Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-664

Numerical evaluation of the long-term performance of energy piles in hot-dominated climates

Évaluation numérique de la performance à long terme des pieux énergétiques dans les climats à dominante chaude

S. ten Bosch*, E. Ravera, L. Laloui
EPFL, Lausanne, Switzerland

**sofie.tenbosch@epfl.ch*

ABSTRACT: Using energy piles to extract geothermal energy for heating needs has been the main focus of research in energy geostructures. In hot-dominated climates, the interest is to inject heat into the ground and extract energy for space-cooling purposes. This study evaluates the feasibility of energy piles in this operation mode through 3D numerical modelling for a case study targeted to provide 40% of the total cooling demand of a typical building in Dubai. The unbalanced energy demand causes an increase in the outlet temperature of the heat carrier fluid in the geothermal pipes and the radial soil temperature over time. Observation of long-term behaviour, however, indicates that the temperature increase is most significant in the initial years and stabilizes over time. The heat pump operating limit in terms of maximum temperature is respected over 50 years due to this stabilization behaviour. The results show that energy piles are highly effective in reducing carbon emissions and supplying renewable energy to buildings in hot climates, addressing a key societal challenge.

RÉSUMÉ: L'utilisation de pieux énergétiques pour extraire l'énergie géothermique à des fins de chauffage a été le principal axe de recherche dans le domaine des géostructures énergétiques. Dans les climats chauds, l'intérêt est d'injecter de la chaleur dans le sol et d'en extraire de l'énergie pour refroidir les bâtiments. Cette étude évalue la faisabilité des pieux énergétiques dans ce mode de fonctionnement à l'aide d'une modélisation numérique en 3D pour une étude de cas visant à fournir 40 % de la demande totale de refroidissement d'un bâtiment type à Dubai. La demande d'énergie déséquilibrée entraîne une augmentation de la température de sortie du fluide caloporteur dans les tuyaux géothermiques et de la température radiale du sol au fil du temps. L'observation du comportement à long terme indique toutefois que l'augmentation de la température est plus importante au cours des premières années et se stabilise avec le temps. La limite de fonctionnement de la pompe à chaleur en termes de température maximale est respectée sur 50 ans en raison de ce comportement de stabilisation. Les résultats montrent que les pieux énergétiques sont très efficaces pour réduire les émissions de carbone et fournir de l'énergie renouvelable aux bâtiments dans les climats chauds, ce qui permet de relever un défi sociétal majeur.

Keywords: Numerical modelling; energy piles; hot-dominated climates; cooling systems; geothermal energy.

1 INTRODUCTION

The pressing challenge of providing sustainable energy for a growing global population while reducing greenhouse gas emissions emphasizes the importance of sustainable energy sources. Space cooling is a major driver of residential energy consumption in hot climates, and its demand is expected to triple by 2050 (IEA, 2018). Dubai, UAE, is a region where cooling represents a substantial portion of energy use. The need for sustainable cooling sources here is underlined by a doubling of CO_2 emissions in the UAE over the past three decades.

Energy geostructures, such as energy piles, can be used as an innovative solution for space conditioning purposes. Energy piles utilize ground-embedded structures for heating or cooling and have demonstrated strong performance in various applications (e.g., Brandl, 2006; Laloui & Rotta Loria, 2019). However, research has primarily focused on its heating applications, with less attention to cooling use in hot-dominated regions. The impact of an unbalanced energy demand has been explored by Akrouch et al. (2020), Olgun et al. (2015) and Sutman et al. (2020), but never with an only-cooling demand in the setting of an arid region.

This study aims to assess the feasibility and long-term energy performance of using energy piles exclusively for cooling in hot-dominated climates, with Dubai as a representative case. The work employs 3D time-dependent numerical modelling to simulate cooling energy extraction, offering insights into system operation in arid regions.

2 METHODOLOGY

Numerical evaluation of a representative case study in Dubai is achieved using a 3D finite element model in COMSOL Multiphysics 5.6.

2.1 Dubai case study description

An energy pile foundation with 33 20m-length and 0.8m-diameter piles is envisaged for a building in the coastal belt region of Dubai. HDPE pipes in the pile have a U-shaped configuration. A sandy soil profile characterizes the project location, and a variation in thermal conductivity over the depth of the profile is included in the study.

It is targeted to provide 40% of the total cooling demand of this building through its energy foundation. The required daily cooling load per energy pile is shown in Figure 1. The limitation of the feasibility of this technology lies in the reversed heat pump characteristics, as also identified by Alshehri et al. (2021). The outlet temperature (T_{out}) of the heat carrier fluid (HCF) in the energy pile should not reach the capacity limit temperature for the heat pump over its lifetime. The reversed heat pump employed in this study has a cooling capacity of 0.68 kW per energy pile, an energy efficiency ratio of 5.07 and the maximum allowable outlet temperature of the HCF is 45°C.

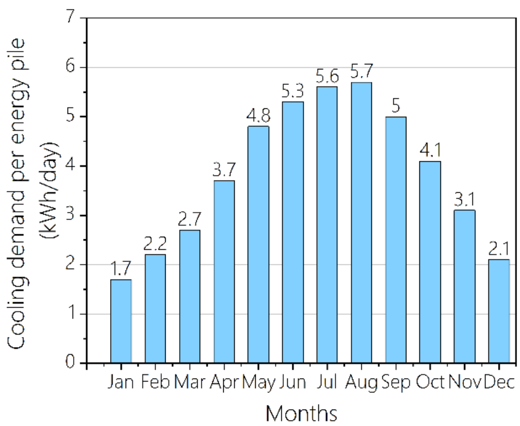

Figure 1. Monthly variation of daily cooling demand per energy pile.

2.2 Mathematical framework

This study employs a numerical modelling framework to simulate the energy piles, the ground and the geothermal pipes embedded within them. Conduction heat transfer characterizes the soil using an equivalent thermal conductivity approach, the concrete of the energy piles, and HDPE pipe wall domains. Similar frameworks have been effectively used in previous evaluations of energy geostructures (e.g., Rotta Loria, 2020) and it is thus not repeated here for concision.

The model simulates daily reversed heat pump operation, where cooling extraction continues until the calculated energy matches the daily energy demand. This approach, previously successful in prior work (Ravera, 2021; Sutman et al., 2020), is repeated for each simulated day. More information about the modelling framework can be found in Ten Bosch et al. (2024).

2.3 Numerical model description

The model, with its boundary conditions and mesh, is shown in Figure 2.

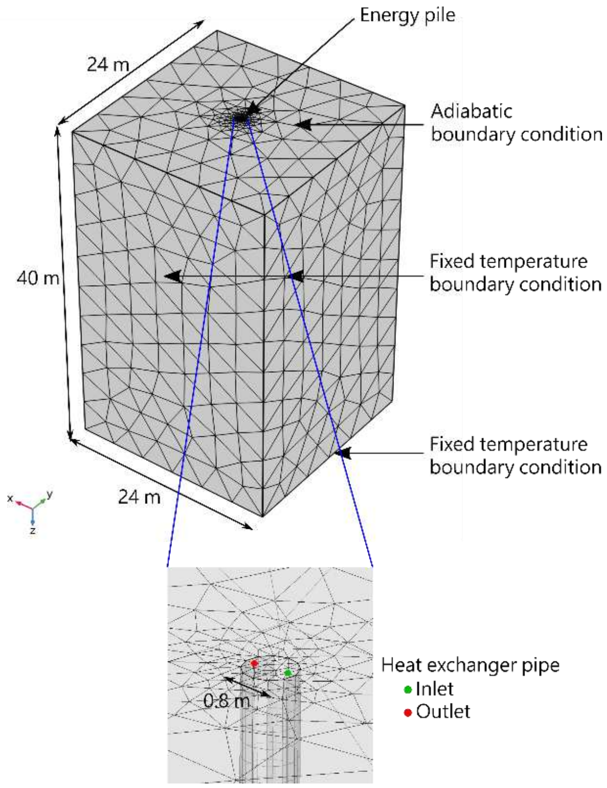

Figure 2. Setup of the numerical model for one energy pile in Dubai showing the applied boundary conditions and meshing.

Table 1. Thermal analysis model parameters.

Parameter	Value
HCF	water
Flow velocity	1.0 m/s
Ground thermal conductivity (variation over depth)	0-3 m: 0.939 W/(m·°C) 3-9 m:0.726 W/(m·°C) 9-13.5m: 1.192 W/(m·°C) >13.5m: 0.798 W/(m·°C)
Ground density	1537 kg/m^3
Ground specific heat	961 J/(kg·°C)
Pipe inner diameter	25.4 mm
Pipe surface roughness	0.0015 mm
Pipe wall thickness	3.25 mm
Pipe thermal conductivity	0.42 W/(m·°C)

Initial and boundary conditions include fixed temperature boundaries at the model's side and bottom, maintaining temperatures at the initial ground temperature of 30°C, representing Dubai's yearly average air temperature. Additionally, a thermal insulation boundary condition is applied at the model's surface. Model parameters that were used in the simulations are shown in Table 1.

3 DUBAI APPLICATION

3.1 One-year evaluation

The analysis of the system's behaviour over a year reveals fluctuations in the HCF outlet temperature. This one-year analysis is repeated with varying HCF flow velocities and internal pipe diameters, representing real-world conditions. The results are shown in Figures 3A, 3B. Daily temperature variations correspond to the activation and deactivation of the heat pump, driven by the cooling energy demand. Peak outlet temperatures coincide with higher cooling demands, notably in August. Despite these fluctuations, the HCF temperature remains within the heat pump's operating range for all model variations, indicating potential for energy-pile-based cooling.

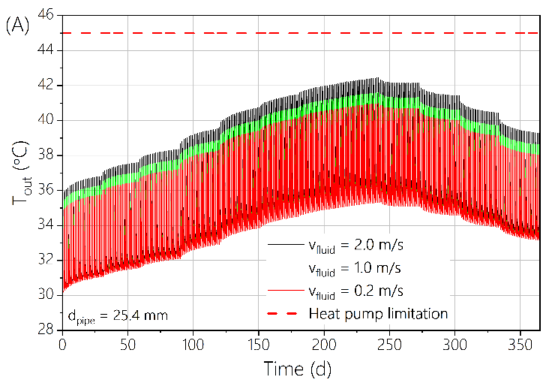

Figure 3A. One-year evaluation of the outlet temperature of the HCF fluid for variation of HCF flow velocity.

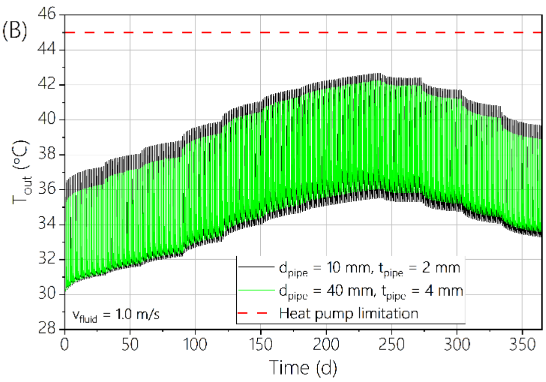

Figure 3B. One-year evaluation of the outlet temperature of the HCF fluid for variations of the pipe diameter.

Considering the sensitivity to the designs parameters, results indicate that lower flow velocities and wider pipe diameters reduce maximum outlet temperatures. Changing HCF flow velocities also affects operating costs and thus requires careful optimization.

3.2 Long term evaluation

A model with an enlarged soil domain (h = 40 m, x, y = 80 m) is used for a long-term case study evaluation to avoid boundary condition interference during the analysis.

Over a 50-year period, the system's energy performance is assessed, with Figure 4 illustrating the gradual increase in outlet water temperature. After an initial rapid response, the temperature increase stabilizes, remaining within the heat pump's capacity range.

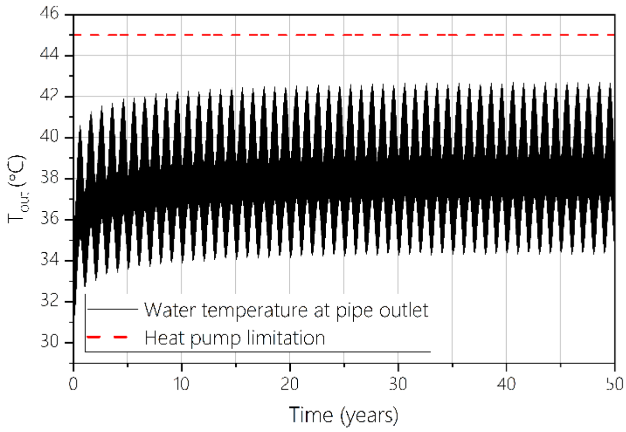

Figure 4. Long-term evaluation of the HCF outlet temperature for the Dubai case study.

Furthermore, the impact on the soil temperature around the energy pile could also be evaluated. The influence of 50 years of cooling energy extraction on soil temperature distribution at the surface level is presented in Figure 5, highlighting the highest temperatures near the pile location.

3.3 Discussion

The presented results are obtained with a single energy pile, thus, for buildings with a pile spacing exceeding the zone of influence, it is demonstrated that geothermal activation of the foundation can meet 40% of the building's energy demand. In cases where piles are closely spaced, interactions among piles should be considered. This overlapping influence can impact system performance. An assessment according to an infinite pile group model similar to Makasis & Narsilio (2022) over one year is used and indicates effects within a 10% increase of outlet temperature at the end

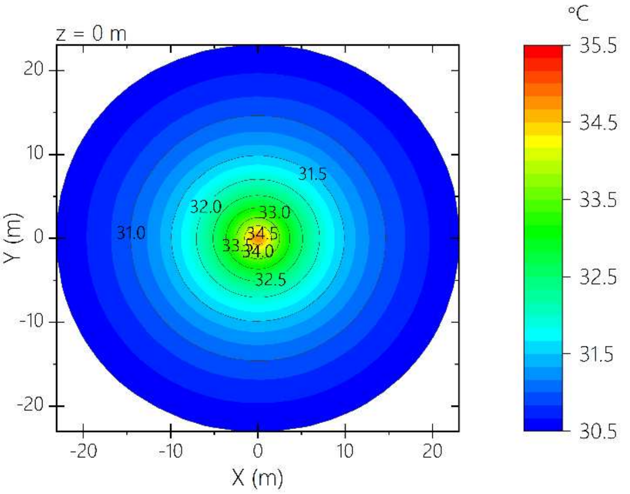

Figure 5. Ground temperature evaluation after 50 years of cooling energy extraction.

of one year for a pile spacing of 6.75 times the pile diameter using the Dubai case study settings.

Potential ground water flow is not considered in this study but is expected to have a positive influence through its cooling effect on the increasing soil temperatures surrounding the energy pile.

4 CONCLUSIONS

This work investigates the long-term behaviour of cooling energy extraction using energy piles in hot-climates. A 3D numerical model is used to assess a case study aiming to supply 40% of a typical building's cooling energy demand through the use of the energy foundation in Dubai. The unbalanced energy demand at this location causes an initial rise in heat carrier fluid and soil temperatures during operation of the energy pile. However, it is found that these increases stabilize over time, indicating the technology's viability even under such conditions. Furthermore, the numerical results for an isolated energy pile suggest it can meet 40% of the total cooling demand for the building over at least 50 years, respective heat pump functionality limitations regarding heat carrier fluid temperature.

ACKNOWLEDGEMENTS

Some of the used data inputs were inspired from measurements made available by E.construct.

REFERENCES

Akrouch, G. A., Sánchez, M., & Briaud, J. L. (2020). Thermal performance and economic study of an energy piles system under cooling dominated conditions. *Renewable energy*, *147*, 2736-2747. https://doi.org/10.1016/j.renene.2018.11.101.

Alshehri, F., Beck, S., Ingham, D., Ma, L., & Pourkashanian, M. (2021). Sensitivity analysis of a vertical geothermal heat pump system in a hot dry climate. *Renewable Energy*, *178*, 785-801. https://doi.org/10.1016/j.renene.2021.06.058.

Brandl, H. (2006). Energy foundations and other thermo-active ground structures. *Géotechnique*, *56*(2), 81-122. https://doi.org/10.1680/geot.2006.56.2.81.

IEA. (2018). *The Future of Cooling: Opportunities for energy-efficient air conditioning*. International Energy Agency. https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf.

Laloui, L., & Loria, A. F. R. (2019). Analysis and design of energy geostructures: theoretical essentials and practical application. Academic Press. https://doi.org/10.1016/C2017-0-04166-6.

Makasis, N., & Narsilio, G. A. (2022). Investigating the thermal performance of energy soldier pile walls. *Geomechanics for Energy and the Environment*, *30*, 100242. https://doi.org/10.1016/j.gete.2021.100242.

Olgun, C. G., Ozudogru, T. Y., Abdelaziz, S. L., & Senol, A. (2015). Long-term performance of heat exchanger piles. *Acta Geotechnica*, *10*, 553-569. https://doi.org/10.1007/s11440-014-0334-z.

Ravera, E. (2021). *Cyclic thermomechanical behaviour of pile-soil interface and design methods for energy pile foundations*. PhD thesis, EPFL, Lausanne, Switzerland.

Rotta Loria, A. F. (2020). Energy geostructures: Theory and application. In *E3S web of conferences* (Vol. 205, p. 01004). EDP Sciences. https://doi.org/10.1051/e3sconf/202020501004.

Sutman, M., Speranza, G., Ferrari, A., Larrey-Lassalle, P., & Laloui, L. (2020). Long-term performance and life cycle assessment of energy piles in three different climatic conditions. *Renewable Energy*, *146*, 1177-1191. https://doi.org/10.1016/j.renene.2019.07.035.

ten Bosch, S., Ravera, E., & Laloui, L. (2024). Performance of energy piles foundation in hot-dominated climate: A case study in Dubai. *Renewable Energy*, *220*, 119632. https://doi.org/10.1016/j.renene.2023.119632.