RESEARCH PAPER / НАУЧНАЯ СТАТЬЯ
UDC 621.154
DOI: 10.22227/2305-5502.2025.1.19

# Geothermal structures: experimental insights into stress redistribution in 2 × 2 pile groups under asymmetrical thermal loading

**Fardin Jafarzadeh, Sina Afzalsoltani**
*Sharif University of Technology (SUT); Tehran, Islamic Republic of Iran*

**ABSTRACT**

**Introduction.** As energy piles are increasingly utilized for sustainable energy solutions, understanding how thermal loading affects stress distribution within pile groups becomes essential for optimizing their design and functionality. The research aims to elucidate the mechanisms of stress transfer and the resultant effects on pile group behaviour.

**Materials and methods.** A 1g physical modelling approach was used to investigate the thermo-mechanical behaviour of 2 × 2 pile groups under asymmetrical thermal loading. Three separate tests were conducted, each featuring a group with 1, 2, or 3 energy piles subjected to cyclic thermal variations. The model employed closed-end aluminum pipes for the piles and dry, fine-grained silty sand for the ground. During thermal cycling, pile-head displacements, axial forces and bending moments along the piles, soil pressure changes beneath the pile tip, and temperature distribution around the group are monitored.

**Results.** The study demonstrates that thermal cycling has a substantial impact on load distribution among energy piles, with load shares rising during heating phases and falling during cooling phases. This results in an irreversible increase in load share due to soil compaction beneath the pile tips. Additionally, the contribution of the pile tip to the estimated head load increases with each heating-cooling cycle, underscoring the effects of thermal softening at the soil-pile interface.

**Conclusions.** Experimental observations suggest that the classic Boussinesq method may underestimate soil pressure beneath the pile tip during heating phases, potentially due to the soil's plastic behaviour.

**KEYWORDS:** physical modelling, energy piles, asymmetrical loading, pile group, geothermal structures

**FOR CITATION:** Jafarzadeh F., Afzalsoltani S. Geothermal structures: experimental insights into stress redistribution in 2 × 2 pile groups under asymmetrical thermal loading. *Stroitel'stvo: nauka i obrazovanie* [Construction: Science and Education]. 2025; 15(1):19. URL: http://nso-journal.ru. DOI: 10.22227/2305-5502.2025.1.19

*Corresponding author:* Fardin Jafarzadeh, fardin@sharif.ir.

# Геотермальные сооружения: экспериментальная оценка перераспределения напряжений в группах свай 2 × 2 в условиях асимметричной тепловой нагрузки

**Фардин Джафарзаде, Сина Афзалсолтани**
*Технологический университет Шарифа; г. Тегеран, Исламская Республика Иран*

**АННОТАЦИЯ**

**Введение.** Энергетические сваи все чаще используются для решения проблем устойчивой энергетики. Понимание того, как тепловая нагрузка влияет на распределение напряжений в группах свай, важно для оптимизации их конструкции и функциональности. Цель исследования — выяснить механизмы передачи напряжений и их влияние на работу группы свай.

**Материалы и методы.** Для исследования термомеханического поведения групп свай 2 × 2 под асимметричной тепловой нагрузкой использован подход физического моделирования 1g. Проведено три испытания, в каждом из которых группа с 1, 2 или 3 энергетическими сваями подвергалась циклическим тепловым колебаниям. В качестве свай в модели использовались алюминиевые трубы с закрытым оголовком, в качестве грунта — сухой мелкозернистый алевритовый песок. Во время периодического воздействия тепловых нагрузок отслеживались смещения оголовка сваи, осевые силы и изгибающие моменты вдоль свай, изменения давления грунта под оголовком сваи и распределение температуры вокруг группы свай.

**Результаты.** Исследование показало, что периодическое воздействие тепловых нагрузок оказывает существенное влияние на распределение нагрузки между энергетическими сваями, при этом нагрузка увеличивается в фазах нагрева и уменьшается в фазах охлаждения. Это приводит к необратимому увеличению доли нагрузки из-за уплотнения грунта под оголовками свай. Кроме того, вклад оголовка сваи в расчетную нагрузку увеличивается с каждым циклом нагрева – охлаждения, что подчеркивает влияние термического размягчения на границе грунт – свая.

**Выводы.** Экспериментальные наблюдения продемонстрировали, что классический метод Буссинеска может недооценивать давление грунта под оголовком сваи во время нагрева, что может быть связано с пластичной работой грунта.

**КЛЮЧЕВЫЕ СЛОВА:** физическое моделирование, энергетические сваи, асимметричная нагрузка, группа свай, геотермальные сооружения

**ДЛЯ ЦИТИРОВАНИЯ:** *Джафарзаде Ф., Афзалсолтани С.* Геотермальные сооружения: экспериментальная оценка перераспределения напряжений в группах свай 2 × 2 в условиях асимметричной тепловой нагрузки // Строительство: наука и образование. 2025. Т. 15. Вып. 1. Ст. 19. URL: http://nso-journal.ru. DOI: 10.22227/2305-5502.2025.1.19

*Автор, ответственный за переписку:* Фардин Джафарзаде, fardin@sharif.ir.

## INTRODUCTION

Geothermal resources can be broadly grouped into shallow and deep geothermal. Shallow geothermal energy is the low-grade heat (10 to 25 °C) that is stored in the shallow subsurface at depths of up to 500 m. Deep geothermal energy is the heat stored at depths greater than 500 m. In a world where energy needs are constantly increasing and where the research for green, local and renewable energy sources is becoming increasingly important, energy geostructures are perfectly suited. They represent an innovative and promising alternative for heating or cooling buildings and infrastructures. The principle is that of shallow geothermal energy; thanks to the fact that the subsoil temperature remains constant throughout the year (except for the first 5 to 10 m), this temperature will be higher than that of the external air in winter and lower in summer. The term shallow geostructures which is subject of this research, includes piles for deep foundations, retaining walls, tunnel lining segments, etc. The heat exchange between the ground and these concrete structures is ensured by a system of tubes arranged inside the structure and within which a heat transfer fluid circulates.

One of the primary sectors consuming significant energy is maintaining comfortable indoor temperatures. In contemporary society, a substantial portion of this energy is derived from the combustion of fossil fuels, which has contributed to numerous environmental disasters over recent decades [1, 2]. Geothermal heat pump systems (GHPs) present a sustainable and energy-efficient alternative to this challenge.

GHPs can be integrated with various geostructures, leading to the development of innovative energy geostructures such as energy piles, energy tunnels, and energy diaphragm walls. Research indicates that soil temperatures at depths greater than approximately 10 m remain relatively stable and unaffected by seasonal fluctuations at the surface. This characteristic enhances the efficiency of GHPs, allowing them to operate more effectively.

All thermoactive geostructures share a fundamental design principle: they utilize a heat transfer fluid to facilitate the exchange of thermal energy between the ground and indoor environments. This fluid circulates through pipes that are embedded in the ground on one end and integrated into the walls and floors of buildings on the other. By leveraging the stable temperatures found underground, GHPs can significantly reduce reliance on traditional heating methods, thus minimizing energy consumption and lowering greenhouse gas emissions.

The integration of GHPs into building designs not only promotes energy efficiency but also aligns with global efforts to combat climate change by reducing the carbon footprint associated with indoor heating. As awareness of sustainable practices grows, the adoption of GHP technology is expected to become increasingly prevalent, paving the way for a more environmentally friendly approach to energy consumption in the built environment.

Energy geostructures are increasingly being recognized for their potential to provide sustainable heating and cooling solutions while serving structural purposes. Several real-world projects have successfully implemented energy geostructures, particularly energy piles, to provide sustainable heating and cooling solutions. The Cleunay station in Rennes [3], France, utilizes energy walls as part of its geothermal heating system (Fig. 1). The Uniqa tower in Vienna, Austria utilize energy diaphragm walls to extract geothermal energy for heating and cooling [4]. In Oxford, UK, energy piles were first used in a new building for Keble college serving as geothermal heat exchangers [5]. Other notable examples include the Laizer tunnel in Vienna (Fig. 2), the Sapporo city university in Japan (Fig. 3), the Dock Midfield terminal at Zurich airport in Switzerland, the Wuxi Guolian Tower in China, and the Jenbach tunnel in Austria [4, 6, 7].

Conventional piles have been extensively analyzed through physical modelling techniques in a variety of research studies [8–12]. Recently, there has been a growing interest among scholars in understanding

**Fig. 1.** Photo of the pipe cages used in the slurry walls at Cleunay station in Renne, France [3]

**Рис. 1.** Фотография трубных обойм для стен в грунте на станции Клёне в Ренне, Франция [3]

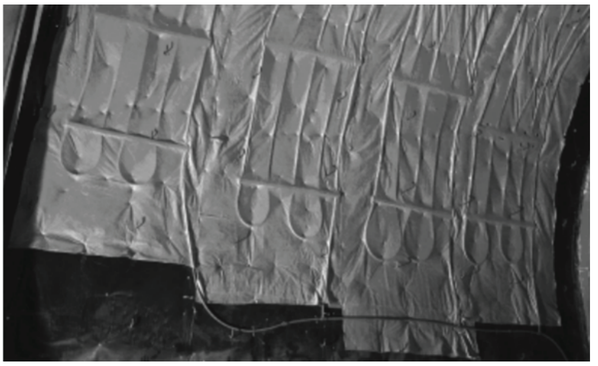


**Fig. 2.** Absorber loops at Laizer tunnel in Vienna, Austria [4]

**Рис. 2.** Поглощающие устройства в туннеле Лайзера в Вене, Австрия [4]

**Fig. 3.** Layout of installed 51 steel foundation piles and inserting of two sets of U-tubes, Sapporo city university, Japan [7]

**Рис. 3.** Схема установки 51 стальной фундаментной сваи и вставки двух комплектов U-образных труб, Университет г. Саппоро, Япония [7]

the behaviour and performance of energy piles [13–30]. For example, Ng et al. [25] investigated the impact of elevated temperatures on a floating aluminum pile situated in saturated sand by conducting centrifuge tests. Their findings revealed a pile head uplift of 0.4 and 1 % D, along with enhancements in overall pile capacity by 13 and 30 % due to temperature increases of 15 and 30 °C, respectively. Further research by Ng et al. [26] involved centrifuge modelling to explore the effects of pile spacing on thermo-mechanical interactions among energy pile groups. Their results indicated that a spacing of 5D was preferable to 3D for meeting serviceability limits. Ng et al. [27] compared the performance of a non-symmetrical, thermally loaded 2 × 2 elevated pile group in lightly over consolidated clay against a piled raft. They concluded that piled rafts experienced less tilting under uneven thermal loads. Senejani et al. [28] focused on the thermo-mechanical behaviour of a single energy pile using a small-scale physical sand model. Their research indicated a decline in the elastic response of the surrounding soil during extended thermal cycles. Foglia et al. [29] conducted large-scale tests on a single pile and two-pile groups for an offshore platform in sandy conditions. Their study highlighted the significant influence of pile spacing and group configuration on the bearing capacity and settlement of the energy pile group. Lastly, Yang et al. [30] carried out physical model tests and numerical simulations to assess various factors affecting the thermo-mechanical behaviour of energy pile groups. They identified that parameters such as pile spacing, diameter, and soil thermal conductivity played crucial roles in the thermal response of these groups.

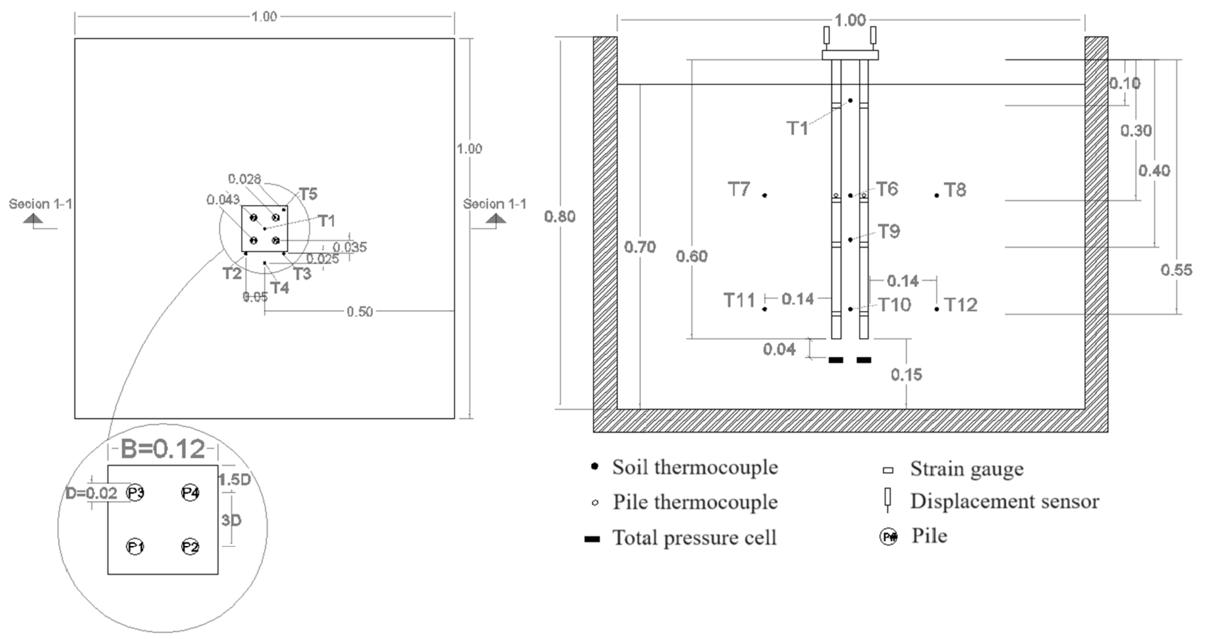
The present study investigates the thermo-mechanical behaviour of energy piles, specifically focusing on the stress distribution within pile groups subjected to asymmetrical thermal loading. Utilizing a 1g physical modelling approach, the research conducts three separate tests featuring groups with 1, 2 and 3 energy piles, each subjected to 10 thermal cycles. The findings reveal important insights, such as the downward movement of the null-point with increasing pile temperature and a positive correlation between soil pressure and pile temperature. While some studies have examined asymmetrical thermal loading, such investigations remain relatively rare, particularly in the context of energy pile groups. This research addresses this gap by elucidating the mechanisms of stress transfer and their implications for the thermo-mechanical behaviour of pile groups under non-uniform heating conditions.

## MATERIALS AND METHODS

The experimental physical models consist of a pile group measuring 2 × 2 (each pile with an outer diameter of $D$ = 2 cm), positioned at a center-to-centre distance of 6 cm (equivalent to 3 times the pile diameter). The soil container, a rigid steel box measuring 100 × 100 × 80 $cm^3$ (width × length × height), holds the model ground. This ground comprises dry silty sand with a relative density of about 70 %, compacted using the dry tamping technique. Fig. 4 illustrates the model configuration, while Fig. 5 showcases the constructed model.

To control pile temperature, water circulates through steel U-tubes placed inside each pile. Initially, the piles are filled with water to ensure effective thermal interaction with the U-tubes. The pile group undergoes mechanical loading in 8 steps, reaching a maximum load of 400 N, with 5-minute resting intervals between steps (the loading shaft itself weighs 1.5 kg). Under constant mechanical load, the energy pile experiences 10 consecutive heating-cooling cycles, with a temperature amplitude of ±6 °C. Three test scenarios are conducted: "Group 1" features Pile1 as the energy pile, while the other piles remain non-energy piles. In "Group 2", both Pile 1 and Pile 2 are energy piles, and in "Group 3", Pile 1, Pile 2, and Pile 3 are energy piles. After each test, the entire model is reconstructed. Refer to Table 1 for the detailed test plan.

The particle size distribution of the model ground, depicted in Fig. 6, reveals fine sand with 40 % passing




*a* *b*

**Fig. 4.** Schematic views of the model configuration: *a* — plan view; *b* — section 1–1

**Рис. 4.** Схематические изображения конфигурации модели: *a* — вид в плане; *b* — разрез 1–1

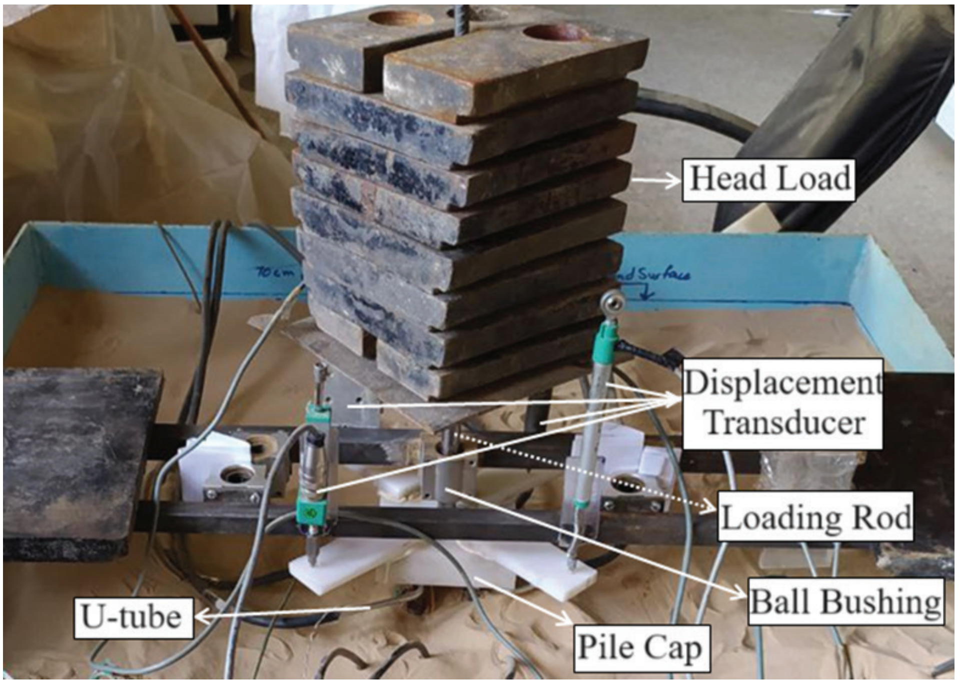



**Fig. 5.** Pile Cap and loading mechanism

**Рис. 5.** Оголовок сваи и механизм нагружения

**Table 1.** Test plan

**Табл. 1.** План проведения испытаний

| Test name | Number of energy piles | Soil type | Mechanical surcharge, kg | Energy pile temperature, °C |
|---|---|---|---|---|
| Group 1 | 1 | Air-dried silty sand (Dr = ~70 %) | 41.5 | 21.5 ± 6 (10 cycles) |
| Group 2 | 2 | Air-dried silty sand (Dr = ~70 %) | 41.5 | 21.5 ± 6 (10 cycles) |
| Group 3 | 3 | Air-dried silty sand (Dr = ~70 %) | 41.5 | 21.5 ± 6 (10 cycles) |

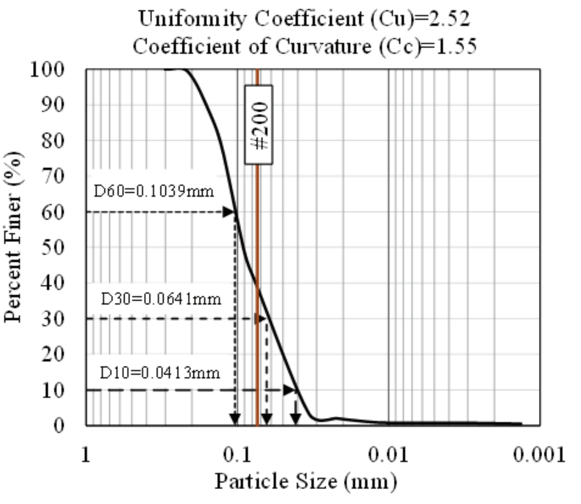



**Fig. 6.** Particle size distribution analysis of the model ground

**Рис. 6.** Анализ распределения частиц по размерам образца грунта

through the #200 sieve. Atterberg tests confirm that the portion finer than the #200 sieve consists of non-plastic silt. Consequently, the soil classification based on the Unified Soil Classification System is SM.

## RESULTS OF THE RESEARCH

### Pile cap rotation

Fig. 7 displays the cap rotation and tilt time histories for tests labeled as "Group 1", "Group 2" and "Group 3". The tilt is determined by comparing the vertical displacements of two points on the cap, divided by the horizontal distance between them in the tilting direction. Notably, heating consistently reduces the tilt, while cooling increases it. There are two exceptions: in both "Group 1" and "Group 2", the first heating phase induces a tilt, and in "Group 1", the second heating phase also causes a slight increase. The amplitude of tilt oscillations is largest in "Group 2" and smallest in "Group 1". These oscillations decrease asymptotically in "Group 1" and "Group 2" but remain constant in "Group 3". Importantly, the tilt in "Group 1" and "Group 2" exceeds the allowable limit of 1/500 (0.2 %) during the second and first cooling phases, respectively, as suggested by Eurocode 7, EN 1997-1 [31]. In "Group 3", the cap tilt touches the limit line during the fourth cooling phase and marginally exceeds the limit in subsequent cooling phases.

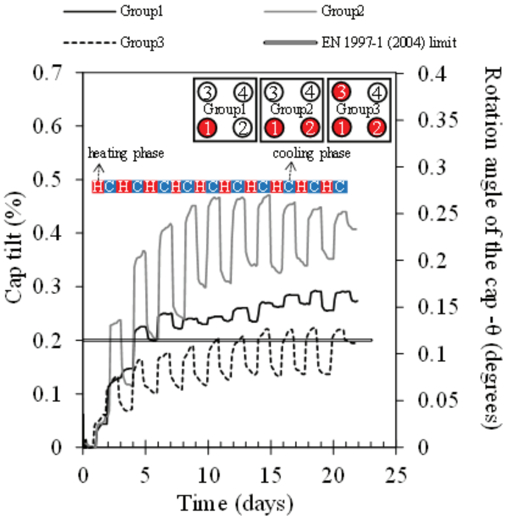



**Fig. 7.** Tilt and rotation angle of pile group caps in each test

**Рис. 7.** Угол наклона и поворота оголовков групп свай для каждого испытания

### Load distribution among piles

The distribution of the group's total mechanical head load between the piles of each group and the share of each pile's tip from its head load are shown in Fig. 8. The load share of the energy piles increased during heating phases and decreased during cooling phases due to thermal expansion and contraction of the pile material. The first stages of thermal cycling did not significantly affect the load share, but after a few cycles, the share of the energy piles started to increase more noticeably with each heating phase. As thermal cycling continued, an irreversible increase in the load share of the energy piles was observed, which was attributed to soil compaction under the pile tip due to excessive settlement and the consequent increase in soil elastic modulus. The share of Pile 1 increased from 25 to 29.3 %, 31.62 % and 28.4 % in tests "Group 1", "Group 2" and "Group 3", respectively. The share of diagonal energy piles (Pile 2 and Pile 3) in test "Group 3" reached 31.4 % for each pile at the end of the test.

In Fig. 8, *d*, *e*, *f* it is evident that the contribution of the pile tip to the estimated head load of energy piles increases with each heating-cooling cycle. Notably, in most instances, heating the energy pile leads to a rise in the proportion of the pile tip's contribution to its head load, while cooling tends to reduce this share. This phenomenon can be explained by the thermal softening occurring at the soil-pile interface during the heating phases, affecting both the pile tip and the pile sleeve. However, in most cases, the softening at the pile sleeve interface appears to have a more significant impact than that at the pile tip interface. It is worth noting that during the initial heating phase in tests labeled "Group 1" and "Group 2", the opposite effect was observed, resulting in a decrease in the pile tip's share of the estimated head load, as illustrated in Fig. 8, *d*, *e*, respectively. At the outset of all tests, approximately 45 % of the head load for each pile was transmitted to its tip. By the conclusion of tests "Group 1", "Group 2", and "Group 3", this percentage increased to 64, 60 and 56 % for Pile 1, respectively. For the diagonal energy piles, Pile 2 and Pile 3, in test "Group 3", the contribution of the pile tip rose to 58 % by the end of the test.

### Soil pressure

The time histories of vertical soil pressure at a depth of 4 cm below the pile tip for various piles in each test were recorded using four *Kyowa* total pressure cells (refer to Fig. 4 for sensor locations) and are presented in Fig. 9. It was

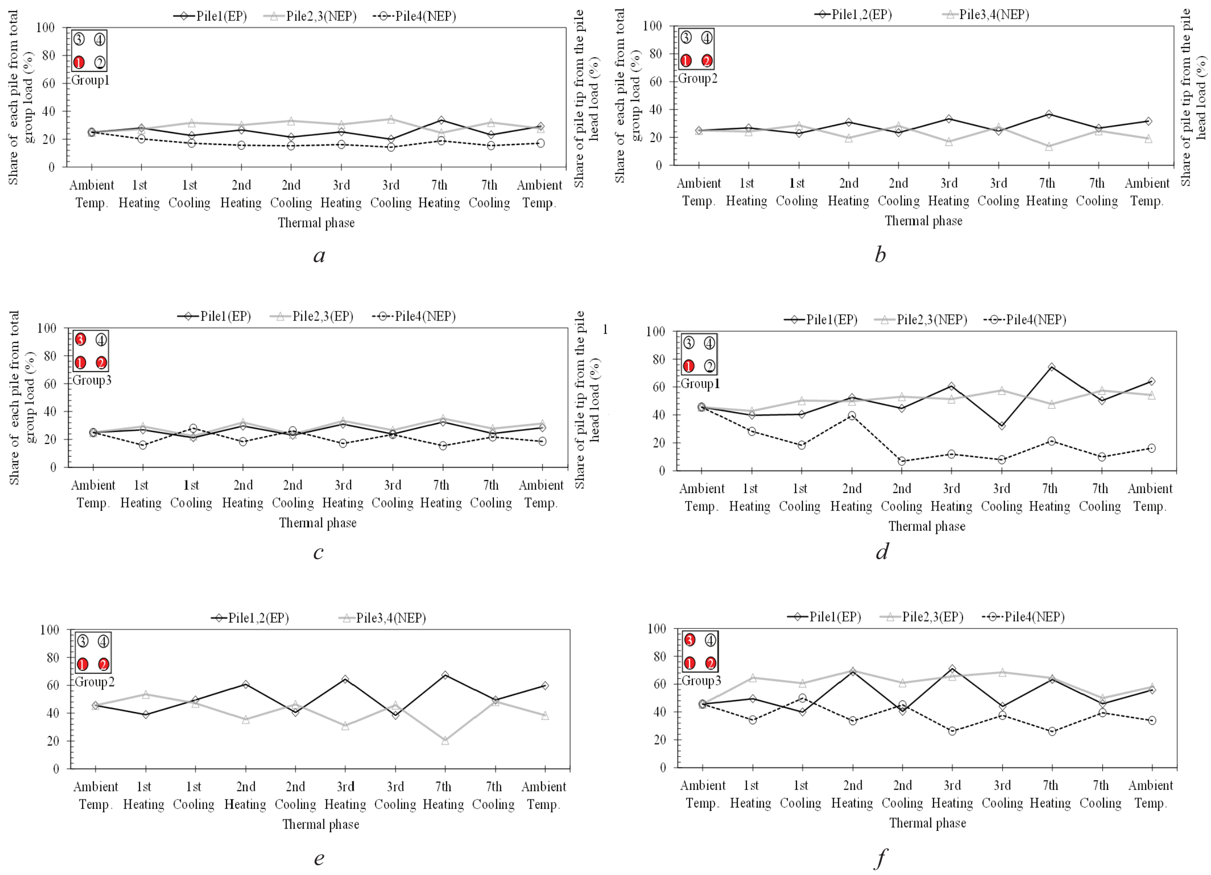



**Fig. 8.** Distribution of each pile's share of the total mechanical head load (415 N) across: *a* — Group 1; *b* — Group 2 and *c* — Group 3, along with the contribution of each pile's tip to its respective head load for *d* — Group 1; *e* — Group 2 and *f* — Group 3

**Рис. 8.** Распределение доли каждой сваи в общей механической нагрузке (415 Н) для: *a* — группы 1; *b* — группы 2 и *c* — группы 3, а также доли оголовка каждой сваи в соответствующей нагрузке для *d* — группы 1; *e* — группы 2 и *f* — группы 3

observed that in all tests, the soil pressure under the energy pile increased during heating phases and decreased during cooling phases. The amplitude of these soil pressure oscillations gradually increased over the first few cycles until it remained relatively constant after the fifth cycle. Additionally, in Fig. 9, the back-calculated vertical soil pressure at the locations of the total soil pressure sensors is plotted based on estimations derived from the Boussinesq equation [32], which is expressed as follows:

$$\sigma_b^{Z_0} = q \cdot \left[ 1 - \frac{1}{\left[ 1 + \left( R/Z_0 \right)^2 \right]^{3/2}} \right] + \sigma_{ini}^{Z_0}, \qquad (1)$$

where $\sigma_b^{Z_0}$ is the estimated vertical soil pressure at depth of $Z_0$ below the pile tip based on J. Boussinesq [32], kPa; $q$ is the uniform distributed load on a circular foundation (here, the pressure at the pile tip), kPa; $R$ is the radius of the pile tip, cm; $Z_0$ is depth of total pressure cell (TPC) measured from the pile tip, cm; $\sigma_{ini}^{Z_0}$ is the initial vertical soil pressure recorded by the total pressure cell, kPa.

In the equation mentioned above, Boussinesq [32] assumed that the soil behaves as a linear-elastic, homogeneous, isotropic, semi-infinite medium. In this study, we aimed to correlate any discrepancies between the total pressure cell (TPC) readings and those predicted by the Boussinesq equation to variations in the soil's state relative to Boussinesq's assumptions. M. Sadek, I. Shahrour [33] noted that the Boussinesq equation tends to underestimate stresses when the soil is in a plastic state. As shown in Fig. 9, *a*, the vertical stresses measured by the TPC beneath Pile 4 in test "Group 1" closely match the values estimated by Eq. 1, suggesting that the soil in that area remained in an elastic state throughout the thermal cycling. It is important to note that during the heating phases of test "Group 1", the TPC readings under the energy pile exceeded the estimates from Eq. 1, indicating that the soil was deviating from its elastic state. Conversely, during the cooling phases, the TPC readings were relatively consistent with the values predicted by Eq. 1.

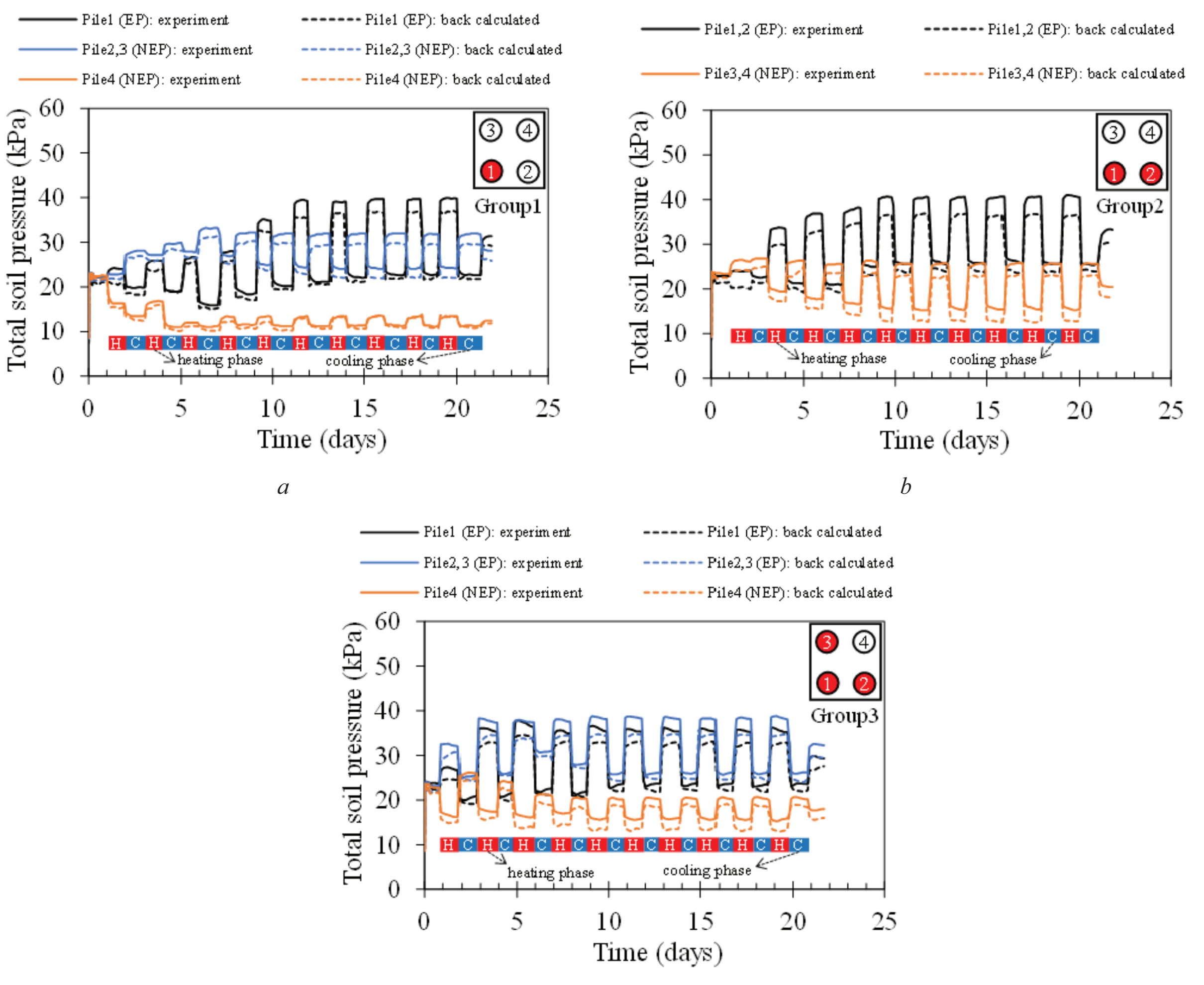



**Fig. 9.** Time histories of total soil pressure measured beneath various piles in each test

**Рис. 9.** Временная зависимость общего давления на грунт, измеренного под различными сваями в каждом испытании

## CONCLUSION

In this study, thermos-mechanical behaviour of pile groups as one of the main types of geothermal structures, is considered. For this purpose, three 1g physical model tests were performed on 2 × 2 pile groups to investigate the impact of asymmetrical thermal loading on the behaviour of the pile group in dry sandy soil. Initially, the pile groups were loaded incrementally to a total of 400 N (415 N when accounting for the weight of the loading shaft) at a constant temperature of 21.5 °C. In tests labeled "Group 1", "Group 2" and "Group 3", one, two, and three energy piles were utilized, respectively, to apply an asymmetrical thermal load to the group. The results showed that in tests "Group 1" and "Group 2", the cap tilt exceeded the 1/500 (0.2 %) allowable limit specified by EN 1997-1 [31] during the second and first cooling phases, respectively. However, in test "Group 3", the cap tilt diagram touched the limit line for the first time in the fourth cooling phase and marginally surpassed the allowable limit in subsequent cooling phases.

The study reveals that thermal cycling significantly affects load distribution among energy piles, with load shares increasing during heating phases and decreasing during cooling phases. An irreversible increase in load share occurs due to soil compaction beneath the pile tips. Overall, the contribution of the pile tip to the estimated head load rises with each heating-cooling cycle, highlighting the impact of thermal softening at the soil-pile interface.

Experimental observations indicate that the famous and traditional Boussinesq [32] method might underestimate the soil pressure beneath the pile tip during heating phases, likely due to the plastic behaviour of the soil.

## REFERENCES / СПИСОК ИСТОЧНИКОВ

1. Barbir F., Veziroğlu T., Plass Jr H. Environmental damage due to fossil fuels use. *International Journal of Hydrogen Energy.* 1990; 15(10):739-749.

2. Lvovsky K., Hughes G., Maddison D., Ostro B., Pearce D. *Environmental costs of fossil fuels : a rapid assessment method with application to six cities.* 2000.

3. Sauvenier J. *Energy geostructures: The case of the Cleunay station in Rennes.* 2023.

4. Adam D., Markiewicz R. Energy from earth-coupled structures, foundations, tunnels and sewers. *Géotechnique.* 2009; 59(3):229-236.

5. Brandl H. Energy foundations and other thermo-active ground structures. *Géotechnique.* 2006; 56(2): 81-122.

6. Laloui L., Di Donna A. *Energy geostructures: innovation in underground engineering.* John Wiley & Sons, 2013.

7. Nagano K. *Energy pile system in new building of Sapporo City University, Thermal Energy Storage for Sustainable Energy Consumption: Fundamentals, Case Studies and Design.* Springer, 2007; 245-253.

8. Haeri S.M., Rajabigol M., Salaripour S., Kavand A., Sayyaf H., Afzalsoltani S. et al. Effects of physical modelling boundary conditions on the responses of 3 × 3 pile groups to liquefaction induced lateral spreading. *Bulletin of Earthquake Engineering.* 2023; 21(5):2469-2502.

9. Kavand A., Haeri S.M., Raisianzadeh J., Afzalsoltani S. Effectiveness of a vertical micropile system in mitigating the liquefaction-induced lateral spreading effects on pile foundations: 1 g large-scale shake table tests. *Scientia Iranica.* 2022; 29(3):1038-1058.

10. Kavand A., Haeri S.M., Raisianzadeh J., Meibodi A.S., Soltani S.A. Seismic behaviour of a dolphin-type berth subjected to liquefaction induced lateral spreading: 1g large scale shake table testing and numerical simulations. *Soil Dynamics and Earthquake Engineering.* 2021; 140:106450.

11. Haeri S., Rajabigol M., Salaripour S., Kavand A., Sayyaf H., Afzalsoltani S. et al. *Effects of liquefaction-induced lateral spreading on a 3 × 3 pile group using 1g shake table and laminar shear box, Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions.* CRC Press, 2019; 2764-2770.

12. Haeri S.M., Kavand A., Raisianzadeh J., Afzalsoltani S. *Effectiveness of a vertical micro-pile system for mitigating lateral spreading damage on pile groups: 1g shake table tests, Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions.* CRC Press, 2019; 3989-3996.

13. Jafarzadeh F., Afzalsoltani S. Pile group behaviour under unsymmetrical cyclic thermal loading in dry silty sand: 1g Physical modelling. *Scientia Iranica.* 2024. DOI: 10.24200/sci.2024.61493.7345

14. Jafarzadeh F., Afzalsoltani S. *Unsymmetrical thermal loading effects on a 2 × 2 pile-group: 1g physical modelling approach, Smart Geotechnics for Smart Societies.* CRC Press, 2023; 2197-2200.

15. Jafarzadeh F., Afzalsoltani S. Energy Piles, Applications and Research Aspects: An Investigation on the Behaviour of a Single Energy Pile in Dry Condition. *International Conference on Geotechnical Engineering-IRAQ.* 2022; 261-277. DOI: 10.1007/978-981-19-7358-1_23

16. Jafarzadeh F., Afzalsoltani S., Arbab A., Shirkhani S. *1g Physical Modelling of a Single Heat-Exchanger pile in Silty Sand, Book 1g Physical Modelling of a Single Heat-Exchanger pile in Silty Sand.* Sydney, Australia, 2022.

17. Afzalsoltani S., Jafarzadeh F. *The effect of mechanical surcharge on single energy pile foundations: 1g physical modelling, Book The effect of mechanical surcharge on single energy pile foundations: 1g physical modelling.* Sydney, Australia, 2022.

18. Song H., Pei H., Xu D., Cui C. Performance study of energy piles in different climatic conditions by using multi-sensor technologies. *Measurement.* 2020; 162:107875.

19. Farivar A., Jafarzadeh F., Leung A.K. Influence of pile head restraint on the performance of floating elevated energy pile groups in soft clay. *Computers and Geotechnics.* 2023; 154:105141.

20. Wang Y., Zhang F., Liu F., Wang X. Full-scale in situ experimental study on the bearing capacity of energy piles under varying temperature and multiple mechanical load levels. *Acta Geotechnica.* 2024; 19(1):401-415.

21. Khoshbakht S., Fakharian K. Numerical Investigation of the Load Movement and Ultimate Load of Energy Piles Embedded in Sand. *International Journal of Geomechanics.* 2024; 24(3):04023297.

22. Pessin J., Tsuha C.H.C. In-field performance of continuous flight auger (CFA) energy piles with different configurations. *Applied Thermal Engineering.* 2023; 224:120113.

23. Moshtaghi M., Keramati M., Ghasemi-Fare O., Pourdeilami A., Ebrahimi M. Experimental study on thermomechanical behaviour of energy piles in sands with different relative densities. *Journal of Cleaner Production.* 2023; 403:136867.

24. Ghaaowd I., McCartney J.S. Centrifuge modelling methodology for energy pile pullout from saturated soft clay. *Geotechnical Testing Journal.* 2022; 45(2):20210062-20210062.

25. Ng C.W.W., Shi C., Gunawan A., Laloui L., Liu H. Centrifuge modelling of heating effects on energy pile performance in saturated sand. *Canadian Geotechnical Journal.* 2015; 52(8):1045-1057.

26. Ng C.W.W., Farivar A., Gomaa S.M.M.H., Shakeel M., Jafarzadeh F. Performance of elevated ener-

gy pile groups with different pile spacing in clay subjected to cyclic non-symmetrical thermal loading. *Renewable Energy*. 2021; 172:998-1012.

27. Ng C.W., Farivar A., Gomaa S.M., Jafarzadeh F. Centrifuge modelling of cyclic nonsymmetrical thermally loaded energy pile groups in clay. *Journal of Geotechnical and Geoenvironmental Engineering.* 2021; 147(12):04021146.

28. Senejani H.H., Ghasemi-Fare O., Cherati D.Y., Jafarzadeh F. Investigation of thermo-mechanical response of a geothermal pile through a small-scale physical modelling. *E3S Web of Conferences.* 2020; 205:05016.

29. Foglia A., Abdel-Rahman K., Wisotzki E., Quiroz T., Achmus M. Large-scale model tests of a single pile and two-pile groups for an offshore platform in sand. *Canadian Geotechnical Journal.* 2021; 99(999):1825-1838.

30. Yang W., Qiang Y., Ju L., Wang F., Liu A. Numerical evaluations on the effects of different factors on thermo-mechanical behaviour of an energy pile group. *Computers and Geotechnics.* 2023; 162:105664.

31. BSI. BS EN 1997-1: 2004. Eurocode 7. Geotechnical design. General rules, Book BS EN 1997-1: 2004. Eurocode 7. *Geotechnical design.* General rules, EditorBSI London, UK, 2004.

32. *Application des potentiels à l'étude de l'équilibre et du mouvement des solides élastiques: principalement au calcul des déformations et des pressions que produisent, dans ces solides, des efforts quelconques exercés sur une petite partie de leur surface ou de leur intérieur: mémoire suivi de notes étendues sur divers points de physique, mathematique et d'analyse.* Boussinesq J., Gauthier-Villars, 1885.

33. Sadek M., Shahrour I. Use of the Boussinesq solution in geotechnical and road engineering: influence of plasticity. *Comptes Rendus Mécanique.* 2007; 335(9-10): 516-520.

*Received August 28, 2024.*
*Adopted in revised form on September 20, 2024.*
*Approved for publication on September 25, 2024.*

Bionotes: **Fardin Jafarzadeh** — PhD, Associate Professor, Civil Engineering Department; **Sharif University of Technology (SUT)**; Azadi avenue, Tehran, Islamic Republic of Iran; fardin@sharif.ir;

**Sina Afzalsoltani** — PhD Candidate, Civil Engineering Department; **Sharif University of Technology (SUT)**; Azadi avenue, Tehran, Islamic Republic of Iran; s.afzalsoltani@gmail.com.

*Contribution of the authors:*
*Fardin Jafarzadeh — conceptualization, methodology, scientific editing of the text, supervision.*
*Sina Afzalsoltani — conceptualization, methodology, data gathering and processing, writing of the paper.*
*The authors declare no conflict of interest.*

*Поступила в редакцию 28 августа 2024 г.*
*Принята в доработанном виде 20 сентября 2024 г.*
*Одобрена для публикации 25 сентября 2024 г.*

Об авторах: **Фардин Джафарзаде** — кандидат наук, доцент, президент Иранского геотехнического общества; **Технологический университет Шарифа**; г. Тегеран, ул. Азади, Исламская Республика Иран; fardin@sharif.ir;

**Сина Афзалсолтани** — кандидат наук; **Технологический университет Шарифа**; г. Тегеран, ул. Азади, Исламская Республика Иран; S. Afzalsoltani@gmail.com.

*Вклад авторов:*
*Фардин Джафарзаде — концептуализация, методология, научное редактирование текста, руководство.*
*Сина Афзалсолтани — концептуализация, методология, сбор и обработка данных, написание статьи.*
*Авторы заявляют об отсутствии конфликта интересов.*