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COOP Project: Energy piles under combined loading

Projet COOP: Pieux énergétiques sous sollicitations combinées

H. Mroueh*
University of Lille, IMT Lille Douai, Univ. Artois, Yncrea Hauts-de-France, ULR 4515 - LGCgE, Laboratoire de Génie Civil et géo-Environnement, Lille, France,

T. Badinier, M. Blanc, T. Dubreucq, J. de Sauvage, F. Szymkiewicz
Univ Gustave Eiffel, GERS-SRO, Marne-la-Vallée, France

J.-M. Pereira, A.-M. Tang
Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France

R. Vasilescu
ENTREPRISE PINTO, Fougères, France

**hussein.mroueh@univ-lille.fr*

ABSTRACT: The growing energy needs of urban areas and the environmental context are leading to the development of new geothermal technologies. In this context, energy geostructures, such as thermo-active (or energy) piles, were developed in the early 1980s and consist of heat exchanger tubes fixed to the reinforcement cages of foundation piles to extract/inject heat from/into the ground to meet the heating and cooling needs of buildings. Their specificity lies in their dual function: structural support and energy exchanger. Therefore, two aspects can be critical and should be considered in their design. The first is the nature of the cyclic thermal load acting along the energy pile, which can affect its mechanical response. Consequently, the cyclic thermal loading can cause a variation in the shear stresses at the soil-pile interface, thereby affecting the pile's load-bearing capacity. The second aspect concerns the adaptation of the design under combined lateral and axial loading, i.e. the interaction between lateral (or axial) loading and the axial (or lateral) behaviour of the energy piles, coupled with volumetric thermal loading acting on the surrounding soil and along the pile. These configurations are the most favourable for the installation of heat exchange tubes, as they mechanically require reinforcement cages along the entire lenght of the pile. The objective of the COOP project, funded by the French National Research Agency (ANR), is to improve the knowledge of the behaviour of energy piles under these complex load configurations by proposing different research topics, from real experimental case studies to physical centrifuge modelling and numerical modelling, with the final aim of providing engineers with a relevant tool for the design of energy piles under combined loading.

RÉSUMÉ: Les besoins énergétiques croissants des zones urbaines et le contexte environnemental conduisent au développement de nouvelles technologies de géothermie. Dans ce contexte, les géostructures énergétiques, telles que les pieux thermoactifs (ou énergétiques), ont été développées au début des années 1980 et consistent en des tubes échangeurs de chaleur fixés aux cages de renforcement des pieux de fondation pour extraire/injecter de la chaleur du/dans le sol afin de répondre aux besoins de chauffage et de refroidissement des bâtiments. Leur particularité réside dans leur double fonction : rôle structural et échangeur d'énergie thermique. Par conséquent, deux aspects peuvent être critiques et doivent être pris en compte dans leur dimnesionnement. Le premier est la nature de la charge thermique cyclique, qui agit sur toute la longueur du pieu et qui peut affecter sa réponse mécanique. Par conséquent, une charge thermique cyclique peut entraîner une modification des contraintes de cisaillement à l'interface sol-pieu et donc impacter la capacité portante du pieu. Le deuxième aspect concerne l'adéquation de la méthode de calcul à une charge transversale et axiale combinée, c'est-à-dire l'interaction entre la charge transversale (ou axiale) et le comportement axial (ou latéral) des pieux énergétiques, associée à une charge thermique volumétrique agissant sur le sol environnant et le long du pieu. Ces configurations sont les plus favorables à l'installation de tubes d'échange de chaleur, car elles nécessitent mécaniquement des cages de renforcement sur toute la hauteur du pieu. L'objectif du projet COOP, financé par l'Agence Nationale de la Recherche (ANR), est d'améliorer la connaissance du comportement des pieux énergétiques sous ces configurations de charge complexes en proposant différents thèmes de recherche, allant d'études de cas expérimentaux réels à la modélisation physique en centrifugeuse et à la modélisation numérique, dans le but final de fournir aux ingénieurs un outil pertinent pour le dimnesionnement de pieux énergétiques sous chargements combinés.

Keywords: Energy piles; combined loading; in situ experiment; centrifuge modelling.

1 INTRODUCTION

The growing energy needs of urban areas and the environmental context lead to the development of new energy technologies. In particular, since the 1980s, a new geothermal method has been developed: energy geostructures, consisting in fixing heat exchanger pipes to the reinforcement cages of geotechnical structures like foundations to extract/inject the heat from/into the ground with the purpose of meeting the building heating and cooling demands. Among them, Energy Piles (EP) have been widely studied because their thermal behaviour is quite similar to the one of usual Ground Source Heat Pumps installations, with the specificity of a dual function: structural support and energy exchanger (Loveridge et al. 2020). These studies provide knowledge about mechanical behaviour upon mainly the axial direction and about the assessment of the energy performance of the system. Despite all economic and ecological advantages of this technology, EP installation in France is still held back by some uncertainties, which among them one concerns the thermo-mechanical behaviour under complex loading.

Indeed, based on the application, EP may be mechanically subjected to predominantly vertical loading due to a supported superstructure, and lateral loading if used in a bridge abutment or embankment stabilization, or combined vertical-horizontal loading (and potentially moment too) in buildings subjected to pile eccentricity (figure 1). Moreover, although wind and earthquakes induce dynamic loads, in common engineering practice their effects are considered as horizontal static loads applied to the pile head (NF EN NF P 94-262, 2017).

All these configurations, where combined vertical-horizontal loading is encountered, are the most favourable for installing heat exchanger pipes since, from a purely mechanical point of view, they require reinforcement cages all along the pile height. It is then crucial to offer to engineers a relevant knowledge to design energy piles under combined loading and this project aims at characterizing the effect of combined loading on energy piles and at the development of open-source and easy-to-use design tools for energy piles, capable of **constructing an overall failure envelope including thermal cycling loading effects**.

2 STATE OF THE ART

In the current design practice, the response of conventional pile under combined axial and horizontal loading is separately analysed and then superposed. This approach neglects the coupling effect of the combined loads while the optimum design of pile foundations requires consideration of the influence of axial loads on their horizontal response. Most previous studies have investigated the behaviour of conventional piles under pure horizontal loads and only a limited number have considered combined axial and horizontal loading (Heidari et al., 2022). Moreover, these studies gave contrasted results and the coupling effects of combined axial and lateral loads still raise complexities and uncertainties, even regarding conventional piles. This might be intensified in the case of energy piles because the thermal variations could affect the pile properties, the behaviour of the surrounding soil, lead to creep effects, or cause ratcheting phenomena in heavily-loaded piles subjected to cyclic thermal loads. Accordingly, it is necessary to identify the influence mechanism of combined axial and compression loads on the global behaviour of energy piles.

Descriptive diagram of combined loads in geothermal piles supporting a building.

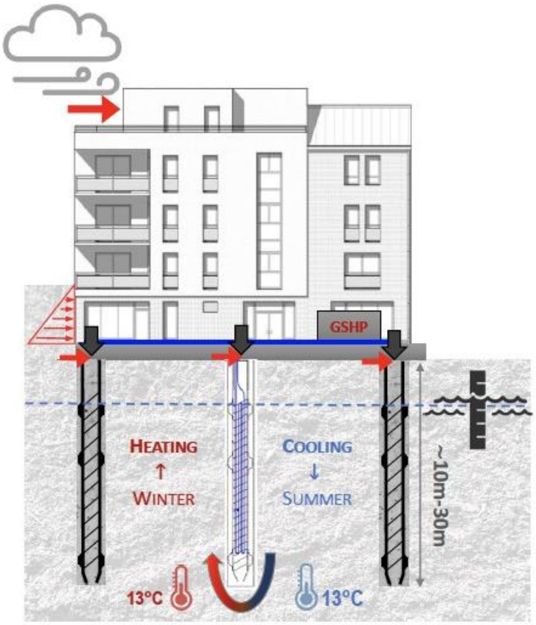

Figure 1. Combined loads acting on energy piles.

Many researchers have put a lot of effort into better understanding the thermo-mechanical behaviour of energy piles during monotonic heating or cooling and one or multiple thermal cycles. The work of Vitali et al. (2021) could be considered as the only available study using centrifuge model tests to investigate the influence of monotonic heating on the flexural behaviour of horizontally-loaded energy piles. Several studies have been performed to assess the behaviour of axially-loaded energy piles during multiple thermal cycles through field scale tests (Sutman et al. 2019), 1-g small-scale physical model tests (Nguyen et al., 2020) and centrifuge model tests (Ng et al. 2015).

A recent critical review of knowledge upon energy piles (Cunha and Bourne-Webb, 2022) draws an accurate picture of the experiments realised until now. It appears that very few experiments have been carried out on real scale energy piles considering combined mechanical loadings. This lack of experiments should be fulfilled even if centrifuge modelling offers alternative results.

The centrifuge modelling approach to characterize the transient thermo-mechanical response of energy foundations during heating-cooling cycles has been first used by Stewart and McCartney (2014). During successive cycles, slight decreases in upward thermal head displacement were observed. Later, Ng et al. (2020) have assessed rigorously scaling effects on the centrifuge modelling of floating energy piles by the so-called 'modelling of models' technique (two centrifuge models tested at two different *g* levels simulating the same prototype). Recently, Zhao et al. (2022) have presented the study on the thermally-induced ratcheting under a constant horizontal load. Yet, this first study has been performed in a dry sample without measurement of the pile strain to compare with numerical modelling.

Complementary to experimental results, numerous numerical studies have been performed to investigate the Thermo-Hydro-Mechanical THM behaviour of energy piles. The key findings are: (i) Heating/cooling of the pile induces stress changes in the pile and at the pile-soil interface; (ii) Heating/cooling cycles can degrade the side friction at the pile-soil interface; (iii) Thermal loads can induce irrecoverable displacement if the mechanical load is high; (iv) Irreversible and accumulating settlement over yearly thermal cycles, with a ratcheting phenomenon, also seems to take place in the long term during cyclic continuous loading. It should be noted that these findings were obtained exclusively from studies investigating piles subjected to axial mechanical load. The unique numerical study investigating the behaviour of energy pile subjected to sustained lateral load, from our knowledge, is Zhao et al. (2022). This study, based on finite-element simulations showed that ratcheting was evident in laterally-loaded piles in sand and its extent was more significant when the working horizontal load was higher. The ratcheting phenomenon was attributed to the accumulation of soil plastic strain due to the cyclic mechanical loading induced by pile thermal horizontal expansion and contraction, soil dilation upon soil-pile interface shearing, and creep. Beside these studies, we can't find any numerical study investigating the mechanical behaviour of energy piles, subjected to thermal cycles, under sustained combined lateral-axial loads. It should be noted that investigating the mechanical behaviour of pile subjected to combined lateral-axial loads itself already requires advanced numerical methods including 3D mesh and soil-pile interface models (Achmus & Thieken, 2010; Suryatriyastuti et al., 2013a-b, 2016; Hazzar et al., 2017).

The experimental and numerical studies mentioned above are focused on the behaviour of energy piles. To transfer this knowledge to the practice, it is crucial to develop engineering tools allowing the design of energy piles. Numerous works have been driven (Knellwolf et al., 2011; Mimouni and Laloui, 2013), but none of them have integrated the effect of lateral component of load in the axial response of pile. Mroueh and Shahrour (2009) have shown that combined load acting on pile may have great effect on its axial response and therefore on its design.

3 OVERALL METHODOLOGY

3.1 Organisation of the project

To investigate the questions raised hereby, the French National Research Agency (ANR) funded a project, called *Combined lOading Of energy Piles* (COOP), driven by Université de Lille and involving Université Gustave Eiffel, Ecole des Ponts ParisTech and the Pinto company. It aims to offer to engineers a relevant tool to design energy piles under combined loading. To achieve this objective, a specific organisation has been designed including a multiscale study of the thermo-mechanical behaviour of energy piles relying on three Work Packages (WP1, 2 and 3) and a Work Package dedicated to the transfer of knowledge to engineering practice (WP4). In addition, the WP0 is dedicated to project management.

The WP1 will allow to study the behaviour of energy piles under lateral loading through testing two experimental energy piles (0.42 m in diameter and 12.0 m in length), which have been installed in the campus of Ecole des Ponts ParisTech (Vasilescu, 2019). They are equipped with PE tubes for the circulation of the heat transfer fluid, PT 100 temperature sensors and optical fibre sensors. Temperature sensors are also installed in the soil, around the piles. The piles will be initially subjected to axial static compressive load (10, 20, or 40% of the ultimate axial load) and then in the subsequent stage, horizontal static load will be incrementally applied (30, 50, or 70% of the ultimate horizontal load), while the axial load is kept constant. The horizontal load will be applied by an actuator between two piles to ensure they are submitted to the same loading. At each level of horizontal load, to simulate the actual operating condition of energy piles, ten thermal cycles with temperature variation of -/+ 10 °C will be repeatedly applied to one of the piles while the mechanical loads are maintained constant. The unheated pile will be used as a control experiment. The principle of this testing is represented on Figure 2.

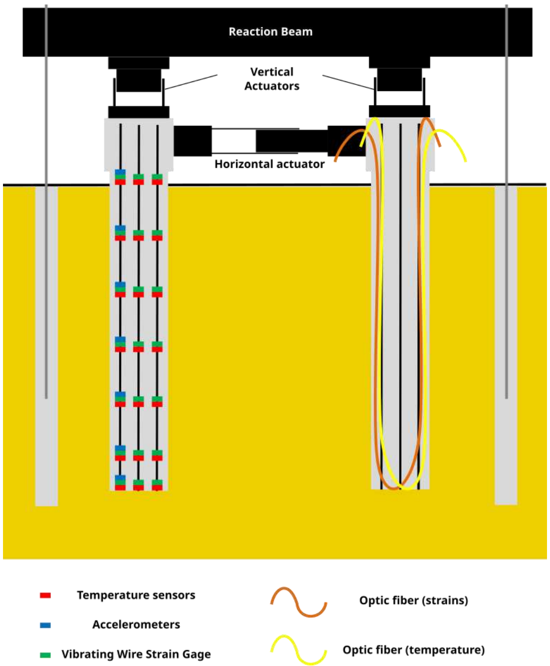

Figure 2. Principle of the real-scale testing.

In WP2, the behaviour of energy piles subjected to lateral loading will be studied through smallscale model tests performed in centrifuge. The advantage of placing these small-scale models in a macro-gravity field is to generate on this model the same stress state that is applied to the prototype in real size. In the perspective of energy piles, the second advantage of the physical modelling in centrifuge is to also reduce the time scale. Thus, the time scale (for diffusion) of a 1/N model subjected to N×g is reduced by N^2 (at 100×g), 1 hour of centrifuge test represents 14 months in the prototype scale ("real scale"). In this way, centrifuge tests can model several years of cyclic thermal loading. Moreover, in the framework of this project, the tests performed in centrifuge are particularly well suited to calibrating the numerical model developed in the WP3. Indeed, in centrifuge, the boundary conditions, the soil homogeneity and the different loadings are very well established and controlled which gives valuable data up to failure.

For this study, the centrifuge test principle consists in applying a thermal cyclic loading inside the pile while the mechanical loads (horizontal and vertical) remain constant. The accumulation of lateral displacement (the ratcheting effect) will be monitored. Several couples of thermal and mechanical loadings will be studied. A parametric study will be conducted on key aspects governing the energy pile response subjected to lateral loading will be studied: i) the pile slenderness ratio, ii) the soil saturation and iii) the soil density. Using a system adapted from (Ouzzine et al., 2023) for the thermal loading, initial tests have been carried out including only horizontal mechanical loading (Figure 3).

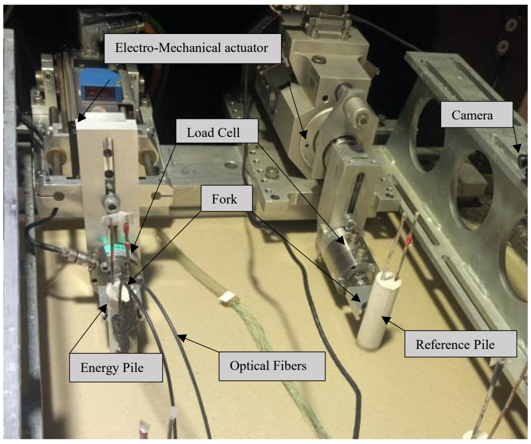

Figure 3. Initial centrifuge tests.

WP3 aims to investigate the thermo-mechanical behaviour of energy pile subjected to thermal cycles under sustained combined lateral-axial loads. This goal will be achieved by using complex 3D modelling on CESAR-LCPC software (Humbert et al, 2005). It is a Finite Element software dedicated to the modelling and analysis of civil engineering projects, particularly well-suited to geotechnical problems and continuously developed by Université Gustave Eiffel. It integrates a wide range of calculation capabilities for extending the analyses to heat transfers and THM couplings.

WP4 will focus on the development of a simplified design tool, accounting for combined loading, which is of paramount importance in the industry uptake and large-scale deployment of energy piles. Drawing from the results obtained from the real scale (WP1) and centrifuge tests (WP2) as well as the results of the parametric study performed in the WP3, an open-source simplified design tool will be developed to bridge the gap between research and engineering practice. The principal goal of this application will be to determine the stresses and displacements resulting from a set of combined thermomechanical loads and a 3D failure envelope corresponding to the energy pile combined axial and lateral response and accounting for thermal cyclic loading.

4 CONCLUSIONS

The first steps towards characterization of the effect of combined loading on energy piles have been hereby presented as well as the organisation of the project COOP whose final goal is the development of an open-source user-friendly design tool.

The development and dissemination of such tool is essential to maximize the development and deployment of energy pile technology in the construction sector. Providing access to such tools to building contractors, design engineers, and control offices will allow to easily design and control energy pile solutions without resorting to complex 3D modelling and experimented engineers. We believe that the easy access to design tools will promote a virtuous cycle of energy geostructures' development, multiplying the examples and proving the performance and necessity of such solution.

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