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Structural and geotechnical effects of thermal loads in energy walls

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Abstract

Geotechnical structures embedded in the ground and equipped with heat exchangers permit to exploit the ground thermal energy. Their design should combine the prior structural function with the energetic function, and their response, under both thermal and mechanical loads, is still being investigated. Considering an energy diaphragm wall, the aim is to investigate, by sequentially coupled thermo-mechanical analyses, the heat transfer effects on the soil temperatures, the wall internal actions and the soil-structure interaction. The results show that the additional thermal loads are admissible, in terms of global stability and structural safety, though generally not negligible, since unusual internal actions, such as tensile axial stresses, may develop that should be taken into account in the design.

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Keywords: Heat transfer; geothermal system; thermo-mechanical analysis; Finite Element analysis

1. Introduction

According to European figures about energy consumption [1], the building sector has surpassed the industry and transport sectors. Heating currently accounts for 40% of building energy demand and the cooling demand is expected to rise in the next years. The promotion of geothermal energy for the thermal conditioning of buildings and infrastructures is crucial for meeting the European targets about renewable energy exploitation [2]. In fact, the geothermal energy represents an efficient solution for its massive potential and its steadiness with respect to the variable atmospheric conditions. In addition, the geothermal energy limited to shallow depth or to the so called near-

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surface is pervasively available and, therefore, optimal for local harvesting and diffuse distribution, that ultimately reduce the transport costs and help local communities to enhance their energetic self-sufficiency [3].

The thermo-active geostructures (piles, diaphragm walls, tunnel liners, etc) are conventional reinforced concrete elements that embed heat exchangers with the purpose to use the subsoil as a reservoir, to disperse or extract heat during, respectively, the summer or the winter seasons [4,5]. With respect to the more traditional borehole heat exchangers, this relatively new system, though limited to new constructions, offers the advantage of using existing foundation elements, without requiring additional works and additional areas. The challenge in their design stems from the connection of several disciplines: designed to serve a prior structural function, but subjected to combined thermal/mechanical loads, their response under various working conditions still requires a thorough investigation, so to reach an optimal combined energetic, structural and geotechnical design [6].

Considering a thermo-active diaphragm wall, or briefly “energy wall”, the aim of this research is to investigate, by three–dimensional numerical analyses, the effects of the heat transfer process on the soil temperatures, on the wall internal actions and on the soil–structure interaction. First, a thermal analysis permits to investigate the thermal working conditions of soil and wall, subjected to heating/cooling cycles and to seasonal variations of atmospheric temperatures. Then, the cyclic thermal loads are applied in a thermo–mechanical analysis to get insights into their effects in terms of global stability and structural safety.

2. Features of thermo-active piles and walls

The thermo-active geostructures that were most installed and investigated are the energy piles. Experimental and numerical analyses highlight the role of the pile-soil interface and of the boundaries at the head and toe in exerting a restraint to the thermal expansion of the pile when heated and contraction when cooled. This restraint leads to internal stresses that act in addition to those induced by the mechanical loads [6-8]. Various influence factors have been considered, such as the thermo-mechanical behaviour of the interface, the variations of lateral pressures induced by the thermal contraction and expansion, the cyclic nature of the thermal load and its possible detrimental action on the shaft resistance [9-11]. As to the behaviour of the soil mass, suitable non isothermal constitutive models have been recently proposed for saturated fine soils, in which the difference in the thermal expansion of soil and water induces a short term increase of pore pressures and a consequent long term consolidation process [12]. In energy piles, significant changes, that should be taken into account at a design stage, were eventually pointed out in the mobilised shaft resistance and in the pile displacement and axial load [13]. Parameter sensitivity analyses help in reaching the optimal energetic and structural design for single piles and pile groups [14,15].

Similar effects are expected also in energy walls. However, the thermally induced strains and stresses are less predictable due to a greater complexity in the geometry (the presence of constraints from adjacent structural components, such as anchors or slabs) and in the thermal boundary conditions (the wall is fully embedded in the soil in its lowest part only, leaving an undetermined thermal condition on the face exposed to the excavation). In addition, the energy walls offer broader choices of different layouts of the heat exchanger, that affect the temperature gradients within the wall panels and the consequent energy performance and thermo-mechanical response [16-19]. In all the reported cases of energy walls [4,20,21] the thermal conditions on the domain boundary and the thermal inputs, linked with the building energy demand, play a crucial role. Due to difficulties in the problem modelling and to the current exiguity of field monitoring data, the thermo-mechanical behaviour of energy walls has not yet been fully investigated.

An energy wall offers a structural function entirely different from the one of a pile, since it is basically subjected to horizontal pressures contrasted by its flexural response and by the supporting action of possible anchors and struts. Variations of pressures induced by the materials thermal contraction or expansion could be of interest, while the possible detrimental action induced by cyclic thermal loads could be neglected, since the interface shear resistance is not a key factor in the structural behaviour of the wall. In addition, temperature gradients in the wall plane develop not only in the vertical direction, but also in the horizontal direction, due to the non negligible distance that usually exists between cool and warm portions of the heat exchangers. As a consequence, two different vertical cross sections are subjected to thermal loads of different magnitude and their mutual interaction leads to three-dimensional effects in the stress-strain distribution and in the internal actions. The conventional 2D plane strain analysis of the energy wall could be therefore inaccurate [22].

3. Geometry, properties and working conditions of the energy wall

The energy wall here considered is assembled with single panels, each of 15 m height, 2.4 m length, 0.5 m thickness, and hosting two heat exchangers. The excavation is 10 m deep and the bottom is covered with a floor slab of 0.5 m thickness (Fig. 1). The occurrence of parallel symmetry planes, at a distance of 1.2 m from each other, allows for the analysis of a three-dimensional domain, 1.2 m wide, corresponding to half of the single panel.

The temperature effects on the materials behaviour are limited to the thermal expansion and the hydro-mechanical coupling effects are neglected. The reinforced concrete elements are modelled as homogeneous, isotropic and elastic. The soil mass consists of silty sand of increasing stiffness with depth, in a saturated condition and hydrostatic regime, and is modelled as isotropic, elasto-plastic, with Mohr-Coulomb failure criterion and non-associated flow rule. A thin layer of elements, adjacent to the wall elements, represents the soil-wall interface, with poorer mechanical properties (Table 1). The heat transfer is modelled by conduction in the concrete and the soil, and by convection in the heat exchanger, assuming the fluid velocity (0.05 m/s) and the fluid temperature at the pipe inlet (2°C from November to April, 30°C from June to August). Thermal boundary conditions are reported in Figure 1.

The finite element analyses are conducted in a sequentially coupled way: first, a thermal analysis of the soil-structure system permits to investigate the energy performance and to calculate the cyclic temperature variations. Then, a thermo-mechanical analysis is carried out, simulating first the construction process and then the effects of the geothermal system, with the application of the cyclic temperature variations as thermal loads.

It should be remarked that the initial temperature field, corresponding to the undisturbed condition, has a natural yearly periodicity that depends on the seasonal atmospheric temperatures. The additional input of the geothermal system modifies the natural heat transfer process, with an initial transient phase that ends when the yearly balance is reached between the overall heat stored in the summer season and lost in the winter season, and the temperatures reach new yearly cyclic steady state values. In a hydrostatic regime, the seasonally alternated energy recharge (i.e. the heating/cooling operating mode) is crucial to limit the thermal drift within the soil mass and to preserve the energy efficiency of the geothermal system in the long term.

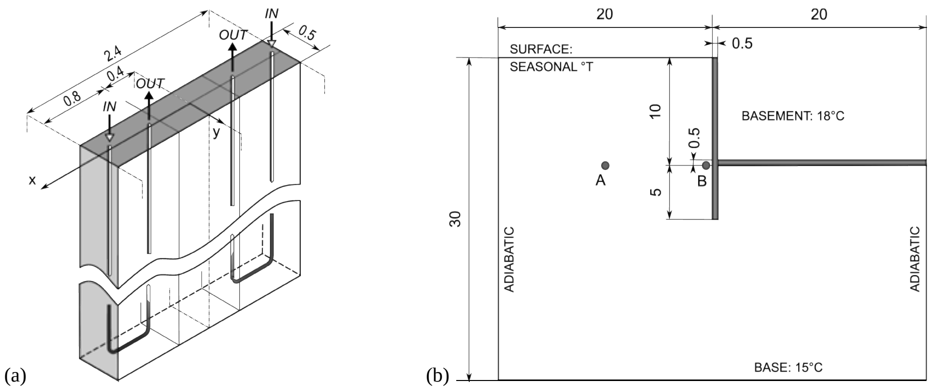

Fig. 1. (a) Sketch of the single panel of the energy wall; (b) Cross section of the excavation and thermal boundary conditions (unit: m).

Table 1. Physical, thermal and thermo-mechanical properties of the materials.

	Density (*kg/m*^{3})	Saturated water content	Thermal conductivity (*W/m°C*)	Specific heat (*J/kg°C*)	Young modulus (*kPa*)	Poisson coeff.	Cohesion (*kPa*)	Friction angle (°)	Dilatancy angle (°)	Thermal expansion (*1/°C*)
Saturated soil	1930.	0.32	2.2	1642.	80-120.	0.3	20.	32.	15.	10^{-5}
Soil-wall layer	1930.	0.32	2.2	1642.	80-100.	0.3	1.	22.6	5.	10^{-5}
Reinf. concrete	2500.	–	2.6	880.	30000.	0.2	–	–	–	10^{-5}
Heat carrier fluid	1000.	–	0.57	4186.	–	–	–	–	–	–

4. Temperature field and energy performance

The heat transfer process induced by the geothermal system modifies the natural temperature field of the soil mass, the highest temperature gradients in the y direction being localized within 2.5-3 m from the wall surface. At a steady state condition, in the proximity of the left side soil-wall interface, the temperature varies between minimum and maximum values governed by the heating/cooling phases and slightly dependent on the depth. Conversely, at a larger distance from the wall the temperatures are governed mainly by the cyclic seasonal variation. A small thermal drift can be observed, that ends after few years and is limited to a maximum decrease of 1°C. As an example, Figure 2a reports the variation of temperature at points A and B shown in Figure 1b.

The temperature within the wall is reported in Figure 2b, with reference to the periods of highest (August) and lowest (April) values. The variation with depth shows the marked influence of the boundary condition represented by the lateral basement (18°C, up to the depth of 10 m). The comparison between the curves associated with the three different cross sections highlights the occurrence of a gradient along the horizontal direction.

The energy performance is analysed with reference to the monthly exchanged energy. The heat flux is calculated from the difference between the fluid temperatures at the pipe inlet and outlet, which are shown in Figure 3a with the variation of the seasonal temperatures at the ground surface (data provided by ARPA-Lombardia). From the heat flux, the exchanged energy is calculated per month and unit area of the energy wall (Fig. 3b). A loss of efficiency is noticed in each heating/cooling phase, for instance up to 21% between November and April, due to the effect of thermal energy storage within the soil mass. The fluid temperature at the outlet undergoes a variation in the years, that reflects in a variation of exchanged energy: an increase in June (16%) and a loss in November (1%). The steady state condition is reached in about four years.

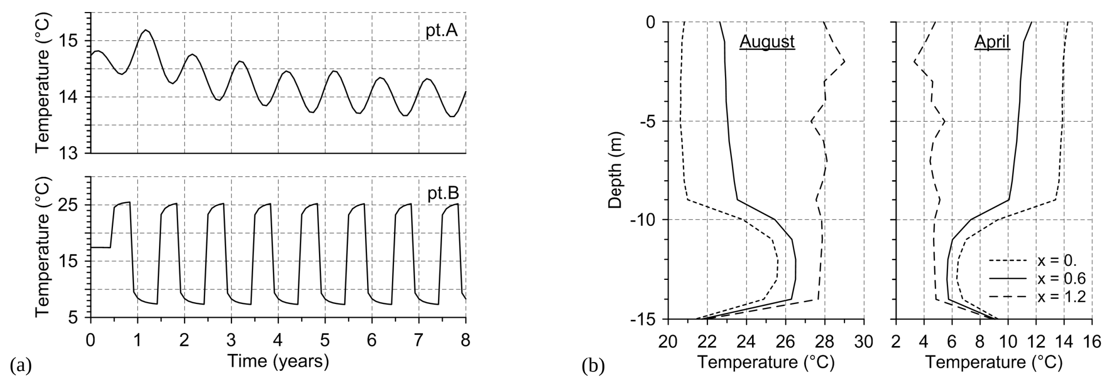

Fig. 2. (a) Variations of temperature induced at points A,B in the soil mass (see Fig.1b); (b) Variations of temperature in the energy wall.

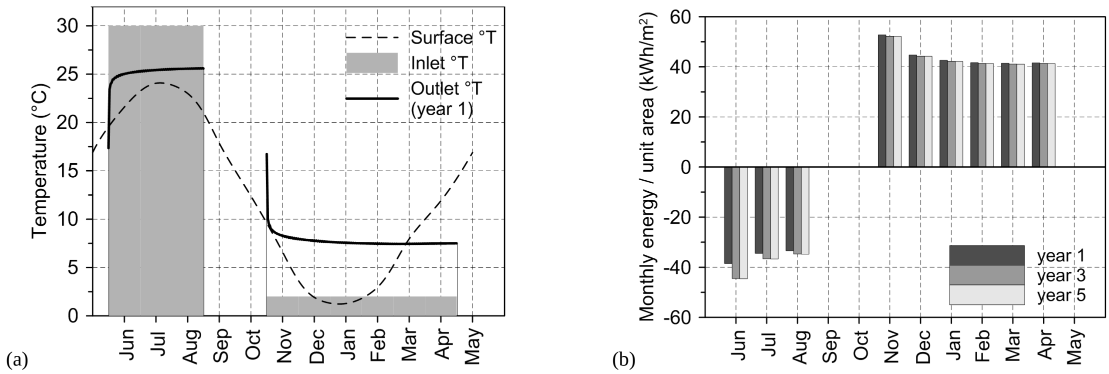

Fig. 3. (a) Temperatures at the ground surface and at the pipe inlet and outlet; (b) Thermal energy exchanged per unit area of the energy wall

5. Geotechnical and structural behaviour

The thermo-mechanical response is analysed with reference to the steady state condition. The lateral earth pressures vary over the year between the lowest (April) and highest (August) values shown in Figure 4a. The thermal expansion of the materials induces an increase in the horizontal pressure, that reaches a maximum of about 31% in the active zone and 9% in the passive zone, at the depth of 12 m. The steady state displacements of the wall top, compared with the response under solely the atmospheric temperatures (solid vs. dashed lines in Fig. 4b) show the accumulation of not reversible displacement occurred in the transient phase, and indicate that in the summer period the wall tends to elongate, with a maximum increase in horizontal displacement of about 8%. These results refer to the section that is mostly influenced by the fluid inlet temperatures (x=1.2 m), but the variations of pressures and displacements in the x direction turn out to be negligible. From these calculated values, the thermal effects seem to be acceptable in terms of geotechnical safety.

The minor variations of wall displacements correspond to major thermally induced stresses that lead to major variations in the wall internal actions. In addition, the temperature gradient arising in the x direction (Fig. 2b) induces a remarkable difference of internal actions in different wall sections. The axial force and bending moment per unit length x of the wall are calculated as integral of the axial stresses and moments at a given section x. As expected, the section x=1.2 m undergoes an increase in compressive axial load in August and an increase in tensile axial load in April (Fig. 5a), due to the restraints that limit respectively its thermal expansion (August) or contraction (April). These restraints, exerted by the adjacent sections of the wall and by the surrounding soil, are reflected in the tensile (August) and compressive (April) axial loads of section x=0.m. The thermal stresses affect also the bending moment per unit length (Fig. 5b), although in this case the variations in the x direction can be considered negligible. The variation over the year is significant only in the upper part of the wall, above the base slab, where in April the wall increases its flexural deformation while undergoing a contraction (see the vertical displacement in Fig. 4b).

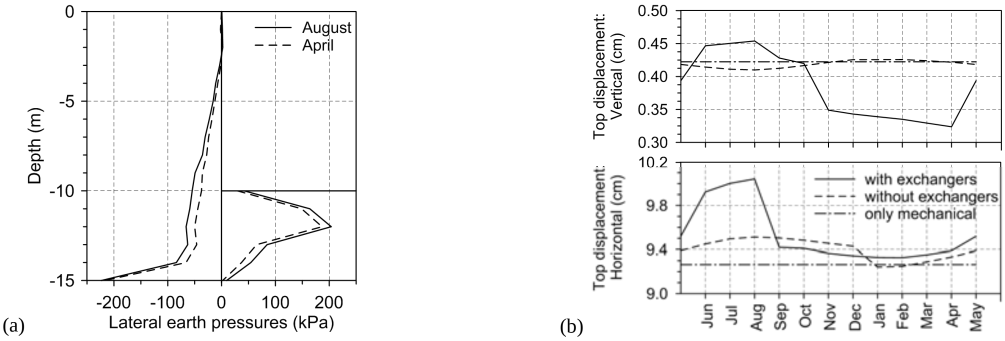

Fig. 4. (a) Lateral earth pressures in two periods of the year; (b) Variation of the displacements at the wall top over the year (x=1.2m)

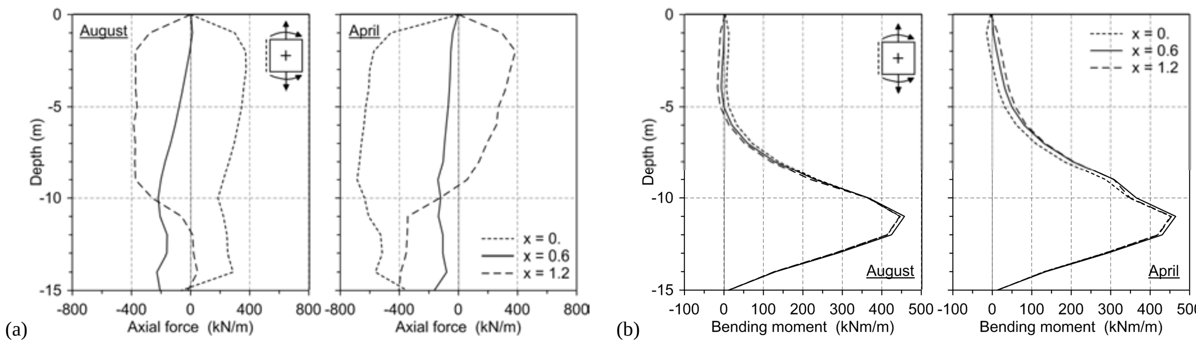

Fig. 5. (a) Axial load and (b) Bending moment within the wall in two periods of the year and in three cross sections.

6. Conclusions

The structural and geotechnical response of an energy wall, as highlighted by sequentially coupled thermo-mechanical analyses, is similar to the one observed in energy piles, but the complexity in the geometry and boundary conditions of the wall make the results not easily predictable. The conventional plane strain analysis has to be replaced by a three dimensional scheme, due to temperature gradients arising the wall longitudinal plane. The thermal loads can be considered not detrimental to the global stability and structural safety of the wall, since they affect mainly the axial elongation/contraction and mildly the flexural response. However, they induce internal actions that are unusual in ordinary diaphragm walls and therefore they should be taken into account for the optimal design. A further investigation is also required on the influence of the additional connected structures and of the thermal boundary condition at the excavation side, the latter affecting not only the thermal loads but also the estimation of the energy performance.

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