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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].

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