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Estimating the geothermal potential of heat-exchanger anchors on a cut-and-cover tunnel

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ABSTRACT

This study addresses the geothermal potential of using the anchors of a cut-and-cover tunnel as heat exchangers with the ground for seasonal heat storage. The influence of the soil properties and water table level were investigated. Various service conditions were examined, optimised and compared using finite-element analyses. The extractable heat from the ground through the anchors, per year and per kilometre of tunnel, ranges from 0.4 to 0.8 GWh. The seasonal heat storage is shown to be an important factor for the efficiency and sustainability of the heat source.

1. Introduction

The heating and cooling of buildings represent an important part of the daily energy consumption in developed and developing countries. For example in 2010, the Swiss Federal Office of Energy reported that 3/4th of the energy consumed in the Swiss households was dedicated to heating and that 75% of this demand was satisfied using fossil fuels (oil and gas). Similarly, half of the total energy used in office and commercial buildings was dedicated to heating and cooling (Kirchner et al., 2011). Thus, finding and promoting alternative and renewable energy sources for heating and cooling the buildings are important challenges for the future energy policies.

Geothermal power represents a significant heat source and there is a ready supply of geothermal resources on Earth (Axelsson, 2010). Ground Source Heat Pumps (GSHPs) were developed to use geothermal energy at shallow depths (Saner et al., 2010). The principle of GSHPs is to connect heat pumps to the ground using Ground Heat Exchangers (GHEs). This system is highly efficient with a Coefficient of Performance (COP) up to 4 (Brandl, 2006) because the ground exhibits a relatively constant temperature year round under natural conditions (10–15 °C at European latitudes). However, the sustainability of the heat production must be addressed as noted by Axelsson (2010) because even if the shallow geothermal energy is renewable, its sustainability depends on how we use it (Rybach and Eugster, 2010). Various production methods such as simple constant production remaining below design limits, or intermittent high-level operations can be considered sustainable, provided that they are correctly designed based on both the production device and the heat source (Franco and Vaccaro, 2012).

To adapt GSHPs to the widest range of uses and conditions, different types of GHEs were developed: from the simple horizontal collectors buried a couple of metres below the soil surface to the deep Borehole Heat Exchangers (BHEs), which can reach depths of several hundred metres (Sanner et al., 2003). However, relatively recent developments of energy geostructures suggested that using the thermal properties of concrete foundations (piles, diaphragm walls, concrete slabs) increases the efficiency of the heat exchange between the ground and the GHE (Brandl, 2006; Pasquier and Marcotte, 2012).

The concept of an energy geostructure was also identified for use in urban tunnel structures. This concept suggested that using tunnel linings, geosynthetics or anchors could provide additional renewable heat sources to the neighbouring infrastructures (Adam, 2008a). Nicholson et al. (2013) also underlined that producing heat from the tunnels could help cooling the galleries.

Several concepts applied to tunnels were examined on sites (Jenbach and Lainzer tunnels) in Austria: thermoactive lining segments (Franzius and Pralle, 2011) and geosynthetics equipped with absorber pipes (Franzius, 2011). Prototype rock bolts were also developed and tested in an embankment during the second project. These were self-drilling anchor bolts whose hollow bore, dedicated

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to flushing or grouting, was equipped with coaxial geothermal probes, the external part of which acted as the bolt (Adam, 2008b). The heat exchanger anchors (in the broad sense) were numerically investigated by Adam and Markiewicz (2009). This concept could be extended to grouted anchors (e.g., Store–Norfors anchors) or strand anchors provided that there is enough space for the absorber pipes to be installed in the anchor borehole. The former type of anchor, grouted in mortar, lends itself well to the installation of absorber pipes as its mechanical performances are hardly sensitive to the actual diameter of the anchor borehole. Mechanical anchors and resin rock bolts are made of rebars that are sealed at the bottom of the anchor borehole. They therefore require boreholes with a diameter adjusted to the anchor mechanism (30–50 mm), which may not allow the installation of absorber pipes.

Therefore, the present study addresses the potential of using the tunnel anchors of a cut-and-cover tunnel, which is a common type of tunnel in Switzerland. No particular anchor technology is identified as the purpose of the study is to provide a first insight in the concept before developing technical solutions for real implementation. The cut-and-cover tunnel is described in Section 2. The anchors are used as the sustainable heat exchangers for GSHPs as defined by Rybach and Eugster (2010). Indeed, the proximity of the soil surface induces significant heat loss during cold periods when the heat demand is important. In addition, unsaturated conditions are often encountered at shallow depths, which significantly modifies the soil thermal characteristics. Therefore, the sustainability of the heat production is fragile and the heat extraction and injection processes must be properly designed. The analyses are performed using thermo-hydraulic finite-element methods whose mathematical formulation is given in Section 3. The corresponding assumptions and the different material characteristics that can have significant implications on the results are listed in Section 4. The numerical setup of the finite-element analyses is detailed in Section 5, which includes the mesh characteristics and the boundary conditions that are applied. The sustainability of the heat source is achieved by preventing the temperature from dropping below 274 K between the anchors in order to avoid freezing the soil. Pure heat production is compared to the seasonal heat storage with heat injection during the hot periods. The efficiency of the seasonal heat storage is assessed by comparing the gained heat production during cold spells to the energy injected during hot spells. The results of the analyses are presented in Section 6.

2. Geometry of the problem

The cut-and-cover tunnel configuration corresponds to a top-down construction method. The space between the diaphragm walls is excavated until the depth of the invert slab. Next, the floor slab is built with the tunnel body on top. Joints are deployed around the tunnel body and the remaining space is backfilled. The anchors are required to maintain the diaphragm walls during the construction period before installing the backfill. Once the construction of the tunnel is achieved, anchors are de-stressed. Because this type of tunnel remains at a shallow depth, the anchors remain close enough to the soil surface so that the thermal influence of the atmosphere can be significant. This impact is accounted for using a time-varying temperature condition at the soil surface (see Section 5.2).

The anchors were designed according to a Swiss Norm (2003) for a silty soil with a longitudinal spacing of 3 m. The resulting design comprises eight anchors per cross section which are 20-m-long and are inclined 20° below the horizontal (Fig. 1). Thus, the anchors are around 2–15 m below the soil surface. The first anchor is between 2 and 9.5 m deep. There is approximately 53 m of anchor per metre of tunnel.

3. Theoretical formulation

The present analyses are performed considering that the thermo-hydraulic couplings are mainly driven by the soil type and its water content. The analyses were achieved using the finite-element code *Lagamine* (Charlier et al., 2001; Collin, 2003; Collin et al., 2002). The mechanical aspect of the problem is neglected because the tunnel structure is shallow. It is assumed that the proximity of the soil surface allows the soil to thermally expand without inducing significant stresses in the tunnel structure because of the buffering effect of the backfill, which limits the interactions between the diaphragm walls and tunnel. Nevertheless, any displacements that could be induced can become significant, but were not investigated in this study because they depend on the nature of the structures at the soil surface. The effects of the heating and cooling cycles on the mechanical behaviour of the anchors are not considered because the heat production begins after the tunnel construction is achieved. Therefore, the anchors have no structural supporting role when they are thermally solicited.

3.1. Balance equations

The compositional approach (Panday and Corapcioglu, 1989) is used to describe the soil mixture, which is made up of a porous medium, liquid water and gaseous air in this study. The mass–balance equations are written for the species whose mass conservations are assumed.

The air flow in the soil matrix is not modelled, but the air pressure is set constant and equal to 100 kPa in the entire domain. Hence, the air is at 100 kPa (1 atm) where unsaturated conditions are encountered and there is no air in saturated areas. No natural groundwater flow is considered. Finally, there is no volumetric source of air or water. Therefore, the mass conservation of water is written as

$$n\frac{\partial(\rho_w \cdot S_w)}{\partial t} + div(\rho_w \cdot \mathbf{q_w}) = 0 \quad (1)$$

where ρ_w is the bulk density of water, n is the soil porosity, S_w is the degree of saturation of the soil, and $\mathbf{q_w}$ is the macroscopic velocity of water. The heat transport is considered to be driven by heat conduction because it is the main mechanism observed in soils without natural groundwater flow (Hermansson et al., 2009). Therefore, the energy balance for the soil is

$$\frac{\partial S_T}{\partial t} + div(\mathbf{q_T}) - Q_T = 0 \quad (2)$$

where Q_T represents the volumetric heat sources and sinks, $\mathbf{q_T}$ is the heat flow, and S_T is the enthalpy of the system given by

$$S_T = \rho c(T - T_0) \quad (3)$$

where T_0 = 284 K is a reference temperature and ρ and c are the bulk density and specific heat of the soil mixture, respectively. These parameters are derived from the individual properties of each phase by

$$\rho c = (1 - n)\rho_s c_s + nS_w \rho_w c_w + n(1 - S_w)\rho_a c_a \quad (4)$$

where ρ_s and ρ_a are the soil grains and air densities, respectively, and c_s, c_w and c_a are the soil grains, water and air specific heats, respectively.

3.2. Constitutive relations

The constitutive relations link the variables in the balance equations to the primary variables, which are the temperature T and the pore water pressure p_w that is introduced below.