Numerical study on the thermo-mechanical interactions of a group of energy piles under cooling loads

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Energy piles are a relatively new technology that couples the structural role of canonical pile foundations to that of heat exchangers. These foundations, already needed for providing structural support to the superstructure, are equipped with pipes filled by a heat carrier fluid circulating into them to exploit the shallow geothermal flow in the upper crust as an energy source for the heating and cooling of buildings and infrastructures. In these systems, heat is exchanged between the foundations and the soil in a favourable way as the temperature of the ground remains relatively constant few meters depth throughout the year and the thermal storage capacities of both media are advantageous for withstanding the process. Geothermal heat pumps are connected to the piles and can transfer the stored heat to building and infrastructures during the winter, whereas collect and inject the heat resulting from spaces conditioning in the soil during the summer. Temperature values adequate to reach comfort levels in man-made environments and advantageous for engineering applications (e.g., de-icing of infrastructures) can be efficiently achieved through this technology.
The geothermal operation of energy piles involves innovative challenges for geotechnical and structural engineers, because in addition to the mechanical loads deriving from the superstructure dead load, temperature variations are applied to such foundations. Depending on the operation of these ground structures (heating/cooling working mode, i.e., superstructure heated/cooled and pile cooled/heated), variations of the stress and displacement fields along their length, and modifications of their shaft and base resistances are observed due to the applied temperature changes. Variations of the behaviour of the soil surrounding these foundations are also observed due the temperature changes, both in terms of shear strength and deformation.
Fundamental investigations on the response of single energy piles to the monotonic variation of thermal and mechanical loads have been obtained in recent years through full-scale *in-situ* tests [1-3], model-scale experiments [4-7], and numerical analyses [8, 9], resulting in the development of design tools [10, 11]. A recent state-of-the-art on the topic can be found in Laloui and Di Donna [12]. Latest numerical analyses [13-16] and experimental tests [17, 18] have considered the response of groups of energy piles to these loads. However, the effects of combined thermal and mechanical actions on the geotechnical performance of groups of energy piles are still poorly understood. The impacts of these loads, for different configurations of energy piles working as heat exchangers, are in particular barely known. Looking at such challenge, this paper presents the results of 3-D thermo-hydro-mechanical finite element analyses devoted to characterise the response of a full-scale group of energy piles subjected to cooling thermal loads and axial mechanical actions. The analyses exploit a 3-D finite element model referred to a group of four energy piles located under the Swiss Tech Convention Centre at the Swiss Federal Institute of Technology in Lausanne (EPFL) in Switzerland (cf. Figure 1), which has been validated by Di Donna *et al.* [16] based on experimental results obtained by Mimouni and Laloui [18, 19] through field tests. The work investigates the impact of cooling thermal loads typical of heating serviceability operations of energy piles on the response of these foundations, with a focus on the effects of different numbers of thermally activated piles on the group behaviour. It addresses hence the understanding of fundamental mechanisms and phenomena denoting groups of energy piles during heating geothermal operations. Three different numerical analyses are performed to deepen in detail the considered problem, with respect to three possible layouts of thermally activated piles (cf. Figure 2(a)). The numerical analyses first consider the application of the mechanical loads characterising the head of the energy piles in the full-scale realisation, then the imposition of temperature variations ΔT = -10 °C throughout a period of 15 days, and finally a period of constant cooling of 6 months (cf. Figure 2(b)).

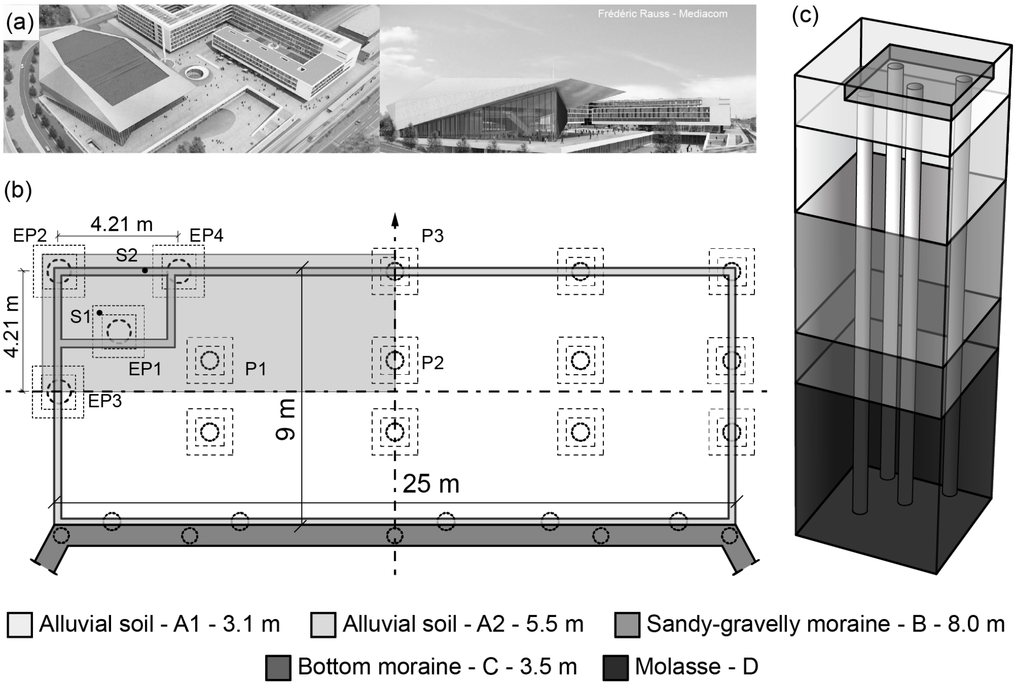

Figure 1: The EPFL Swiss Tech Convention Centre (http://www.tstcc.ch/, author: FrédéricRauss); (b) Plan view of the foundation including the four energy piles; (c) Scheme of the soil stratigraphy.

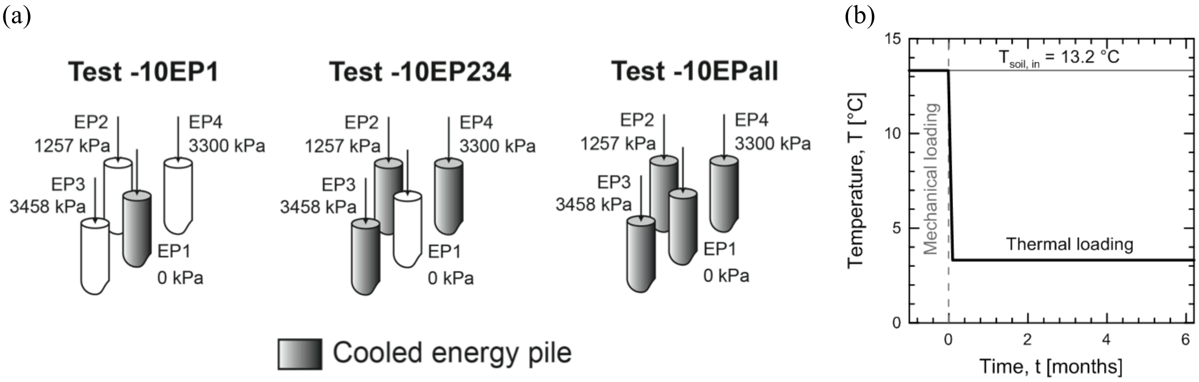

Figure 2: (a) Configurations for Test -10EP1, Test -10EP234 and Test -10EPall. (b) Thermo-mechanical loading paths applied in the numerical analyses.

From the analyses presented in this paper it can be concluded that cooling thermal loads characteristic of heating operation modes of energy piles do not yield to critical stress and displacement developments for the foundations according to current norms [20], preserving thus their geotechnical stability and serviceability performance. Remarkable thermo-mechanical interactions are however observed in the considered group of energy piles. The lower is the number of cooled energy piles, the higher are the stress reductions along their lengths (with potential tensile stress developments for low magnitudes of head mechanical loads) and the lower are the settlement enhancements. Conversely, the higher is the number of cooled energy piles, the lower are the stress reductions along their lengths but the higher are the settlement enhancements. The energy piles within the group that are not thermally activated are subjected to an increase of compressive stress along their length and to downward movements of their heads due to pile-raft-pile interactions. The thermal flow diffusion in the system associated to the cooling of the thermally activated piles plays a major role on the foundation mechanical behaviour, as it induces noteworthy group interactions for periods of constant thermal loading due to volumetric variations (e.g., contractions) of both the soil deposit and the inactive piles.

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