Abstract of Research Project
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RESEARCH PROJECT (max 3 pages):

Introduction and state of the art

The world energy demand is constantly growing and currently primarily based on the use of fossil fuels, the main responsible of the critical air pollution condition. Therefore, there is an urgent need to develop technologies for the exploitation of renewable resources which can reduce the dependence on traditional sources at the national level. The heat contained in the most superficial layers of the Earth's crust (Low Enthalpy Geothermal Energy - LEGE) represents one of the most common forms of renewable energy and it can be effectively exploited in various practical applications. The first examples of exploitation of this resource are based on heat pump systems (GSHP), used for heating, ventilation and air conditioning (HVAC) systems for buildings, with a significant reduction in CO2 emissions compared to the traditional systems. More recent applications involve the use of foundation structures on piles and micropiles (Energy Piles – EP, and Energy MicroPiles – EMP), where the mechanical role is associated with the energetical one of heat exchange with the ground, with the advantage of avoiding additional construction costs. This research project aims to improve the current state of knowledge on the thermo-hydro-mechanical effects generated by the interaction between the ground and the energy structures in order to promote their diffusion in civil engineering.

The understanding of the thermo-hydro-mechanical behavior of Energy Structures has been the subject of numerous studies in the literature, which offer a broad view of the analysis methods and experimentation for evaluating the effects induced by the use of the geothermal resource. The two pioneering works are attributed to Laloui et al. (2006) and Bourne-Webb et al. (2009), who conducted experimental field tests of full-scale Energy Piles at the Swiss Federal Institute of Technology in Lausanne and at the Lambeth College in London, respectively. More recently Rotta Loria and Laloui (2016) demonstrated that significant thermally-induced group effects characterize closely-spaced Energy Piles; Murphy and McCartney (2014) tested two full-scale Energy Piles during the operation of a heat pump in the long term and with significant temperature variations. Energy MicroPiles represent a different perspective in the field of civil engineering applications of energy structures, mainly related to the retrofitting of existing buildings. Some of the earliest applications are attributed to Akrouch et al. (2014), who presented the result of an in-situ thermo-mechanical test on a small diameter EP in a very stiff high plasticity clay. More recently, two full-scale prototypes were installed at the Engineering Campus of the University of Perugia by Salciarini et al. (2018), with the aim of performing a series of thermo-mechanical load tests under full monitoring of the field data. The results have shown that, in terms of specific heat flux, the thermal performance of EMP falls within the range of typical values of conventional EP and it is largely influenced by the soil thermal conductivity. The thermal characterization of soils is extremely important, both in terms of energy efficiency of the geothermal system and in terms of the effects induced in the soil. Over the past two decades, many researchers focused on the effects of thermal loads in soils associated with the geothermal operation of EP. Due to its multiphase microstructure, the soil exhibits complex thermo-hydro-mechanical behavior, in which particle size, mineralogy and history of the stress state play an important role. The experimental investigation using lab tests by Di Donna and Laloui (2014) has shown that soils subjected to thermal load have a thermo-elastic response under over-consolidated conditions (OC) and thermoplastic response under normal-consolidated conditions (NC) and both the ratio of the void index both the plasticity index are considered responsible for the observed differences in terms of stabilization and irreversible deformation. To thermally characterize different soil types, by means of lab tests, Tarnawski et al. (2009) used a thermal needle probe while Nikolaev et al. (2013) employed a guarded hot plate apparatus: these are some of the most recent and comprehensive studies on the dependence of the thermal conductivity of soils at different degrees of saturation over a range of temperatures. The study of the thermo-hydro-mechanical behavior of soils, their characterization and what happens at the soil-structure interface in operating conditions becomes fundamental for an optimal analysis. The use of finite element software for accurate numerical modeling of the Energy Structures is an important resource for comparing and validating experimental results. The thermal characterization of the soil is a consequence of an adequate choice of a constitutive law capable of determining the main thermal parameters i.e. thermal conductivity and thermal resistance, and capturing the most significant thermo-mechanical effects.

Research objectives

The correct design of an Energy Structure requires the knowledge of the thermo-hydro-mechanical effects induced in the soils as well as the thermo-mechanical response of the structure itself, to obtain the maximum performance of the system. The present research plan aims to provide a contribution towards a better understanding of thermal operation conditions in EP and EMP installed in different types of soil. The list of goals to be pursued in this PhD project, identified by a careful analysis of the aspects for which the state of the art is not yet exhaustive, is the following:

1. <u>Study of soil thermo-mechanical behavior when subjected to thermal loads by means of triaxial lab tests with temperature control, using different specimens of coarse-grained and fine-grained soils</u>. The deformation and the failure behavior of different soil samples during a triaxial lab test in controlled thermal conditions will be analyzed and quantified. The effects due to the increases or decreases in temperature will be evaluated, which simulate the condition of soil in the heat exchange mechanism induced by the operation of energy structures.

2. <u>Monitoring of the response of full-scale EMP prototype during thermo-mechanical tests at the experimental field of the Engineering Campus of the University of Perugia.</u> In situ tests will be carried out on one of the two prototypes of EMP installed in the experimental field, called "EMP_n1", not tested yet during previous experimental campaigns. The influence of significant variables (fluid inlet temperature, groundwater level, external environmental temperature, seasonal climate, etc.) will be studied, to better understand how these parameters can modify the performance of the energy structure. Temperature and deformations will be continuously monitored in the different phases of operation, thanks to the sensors embedded in the EMP and in the ground. Winter and summer operation conditions, as well as cyclical heating and cooling phases will be considered in the experimentation.

3. <u>Numerical modeling of the thermo-hydro-mechanical behavior of Energy Structures by means of Finite Element codes.</u> The numerical simulations will be carried out, firstly, to reproduce the observed experimental response of the EMP full-scale prototypes; and, secondly, for assessing predictions of their long-term behavior in different operating conditions. Elastic and inelastic constitutive models for the soils will be adopted, to capture the key features of typical soil behavior under cyclic loading conditions (i.e., irreversibility of the deformations).

Methodology

In order to pursue the aforementioned objectives, the methodology used will be the following:

1. The soil thermal characterization is a crucial aspect in the energy structures design, since it has been demonstrated that the expected performance of the installed geothermal system depends primarily on the conductivity and thermal resistance parameters. These parameters can be measured by means of in-situ and lab tests. In the present PhD plan, lab tests will be carried out at the "Materials Testing Laboratory" of the Department of Civil and Environmental Engineering, using a temperature-controlled triaxial cell that allows the evaluation of the deformation and failure behavior of soil samples subjected to given thermal loads. The tests will be carried out on cylindrical soil specimens with a diameter of 10 cm and an h/d ratio equal to 2, using both coarse- and fine- grained soils, with different initial densities and different initial water volumes, subjected to different thermal loads (monotonic and cyclic). For the thermal characterization of the samples, they will be tested by heating in the steady state with a test apparatus consisting of a guarded hot plate apparatus and in the transient state using a needle probe.

2. The available experimental field will be used to study the performance and the mechanical response of the EMP full-scale prototype still not tested in previous campaigns (called "EMP_n1). Summer and winter operation conditions will be studied by injecting heating/cooling the system according to different seasonal temperature ranges. Also, the experimental field will be used for distributed and advanced thermal response tests (TRT). Both methods are based on temperature measurements made deeper along the shaft of the EMP using sensors placed in the ground, inside and outside the heat exchanger. In addition to temperature sensors, mono-axial strain gauges and strain gauge piezometers will also be used to monitor the thermo-hydro-mechanical response of the micropile-soil system in terms of deformations induced by thermal loads.

3. Finite element software (Plaxis for 2D modeling and Abaqus for 3D modeling) will be used to conduct complete coupled thermo-hydro-mechanical analyses of Energy Structures, using thermo-elastic or thermo-viscoelastic constitutive models for the soil volume around the piles involved in heat exchange processes, starting from the definition of the geometry of the system, the materials characterization and boundary conditions. A special focus will be reserved to the thermal and mechanical modeling of the heat exchange interface identified by the structure-ground contact, where the main thermal process occurs and where the shaft resistance acts.

Expected results

1. From the laboratory tests, information on the deformation and failure behavior of fine-grained and coarse-grained soil specimens subjected to different thermal loads will be obtained. The aim is to understand the physical mechanisms and variables that control the thermally induced stresses and deformations of the soil and to obtain a thermo-mechanical characterization of the most common soils where installations and operations of energy foundations on piles and micropiles take place.

2. From the in situ experimental tests, through the monitoring of thermal and mechanical parameters of both the energy structure and the ground, practical information for geotechnical and energy design will be obtained. Particulary, they will refer to the influence of: soil conductivity, position of the water table, inlet temperature of the heat carrier fluid, winter and summer operation conditions.

3. From the numerical modeling of Energy Structures by means of finite element computational codes, further insights on the thermal-mechanical behavior will be obtained. The mechanism of the interaction at the interface between the Energy Structure and the ground will be understood in detail through parametric studies with different thermal input. Finally, modeling will be useful for making predictions of the long-term behavior of the Energy Structure.

Summarizing, the PhD research project aims to broaden the frontier of experimentation and analysis of energy foundations on piles and micropiles and to expand the literature already available in terms of thermo-mechanical characterization of soils when they are involved in geothermal processes. The research aims to be a contribute from which designers can draw guidelines on the recommended ranges of thermal inputs, materials and geometric parameters in geothermal operations to achieve maximum efficiency in the installation of energy structures with low environmental impact and penetrate these installations as much as possible into current engineering practice.

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