5th ECPMG Delft · 2024

Proceedings of the 5th ECPMG 2024
5th European Conference on Physical Modelling in Geotechnics
2-4 October 2024, Delft, the Netherlands
© 2024 the Authors

Centrifuge study of a reduced model of a geothermal pile loaded horizontally

E. Khamis
Univ. Gustav Eiffel, GERS-CG, F-44344 Bouguenais, France, eva.khamis@univ-eiffel.fr

T. Dubreucq, M. Blanc
Univ. Gustav Eiffel, GERS-CG, F-44344 Bouguenais, France, thierry.dubreucq@univ-eiffel.fr, matthieu.blanc@univ-eiffel.fr

J. De Sauvage
Univ. Gustave Eiffel, Univ Lyon, GERS-RRO, F-69675 Lyon, France, jean.de-sauvage@univ-eiffel.fr

T. Badinier, F. Szymkiewicz

Univ Gustave Eiffel, GERS-SRO, F-77454 Marne - la- Vallée, France, thibault.badinier@univ-eiffel.fr, fabien.szymkiewicz@univ-eiffel.fr

J.M. Pereira, A. Tang

Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France, jean-michel.pereira@enpc.fr, anh-minh.tang@enpc.fr

R. Vasilescu

PINTO, F-35300 Fougères, France, rvasilescu@pintogc.com

H. Mroueh

University of Lille, IMT Lille Douai, Univ. Artois, Yncrea Hauts-de-France, ULR 4515 - LGCgE, Laboratoire de Génie Civil et géo-Environnement, F-59000 Lille, France, hussein.mroueh@univ-lille.fr

ABSTRACT: As part of the ANR "COOP" (Combined lOading Of energy Piles) project, the Geotechnical Centrifuge Laboratory at Gustave Eiffel University has studied the bending behaviour of a small geothermal pile, subjected to temperature cycles and horizontal head loading. It simulates a prototype pile 16 m long and 0.8 m in diameter. This study aims to predict the horizontal behaviour of reinforced concrete geothermal energy piles (GEPs) subject to lateral loads, followed by thermal loads with alternating heating and cooling cycles in saturated dense sand. The study examined three piles: a capacity pile to measure its ultimate load (*Fu*), a reference pile and an energy pile tested at 50% of *Fu*. A four-point bending test highlighted a low Young's modulus, confirming soft characteristics in the pile. Thermal loading led to significant displacement accumulation, potentially impacting both pile and soil properties. The study provided insights into failure characteristics and the impact of thermal loading on energy piles.

1 INTRODUCTION

The current growth of urban areas generates a demand for energy, while the environmental and climatic conditions promote the use of renewable energy sources. New energy technologies are therefore being developed, such as thermal geo-structures that extract or inject heat from or into the ground to meet the heating and cooling needs of buildings. Among them, energy piles (EP) have received the most attention because of their thermal behavior, which is similar to that of conventional Ground Source Heat Pumps, and has the particularity of serving as both a structural support and an energy exchanger (Loveridge et al., 2020).

Previous research has primarily focused on axial loads. The work done by Vitali et al. (2022) is possibly the sole investigation using centrifuge model tests to examine the impact of monotonic heating on the flexural performance of horizontally loaded energy piles.

Zhao et al. (2023) conducted a distinctive numerical study exploring the behavior of energy piles subjected to sustained lateral loads. This study, utilizing finite-element simulations, revealed the presence of ratcheting in laterally-loaded piles embedded in dry sand. The observed ratcheting phenomenon was found to be more pronounced when the applied horizontal load was higher. However, the reviewed results on GEP systems indicate that the heat flux is highly influenced by soil saturation conditions, and the thermodynamic efficiency decreases in unsaturated soils (Cunha et al., 2022)

This paper aims to provide a more precise understanding of the bending behaviors of EP subjected to both constant lateral head load and alternating cycles of thermal load in saturated Fontainebleau sand NE34 (Density index I_D= 0.75 where density index is the ratio of the difference between the void ratios of a cohesionless soil in its loosest state and existing natural state to the difference between its void ratio in the loosest and densest states, friction angle= 38°).

2 MODEL ENERGY PILE

2.1 Manufacture of Energy Pile

A cylindrical reinforced cement energy pile with an embedded length of 60 cm and a diameter (*D*) of 3 cm was developed. During the tests, a centrifugal acceleration of 26.7g was applied to simulate a prototype pile 16 m long and 0.8 m in diameter, according to the rules of similarity for soil-structure interactions. The cement was used without the aggregates due to the small size of the pile and the incapability of fitting such aggregate size inside the model pile. The EP is equipped with a U-shaped copper pipe for full-height water circulation, and a 0.2 cm-diameter galvanized steel mesh around the periphery to act as a reinforcement (Figure 1). Optical fibers (OF) were fixed on two opposing sides of the energy pile to measure the load transfer of the model pile, the strain distribution, the transversal displacement and the temperature variations. Within each fibre embedded into the pile 15 Fibre Bragg Gratings (FBGs) were located and distributed over a span of 540 mm.

2.2 Four-Point Bending

The four-point bending method was used to evaluate the flexural stiffness and strength of material. This test was conducted on the EP following the centrifuge experiments and was representative of all three piles. The energy pile is placed on two supports *L* distance apart. Two forces directed vertically downwards, *F*/2, situated at equal distances from the center, were applied to the pile.

Having two optical fibers attached on opposing sides of the pile's surface, the values of the OF readings are transformed to strain (as shown in Figure 2) and the stress values at each load application are calculated using the bending stress formula. Thus, the Young's modulus can be calculated using Hooke's law, which resulted in a 2.2 GPa value.

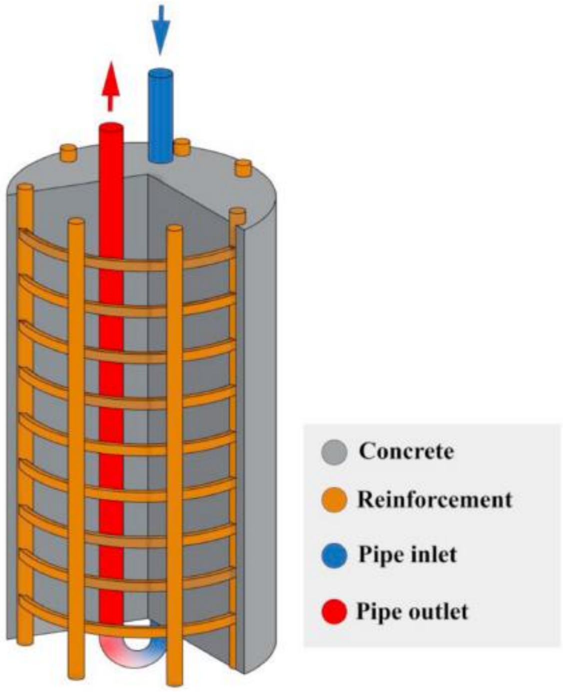

Figure 1. 3D illustration of energy pile (adopted from (Asadinik A. 2022))

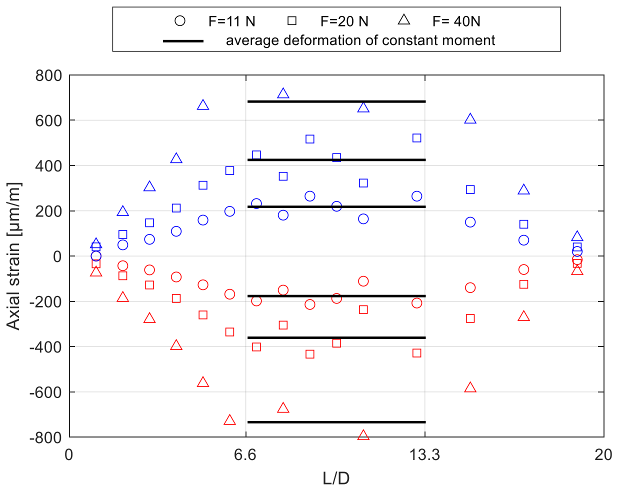

Figure 2. Strain along the length of pile at increasing load application

A displacement sensor is put in the center of the pile. Siswanto et al. (2019) presents the use of the elastic bending formula in the 4-point bending method; thus, Young's modulus can be calculated using equation (1).

$$E = \frac{F.\left(\frac{L}{3}\right).(3L^2 - 4(L/3)^2)}{48.I.f} \tag{1}$$

where: E (Pa) is Young's modulus, F (N) bending force, L (m) distance between supports, I (m^4) moment of inertia and f (m) deflection.

After completely removing the load (Figure 3), the pile did not return to its initial position; instead, it displaced halfway, indicating signs of plasticization. This displacement corresponds to the elastic portion of the pile, which gave 2.1 GPa for the Young' modulus (E). On the other hand, as the equation for elastic bending stress is applicable only within the elastic range, the secant modulus was obtained, giving a value of 1.8 GPa. The Young's modulus is low for both values.

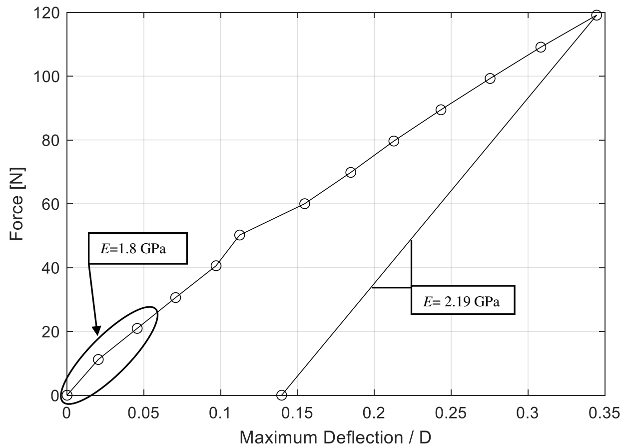

Figure 3. Force with respect to the deflection

3 CENTRIFUGE MODELING

3.1 Set-up

A uniform bed of dry sand was produced with Fontainebleau sand using sand rain method within the model box and then saturated. The pile was installed "wished in place" for an embedded depth (L) of 60 cm (i.e., 20 times the pile diameter - 20D). A free-standing pile length of 10 cm (i.e., 3D) was above the soil surface which is the part of the pile that is subjected to horizontal load. To ensure that the analysis focused on the behaviour of the pile and not influenced by the proximity to the sand box walls, the front of the model pile was positioned at a distance of 28 cm (i.e., about 9.5D) from the walls. As stated in Zhao et al. (2023), any potential boundary effect caused by lateral load on the pile was negligible when the pile was at least 8D away from the vertical boundaries of the box.

Lateral loading was applied 2D above ground level perpendicular to the surface of the pile using an electro-mechanical actuator. Displacement transducers positioned at 1D and 3D above ground level were attached to the pile to measure the resulting deflection. Thermocouples were located on the surface of the pile to help understand how the thermal load affects the temperature of both the pile and the surrounding soil.

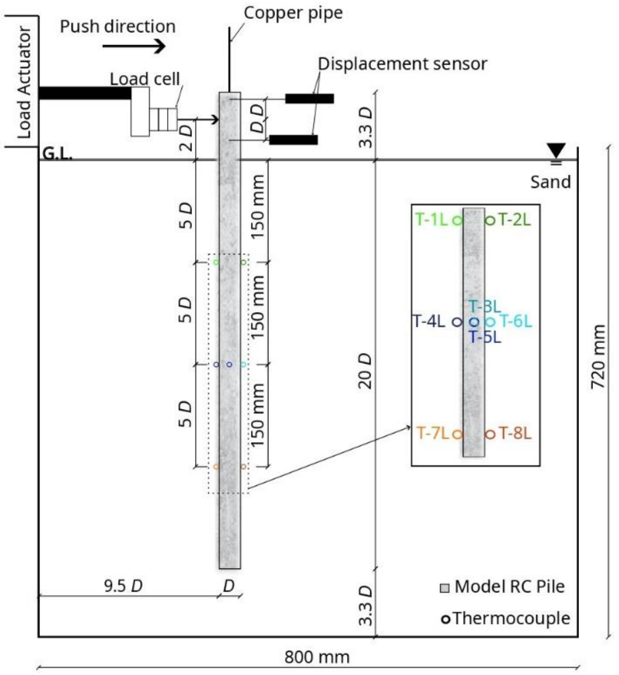

Figure 4. Schema of mechanical set-up

The thermal cycles inside the EP are provided by a thermal circuit (Figure 5), which includes a Peltier device to cool and heat the water, a pump to regulate the specific flow rate of 350 ml/min, a bubble trap to remove bubbles from the circuit, temperature sensors to measure the water temperature at the inlet and the outlet of the pile and Peltier device, and pipes to interconnect the circuit which are carefully insulated.

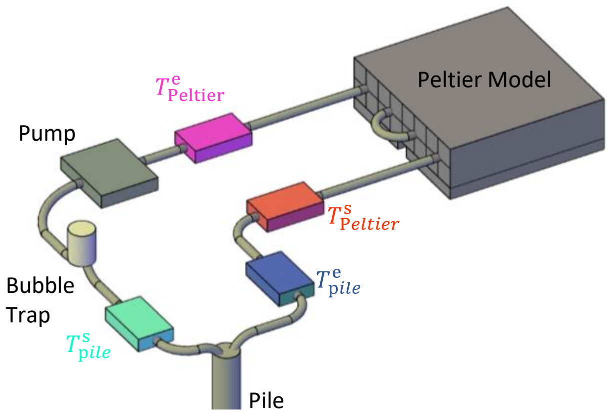

Figure 5. Schema of thermal set-up

3.2 Experimental Procedure

The experimental procedure was divided into two phases using 3 concrete piles manufactured similarly as detailed before. First, the concrete pile is loaded to failure on the so-called capacity pile (CP), by increasing the horizontal load applied until the ultimate load (*Fu*) is reached. The ultimate load is considered to be the value of the load prior to pile's breakpoint. In the second phase, an admissible load equal to 50% of *Fu* from the CP is applied to the reference pile (RP) to assess the effect of creep alone, and then to the EP. After 24 minutes of creep, the energy pile was subjected to thermal loading with alternating cycles of cooling and heating water between 5°C - 40°C (ΔT= 35°C).

4 RESULTS AND DISCUSSION

All results are expressed in prototype dimensions, unless otherwise indicated.

As shown in Figure 6, the failure of the pile was 214 kN. Subsequently, 50% of the *Fu* (107kN) was applied to the RP and the EP, resulting in a deflection value equivalent to 20% of the deflection observed in the CP. The mechanical behaviour of all three piles up to 107 kN load is visibly similar, with deflection values reaching around 0.06*D* in all cases.

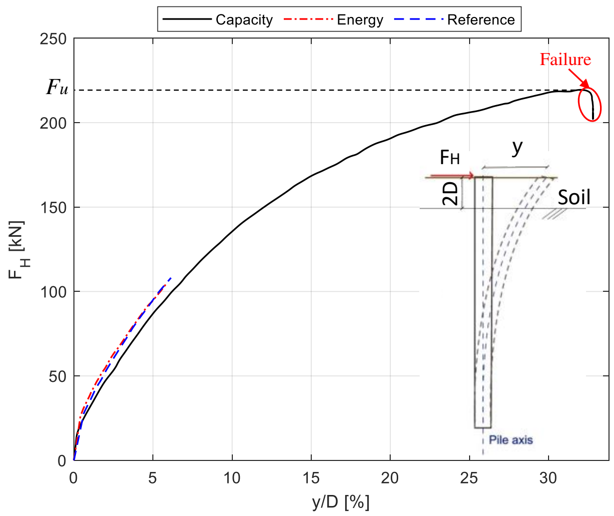

Figure 6. Applied horizontal load- deflection curves of CP, EP, and RP

Figure 7(a) shows the deflection of the EP and the RP over time after the application of a 107 kN horizontal load followed by thermal cycles on the EP. The RP shows the occurrence of creep in the pile following the load was applied. The dotted energy-creep line illustrates the expected response of the energy pile to the applied horizontal load, based on the results obtained from the study of the reference pile's behaviour. On the other hand, the energy pile's deflection results from both sand creep and the application of thermal cycles. As the temperature rises up to 40°C, the deflection increases, and once the temperature drops back down to 5°C, the deflection slightly decreases. This can be attributed to the behaviour of the pile, which expands and contracts with increasing and decreasing temperature respectively.

Figure 7 (b) illustrates the relative increase in deflection resulting from the application of a thermal load only on the EP, excluding any contribution from creep. This was achieved by subtracting the creep deflection from the total deflection of the EP, as shown in Figure 7(a), then dividing by the initial deflection (y_0) before the start of the thermal cycles. It can be observed that the 12 thermal cycles lead to a 24% increase in deflection. After the first cycle, the deflection accumulation was already 15%. After 6 cycles, deflection seems to reach a plateau. However, the failure of an optical fiber does not allow a more detailed analysis of the pile's behavior in the soil.

Figure 7(c) shows the evolution of the temperature measured at the inlet and outlet of both the Peltier and the pile as a function of time. A significant temperature difference between the pile inlet and outlet is observed after the second thermal cycle. Furthermore, the maximum temperature reached by the PT100 sensors placed at the inlet and outlet of the pile thermal circuit shows a noticeable phase shift, indicating a flow level too low to maintain a substantially constant temperature in the thermal circuit inside the pile.

Figure 7(d) displays the variations of temperature measured by the thermocouples located at 3 depth levels on the surface of the energy pile in the sand, as shown in Figure 4, as a function of time. The temperature is detected at the interface between the pile and soil. The curve shows a decrease in temperature during time. It is suggested that the temperature of the sand decreases with each thermal cycle. This phenomenon was also observed for the pile outlet temperature. A decrease in flow rate could be the cause, as the soil is homogeneous. Furthermore, the thermocouples measured different values at the same time, which could be attributed to imprecise positioning or poor contact of the thermocouples with the lateral surface of the EP.

The thermocouples and temperature sensor at the pile outlet and Peltier inlet (T_{pile}^{out} and $T_{Peltier}^{in}$ respectively) show the same phenomenon, with high oscillation in the first two cycles, followed by a decrease in temperature.

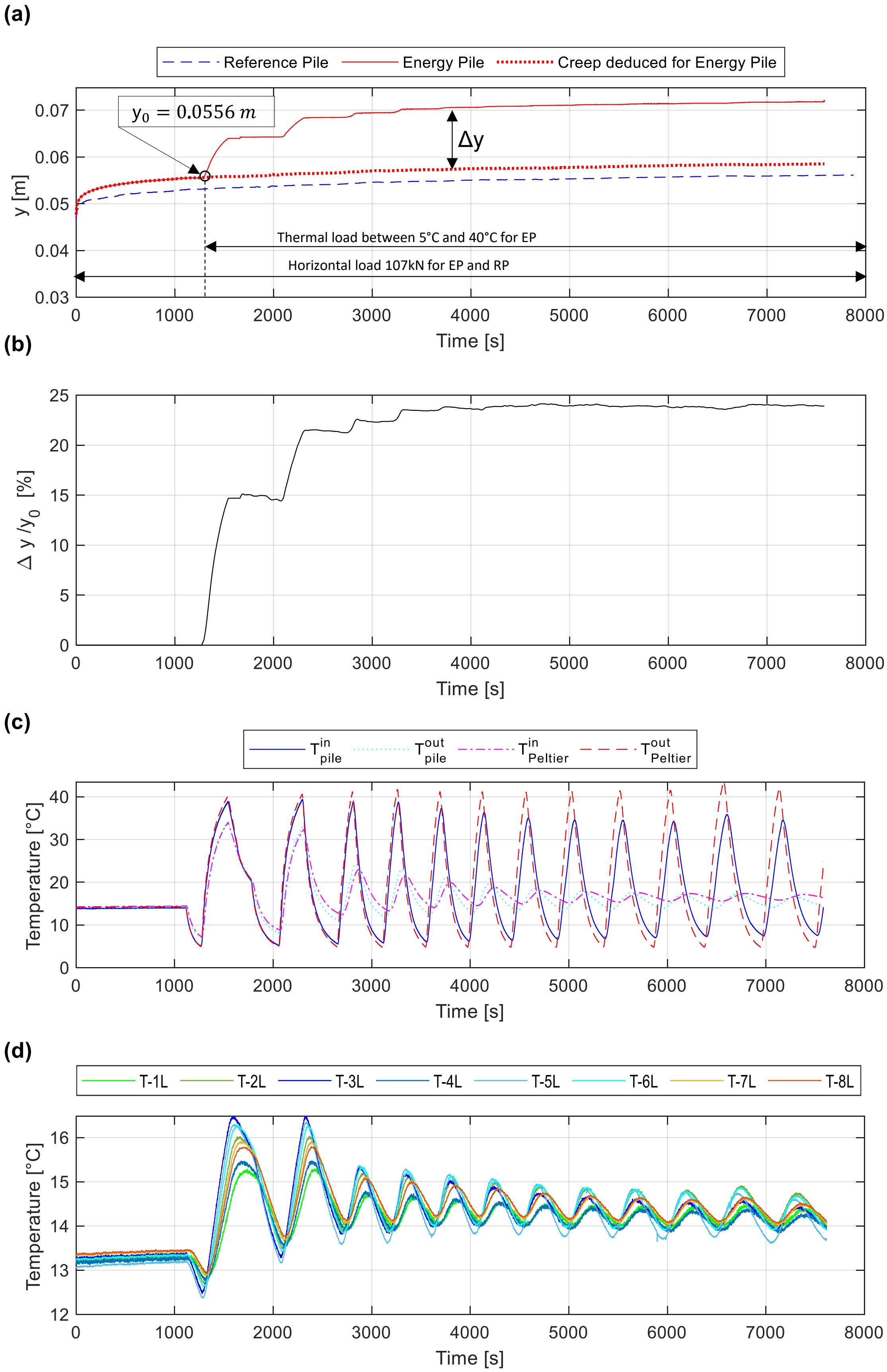

Figure 7. Evolution of the (a) Deflection « y » of EP and RP (b) Percentage relative deflection of EP (c) Temperature sensors in thermal circuit (d) Temperature on the interface soil-pile in 3 levels versus time

5 CONCLUSION AND PERSPECTIVE

This paper presents an evaluation of the mechanical and thermal behaviour of reinforced cement energy piles in saturated dense sand, which are laterally and thermally loaded in order to accurately predict its behaviour.

The conclusions drawn from the centrifuge test results are as follows:

- The low value of the pile's Young modulus indicates a soft pile.
- High displacement accumulation due to thermal loading was observed. Thermal variations can affect not only the properties of the pile itself, but also the behaviour of the surrounding soil.
- The temperature amplitude decreases after few cycles, leading to a reduction in the rate of displacement accumulation caused by cyclic loading. This suggests that there may be a decrease in heat transfer fluid flow during the test.

Future suggestions are proposed to better understand the lateral response of energy pile:

- The flow water rate should be examined more to understand its effect on thermal circulation.
- A scale model of a reinforced cement pile is not rigid enough to adequately model the full-scale prototype. The possibility of using another material will be investigated.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by funding agency Agence nationale de la recherche (ANR).

REFERENCES

Asadinik, A. (2022). Energy Pile: A Source of Green Energy Under Our Buildings. https://www.linkedin.com/pulse/energy-pile-source-green-under-our-buildings-asadinik-m-sc-p-eng/

Cunha, R. P. and Bourne-Webb, P. J. (2022). A critical review on the current knowledge of geothermal energy piles to sustainably climatize buildings. *Renewable and Sustainable Energy Reviews*, Vol. 158, 14 pp.. https://doi.org/10.1016/j.rser.2022.112072

Loveridge, F., McCartney, J. S., Narsilio, G. A., & Sanchez, M. (2020). Energy geostructures: a review of analysis approaches, in situ testing and model scale experiments. *Geomechanics for Energy and the Environment*, Vol. 22, 30pp.. https://doi.org/10.1016/j.gete.2019.100173

Siswanto, W. A. and Martama, B. P. (2019). Stress and Deflection of a Concrete Block in a Four-Point Bending (FPB) Test. *Department of Mechanical Engineering, Universitas Muhammadiyah Surakarta, Indonesia.* 7(6): 307-317. https://doi.org/10.13189/ujme.2019.070601

Vitali, D., Leung, A. K., Feng, S., Knappett, J. A. and Ma L. (2022). Centrifuge modelling of the use of discretely-spaced energy pile row to reinforce unsaturated silt. *Géotechnique,* 72(7): 618-631. https://doi.org/10.1680/jgeot.20.P.157

Zhao, R., Leung, A. K., & Knappett, J. A. (2023). Thermally-induced ratcheting of a thermo-active reinforced concrete pile in sand under sustained lateral load. *Géotechnique*, 73(9): 826-839. https://doi.org/10.1680/jgeot.21.00299

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 5th European Conference on Physical Modelling in Geotechnics and was edited by Miguel Angel Cabrera. The conference was held from October 2nd to October 4th 2024 at Delft, the Netherlands.

To see the prologue of the proceedings visit the link below:

https://issmge.org/files/ECPMG2024-Prologue.pdf