A flowchart for early-stage thermal design of Energy Walls

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Objectives of the study

Thermo-active diaphragm walls, also known as energy walls (EWs), are geotechnical structures typically used for multi-floored basements, shallow train tunnels and underground car parks. Diaphragm walls (DWs) are composed by reinforced concrete panels and are constructed using a top-down technique. Typical geometrical features for DWs are: 15-50 m depth, 0.8-1.2 m thickness. Depending on the depth of the excavation, props or anchors may be needed in order to satisfy the structural and geotechnical safety requirements. The thermal activation of diaphragm walls is made by inserting pipes (usually high-density polyethylene pipes) attached to the reinforcing cage. Such civil structures present the top part of the wall exposed to the soil on one side and to the air void on the other side, while the bottom part is embedded in the soil on both sides. Due to the large surface exposed to the soil, these structures show a great potential for geothermal activation. EWs represent a modern and innovative solution to provide heating/cooling to buildings (Brandl, 2006). The objectives of this study are: (i) to analyze the 3D seepage problem in presence of a thermo-active wall; (ii) to understand how environmental conditions affect the thermal exchange and to estimate the geothermal potential of EWs (without heat pump operation) starting from basic thermo-hydraulic knowledge of the site; (iii) to propose a methodology for the early-stage design based on a flowchart.

Hydro-thermal analyses on energy walls

In order to study the aforementioned objectives (i) and (ii), an extensive campaign of numerical analyses have been planned, which accounts for the high number of thermo-hydraulic parameters playing in this problem. When analyzing the seepage around an impervious plane, two velocity directions have to be considered: perpendicular and parallel to the wall plane (Kuerten, 2015). In the case of EWs, there is a heat exchange within the wall and the soil and the presence of the groundwater flow (imposed by means of hydraulic heads at the boundaries) moves the heat around the geostructure following the flow direction. The main parameters that are governing this problem are: soil and concrete thermal conductivities, temperature distribution in the soil profile, tunnel air temperature and convective coefficient (Bourne-Webb et al., 2016), inflow temperature in pipes, wall depth. The numerical analyses account for two solvers: a stationary solver in which the application of the thermal and hydraulic boundaries takes place, and a time-dependent one in which the geothermal system is activated which is fixed up to a condition where steady-flux, e.g. temperature difference between the heat exchangers and the soil is constant, is attained. The modelled wall and raft have the following dimensions: wall thickness $t_{wall} = 1.20\ m$, longitudinal length $L_{wall,tot} = 8 * H_{wall}$, wall height $H_{wall} = 25.5\ m$; raft width $L_{raft} = 30\ m$, raft height $h_{raft} = 2.50\ m$. The full 3D model accounts for the following geometrical features in the x,y,z components: $8H_{wall}$, $16H_{wall}$,$5H_{wall}$, respectively. The hydraulic boundaries are set as follows: hydraulic heads are applied at the groundwater inflow and outflow boundaries in order to define suitable velocity fields, all the other boundaries are set as impervious. From a thermal perspective, a temperature distribution is set at the groundwater inflow region, constant temperature is applied at the ground and at the bottom surfaces, the outflow boundary is adiabatic, the wall-tunnel interface is a convective boundary while the top part of the tunnel is adiabatic. The heat exchangers are modelled as linear entities (Batini et al., 2015). The fluid flow and the associated convective heat transfer inside the pipes are simulated by means of an equivalent solid having the same thermal properties (i.e. heat capacity per unit volume and thermal conductivity) of the circulating fluid. The circulating fluid is water.

In order to account for the hydro-thermal coupling, the numerical model has been implemented in the commercial software Comsol Multiphysics®. The soil is considered as a porous medium composed by a solid matrix and a liquid phase, the concrete is considered as a solid. The hydro-thermal coupling in the porous medium is accounted by means of the local thermal equilibrium hypothesis, which assumes pointwise equality of temperature in the solid and liquid phases (Nield et al., 2002). The governing equations are the mass conservation equation, the Darcy's law, and the energy conservation equation. The energy conservation equation related to the incompressible fluid flow in the embedded pipes accounts for the convective heat transfer within the fluid and the conductive heat transfer through the pipe wall (Gnielinski, 1976; Haaland, 1983).

The performed simulations allow to make the following considerations for the objectives of the study.

1- Analysis of the 3D seepage problem

The hydro-thermal interaction results in a slight modification of the seepage grid with respect to the isothermal case because of the temperature dependency of water density and dynamic viscosity. As assumption of the model, the hydro-thermal properties of the solid skeleton are not temperature-dependent. It is essential to consider the 3D nature of the problem, hence the modifications of the seepage grid are a local effect, limited to the regions where the thermal exchange takes place. In the case of groundwater flow perpendicular to the wall, the flow at the soil-wall interface acts in vertical direction in a zone with almost constant temperature due to the uniform presence of the pipes. Very little modifications of the seepage grid are detected with respect to the isothermal case, which are mainly due to the temperature difference between the pipe inflow and outflow zones. In the case of groundwater flow parallel to the longitudinal direction of the wall, the thermal exchange acts perpendicularly to the groundwater direction, hence local modifications of the Darcy velocity components at the soil-wall interface are highlighted. This case is particularly interesting because, similarly to what happens on energy piles, the presence of the groundwater flow significantly enhances the thermal interactions among subsequent pipe loops, hence the thermal efficiency of each loop decreases.

2- Estimation of the geothermal potential by using EWs

The goal of this work is to propose a tool with which a user, by having a basic thermo-hydraulic knowledge of the site, can estimate the energy extraction/injection potential of using EWs. In the analysis of the power extraction/injection at steady-flux conditions, the most important parameter to account for is the average temperature of the soil deposit due to the large, continuous surface between wall and soil which is exposed to thermal exchange. The presence of groundwater flow can significantly improve the thermal performance, especially if the velocity component parallel to the wall longitudinal direction is significant. On the other hand, groundwater flow inhibits the possibility of thermal storage (Fromentin et al., 1999). Thermal conductivity of soil and concrete play an important role. Particularly, the concrete thermal conductivity can significantly vary in function of the water content: a significant variation of the water content in the concrete between the fully embedded zone and the upper part of the wall can be attained. This will result in variations of the thermal performance. The results of this work show that the thermal performance of the heat exchangers ranges between 10-25 W/m^2 for winter and 15-35 W/m^2 for summer modes.

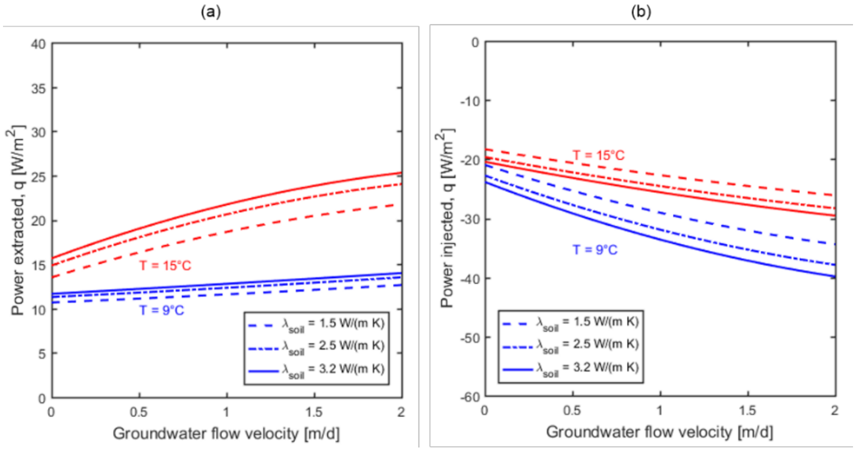

Fig. 1: Thermal behaviour of an EW at steady-flux condition for (a) winter and (b) summer operation

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