}_0=\mathbf{C}:\left(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}_0-{}^{\beta}\!/_{3}\left(T-T_0\right)\mathbf{I}\right)-\alpha p\mathbf{I} \tag{8}$$

with Biot constant α. For high Biot constants there is a strong coupling, for low α there is a weak coupling. The backward link from mechanics to hydraulics is given by an additional term in the fluid equation (6):

$$\rho S\frac{\partial p}{\partial t}+\nabla\cdot\left(\rho\mathbf{q}\right)=Q-\rho\alpha\frac{\partial\varepsilon_V}{\partial t} \tag{9}$$

with volumetric strain ε_V, which includes the Biot constant, too.

Also hydraulics and geothermics are coupled. In the heat equation (4) we add a term describing heat convection

$$\left(\rho C\right)\frac{\partial T}{\partial t}+\nabla\cdot\left(\left(\rho C\right)_f T\mathbf{q}\right)=-\nabla\cdot k_T\nabla T \tag{10}$$

with heat capacity of fluid $(\rho C)_f$. The hydraulics affects heat transport via the velocity $\mathbf{q}$. Thus we extend the mathematical formulation of Salciarini *et al.* (2012). The backward coupling is given by the temperature dependency of the fluid parameters density ρ and viscosity μ (see for example: Holzbecher 1998).

For a complete description of the heat pile problem equations (1) with stress-strain relationship (8) together with (9) and (10) have to be solved simultaneously.

3. Model set-up

Model results presented here deal with the axi-symmetric 2D steady-state. We can do that as we focus on the pile and the surrounding ground, and neglect the details of the heat exchanger. For simplicity we also assume that there is no groundwater flow.

A generic model for a single pile and a homogeneous surrounding was published by Bodas Freitas *et al*. (2013). The 2D model region in an axi-symmetric coordinate system is shown in Figure 2. The upper inner sub-region (green) represents the pile, while the remaining (blue) represents the ground.

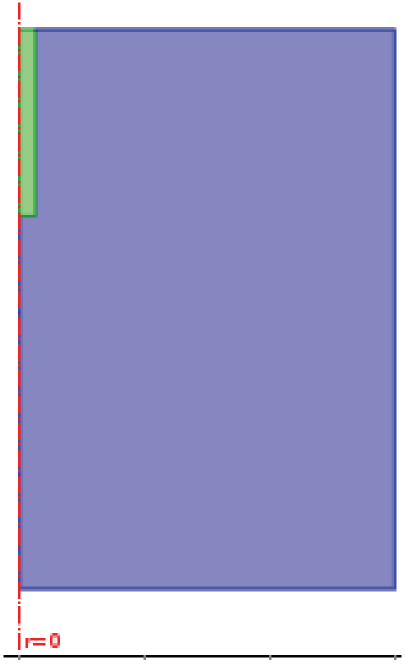

Figure 2: Geometry for single pile in axi-symmetric coordinate system, with sub-regions for pile (green) and ground (blue)

Concerning the stress-strain relation we assume linear elastic conditions and use the Young modulus and the Poisson ratio as parameters (see for example: Wang 2000). The boundary conditions are as follows:

- concerning mechanics: boundary load with specified pressure at top of the pile, symmetry condition on the left side, roller condition on the right side (no deformation in radial direction), and fixed constraint condition at the bottom
- concerning heat: symmetry condition on the left side, adiabatic condition on the top, high temperature at the outer pile boundaries, and low temperature at left side and bottom.

At the interface between the two sub-domains we require continuation. Thus there no additional conditions set.

The model was implemented using COMSOL Multiphysics (2014). Infante Sedano *et al.* (2012) were the first to publish modeling work concerning energy piles using that software. For the verification of our approach we compare output obtained using the solid mechanics approach in COMSOL Multiphysics with published results; see details in the verification section below.

We extend the verification model assuming the ground to be poroelastic and not solid. In this first application we neglect groundwater flow, i.e. we assume hydrostatic conditions. Thus we use the following boundary conditions for hydraulics: axi-symmetric at inner boundary, zero pressure at top and no flow at the outer and bottom boundaries. At the interface between pile and ground we require equal displacements on both sides. Thus we neglect any friction or sliding processes that may occur. Concerning stress we require the Terzaghi definition for effective stress, i.e.:

$$\boldsymbol{\sigma}_{pile} = \boldsymbol{\sigma}_{ground} - \alpha p \mathbf{I} \qquad (11)$$

Initial conditions are taken from a stationary model run for the ground only, in which we account for the gravity effect only. Thus we obtain a solution with zero pressure at the top and non-zero displacement. The effect of the couplings result in additional (positive or negative) displacements in relation to the initial case.

Concerning meshing, we chose free triangular elements with standard quadratic shape functions, with refined mesh within the pile model region. Additionally there was refinement in the solid and porous regions in the vicinity of the four corners of the rectangular pile region. Altogether the model has 5440 elements, which corresponds to 36790 degrees of freedom.

The input parameters for the extended model are listed in Table 1. For the fluid we use water properties in dependence of temperature. The output is shown in the results section below.

4. Verification

For the verification of the approach we compared output from our model with published results. Bodas Freitas *et al.* (2013) gave a description and model of a typical set-up of energy piles, concerning the response of energy foundations under thermo-mechanical loading. In their publication Bodas Freitas *et al.* use ADINA (2014) and the TM coupling, they treat the ground as solid medium and thus neglect pore pressure.

Parameter	**Value/Unit**
Model region length, radial	60 m
Model region length, vertical	90 m
Young modulus, concrete	30 GPa
Young modulus, ground	10 MPa
Poisson ratio	0.3
Permeability	10^{-14} m^2
Porosity	0.25
Biot parameter	0.9
Load	6 MPa
Thermal expansion coefficient, concrete	$3\cdot10^{-5}$ 1/°K
Thermal expansion coefficient, ground	$7.5\cdot10^{-5}$ 1/°K
Thermal conductivity, concrete	2.33 W/m/°K
Thermal conductivity, ground	2.22 W/m/°K
Heat capacity, concrete	$1.95\cdot10^{6}$ J/m^3/°K
Heat capacity, ground	$1.5\cdot10^{6}$ J/m^3/°K
Heat pile temperature	60 °C
Background temperature	10 °C
Fluid compressibility	4.4 10^{-14} 1/Pa

Table 1: Model parameter values

As the effect from hydraulics can be neglected in this comparison, solid mechanics and heat transfer are chosen as physics modes in the COMSOL model. The outcome of our model is shown in Figure 3, for changes due to thermal stress: of axial stress along the pile and of interface shear along the interface.

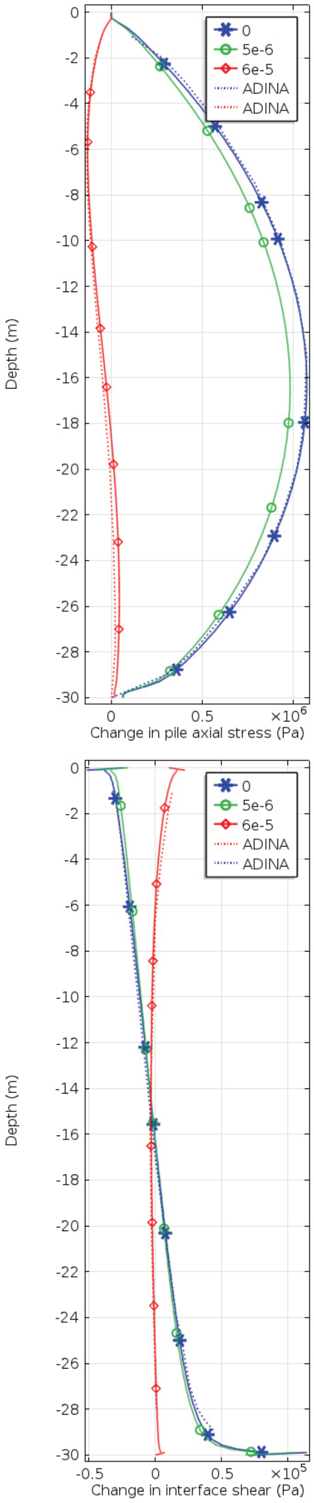

Figure 3: Change in pile axial stress (top) and in interface shear (bottom) for the verification problem; due to consideration of thermal expansion; in dependence of ground thermal expansion factor β_{soil}.

The outcome of our model fits well with the published results obtained using ADINA software (2014) by Bodas Freitas *et al.* (2013). Small deviations may be explained due to the differences of numerical approaches.

5. Results

In the extended model, in which solid and poroelastic materials are connected, several modifications became necessary. In contrast to the pure solid mechanics approach it is crucial to take gravity effects into account, which becomes relevant in the last term of equation (8). Results for the extended model are shown here.

In particular we focus on the relevance of several coupling approaches. A series of runs was started in order to check the influence of various model couplings. We started with an initial run, in which the soil displacement under the influence of gravity is studied. The pile is not considered in that model, in which we obtain a consolidation of the ground surface of 2.5 m. All further results have to be related to that reference value. The pile is included in the model by connecting the pile domain and the ground domain at the interface. Under loading this leads to a deformation of 28.5 cm at the top of the pile and 19.3 mm at the bottom. The maximum deformation of the ground is smaller than in the reference situation, only 2.44 m.

Step by step we take several more couplings into account. The initialization is performed for the ground only, modeled in poroelastics mode, with roller boundary condition on the interface between pile and ground and free deformation of horizontal boundaries except from the base. In a next step we couple the pile, modeled in solid mechanics mode, and the ground. In addition a load of 6 MPa is applied on the top of the pile. In the next step we take water compressibility into account. In a further step the coupling with temperature comes into play. We consider water viscosity and density as temperature dependent and thus have a back-coupling from the thermal regime on the mechanics of the system. Finally we consider thermal expansion for pile and ground.

Typical output results are shown in Figures 4 and 5, which depict distributions of temperature and vertical displacement in a 3D view. These pictures were obtained using all couplings, except thermal stress in the porous medium.

In Table 2 all results concerning deformations of pile and ground are summarized. The pile sinks 27 cm deep into the ground. As a result in the direct vicinity of the pile the ground comes up. Changes in displacement (Δ) values have to be computed in relation to the initial state. Thus pile changes are negative (deformation downward), while ground changes are positive (deformation upward). Deformation is mainly in the vertical direction. Thus values in the table for total displacement correspond very much with the vertical displacement results.

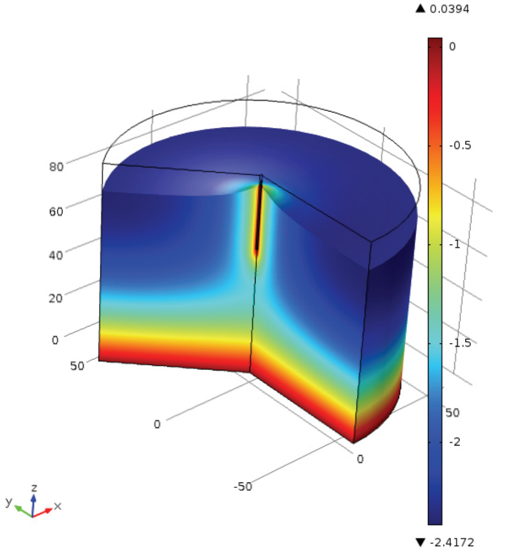

Figure 4: Temperature [°C] distribution [m] with heat coupling around a single energy pipe during heating; deformation exaggerated by factor 5

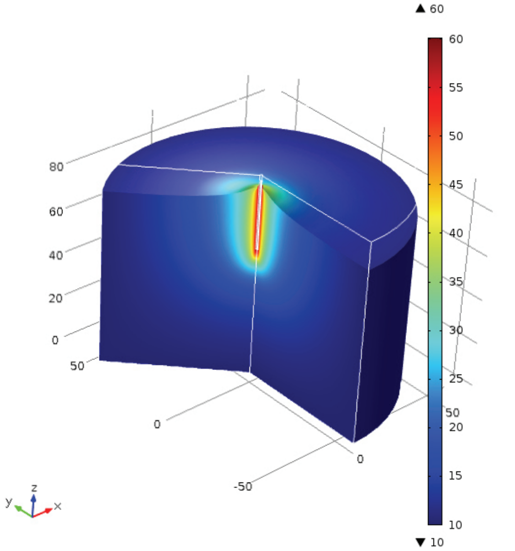

Figure 5: Vertical displacement [m] distribution around a single energy pipe during heating; coupled THM approach; deformation exaggerated by factor 5

The fluid is almost incompressible, and thus there is no effect to be seen, if water compressibility is taken into account. The temperature dependencies of fluid properties are small, but visible. It is mainly the viscosity, which changes by 36 % in the chosen temperature range, and which via hydraulic conductivity as parameter affects the pressure regime. As result of hydraulic parameter variations the penetration of the pile increases (by 0.1 mm in our study), while the consolidation of the soil decreases. For the pile thermal stress is of greater influence than the other couplings: compared to the reference it penetrates less (by 1 cm in our study) into the ground.

Max. displacement [m]	**Pile =-Δ-pile**	**Ground**	**Δ-ground**
Initial	0	2.5	0
Coupled interface	0.285	2.438	0.062
Water compressibility	0.285	2.438	0.062
Temperature-dependencies	0.283	2.421	0.079
Thermal stress	0.268	2.412	0.088

Table 2: Maximum deformation of pile and ground; with increasing complexity due to couplings;

Figure 6, where axial stress along the centerline of the pile is shown, highlights the importance of thermal coupling. Axial stresses almost double in this model if thermal expansion is taken into account. Comparison with Figure 3 also shows that the stress profile is quite different for the case with poroelastics coupling. The maximum stress can be observed near to the bottom of the pile. Also absolute values are by far bigger in the coupled case.

6. Conclusions

Using COMSOL Multiphysics a model concept is developed that enables the simulation of coupled mechanical, hydraulic, thermal processes, which may be relevant for energy piles. The concept can be utilized for 1D, 2D and 3D models in cartesian or axi-symmetric coordinates, for steady-state as well as for transient problems. Convective processes resulting from groundwater or seepage flow can be included in addition, which are neglected in this paper.

The concept was tested against literature data, which are available for the 2D steady state axi-symmetrical case and for the pure solid mechanical approach only.

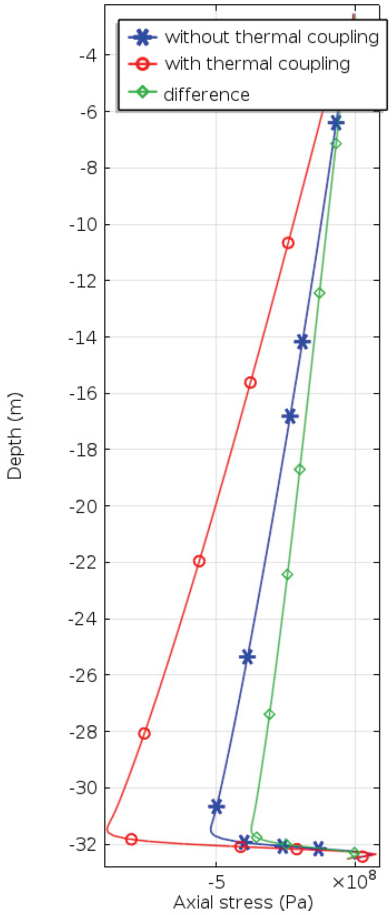

Figure 6: Axial stress on symmetry axis; simulations with and without thermal coupling, i.e. taking into account thermal stress; and difference

In fact the ground in the sub-surface hardly can be considered as a solid. Pile foundations are especially necessary in soft ground, which is often saturated by groundwater below a few meters under the ground surface.

Various couplings have to be considered. Thus modeling becomes rather complex. The solid mechanics of the pile has to be coupled with the poroelastics of the surrounding ground. Fluid properties may change due to changed temperatures. Thermal expansion or contraction have to be taken into account. In our approach groundwater flow can be considered, which was

not demonstrated here. Then the effect of the various couplings can be expected to be bigger.
The here presented results show that

- fluid compressibility can be neglected
- temperature dependent properties of the fluid are responsible for small changes
- thermal expansion plays a role, in particular for the pile

Finally the paper demonstrates how solid mechanics can be coupled with poroelastics, for which there are hardly any other references can be found hitherto. The major differences in results can the attributed to the assumption of a poroelastic ground. Moreover in this new model approach the dependencies on coupling parameters turn out to be higher than for the simplified assumption of a solid ground.
The new approach, presented here, is quite unique and has to be explored further.

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