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3D FE modeling of a real-world energy piled foundation

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Nowadays the growth in the consumption of fossil fuels, especially in the building sector, has become increasingly impacting, being closely related to the worsening of atmospheric pollution. Numerous efforts are therefore being made to resort to the use of technologies that allow the use of clean energy [1, 4]. The heat contained in the most superficial layers of the Earth's crust is called Low Enthalpy Geothermal Energy (LEGE) and represents one of the most common forms of renewable energy [3]. This resource can be effectively exploited in various applications: among these, Energy Piles (EPs) associate the traditional mechanical function with the energetical one by exchanging the heat with the ground [2, 6, 7]. The heat exchange is obtained by means of a fluid that circulates in pipes anchored to the reinforcement cages of the piles. This system allows for satisfying a large part of the energy needs of a building, providing for heating and cooling according to seasonal needs.

In this work, a case study of a private building located in the area of Perugia City (central Italy) is presented. The building is founded on n.55 bored and cast-in-place piles, with a length of 10 m. To supply the heating and cooling needs of the building for about 290 m^2 living area, all the piles have been instrumented to operate as heat exchangers with the ground. Thermo-energy monitoring was designed for n.4 foundation piles: for each one, n.10 K/PT100 thermocouples were installed in 5 cross-sections; other n.12 thermocouples were installed in the ground along 4 vertical metal pipes, placed symmetrically at distances of 0.5 and 1.5 m from the pile axis, and at 3 depths.

To experimentally study the Thermo-Mechanical (TM) behavior of the soil involved in the heat exchange process during the EPs operation, an initial TM characterization has been performed by means of laboratory tests. For the mechanical characterization of the soil under thermal load, thermally-controlled direct shear (DS) tests have been performed; while for defining the soil thermal properties, a Hot Disk TPS 2500S apparatus and an ATT DM 340 SR climatic chamber have been used. As for the DS tests, soil samples have been obtained from the cores extracted on-site at a depth of 10 m. The aim of the experimentation was to evaluate the effect of temperature on soil strength and at the soil-concrete interface, by using a modified direct shear test equipment described in [5]. Specifically, in the traditional shear box, a silicon heating mat featuring a nominal power of 2.5 W has been installed at the bottom of an R_{ck350} concrete plate to heat the sample. A temperature probe has been inserted into the plate, and the device has been connected to an external control box, with temperature regulation. Two different cement plates were used: a first one of 9 mm thick, to test the influence of temperature in the soil sample; and a second one of 19 mm thick, equal to the upper edge of the lower half-box, to allow the execution of the test at the interface between the two materials. The Hot Disk TPS 2500S apparatus has been used to estimate thermal conductivity, thermal diffusivity, and volumetric specific heat (with a nominal error of 3%, 5%, and 7%, respectively) of the samples, according to the ISO 22007-2 standard, which describes the Transient Plane Source (TPS) method. The experimental methodology was the following: *i)* drying of all the samples at 100°C, up to weight variation lower than 0.1%, and partial saturation of some, with a water content within the range 19–36%; *ii)* samples placement in the controlled environment of the climatic chamber, which can be artificially controlled in terms of temperature (within the range -40–80°C ±1°C) and relative humidity RH (within the range 10% ± 3%). The thermal properties have been evaluated after exposing the dry and partially-saturated samples to the following climatic conditions for at least 3 days and upon weight stabilization (0.1% variation).

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Referring to the available data of the building design and to the experimental results obtained, a 3D Finite Element (FE) model of the EP foundation has been reconstructed to analyze its thermo-hydro-mechanical behavior during normal operating conditions, using the FE code *Comsol Multiphysics*. The geometry of the entire foundation has been modeled in the central part of a volume of homogeneous soil. The domain has a dimension of 200 x 200 m, and the bottom boundary has been placed at a depth of 50 m from the ground surface. All the problem domain has been modeled and discretized, adopting a user-defined mesh with tetrahedral elements (Figure 1). Piles have been modelled with a linear-elastic material, the soil has been modelled as linear elastic–perfectly plastic with a non-associated Mohr-Coulomb failure criterium, while the pile-soil interface has been considered as perfectly rough. The mechanical load has been modelled as a uniform pressure acting on the top surface of the raft. An initial constant temperature of T_0=20°C has been assumed throughout the domain, and the temperature of each single EP has been increased/decreased linearly to simulate the normal operation of the EPs system, for a total duration of 1 year. The results of TM interaction between the EPs, considering different possible configurations of thermal activation/inactivation of EPs groups, have been analyzed. The axial load and the thermally induced vertical displacements in the EPs were found to strongly depend on pile spacing. Significant thermal interaction effects between EPs may occur for closely spaced thermally activated piles, in the case of cyclic heating and cooling. A sensitivity study performed on the thermal properties of soil, depending on the considered water content, confirmed that proper soil thermal characterization is of great importance for an accurate prediction of the THM effects. Since the site is still under construction, and the monitoring system is not operating yet, further analyses will be devoted to comparing the numerical results with the temperature distribution field obtained from the monitoring system.

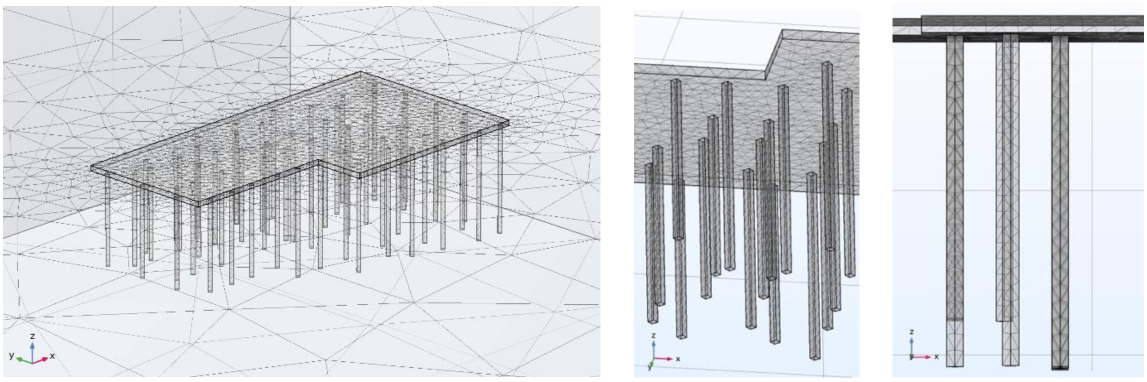

Figure 1: a) 3D view of the FE model geometry and domain spatial discretization.

Contributor statement

Conceptualization (Lupattelli, Salciarini), Formal analysis (Lupattelli, Salciarini), Project administration (Salciarini), Visualization (Lupattelli, Salciarini), Writing – Original Draft (Lupattelli), Writing – Review & Editing (Salciarini).

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