Numerical modelling of ground settlement induced by long-term operation of an energy tunnel

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Abstract. Energy tunnels are innovative geotechnical facilities to make use of shallow geothermal energy. Although this technology is getting increasingly popular, the behaviour of energy tunnels is still not fully understood. The coupled thermal and mechanical loading conditions of the energy tunnel pose several challenges for geotechnical engineers. Most of the existing studies only focus on the thermal performance of energy tunnels, while the thermo-mechanical response is still investigated in the literature rarely, especially the serviceability limit state of energy tunnels. Regarding the thermo-mechanical behaviour of soil, there are quite a few experimental studies and several advanced constitutive models proposed. However, none of them have been applied to the research of energy tunnels. In this research, a thermodynamic based advanced constitutive model is implemented into a commercial finite element software COMSOL. A coupled thermo-mechanical model is developed for energy tunnels under long-term cyclic thermal loading. A 10-year heating-cooling operation of the energy tunnel is simulated. Temperature variation induces volume change of soil, leading to accumulated ground settlement eventually. Without a full consideration of the thermal response of soil, the traditional numerical approach may not be conservative enough when evaluating the serviceability of energy tunnels.

1. Introduction
The ground temperature remains nearly constant throughout the year at a depth of about 10 meters below the ground surface. To exploit the heat capacity of the ground, Ground Source Heat Pump (GSHP) systems are developed as a renewable and environmentally friendly alternative to traditional heating, ventilation, and air conditioning systems. The GSHP extracts heat from the ground and pumps it to the building in winter and vice versa in summer. Recently, “energy tunnels” have been developed by incorporating the GSHP into tunnels. An energy tunnel can extract a significant amount of heat from surrounding ground. The extracted heat can be used for heating/cooling of railway stations and buildings, or for protecting platforms, bridges, pavements, passages from freezing.

Full-scale field tests about energy tunnels have been carried out in Austria (Brandl, 2006; Adam & Markiewicz, 2009; Franzius & Pralle, 2011), Germany (Franzius & Pralle, 2011; Buhmann et al. 2016), South Korea (Lee et al., 2012), China (Zhang et al., 2014), and Italy (Barla et al., 2019). These tests are mainly focused on the thermal response and commercial benefits of energy tunnels. The measured heat flux from the surrounding ground is typically in the range of 5–30 W/m² (Franzius & Pralle, 2011; Lee et al., 2012). The energy tunnel system can gain benefits from a broader area for heat exchange. Hence, it provides a lower unit energy price, compared with energy piles and vertical borehole loops (Nicholson et al., 2014).
However, since energy tunnel lining serves as supporting the ground and extracting ground energy, it will be subjected to mechanical and thermal loads simultaneously. Very few studies dealing with the thermo-mechanical behaviour of energy tunnels have been carried out (Nicholson et al., 2014; Barla and Di Donna, 2018; Barla et al., 2019). It is found that thermally induced stress in the tunnel lining could not lead to plastic yielding (Barla et al., 2019), and can be neglected in the performance-based design of the lining at the ultimate limit state (Insana et al., 2020). However, caution still needs to be taken to the effects of thermal loads on the serviceability limit state. Gawecka et al. (2020) carried out predictive modelling of energy tunnels in London Clay to study the thermo-mechanical behaviour of energy tunnels under coupled mechanical and thermal loading conditions. Although the reversible thermal expansion of soil is considered, the irreversible thermally induced volume change of soil is neglected, which has vital influence on the performance of thermo-active structures (Ng et al., 2021).

To get a better understanding of the serviceability of energy tunnels, the thermo-mechanical response of soil needs to be fully considered. In this research, an advanced soil model is implemented in finite element software to carry out a thermo-mechanical coupled numerical simulation for the performance of an energy tunnel.

2. Implementation of an advanced thermo-mechanical soil model

The Tsinghua ThermoSoil model (TTS) was developed based on a non-equilibrium thermodynamic approach to simulate the coupled thermo-mechanical response of clays (Zhang & Cheng, 2017; Zymnis et al., 2018). In this section, basic formulations of this model are briefly introduced. Then, the simulations of the thermo-mechanical behaviour of Geneva clay are presented.

2.1. Mathematical formulations of TTS model

The total strain $\varepsilon_{ij}$ is divided into the elastic strain $\varepsilon_{ij}^e$, the thermo-elastic strain $\varepsilon_{ij}^{te}$, and the plastic strain $\varepsilon_{ij}^p$,

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^e + \dot{\varepsilon}_{ij}^{te} + \dot{\varepsilon}_{ij}^p$$  \hspace{1cm} (1)

where an over-dot denotes the time derivative. Through the elastic strain, the elastic potential energy is stored in the soil:

$$\omega_e = B(e_v^e)^{n+2} + B_0(e_v^e + \varepsilon_c)^n(e_v^e)^2$$  \hspace{1cm} (2)

where $e_v^e = e_{ij}^e$, $e_s^e = e_{ij}^p$, $e_{ij}^p = e_{ij}^p - \delta_{ij}e_v^e/3$ and $B, n, \xi, \varepsilon_c$ are model parameters. This energy function is derived by considering the dependence of the elastic moduli on mean effective stress (Jiang & Liu, 2009). According to the well-recognized Hardin’s equation for small-strain stiffness of soil, $G_0 \propto \sqrt{p'}$, the nonlinear parameter, $n$, is taken as 1 in this study. To capture the density dependence of soil stiffness, the stiffness parameter $B$ is taken as a function of soil dry density $\rho_d$, $B = B_0\exp(B_1\rho_d)$. As a hyperelastic model, the effective stress is expressed as the derivative of the elastic potential energy function:

$$\sigma'_{ij} = \frac{\partial \omega_e}{\partial e_{ij}^e} = B[3(e_v^e)^2 + \xi(e_v^e)^2]\delta_{ij} + 2B\xi(e_v^e + \varepsilon_c)e_{ij}^p$$  \hspace{1cm} (3)

To model the reversible thermal response of soil, a linear thermo-elastic relation is adopted:

$$\dot{\varepsilon}_{ij}^{te} = \alpha_s \dot{T}\delta_{ij}$$  \hspace{1cm} (4)

where $\alpha_s$ is the coefficient of linear thermal expansion of the soil skeleton.

To account for the energy dissipation of granular material at both the macro and micro levels, Jiang and Liu (2009) proposed a double-entropy formulation. A granular entropy, $s_g$, together with its conjugate variable, granular temperature, $T_g$, was introduced in addition to the actual entropy...
temperature. The evolution of granular temperature is then modified by Zhang & Cheng (2017) to consider the effects of temperature change:

\[
\dot{T}_g = (m_v \dot{\varepsilon}^v + m_s \dot{\varepsilon}^s + \frac{m_T r \alpha_{bf} \varphi_{bw} r^2}{1-\varphi} - T_g) \frac{m_r}{\rho_d}
\]  

(5)

where \(m_v, m_s, m_T\) are model parameters indicating the contributions of volumetric strain rate, shear strain rate, and temperature changing rate to granular temperature, and \(m_r\) affects the rate dependence. \(\varphi_{bw}\) is the bound water porosity at the current temperature, which decays due to an increasing temperature:

\[
\dot{\varphi}_{bw} = -\varphi_{bw} \frac{\alpha_{bf} - \beta_w (1-\beta_w \Delta T)}{T}
\]  

(6)

where \(\beta_w = 3.4 \times 10^{-4/\circ C}\) is the volumetric thermal expansion coefficient of water and \(\alpha_{bf}\) is a characteristic material property affecting the rate of bound water decay. As a result of the energy dissipation, the plastic strain is influenced by granular temperature:

\[
\dot{\varepsilon}^p_{ij} = \sqrt{T_g (\varepsilon^p_{ij} - \varepsilon^h_{ij})} + [1 + L_T (T - T_0)] \sqrt{T_g (\varepsilon^v_{ij} - \varepsilon^h_{ij})} \delta_{ij}
\]  

(7)

where the parameter \(L_T\) describes the dependence of volumetric deformation on temperature. \(\varepsilon^h_{ij}\) and \(\varepsilon^v_{ij}\) are deviatoric and volumetric hysteretic strains, respectively:

\[
\dot{\varepsilon}^h_{ij} = \dot{\varepsilon}^p_{ij} - \frac{[\varepsilon^p_{ij} \varepsilon^h_{ij}]}{\varepsilon^h_{ij} \varepsilon^h_{ij}} \varepsilon^h_{ij}
\]  

(8)

where \(h\) is a parameter affects hysteretic behaviour of soil.

The TTS model is newly implemented in the FEM software COMSOL, thus providing a platform to simulate boundary value problems, such as thermal operation of energy tunnels.

2.2. Simulations of thermo-mechanical behaviour of Geneva clay

Di Donna and Laloui (2015) carried out a series of drained thermal cyclic tests on saturated Geneva clay at both normally consolidated and overconsolidated states by using a temperature-controlled oedometer. The values of model parameters for Geneva clay are calibrated and summarized in Table 1. The detailed calibration procedures of all the parameters refer to Zymnis et al. (2018).

Figure 1 presents the measured and computed 1-D compression and unloading response of Geneva clay. The normally consolidated (NC) clay is monotonically compressed up to \(\sigma'_v = 125\text{kPa}\). The overconsolidated (OC) clay is first compressed up to \(\sigma'_v = 1000\text{kPa}\) and then unloaded to \(\sigma'_v = 60\text{kPa}\), resulting in an over-consolidation ratio (OCR) of 16.7. After mechanical loading and unloading, both NC clay and OC clay are subjected to thermal cycles. Figure 2 shows the details of measured and computed volumetric strains at various temperatures. Accumulation of compressive strains for NC clay and dilative strains for OC clay are observed, thus showing clear evidence for thermoplasticity of soil. Most of the irreversible deformation occurs during the first heating-cooling cycle. Increments of irreversible deformation generally become smaller with the increasing of thermal cycles. There is no further irreversible deformation after 4th cycle. In the end, only a reversible response can be observed, which can be called thermoelasticity. Figure 3 shows the model predictions for thermally induced volumetric strain of Geneva clay with different OCRs. All of them qualitatively follows the same trend as the measured results. Irreversible volumetric strain accumulates and stabilizes within less than four thermal cycles. The total irreversible deformation developed under thermal cycles are highly dependent on the stress history of soil. With an increasing OCR from 1.3 to 1.5, irreversible contraction decreases by 0.25%. On the contrary, irreversible dilation increases by 0.05% when OCR increases from 2 to 16.7.

| Table 1. Model parameters for Geneva Clay. |
|-------------------------------------------|
| Parameter | Value | Unit | Calibrated by |
|------------|-------|------|---------------|


The table contains the following parameters:

| Parameter | Value | Description |
|-----------|-------|-------------|
| $B_0$     | $1.26 \times 10^{-4}$ Pa | The location of NCL |
| $B_0$     | 0.0162 m$^3$/kg | The slope of NCL |
| $\xi$     | 0.5 | Coefficient of earth pressure at rest |
| $\varepsilon_c$ | 0.0247 | Critical state |
| $h$       | 0.03 | The slope of unload curve |
| $m_v$     | 6000 s$^2$ | Contribution of volumetric strain rate on $T_g$ |
| $m_d$     | 6000 s$^2$ | Contribution of deviatoric strain rate on $T_g$ |
| $m_T$     | $5.85 \times 10^{-5}$ m$^3$/kg/K | Contribution of temperature change on $T_g$ |
| $m_r$     | 60000 kg/(m$^3$/s) | Rate dependence |
| $\alpha_{bf}$ | 0.0237 1/°C | Conversion of bound water to free water during heating |
| $\alpha_s$ | $6 \times 10^{-6}$ 1/°C | Linear thermal expansion of the soil skeleton |
| $L_T$     | 0.02 1/°C | Thermo-plasticity |

**Figure 1.** Measured and computed 1-D compression and unloading response of Geneva clay.

**Figure 2.** Measured and computed cyclic thermal response of Geneva clay.
3. Numerical simulation of an energy tunnel

3.1. FEM model

To better understand the cyclic thermo-mechanical response of an energy tunnel and the surrounding ground, a 3D coupled thermo-mechanical finite element numerical model was built in COMSOL. Figure 4 shows the geometry of the finite element model adopted in the thermo-mechanical simulation. The discretized domain is 60 m high, 120 m wide, and 1.4 m thick. The mesh consists of 14112 elements and 3810 nodes. The mesh becomes finer at the domain close to the tunnel. Due to the symmetry, only half of the tunnel and the ground are modelled. Since the temperature field and stress field remain constant in the longitudinal direction of the tunnel, only a slice is modelled. All the vertical and bottom boundaries are specified as roller fixities. For the top boundary, a surcharge loading of 150 kPa is applied to model the stress history of the ground. After the surcharge is released, the nodes at the top boundary are fully free. The tunnel axis is 21.5 m deep, and the tunnel internal diameter is 6.8 m. The tunnel lining is 0.3 m thick. The soil is simulated as the TTS model (see Table 1) and is assumed to be fully drained. A simple elastic model is used for concrete lining. All the parameters of concrete lining and thermal parameters of soil are summarised in Table 2.
The initial ground temperature was set to 17°C. All the boundaries are adiabatic. The heating and cooling processes are modelled by prescribing a heat flux of sine-type function at the inside boundary of the tunnel lining. The peak heat flux is 20 W/m², corresponding to the heating phase during summer, while -20 W/m² corresponds to the cooling phase during winter. Primary heat transfer is through thermal conduction, while convection is not considered. This assumption holds when the groundwater flow is negligible (Franzius & Pralle, 2011). It errs on the conservative side during the estimation of thermally induce ground settlement. Thermal properties of the ground and the tunnel are assumed to be isotropic and homogenous, as shown in Table 2. A period of 10 years is simulated.

Table 2. Input parameters in numerical analysis.

| Material | Parameter                      | Value | Unit      |
|----------|--------------------------------|-------|-----------|
| Soil     | Thermal conductivity, $\lambda_s$ | 2.8   | W/(m·K)   |
|          | Specific heat capacity, $c_s$    | 1100  | J/(kg·K)  |
| Concrete | Thermal conductivity, $\lambda_c$| 1.1   | W/(m·K)   |
|          | Specific heat capacity, $c_c$    | 900   | J/(kg·K)  |
|          | Coefficient of linear thermal expansion, $\alpha_c$ | $8 \times 10^{-6}$ | 1/°C |
|          | Young's modulus, $E$             | 30000 | MPa       |
|          | Poisson’s ratio, $\nu$           | 0.2   | 1         |

3.2. Numerical results

Figure 5 shows the temperature evolution at the crown of tunnel, as well as 1.0 m, 2.5 m, 4.5 m, and 7.0 m above the crown. As expected, the crown experiences the greatest temperature variation. The magnitude of temperature variation reduces with the increase of distance from tunnel crown. Due to the process of heat transfer, there is a phase shift between the temperature peaks at different locations.

Figure 6 presents thermally induced volumetric strain along with the temperature at different locations above the tunnel crown. For the soil at 1 m above the tunnel crown, a volumetric contraction of 0.25% is observed. When the location becomes shallower, the OCR increases, leading to a smaller contraction at 2.5 m above the crown. At 4.5 m above, almost no irreversible volumetric strain is accumulated. Interestingly, for the soil at 7 m above the crown, a slight dilative strain can be observed. These observations clearly highlight the significance of stress state on the thermal response of the soil. As a result of the volumetric strain of the soil, the ground settlement develops along with yearly thermal cycles.
Figure 7 shows the computed ground settlement after 2, 4, 6, 8, and 10 years of thermal operation of the energy tunnel. Due to cyclically thermally induced soil deformation, the irreversible ground settlement is accumulated along with time. 60% of the ground settlement occurs during the first 4 years. In the following years, accumulation of ground settlement generally becomes smaller. After 10 years of operation, the accumulated settlement of the ground is up to 15 mm, which is the limit suggested by LTA (2004). Gawecka et al. (2020) simulated continuous cooling of a tunnel for 3 years. Even though it is an extreme case of thermal operation, the obtained result is still not conservative when evaluating the serviceability of an energy tunnel. It is because the adopted model in Gawecka et al. (2020) does not consider thermo-plasticity of soil, resulting in an underestimation of the ground settlement. The results imply that the thermal response of soil should be taken into account in order to obtain a conservative evaluation of the serviceability of energy tunnels.

Figure 6. Computed volumetric strain of soil at different locations above the tunnel crown.

Figure 7. Computed ground settlement after 2, 4, 6, 8, and 10 years of thermal operation.

4. Conclusions
This study numerically investigates the thermo-mechanical behaviour of an energy tunnel and the surrounding ground, with special attention paid to cyclically thermally induced ground settlement. An advanced constitutive soil model is implemented in FEM software to carry out a thermo-mechanical coupled numerical simulation for a long-term operation of an energy tunnel. It is clearly shown that the
thermal response of soil is of great importance in the assessment of energy tunnels. At different depths of the ground, the soil experiences different stress histories and temperature variations, leading to different thermal responses. As a result, the ground settlement accumulates with yearly heating-cooling cycles. Without considering thermal response of soil, the traditional numerical approach is not conservative when evaluating the serviceability of energy tunnels. Due to the lack of experimental data to verify the computed results presented, the findings from this paper should be treated with caution. Further experimental investigation is required to improve the understanding of the serviceability of energy tunnels.

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