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Numerical Simulation of a Shallow Geothermal Heating/Cooling System

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ABSTRACT: In recent years, sustainability concerns have played an increasingly important role in building design leading to rapid adoption of shallow geothermal heating/cooling systems. Understanding the heat exchange with the ground and associated thermo-hydro-mechanical processes involved is critical in order to ensure safe, efficient long-term performance of these geothermal systems. The current study considers heating/cooling loads for a large office building in Chicago, based on recommendations for typical DOE Commercial Benchmark Buildings and solves the coupled thermo-hydro-mechanical response of different soil types using the Code_Bright program (Olivella et al., 1996). The paper considers a closed-loop system comprising an array of 80m deep vertical heat exchangers that operates on a seasonal cycle with zero net heat transfer to the ground, and can supply a heating load up to 2440kW. Using estimated thermal properties of the Chicago clays, the THM analyses show negligible drift in the temperature within the surrounding ground for long-term operation of the geothermal system. However, when thermo-elastoplastic properties are considered, the analyses show that thermal cycling induces long-term settlements of the building.

INTRODUCTION

Shallow geothermal energy can provide heating and cooling to buildings, using significantly less energy compared to conventional systems and resulting in considerable carbon emission reductions. In recent years the use of shallow geothermal energy systems has become increasingly popular. Although ground response plays a key role for the effectiveness of the system, most of the current geothermal installations are designed by building services engineers, with very little information on effects of subsurface stratigraphy, hydrogeology and engineering properties of the subsurface soils. Preene and Powrie (2009) recommend that coupled heat and fluid flow models should be undertaken for the detailed assessment of large ground energy systems where site specific thermal properties of the soil are crucial for achieving reliable designs.

The purpose of this paper is to study the coupled thermo-hydro-mechanical response of the ground to the continuous operation of a vertical heat exchange system that was designed for a large office building in Chicago. The heating and cooling loads of the building were calculated using the DOE EnergyPlus simulation program for a large office building (12 stories high, with one basement level and a floor area of 43000 m^2) located in climate zone 5A (Chicago). The vertical heat exchange system was based on standard design methods proposed by Kavanaugh and Rafferty (1997) and was then modeled numerically in Code_Bright (Olivella et al., 1996), considering thermo-elastic and thermo-elastoplastic properties of the surrounding soils. The analyses enable first order predictions of the long-term ground response based on limited available information of thermal properties of the clays.
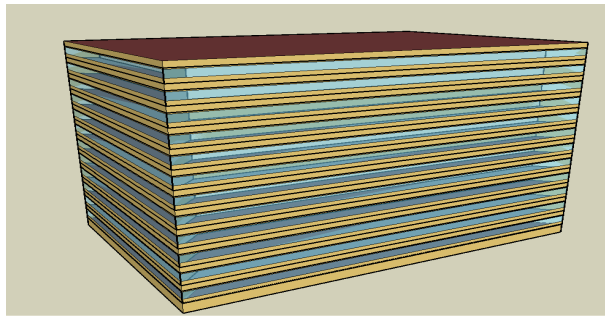
a) Large commercial office building simulated by EnergyPlus for climate zone 5A
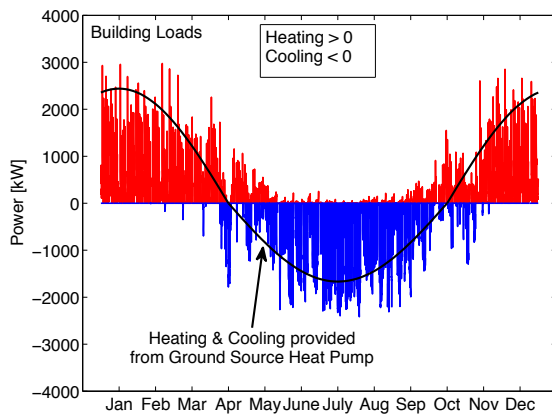
b) Building heating and cooling loads
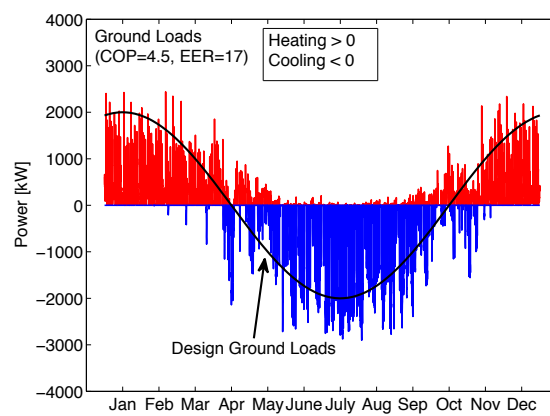
c) Ground heating and cooling loads

FIG. 1. Heating and cooling loads for large office building in Chicago

HEAT EXCHANGER DESIGN

A hybrid shallow geothermal energy system was designed based on ASHRAE recommendations (Kavanaugh and Rafferty, 1997), to accommodate the heating and most of the cooling needs of the office building in Figure 1, while the remainder of the cooling needs will be supplied by traditional systems. Hybrid systems reduce the size of the subsurface borehole heat exchange system and hence, result in substantially reduced capital costs, while still allowing significant reductions in energy costs and carbon

dioxide emissions (Preene and Powrie, 2009). According to Kavanaugh and Rafferty (1997) the total required length of vertical heat exchanger, L_h, can be found from:

$$L_h = \frac{q_a R_{ga} + (C_{fh} \times q_{lh})(R_b + PLF_m R_{gm} + F_{sc} R_{gd})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p}$$
(1)

where q_a is the net annual average heat transfer to the ground, q_{lh} is the building design heating load, R_b is the equivalent thermal resistance of the heat exchanger pipe, R_{ga}, R_{gm} and R_{gd} are 'effective thermal resistances of the ground' based on constant heating (from a cylindrical source) over periods of one year, one month and one day, respectively, C_{fh} is the correction factor to account for the heat absorbed by the heat pump during heating, PLF_m is the part-load factor during the design month, F_{sc} is the short-circuit heat loss factor, t_g is the undisturbed ground temperature, t_{wi} and t_{wo} are the liquid temperature at heat pump inlet and outlet and t_p is the temperature penalty for the interference of adjacent bores.

For the current geothermal system it was assumed that the net annual average heat transfer to the ground $q_a = 0$. The amount of heat exchanged with the ground is calculated by multiplying the heating and cooling loads of the building shown in Figure 1b with the correction factors C_{fh} and C_{fc} respectively, in order to account for the amount of heat absorbed or rejected by the heat pump. Figure 1c shows the heating and cooling loads exchanged with the ground assuming conversion factors C_{fh}=0.82 and C_{fc}=1.20, which correspond to a ground source heat pump with a coefficient of performance, COP=4.5 and, energy efficiency ratio, EER=17 respectively. In order to assume equal amounts of heating and cooling exchanged with the ground (ie $q_a = 0$), the ground heating and cooling loads (Fig. 1c) were fitted as a first approximation by a sinusoidal function of amplitude 2000kW and of equal durations for the heating and cooling periods, with the peaks occurring at the months of January and July, according to the EnergyPlus simulations. The fitting of the building heating loads (Fig. 1b) was found by dividing the ground heating load sinusoidal function by the correction factors C_{fh} and C_{fc} resulting to a design heating $q_{lh} = 2440$kW. Since the correction factors are different, the peak building heating load is higher than the peak building cooling load. The part-load factor for the design month (i.e., January) represents the percentage of time that the GSHP operates at full capacity. For the assumed sinusoidal curve in Figure 1b, PLF_m=95%.

Figure 2 shows the typical soil profile encountered in downtown Chicago (Finno & Roboski, 2005), which includes 9m of fill and sand, above 10m of clay overlaying limestone. Using weigthed average thermal properties for these types of material (as reported by ASHRAE; Kavanaugh and Rafferty, 1997) we selected an average thermal conductivity λ=2.75W/mK and thermal diffusivity α=0.097m²/day. The equivalent thermal resistances of the ground are then calculated based on a modified version of Carlslaw and Jaeger (1947) presented in ASHRAE and correspond to R_{ga}= 0.140mK/W, R_{gm} = 0.150mK/W and R_{gd} = 0.106mK/W. The heat exchanger pipes comprise polyethylene U-tubes (SDR 11, 75mm diameter), while the borehole is backfilled with a mix of concrete and borehole cuttings, corresponding to an equivalent thermal resistance of the bore R_b = 0.052mK/W. In order to reduce heat losses, three bores are connected in each parallel loop (Fig. 2a) and flow rates of more than 3 gpm/ton must be ensured within

the pipes, corresponding to F_{sc} = 1.01. The undisturbed ground temperature t_g = 10°C and the temperature of the water entering and exiting the heat pump is t_{wi} = 4°C and t_{wo} = 1°C. Finally, the temperature penalty for the interference of adjacent bores t_p=0.75°C. Using equation 1, the total required length of heat exchanger is 89.4km. For a floor area of 43000 m^2 the current design considers an array of 1118, 80m deep wells spaced in a regular array at 6.2m centers (see Fig. 3).
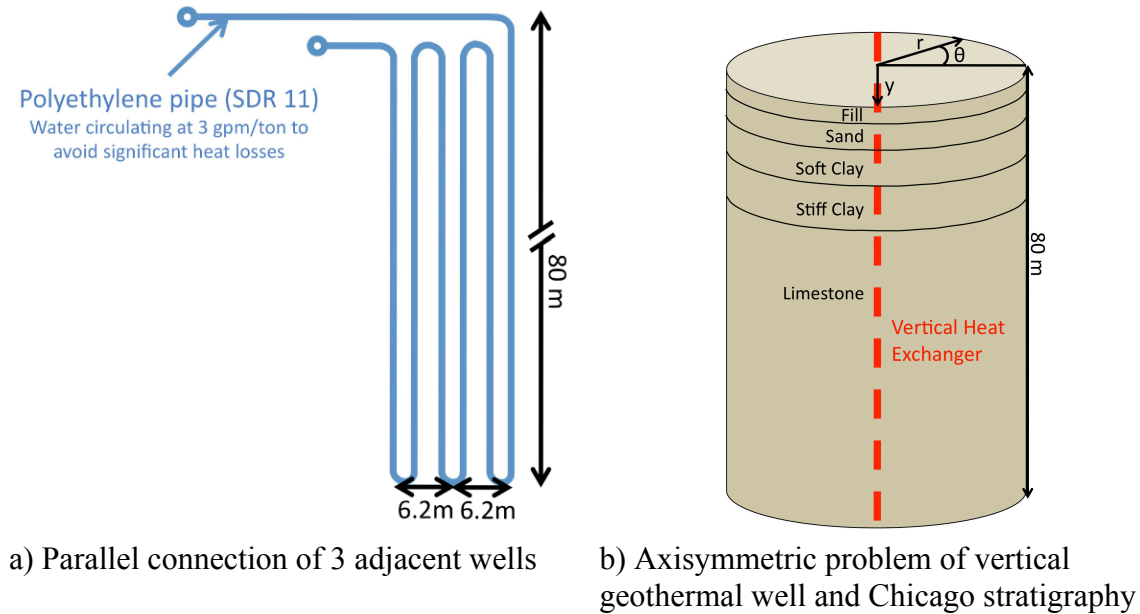

a) Parallel connection of 3 adjacent wells

b) Axisymmetric problem of vertical geothermal well and Chicago stratigraphy

FIG. 2. Axisymmetric representation of single geothermal well, Chicago stratigraphy and parallel arrangement of adjacent wells

NUMERICAL SIMULATION OF SINGLE GEOTHERMAL WELL

Numerical simulation of a single geothermal well was undertaken, using the finite element Code_Bright program (Olivella et al., 1996), in order to study the full thermo-hydro-mechanical response of the soil due to continuous cycles of heating and cooling. Figure 3b shows the soil layers, mesh and boundary conditions used in the numerical model. The depth of the model is 80m, equal to the depth of the bore, while the width is 3.1m, equal to half the distance between two adjacent bores, as shown in Figure 3a. The vertical heat exchanger is modeled as a line heat source. Closed heat and water flow is assumed in the left vertical boundary due to symmetry of the problem and in the right boundary due to the existence of the adjacent wells that produce the same heat exchange with the ground. Finally, closed heat flux is assumed at the top, which represents the interface between the ground and the building.

The vertical heat exchanger was studied using two sets of soil properties: 1) thermo-elastic properties in all units ("TE Model") and 2) thermo-elastoplastic properties for the clay layers only ("TEP Model"), using the thermo-mechanical constitutive model presented by Hueckel and Borsetto (1990) [HB90 model], a thermal variant of Modified Cam Clay (MCC; Roscoe and Burland, 1968). The mechanical properties of the Chicago glacial clays are available from Finno and Cho (2011). Thermal properties for the TE

model, Table 1, are based on parameters quoted by Kavanaugh and Rafferty (1997). The volumetric thermal expansion coefficient for all soils $\alpha_T = 3 \times 10^{-5}$ °C^{-1}. As there were no available measurements of the thermo-elastoplastic behavior for the Chicago clays, the current study calibrates the HB90 model using thermo-mechanical laboratory tests reported by Abuel-Naga et al. (2006) on specimens on Bangkok clay, as reported in Table 2. It should be noted that in spite of differences in the index/mineralogical and in situ water contents of the Chicago and Bangkok clays, the two clays are characterized by the same MCC compressibility and critical state shear strength parameters. Given this approximation, the current analyses should be viewed as preliminary, pending more studies on thermo-mechanical properties of the local clays.
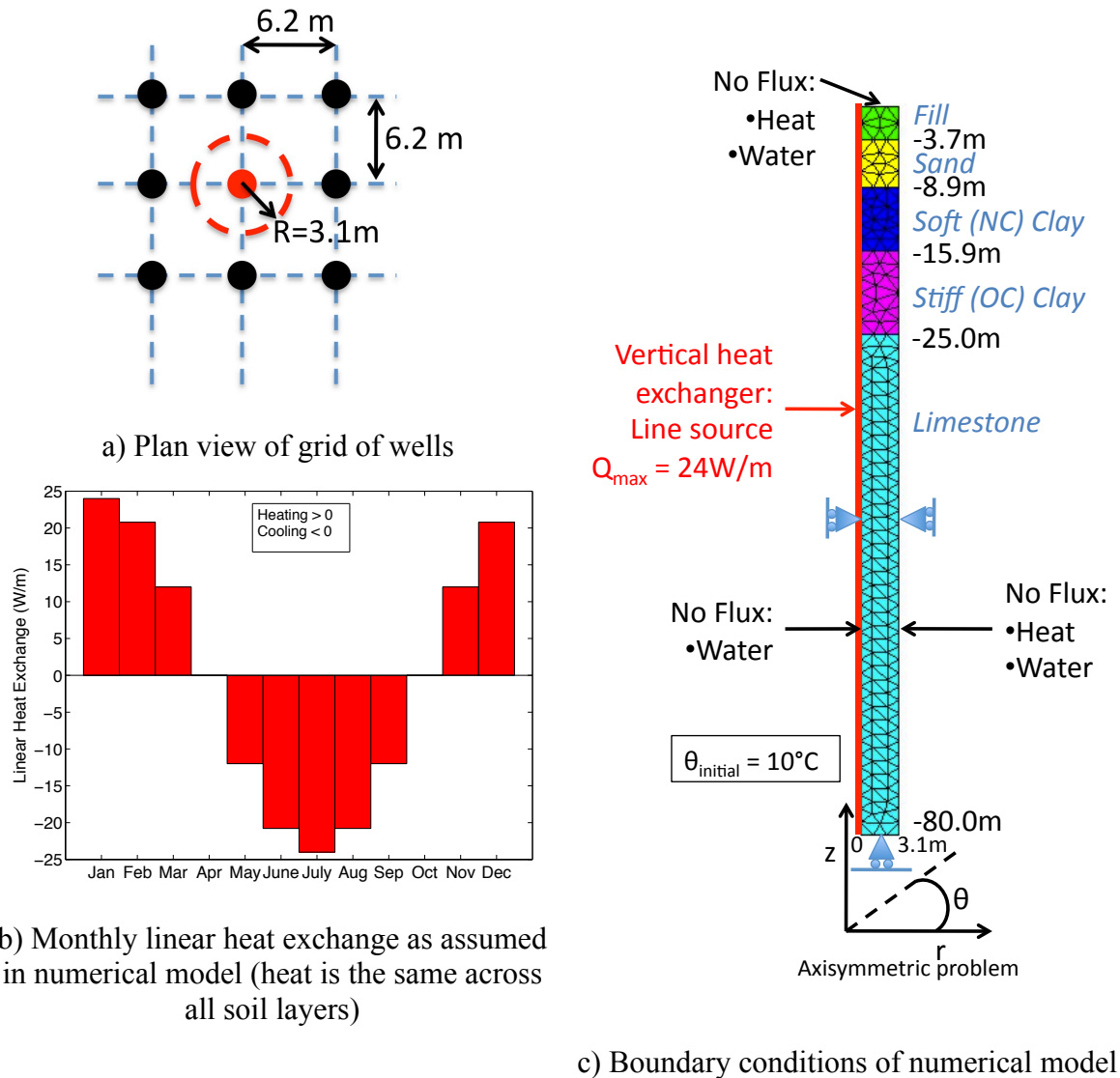
a) Plan view of grid of wells

b) Monthly linear heat exchange as assumed in numerical model (heat is the same across all soil layers)

c) Boundary conditions of numerical model

FIG. 3. Details of numerical model (solved using Code_Bright)

Table 1. Thermo-elastic properties for the TE model

Layer	Unit Weight (kN/m^3)	e_0	E (MPa)	ν	k (m/day)	λ (W/mK)	α (m^2/day)	C_p (J/kg K)
Fill	18.9	0.3	21	0.3	8.64E-01	2.94	0.09	946
Sand	19.7	0.3	85	0.3	8.64E-02	2.94	0.09	921
Soft Clay	18.9	0.3	121	0.3	8.64E-05	1.38	0.05	810
Stiff Clay	18.9	0.3	446	0.3	8.64E-05	1.38	0.05	810
Limestone	19.7	0.3	600	0.3	8.64E-05	3.11	0.11	921
Design values (weighted average):						2.79	0.10	

Table 2. Assumed thermo-mechanical properties of clay layers for Hueckel-Borsetto (HB90) soil model used in TEP analyses

κ	0.03	α_0 α_2 α_5 α_6	1.8e-4/°C -1.5e-6/°C^2 -5.3e-4 MPa/°C 3.8e-6 MPa/°C^2
λ (C_c)	0.20 (0.46)	α_1, α_3, α_4	0
M (ϕ')	1.29 (32°)	OCR Soft Clay Stiff Clay	1.0 2.0
ν'	0.30		
e_0	0.28		

Thermal Components of Hueckel & Borsetto (1990) model as implemented in CODE_BRIGHT:	
Preconsolidation stress	$p_c(T) = p_{c0} + 2\left(\alpha_5\Delta T + \alpha_6\Delta T|\Delta T|\right)$
Elastic volumetric strain	$d\varepsilon_v^e = \dfrac{\kappa}{1+e}\dfrac{dp'}{p'} + \left(\alpha_0 + 2\alpha_2\Delta T\right)dT$

where

p_{co}: initial preconsolidation mean stress

ΔT: change of temperature from initial value $T_0 = 10°C$

e: void ratio

RESULTS

The numerical analyses were carried out for a total design life of 600 months (50 years) to observe the long-term response of the ground. Figure 4 shows the temperature developed near the top of the clay layer (10m depth) at three different radial distances

from the heat source, in response to the sinusoidal heat exchange with the well. As expected, the same temperature distribution is observed in both the TEP and TE models, confirming that temperatures are largely independent of the mechanical properties of the soils. From Figure 4a it is observed that the temperature at r = 0.5m ranges from 4°C to 17°C, while seasonal fluctuations in temperature decrease with distance from the heat source. Figure 4b shows a small decrease (1°C) in the average temperature within the soil over the 50-year design life of the system.
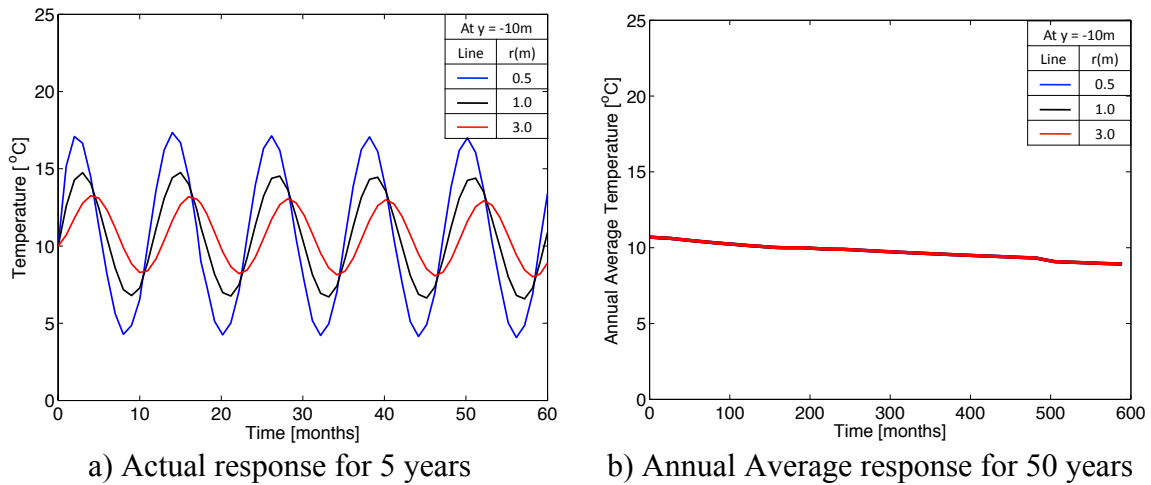

a) Actual response for 5 years   b) Annual Average response for 50 years

FIG. 4. Temperature prediction at different distances from the heat source

Figure 5a shows that there is a progressive accumulation of ground surface displacements predicted by the TEP Model, while the TE model shows very small net heave at the surface. The current TEP analyses predict that thermal cycling of the ground will cause a net settlement of 20mm after 50 years of operation (Fig. 5b). This could be an important long-term response that needs to be more carefully evaluated in design.
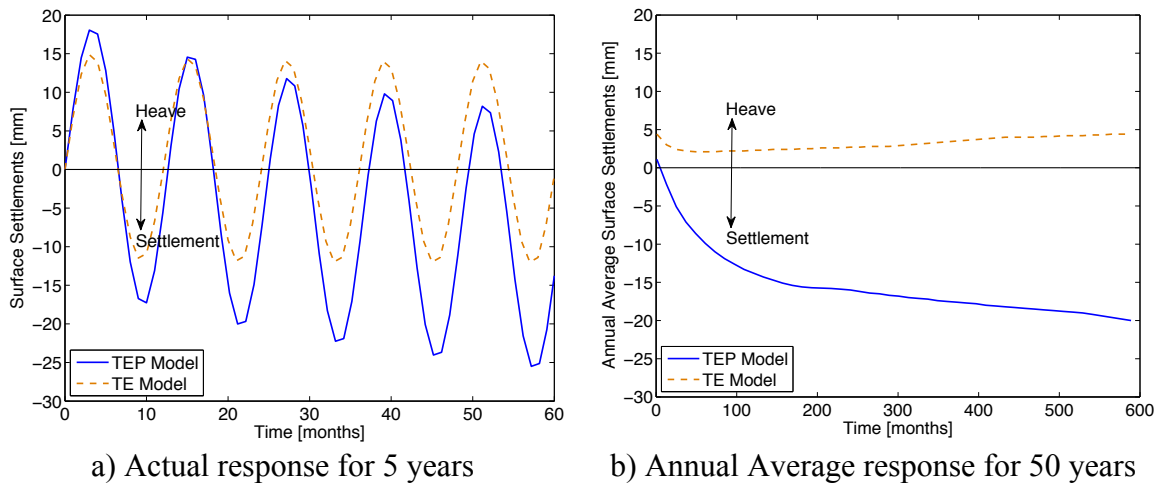

a) Actual response for 5 years   b) Annual Average response for 50 years

FIG. 5. Comparison of surface settlement predictions by the TEP and TE Models

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Figures 6 and 7 consider the volumetric strains and excess pores pressures within the soft (NC) and stiff (OC) clay units (cf. Fig. 3b). The results for the TE model (thermo-elastic properties) show negligible accumulation of volumetric strains with seasonal thermal cycling in Figure 6. Larger cyclic volumetric strains occur in the OC clay due to thermoplastic properties considered in the TEP analysis using the HB90 soil model ($\varepsilon_{vol} \approx \pm 0.1\%$). However, the net accumulation of strain over the design life is small. Much larger volumetric strains occur in the NC clay unit, with a progressive annual accumulation of strains (up to 0.3% after 50 years) that account for much of the computed surface settlement reported in Figure 5b. Figure 7 shows that significant excess pore pressures (up to ± 20kPa for the OC unit using the TEP model) develop in the clay due to seasonal heating and cooling. In general, the thermo-elastic analysis predicts larger cyclic excess pore pressures than the TEP analysis using the HB90 model. However, there is no apparent accumulation of excess pore pressures within the clay over the design life of the system.
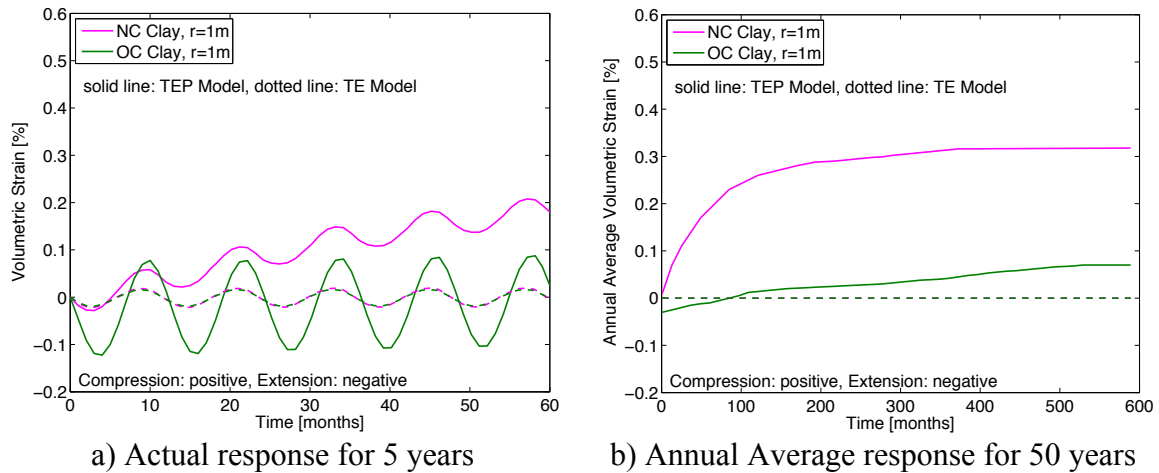

a) Actual response for 5 years   b) Annual Average response for 50 years

FIG. 6. Comparison of volumetric strain predictions by the TEP and TE Models

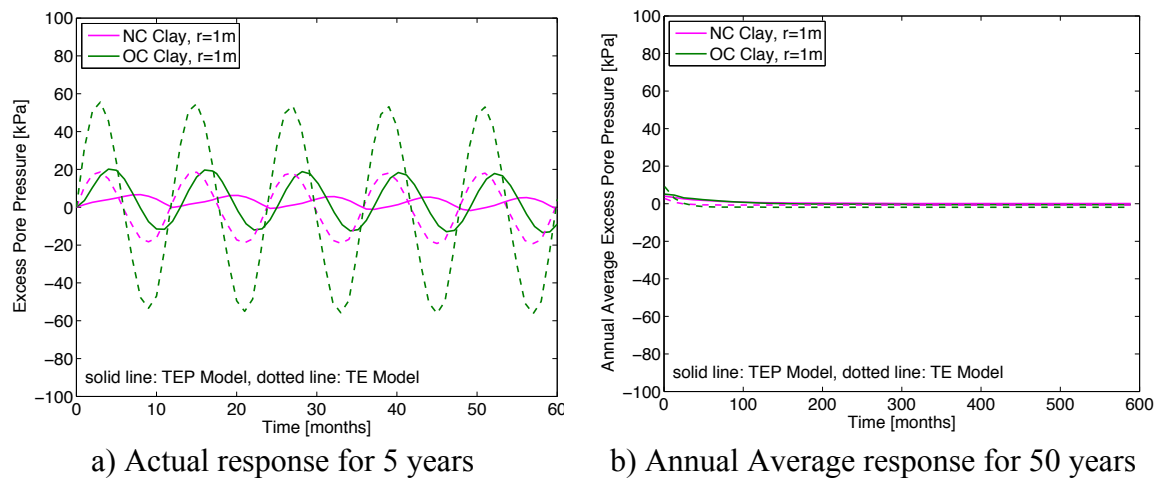a) Actual response for 5 years   b) Annual Average response for 50 years

FIG. 7. Comparison of excess pore pressure predictions by the TEP and TE Models

CONCLUSIONS

Numerical analyses of the coupled thermo-hydro-mechanical (THM) response of the clays have been used to evaluate long-term ground response for a shallow geothermal system designed to meet the heating and (most of the) cooling of a large commercial building in Chicago (DOE climate zone 5A). The analyses use an established thermo-elastoplastic soil model (HB90; Hueckel & Borsetto, 1990), with best estimates of thermal properties based on currently available data. The results show that seasonal heating and cooling of the ground can induce a small (but not insignificant) long-term settlement of the building over an assumed 50year design life of the system. Further studies of this type are essential for understanding and predicting the performance of shallow geothermal systems. There is clearly a need for more extensive information on site-specific thermo-mechanical properties of clays for these analyses.

ACKNOWLEDGMENTS

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