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Investigation on the behaviour of a thermo-active diaphragm wall by thermo-mechanical analyses

Donatella Sterpi[a,b,*], Andrea Coletto[a], Luca Mauri[a]

[a] *Department of Civil and Environmental Engineering, Politecnico di Milano, Italy*

[b] *P. Leonardo da Vinci, 32, 20133 Milano, Italy*

HIGHLIGHTS

- The layout of the exchanger pipe loop governs the energy performance.
- A realistic definition of the thermal boundary conditions and thermal inputs at the pipe inlet is crucial.
- The thermally induced variations of the wall axial forces and bending moments are not negligible.
- Different cross sections of the wall behave differently and mutually interact.
- A three-dimensional analysis is required, instead of the more conventional plane strain analysis.

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ABSTRACT

The thermo-active diaphragm walls are traditional retaining structures that embed heat exchangers for the exploitation of the near surface geothermal energy, used in the thermal conditioning of buildings and infrastructures. The coupled energetic and structural function of these so called energy walls requires some investigation in order to optimize the embedded circuit and assess the possible occurrence of significant consequences, in terms of temperature variations within the soils mass and thermal effects on the stress/strain state of the structure. In this contribution, the behaviour of an energy wall is assessed by finite element thermal analyses, that allow to investigate the energy performance and the short and long term influence on the soil temperatures, and by finite element thermo-mechanical analyses, to highlight the wall geotechnical and structural response. A one year cycle of heating/cooling operating mode of the geothermal system has been considered and the effects have been discussed in terms of soil–structure interaction and structural internal actions. The results show that the thermally induced mechanical effects are not negligible, especially as variations of the internal axial forces and bending moments. Although they seem to be not detrimental to the geotechnical and structural safety, they require a careful evaluation in order to predict possible situations of unexpected overstress conditions.

1. Introduction

Recent statistics report that the worldwide energy supply and consumption have more than doubled over the last forty years and that fossil fuels still cover more than 80% of the total energy supply.[1] The energy demand is expected to increase due to the demographic and economic growth of large geographic areas of the developing world.

* Corresponding author.
E-mail addresses: donatella.sterpi@polimi.it (D. Sterpi), andrea.coletto@mail.polimi.it (A. Coletto), luca1.mauri@mail.polimi.it (L. Mauri).

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The production and consumption of energy based on fossil fuels are responsible for large part of greenhouse gases and air pollutants, with consequent environmental and climate impacts. The use of renewable and green energy sources nowadays represents a necessary choice in order to cope with the growing energy demand, with the predictably increasing energy costs, and with the need for an environmentally sustainable progress. Among these sources, the geothermal energy represents an efficient solution for its massive potential, the steadiness with respect to the variable atmospheric conditions, the low environmental impact and the cost competitiveness. If in actual fact deep geothermal reservoirs, exploited for electrical energy production, can be localized only in particular geographic areas, the geothermal energy at low depths or at the near-surface, for direct use as thermal energy, is pervasively available.[2] This characteristic makes it optimal for a local harvesting and diffuse distribution.

Building and space heating and cooling technology is among the most important direct applications of shallow geothermal energy. In fact, the sector of buildings and spaces for domestic, commercial and public service use, has surpassed the sectors of industry and transport, heating currently accounts for 40% of building energy demand, and the cooling demand is expected to rise significantly in the next years.[1,3] In addition, buildings have an impact on long-term energy consumption, due to their long renovation cycle, for which reason new buildings should be designed in respect of a high energy performance. The majority of energy consumption takes place in the centre of large urban areas, due to their higher population density and higher living standards. District heating and cooling systems may therefore represent a critical infrastructure where renewable energy sources could be used in an integrated system.[4] In this framework, the use of near-surface geothermal energy is crucial for meeting the European targets about renewable energy exploitation and greenhouse gas emissions reduction.[5]

The so called energy geostructures are conventional reinforced concrete elements, embedded in the ground and designed to serve a primary structural function, that are in addition thermally active since they host heat exchanger pipes with the purpose to use the subsoil to disperse heat in summer and extract heat in winter. This system, although basically limited to the new constructions, offers the advantage of using existing structural components without requiring additional works and the availability of additional areas, with the associated costs. The energy geostructures can provide thermal conditioning to buildings and spaces and also to large infrastructures, such as airport runways and bridge decks, to mitigate the effects of high temperatures in summer or freezing temperatures in winter.[6,7]

In general, the challenges in the design of energy geostructures stem from their coupled structural and energetic function and from the strict connection of several disciplines,[8,9] as outlined by the broad spectrum contributions in Laloui and Di Donna,[10] and in the comprehensive review by Brandl.[11] Thermo-active piles were the first geostructures to be designed in the 80s mainly in Austria, closely followed by diaphragm walls and floor slabs, often associated with the cut-and-cover construction of shallow tunnels.[12–16] In the 2000, the technology spreads to bored tunnels segmental liners[17–20] and, more recently, to anchors for tunnel reinforcement and retaining walls.[21]

The energy performance of these geostructures firstly depends on the ground hydro-geological conditions and thermal properties. The preliminary investigation can be considered similar to the one conventionally carried out for the design of shallow ground source thermal systems, aimed at recognizing the subsoil and the excavation feasibility, especially in urban areas.[22–24] The thermal properties can be identified from the properties of the soil constituent phases or from on site thermal response tests.[25,26] The energy performance depends also on the geometry of the geostructure, i.e. the overall surface extension on which the heat transfer can take place, the depth that the geostructure reaches, and the presence of exposed surfaces. For instance, piles can reach high depths, diaphragm walls have a wide surface extension and tunnels take advantage of both depth and surface extension. In addition, piles are fully embedded, while diaphragm walls and tunnels have exposed surfaces with specific conditions of heat flux.[27] Finally, an analysis is required about the climate conditions and the building physics, including the natural thermal energy transfer between the building and the atmosphere and the building and the ground.[28,29]

The role of the groundwater flow has been considered firstly for traditional borehole heat exchangers[30] and then for geostructures such as piles, diaphragm walls and tunnels.[7,31–33] A positive influence of the flow in high permeability soils has been recognized whenever there is a need to seasonally restore the ground thermal energy, i.e. when the geothermal system is used yearly in one season only, for either cooling or more often heating. Conversely, when it is used in dual operating mode and the soil works as seasonal thermal energy storage mass, the groundwater flow is detrimental to the system efficiency.

The behaviour of thermo-active piles, or energy piles, has been largely investigated, in terms of both energy efficiency and thermo-mechanical response. Monitoring data from instrumented full scale energy piles[13,34,35] provided major insights in the geotechnical and structural consequences of the heat transfer and established important databases for the validation of numerical analyses and the calibration of the relevant parameters.[36–39] Taking advantage of ideal, controlled and repeatable conditions, also laboratory tests on small scale models helped in identifying the pile response capacity.[40–44] The thermal effects represent additional contributions to the mechanical loads and highly depend on the level of constraint that the soil exerts on the pile in terms of lateral friction and base bearing.

Similar consequences are also expected in thermo-active reinforced concrete diaphragm walls, briefly referred to as energy walls, but the effects of thermal loads on energy walls are less investigated and also less predictable than on energy piles, due to a greater complexity in geometry and constraints and uncertainties in the thermal boundary conditions. For the same reasons, also heat transfer models developed for borehole heat exchangers or energy piles cannot be straightforwardly extended to energy walls and suitable models need to be introduced. In order