Predicting Long-Term Operation of Energy Foundations Using a Fully Coupled Thermo-Hydro-Mechanical Model

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Abstract

An energy pile harvests geothermal energy to heat and cool a building by integrating ground heat exchanger (GHX) pipes into the building's deep foundation, and extracts heat from the ground in the winter to heat buildings and injects heat into the ground during the summer. In areas with moderate climates, the heating and cooling loads are relatively balanced; thus the long-term performance of the energy pile is sustainable. On the other hand, energy piles in warmer climates require more cooling such as in the southern US, or in large high-rise buildings, where internal heat generation requires a greater cooling capacity, excess heat will accumulate in the ground after each year of operation. After years of operating energy piles in imbalanced heat injection/extraction cycles, accumulated heat can increase the ground temperature, leading to potential decrease of energy piles' efficiencies, complex soil properties and volume change, as well as ground surface displacement. Unfortunately, long-term experimental data or analytical solutions are not available for a complete understanding of these problems and their effects.

This study aims to develop a 3D fully-coupled thermo-hydro-geomechanical model in COMSOL by integrating "Porous Media and Subsurface Flow", "Heat Transfer in Porous Media" and "Geomechanical" modules in COMSOL, to predict the system performance of GHX in a long term operation in terms of COP and exergy efficiency. The coupling of three modules will strongly rely on the inter-connected material properties of water and soil, such as thermal conductivity, specific heat capacity, thermal expansion coefficient and other related moduli, for example due to the strong effects from thermal conductivity of soil to GHX performance, the thermal conductivity of soil will be inputted as a function of water content, degree of saturation and temperature. The proposed numerical model will be used to analyze complex thermal-hydro-geomechanical responses of soil and a complete energy pile under heat accumulation from long-term operation of a cooling-dominated energy pile accounting for the effects of ground water movement. Furthermore, the stress, contact pressure and displacement of the energy pile caused by mechanical and thermal loading will also be studied. To verify the proposed 3D fully-coupled numerical model, the ATLAS III Boom Clay heating/cooling test model will be chosen and recreated. By comparing the data obtained by the model and the results documented in the paper, the model can be validated and improved. Validating the

model is a proof of concept to further develop a similar model measuring the change in moisture content in the soil from prolonged heat injection.

It is important to mention that in this study the convective heat transfer of water vapor has been neglected, therefore only liquid water convection will be considered. A future work will be to integrate the multiphase transition from liquid to vapor with the proposed model, in order to further reveal the complete thermo-hydro-geomechanical effects to the performance of the prolonged heat injection of GHX.

Introduction

In 2017, approximately 11% of total energy use in the United States was used for the heating and cooling of residential and commercial buildings. To reduce the cost of energy and move away from fossil fuel dependence, municipalities such as that of New York City require the implementation of energy foundations and ground heat exchange (GHX) systems on new projects. Despite the ambient temperature changing depending on climate and location, temperature below ground remains consistent throughout the year, and energy foundations use this temperature difference to extract heat from the soil into a building or inject the heat from the building into the soil. However, little is known about the long term effect this alternative energy source has on the soil properties. While some regions with temperate weather experience a seasonal balance between heat injection and extraction, hotter regions such as South Texas would require a disproportional amount of heat injection throughout the years of operation.

Unfortunately, there is a gap in knowledge pertaining to the geomechanical effect of long term heat injection which could prove to be a challenge as problems with the soil wouldn't necessarily arise until decades after energy foundation installation. Because of this, it is imperative to design a numerical model that accurately predicts the change in soil behavior over a longer period of time.

Initial Study

The ATLAS III is a large scale thermal injection test meant to measure the effect of geological disposal of heat emitting radioactive material. The original test was conducted in an underground research facility in Mol, Belgium from 2007-2008 using a stepwise heating cycle. The scope of the model is to measure the long term thermo-hydro-mechanical effects the heat injection has on Boom Clay, specifically pore water pressure (*pwp*) and total stress change. The model consists of a quarter cylinder of Boom Clay with a radius of 100m and a depth of 119m. At the center is an AISI 4340 Steel tube with an outer radius of .095m, an inner radius of .08m, and a depth of 19m from the ground surface. The mechanical model of the clay is an elastoplastic Isotopic Drucker-Prager Model.

COMSOL has the capability of utilizing a variety of physics and multiphysics couplings. In order to replicate the heat transfer, groundwater flow, and the solid mechanics throughout the geometry, Heat Transfer in Porous Media (*ht*), Darcy's Law (*dl*), and Solid Mechanics (*sm*) modules were used respectively. The heat rate of the tube was written as a piecewise function according to the heating cycle in the paper. *dl* and *sm* modules are used to measure the change heat injection has on soil properties such as pore water pressure and total stress.

The initial study found that as the temperature increased, the pore water pressure also increased and starts to reach a steady state after 60 days of stabilization. However as the heater undergoes a heating phase there is a temporary decease in pore water pressure followed by a steady increase. When the model begins the cooling phase, there is a temporary increase in pore water pressure followed by an immediate drop that slowly stabilizes back to the initial *pwp* after 160 days. The change in total stress as a result of increased heat injection follows a very similar pattern.

The total stress increases with stable heating, reaches a steady state after 60 days, and experiences a sudden drop during the increased heating cycles. When the cooling cycle begins, the total stress drops dramatically and reaches a steady state after 30 days.

Table 1 Heating and cooling cycle as a function of time in watts and days

Day no.	P(t)
0-4	$-25(t-4)^2+400$
4-49	400
49-54	$-10(t-54)^2+900$
54-120	900
120-125	$-10(t-25)^2+1400$
125-381	1400
381-945	0

Table 2 THM parameters

Mechanical Parameters			
Initial stress	σ	MPa	4.5
Elastic Modulus	E	MPa	300
Shear Modulus	G	MPa	133.3
Poisons ratio	*v*		.125
Cohesion	*c*	MPa	.3
Initial Friction angle	ϕ_0	°	5
Final Friction angle	ϕ_f	°	18
Dilation angle	Ψ	°	0
Hardening parameter	β_0		0
Thermal expansion coefficient	β_s	$°C^{-1}$	$1.0x10^{-5}$
Hydraulic Parameters			
Intrinsic permeability	*k*	m^2	$4x10^{-20}$
Initial PWP	*p*	MPa	2.25
Liquid compressibility coefficient	β	MPa^{-1}	$-3.4x\ 10^{-4}$
Liquid thermal expansion coefficient	α	$°C^{-1}$	$4.5x\ 10^{-4}$
Thermal Parameters			
Initial Temperature	T	°C	16.5
Solid phase specific heat	Cs	J/kg·K	740
Thermal conductivity	λ	W/m·K	1.35
Physical parameters			
Solid density	ρ_s	Kg/m^3	2682
Porosity	*n*		.39

Governing Equations

Heat transfer in porous media

Conductive heat transfer follows Fourier's Law:

$$\boldsymbol{i_c} = -\lambda \nabla T \tag{1}$$

Where $\boldsymbol{i_c}$ is the heat flux in W/m^2; lambda is the thermal conductivity of the soil and steel pipe in W/m·K and T is the temperature gradient in K/m.

Subsurface flow

$$q_l = -\frac{k}{\mu_l}(\nabla p_l - \rho_l \mathbf{g}) \qquad (2)$$

Where q_l is the liquid flow rate, k is the intrinsic permeability, μ_l is the dynamic viscosity, p_l is the liquid pressure, ρ_l is the liquid density, and **g** is the acceleration due to gravity.

The liquid viscosity is set as a function of temperature:

$$\mu_l(T) = 2.1 \times 10^{-12} \exp \frac{1808.5}{273.15+T} \qquad (3)$$

The liquid density is also set as a function of temperature and pore pressure:

$$\rho_l(T, p_l) = \rho_0 \cdot \exp(\beta(p_1 - p_0) + \alpha T) \qquad (4)$$

Where ρ_0 is the reference liquid density, β is the liquid compressibility, α is the liquid thermal expansion coefficient, and p_1 is the pore water pressure.

Geomechanics

The static equilibrium equation is used as inertial terms are neglected:

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = 0 \qquad (5)$$

Where **σ** is the total stress in Pa, and **b** is the body force.

The mechanical model used is isotropic non-associated elastoplastic constitutive law for calculating elastic deformation. The model uses Drucker-Prager yield criteria given by the following equation:

$$F = \sqrt{J_2} + \alpha I_1 + k \qquad (6)$$

Where J_2 is the second invariant of the Cauchy stress, I_1 is the first invariant of the Cauchy stress. α and β are material parameters defined as:

$$\alpha = \frac{2 sin\phi}{\sqrt{3}(3 - sin\phi)} \qquad (7)$$

$$k = \frac{2\sqrt{3} c cos\phi}{(3 - sin\phi)} \qquad (8)$$

to match the Mohr-Coulomb criterion where ϕ is the friction angle, and c is the cohesion in MPa.

Geometry

The model is an axisymmetric cylinder in the *z*, *r*, and *phi* plane. The model consists of a cylinder of Boom Clay and a hollow steel pipe at the center. The depth of the cylinder is 119 meters with a radius of 100 m. The steel pipe is bored at a depth of 19 m with an outer radius of .095 m and an inner radius of .08 m. The pipe is AISI 4340 steel found in the default materials list.

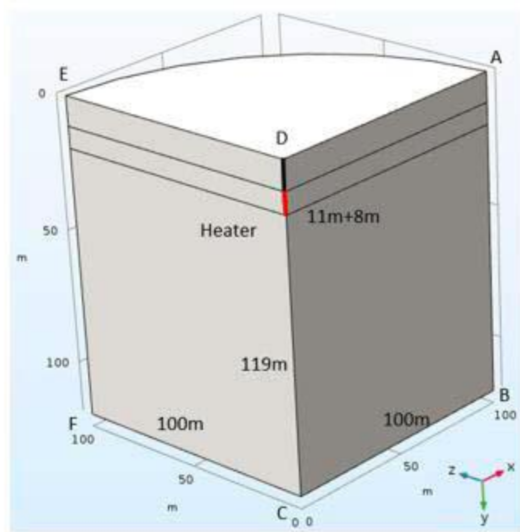

Fig. 1. Model Geometry

Mesh

The mesh is a free triangular consisting of 65687 elements, with a maximum element size of 1 m, a minimum of .001 m and a maximum element growth rate of 1.1. The model solves for 228390 degrees of freedom.

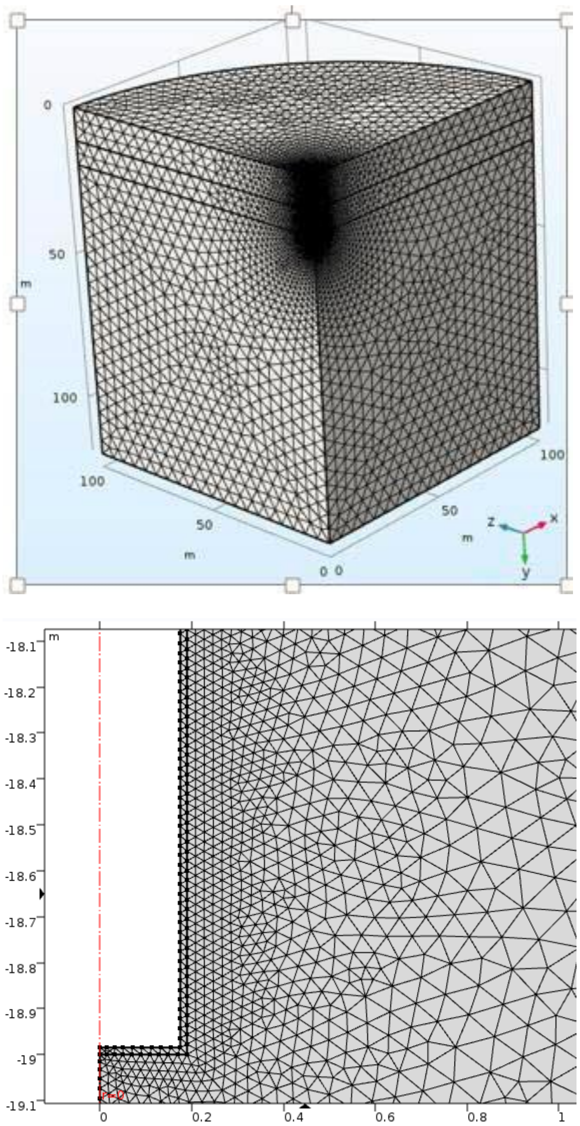

Fig. 2. Mesh

Boundary Condition

The model uses the Heat Transfer in Porous Media (*ht*) physics module to simulate a heater on the lower 11 meters of the steel tube's inner radius. Under the porous media node, the Boom Clay domain is selected with water as the media fluid. The steel pipe domain is selected under the Solid submodule. The *heat flux 1* submodule is set as a piecewise function of time shown in Table 1 and is set to the EF boundary. All other surfaces have a heat flux of 0. All domains have an initial temperature of 16.5°C. For all physics modules, the ED domain is the axis of rotation.

To simulate the subsurface fluid flow, the Darcy's Law physics module is used as the clay is fully saturated making this a single phase problem. Only the Boom Clay domain is selected for Darcy's Law with an initial pressure of 2.25 MPa. Edge domains BC and CD also have a constant pressure of 2.25 MPa. All remaining edge domains experience no flow. The domain fluid is water found in the default materials list.

The Solid Mechanics module is used to measure the effects of temperature on the soils mechanical behavior. Displacement in the z direction is fixed on the AB and CD domain, displacement in the r direction is fixed on the BC domain. The model was also constrained on the interface boundary between the clay and steel pipe domains.

Results and Discussion

Figure 3 shows the measured temperature from the initial study compared to the temperature acquired from the model. The model shows similar trends as the model undergoes increased heating as well as a similar steady state when the heater is shut off, however the model experiences its peak temperature almost 50 days before the initial study. The model also shows incremental temperature increases as much as 20 days before the initial study showed similar trends. This deviation in trend can be attributed to the assumption that the soil properties were homogenous throughout the domain. The clay in the initial study likely had impurities such as rocks or empty spaces throughout the soil medium while the model assumed the domain was homogenous.

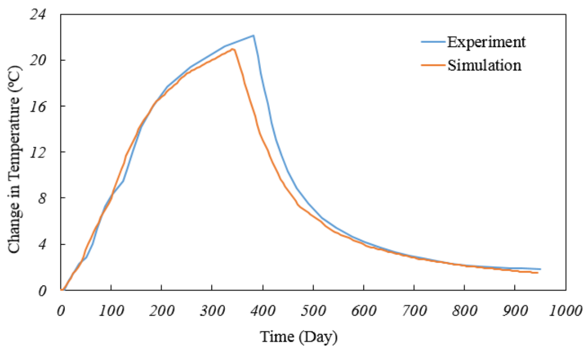

Fig. 7: Preliminary analysis: Comparison of our simulation results with ATLAS experimental data.

The initial study measured the change in pore water pressure and stress, however due to time constraints sufficient data could not be obtained. The model will be improved in the future to show the proper correlation between soil temperature and pore water pressure change as well as change in stress.

Conclusion

As the installation of energy foundations becomes a more common solution for mitigating electricity costs for domestic and commercial climate control, the effects of such technology in regions where heat is disproportionately injected is unknown. In order to accurately predict the soil behavior over a longer period of time, a finite element model was created using COMSOL Multiphysics using the boundary conditions and governing equations obtained from the ATLAS III Boom Clay research. The model was validated by comparing the results to the data of said study.

Based on the obtained data, it can be concluded that the model successfully depicts the heat transfer in Boom Clay. Discrepancies in the model are likely due to the non-homogenous nature of soil in that there were likely other elements present in the model that couldn't otherwise be assumed. Due to time constraints, the data depicting a change in pore water pressure and internal stresses could not be obtained but will be improved in the future.

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