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Numerical investigation on the thermal performance of energy tunnels under groundwater flow and tunnel airflow

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The integration of underground tunnels with ground heat exchangers (GHEs), also known as energy tunnels, is a promising technology that has gained attention in energy geotechnics research. This study investigates the coupled effects of groundwater and tunnel-air flows on the energy tunnel system via 3D thermo-hydraulic numerical modelling. It is found that the combination of groundwater flow parallel to the tunnel and limited airflow velocity results in reduced operational efficiency of ground source heat pump (GSHP) due to the strong thermal interference along the tunnel. The study also highlights the importance of real-scale modelling to evaluate the thermal yield of long energy tunnels, particularly when dealing with parallel groundwater flow in geothermal tunnel design.

The use of shallow geothermal energy is a renewable solution towards net-zero carbon emissions. In recent years, a variety of conventional geotechnical structures, such as piles, retaining walls and tunnels, have been transformed into energy geostructures to also serve as GHEs to harness renewable energy for space heating and cooling purposes [7]. The thermal performance of energy tunnels is significantly affected by the presence of groundwater flow [1, 6] and the airflow in the tunnel [2, 4]. The groundwater flow and tunnel airflow can both be present in the field, however, their coupled effects on the energy tunnel system are hardly explored in the literature. This study aims to bridge this gap via real-scale numerical investigations.

This study uses 3D thermo-hydraulic numerical modelling developed with the finite element package COMSOL Multiphysics [3]. The numerical model was successfully validated against an energy tunnel model-scale laboratory experiment [5]. Figure 1 shows the overall geometry and boundary conditions of the numerical model. A 48 m long tunnel section is thermally activated with the embedment of HDPE pipes (outer diameter of 25 mm and 2.3 mm thickness) placed in the lining segments at a spacing of 200 mm. A single tunnel ring consists of six segments with absorber pipes joined between them. Every four adjacent rings are connected in series to form a complete loop (with a single inlet and outlet), which is then connected in parallel to a flow and return header pipe(s). The entire thermally activated section comprises six loops, with identical fluid inlet temperature and flow rates, as they are fed by the same flow header pipe. The outlet fluid from each loop is mixed along the return header pipe to the GSHP. A constant 36 kW cooling thermal load is applied, and the simulation is run for ten years to allow the system to reach a steady state condition considering the minimum groundwater flow and airflow. The thermal properties of the ground are prescribed as 2 W/(m·K) and 1100 J/(kg·K) for thermal conductivity and specific heat capacity, respectively.

Figure 2 shows the entering water temperature (EWT, header outlet) and the coefficient of performance (COP) of the GSHP after 10 years of operation for different groundwater flow velocities and directions for tunnel air velocities v_a = 0.05 m/s and 2 m/s.

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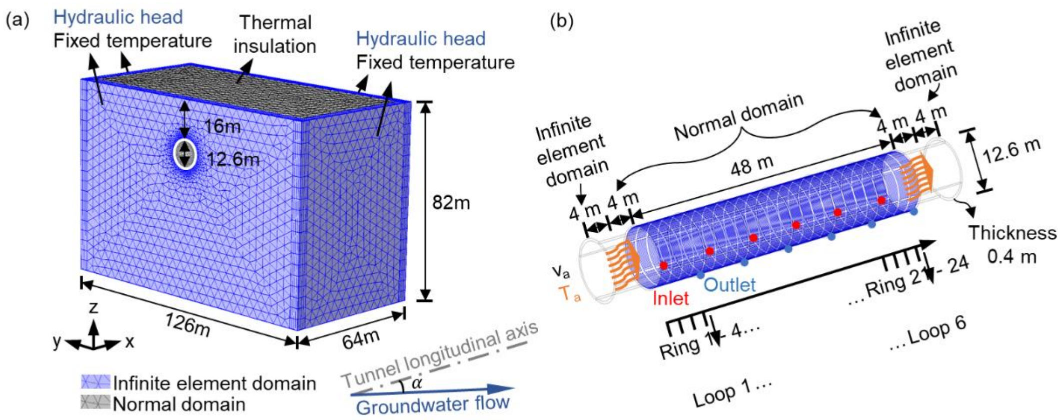

Figure 1: Numerical model: (a) geometry, mesh, and key boundary conditions, and (b) tunnel details and heat absorber pipes.

Results show that an increase in v_w and v_a leads to a decrease in EWT and an increase in COP. However, the effect of groundwater direction and velocity is more significant when airflow is limited (v_a = 0.05 m/s). The parallel groundwater flow leads to a higher EWT and lower COP than when the flow is inclined and perpendicular to the longitudinal tunnel axis. Consequently, the thermal performance of the system under parallel flow with a higher v_w can be even worse than the perpendicular and inclined flow with a lower v_w. When v_a = 0.05 m/s, the EWT of parallel flow increases by 15% to 20% compared to the perpendicular flow, resulting in a maximum decrease of 15% in the COP. The effect of groundwater flow is much less significant when airflow is fast (v_a = 2 m/s): for v_w increases from 0.05 to 2 m/d, EWT and COP change by no more than 13% and 5%, respectively, and the impact of groundwater flow direction is minor.

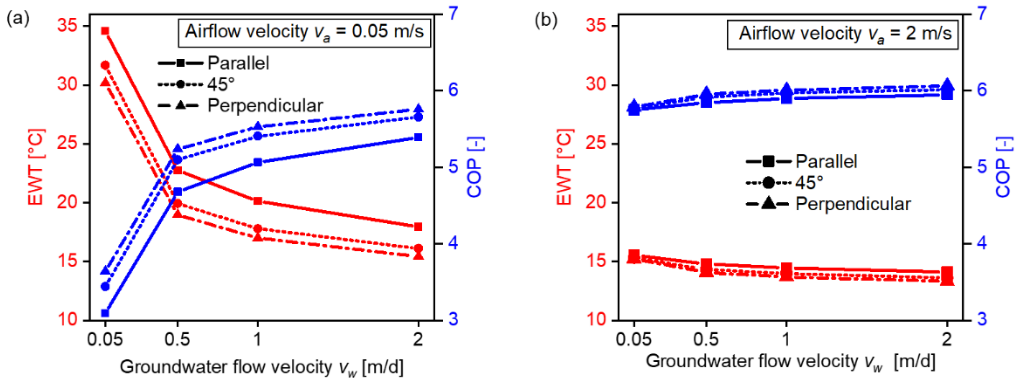

Figure 2: Results: average entering water temperature and the COP of the GSHP for (a) v_a = 0.05 m/s, and (b) v_a = 2 m/s.

Contributor statement

Xiangdong Dai: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft. Asal Bidarmaghz: Conceptualization, Methodology, Supervision, Formal analysis, Visualization, Writing – review & editing. Guillermo A. Narsilio: Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing.

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