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Numerical modelling of energy piles in saturated sand subjected to thermo-mechanical loads

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HIGHLIGHTS

- Null point movement appears to be a critical characteristics of energy piles.
- Null point movement is controlled by distribution of forces at pile–soil interface.
- Plastic strain at pile–soil interface markedly influences null point shifts.
- Capturing null point shifts is crucial for the mechanical analysis of energy piles.
- A suitable plasticity model for pile–soil interface and soil behaviour is essential.

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ABSTRACT

This study investigates the impact that different magnitudes and combinations of thermal and axial mechanical loads have on the mechanical behaviour of energy piles in saturated sand. The work is based on the results of a series of thermo-hydro-mechanical finite element analyses, which are compared with centrifuge data, and parametric numerical runs. The analyses prove that an increase in heating loads induces a significant amount of stress and displacement in energy piles, with a remarkable mobilisation of their shaft and end-bearing capacity. Temperature variations up to $\Delta T = 50$ °C induce axial stress up to $\sigma_{th} = 716$ kPa and pile heave up to $dy_{th} = -14.09$ mm. These temperature variations mobilise an average side shear resistance and an end-bearing load normalised with respect to those mobilised at failure up to $q_{s,ave}/q_{s,ULT,ave} = -14.11\%$ and $Q_b/Q_{b,ULT} = 27.35\%$, respectively. The magnitude of these phenomena depends on the significance of the applied temperature variation, the significance of the applied mechanical load to the foundation head prior to thermal loading with respect to the pile axial capacity and the soil response to additional loading/unloading processes. These aspects serve a major role in the evolution of the foundation constraint, which governs the mechanical performance of energy piles when subjected to thermo-mechanical loads.

1. Introduction

Energy piles are an innovative technology that couples the role of the structural foundation to the role of the heat exchanger to satisfy the energy needs of buildings and infrastructures. During their geothermal and structural support operation, these ground structures can be subjected

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to various combinations of thermal and mechanical loads, i.e., temperature variations and mechanical charges deriving from the superstructure dead load. Fundamental investigations of the effects of the monotonic variation of these loads on the mechanical response of single energy piles have been obtained in recent years via a series of full-scale *in-situ* tests.[1–6] Numerical analyses[7–13] and model-scale experiments[14–21] have also been performed to obtain additional observations on the problem, enabling the response of energy piles to thermo-mechanical loading to be further characterised. Despite the increasing number of studies on this scope, knowledge about the dual role of thermal and mechanical actions on the mechanical behaviour of energy piles is still lacking in a range of applications and design conditions. To investigate the heating effects on the head settlement patterns and axial capacity of single energy piles in medium dense saturated sand, Ng et al.[22] recently performed a series of centrifuge tests. These tests have demonstrated the significant impact that increasing temperature variations have on the behaviour of energy piles by the development of greater stress and displacement variations along their length and null point and shaft and base resistances mobilisations, as well as increasing axial capacities. Due to the lack of an in-depth knowledge on the physical mechanisms governing the development of these processes with reference to the phenomena occurring in the soil region adjacent to the pile (e.g., mobilisation of forces at the pile–soil interface and pile toe, potential development of plastic mechanisms in these regions and related impact on the foundation constraint) this work proposes a follow-up study that extends the previously mentioned analyses. The objective of this paper is in particular to expand the effects of (i) different magnitudes of monotonic heating loads and (ii) axial mechanical loads, which are applied prior to the temperature changes, on the response of energy piles for additional loading. It addresses hence a better understanding of the fundamental interplay between thermal loads and mechanical loads and the consequent mechanical performance of single energy piles. The study is based on the results of a series of thermo-hydro-mechanical finite element analyses, which are compared with centrifuge data, and parametric numerical runs. The corroboration of the numerical approach with experimental data allows gathering information with adherence to physical reality on the considered aspects in a broad range of conditions, which may only be investigated employing noteworthy resources and time through an experimental approach. The finite element analyses were performed at the Swiss Federal Institute of Technology in Lausanne (EPFL), whereas the centrifuge tests were performed at the Geotechnical Centrifuge Facility of the Hong Kong University of Science and Technology (GCF-HKUST).[22] Because at the time of the numerical simulations described in this paper the centrifuge tests were being performed and the results about the experimental events were not available to the numerical modellers, the following finite element analyses are classified as ''Class B'' predictions.[23]

First, the key features that characterise the centrifuge modelling of energy piles are described. Second, the summary of the experimental programme is presented. Third, the details of the finite element model are summarised. Fourth, the comparison between the numerical and the experimental results are presented. Afterwards, data belonging to the numerical sensitivity analyses are described. Finally, general insights about the impact of different magnitudes and combinations of thermal and mechanical loads on the behaviour of energy piles are discussed.

2. Centrifuge modelling of energy piles

2.1. The centrifuge testing technique

The centrifuge testing technique enables the analysis of large engineering problems at the laboratory scale. This technique relies on the concept that a model-scale problem experiences a similar stress field as a N time bigger full-scale prototype problem if subjected to a centripetal acceleration N times greater than the Earth's gravitational acceleration.[24–26] Analogously to the use of hydraulic presses in structural engineering, wind tunnels in aeronautical engineering and flumes in hydraulic engineering, centrifuge model testing is employed in geotechnical engineering to replicate an event that is comparable to a prototype, i.e., real-scale, problem. The use of appropriate scaling factors and experimental methodologies have proved to be crucial for this purpose [e.g.,[26]], allowing in many cases a realistic similarity between the model and the prototype-scale problem by means of geometric and dynamic similitudes. A summary of relevant scaling factors proposed by Schofield[24] and Taylor[26] is reported in Table 1.

In this study, three pile tests have been performed at 40-g. The features of these tests are summarised in the following and analysed in detail by Ng et al.[22]

2.2. Centrifuge model package

Fig. 1 shows a schematic diagram of the centrifuge model package. The tests are performed in a container with internal dimensions of 1245 mm × 350 mm × 850 mm (length × width × height). The internal walls of the container are thermally insulated by an 18 mm thick wooden layer. The wooden layer is coated with plastic membranes to prevent water from seeping into it. Three piles are installed in Toyoura sand, i.e., one reference pile, RP, and two energy piles, EP15 and EP30. Each pile has a diameter D of 22 mm and is embedded to a depth of 490 mm. According to previous studies,[27,28] the spacing between the piles and the insulation boundary are sufficient to prevent boundary effects.

2.3. Model piles and instrumentation

All model piles are pipe piles made of aluminium alloy with an inner diameter, outer diameter and length of 13 mm, 19 mm and 600 mm, respectively. The top of the pipes is connected to a pile cap, whereas the bottom of the pipes is connected to a conical pile shoe with an inclusion angle of 60 °C. Ten levels of strain gauges are installed at 60 mm intervals, beginning at 40 mm from the pile cap. With the exception of the reference pile, thermocouples