# A physical model study on the thermal resistance of steel energy piles filled with different materials

M.V.F. Murari
*School of Engineering of São Carlos of the University of São Paulo, São Carlos, Brazil, milena@adconconstrutora.com.br*

C.H.C. Tsuha
*School of Engineering of São Carlos of the University of São Paulo, São Carlos, Brazil, chctsuha@sc.usp.br*

**ABSTRACT:** Geothermal energy piles, when integrated with ground source heat pump systems, offer an efficient solution for building heating and cooling. This study presents preliminary model-test results from an energy pile project implemented for a building in São Paulo, Brazil. In this project, driven steel pipe piles serve as ground heat exchangers, enabling thermal energy transfer between the building and the surrounding soil. To support the selection of an optimal filler material aimed at minimizing pile thermal resistance, laboratory-scale model tests were conducted. Thermal load tests were performed on pile sections equipped with a single U-loop and installed at the center of a circular tank (1.25 m in diameter and 0.67 m in height) filled with either dry or saturated sand. The filler materials tested included sand, concrete, concrete with steel fibers, and water. A steel pile section (0.22 m in diameter and 0.55 m in height) was used to simulate radial heat transfer from a segment of an energy pile. Temperature sensors were installed at various distances from the pile wall to monitor the thermal response of the surrounding sand. This paper presents temperature measurements at the pile–soil interface and in the surrounding soil under thermal loading in saturated sand, reflecting field conditions where the steel pipe energy piles are installed below the groundwater table.

## 1 INTRODUCTION

The use of renewable energy has received increasing attention in recent years as a means to reduce global energy consumption and carbon dioxide emissions (Glassley, 2014). Ground heat exchangers (GHEs) coupled with ground source heat pumps (GSHPs) represent a promising solution, as they are relatively low-cost and can achieve high efficiency. GHEs interact with the soil through the circulation of a heat-carrying fluid within pipes embedded in the ground.

Borehole heat exchangers have long been used as geothermal heat exchangers (Rybach et al., 2000). More recently, piled foundations of new buildings have begun to serve as ground heat exchangers—commonly referred to as energy piles—offering economic advantages by reducing excavation requirements (Brandl, 2006; Wood et al., 2010). By incorporating heat exchange functionality into structural elements, energy piles offer a practical and efficient means of harnessing geothermal energy while simultaneously functioning as part of a building's foundation.

While the use of energy foundations has been successful in countries with temperate climates, little is known about their performance under Brazilian tropical conditions, where cooling demand dominates throughout the year. There is a notable lack of experimental studies and demonstration projects evaluating the local feasibility and thermal efficiency of this technology in hot-dominant climates.

To address this gap, investigations on thermo-active pile foundations installed in saturated sand have been conducted at the University of São Paulo. A new building incorporating energy piles, named the CICS Living Lab, is currently under construction on the university campus in the urban zone of São Paulo, Brazil. Part of its foundation system consists of driven steel pipe piles (Figure 1) equipped with a single U-tube for heat exchange.

The thermal efficiency of a heat exchanger pile (GHE) depends on the thermal properties of the surrounding soil as well as on the characteristics of the pile heat exchanger, including its dimensions, geometry, pile material, and pipe configuration. The infill material plays a particularly important role in heat transfer, as it is directly related to the thermal resistance of the GHE. Several studies have investigated the effect of different infill materials on the thermal resistance of heat exchangers, including Desmedt et al. (2012), Cecinato and Loveridge (2015), and Erol and François (2014).

The present study investigated different infill materials for steel pipe piles used as energy foundations in the CICS Living Lab building through laboratory model tests. These tests were designed to inform the selection of a filler material that would optimize heat transfer within the building foundation. The infill materials analyzed included sand, concrete, concrete reinforced with steel fibers, and water.

*Figure 1. Steel pipe energy pile installation at the University of São Paulo (de Freitas Murari et al., 2022).*

## 2 EXPERIMENTAL PROGRAM

### 2.1 Materials, equipment and instrumentation

The laboratory model tests were conducted in a circular tank with a diameter of 1.25 m and a height of 0.67 m, filled with sand under both dry and saturated conditions. In this paper, however, only the results from the tests performed in saturated sand are presented.

A steel pipe section measuring 0.22 m in diameter, 0.01 m in thickness, and 0.55 m in height was installed at the center of the tank. The steel pipe piles were backfilled with different materials commonly available on construction sites. Low-cost materials with relatively good thermal conductivity were selected.

The materials chosen for the tests were sand, concrete, steel-fiber-reinforced concrete, and water. Because the soil at the CICS site is saturated, the use of water as a backfilling material was intended to simulate the natural filling of the pile by groundwater. To compare the thermal performance of the steel pipe piles, a circular concrete pile of the same height as the steel pile and with a diameter of 0.21 m was also evaluated.

The concrete used to backfill the steel pipe piles does not serve a structural purpose. Therefore, a high water–cement ratio was adopted to minimize additional costs associated with the energy pile foundation. Table 1 presents the concrete mix proportions, expressed as volume ratios of cement, sand, and gravel, along with the corresponding water–cement ratio. The table also includes the mix design used for the concrete pile.

*Table 1. Concrete mix characteristics.*

| Concrete | volume proportions | steel fibers (Kg/m³) | water/ cement ratio |
|---|---|---|---|
| Concrete used in the pipe pile | 1:3:6 | - | 0.75 |
| Steel fiber concrete used in the pipe pile | 1:3:6 | 25 | 0.75 |
| Concrete (of the concrete pile) | 1:2:2.5 | - | 0.55 |

Each pile contained two parallel high-density polyethylene (HDPE) pipes, spaced 15 cm apart (Figure 2), with a height of 0.62 m and inner and outer diameters of 26 mm and 32 mm, respectively, to simulate a single U-tube configuration. Figure 2 presents photographs of the tested pile sections, including both concrete and steel pipe piles.


*Figure 2. Piles constructed for physical model tests (concrete and steel pipe pile section), and concrete with and without steel fiber used as pile filled material.*

The assembly steps illustrated in Figure 3, show the sequence from filling the tank for the tests conducted in dry sand, installing the pipe, positioning the temperature (PT100 type) sensors and HDPE tubes, filling the pile with the material under investigation, and completing the tank filling with sand. After the test setup, a period of 24 hours was allowed for temperature stabilization.


*Figure 3. Test assembly steps for the tests in dry sand.*

For the steel pile filled with steel-fiber-reinforced concrete, the fibers used in this study were Dramix brand fibers, with a diameter of 0.62 mm and a length of 30 mm. The fibers were mixed into the concrete, as shown in Figure 2. Steel fibers were added because they are expected to enhance the thermal conductivity of the concrete, thereby improving the heat exchange between the pile and the surrounding soil.

For the pile thermal loading tests, the bases of the HDPE pipes were sealed and the pipes were filled with water. Two thermostatically controlled heaters were used to raise the water temperature inside the pipes to 32 °C. To prevent vertical heat transfer, the tank was insulated with 5 cm thick polystyrene at both the top and the base (Figure 3). This configuration simulates a section of a field energy pile, ensuring that heat transfer occurs primarily along the radial axis of the pile. With similar initial soil and constant ambient temperatures and short test durations, radial boundary effects were likely negligible. Additionally, during the final 24 hours of testing, temperature increases at all radial distances stabilized similarly.

One section of the energy pile was instrumented with PT100 sensors to measure temperature at the pile-soil interface and at fixed radial distances from the pile center (0.5 R, 1 R, 1.5 R, and 2 R), as shown in Figure 4. The sensors were installed in two directions around the pile: aligned with the HDPE pipes, refered as [0º], and perpendicular to the HDPE pipes, refered as [90º]. In total, ten temperature sensors were used, with five sensors in each direction. Temperature evolution was recorded continuously over a period of 96 hours using a data acquisition system.

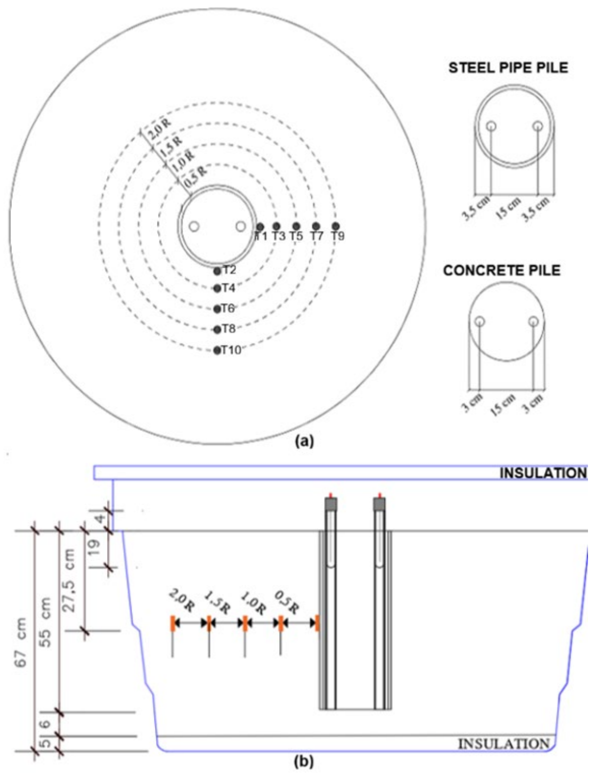


*Figure 4. Laboratory test set up (a) planar instrumented section (b) tank instrumented profile.*

Two soil conditions around the piles were simulated in the physical models: dry sand and saturated sand, with a total of nine tests performed. However, only the results obtained in saturated sand are presented in this paper. Table 2 provides a list of the tests conducted. For the test on the pile filled with water (P5), a PT-100 temperature sensor was placed at the center of the pile in the section where radial temperature variation was analyzed.

*Table 2. Model tests performed in the saturated sand tank.*

| Pile ID | Pile | Backfill material |
|---|---|---|
| P1 | Steel pipe pile | Concrete |
| P2 | Steel pipe pile | Steel fibre concrete |
| P3 | Steel pipe pile | Sand |
| P4 | Concrete | - |
| P5 | Steel pipe pile | Water |

For the saturated sand tests, a 6 cm-thick gravel drainage layer was placed at the bottom of the tank, directly above the foam insulation, and covered with a geotextile blanket to separate the gravel from the sand. The drainage layer was used to saturate the sand by capillarity, as illustrated in Figure 5.

The tests were conducted in two main phases: (1) a heating phase, in which thermal loading was applied for 96 hours with the heaters on, and (2) a natural cooling phase, during which the heaters were turned off and the pile system cooled naturally for 48 hours. For the saturated sand tests, the heating phase duration was the same (96 hours), while natural cooling was monitored only for the concrete pile test (P4) and the steel pipe pile filled with water (P5), each for 48 hours (2 days). Temperature variations from the PT100 sensors were recorded using an ADS 2000IP data acquisition system from Lynx Tecnologia, with an acquisition rate of 0.5 Hz.

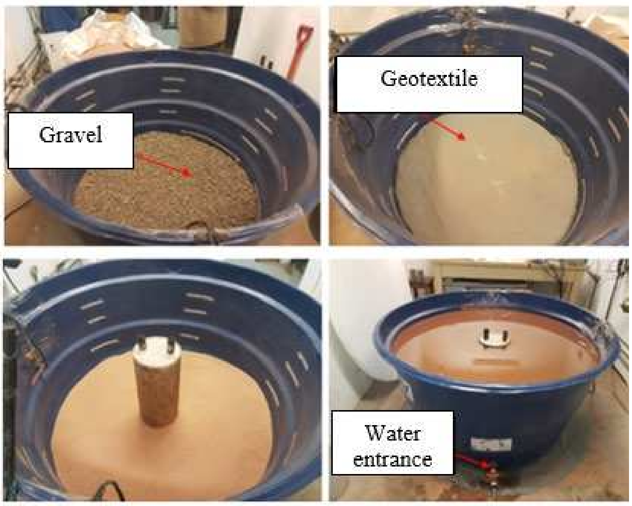


*Figure 5. Assembly steps of the test in saturated sand condition*

The tests were carried out in an air-conditioned room and the temperature was kept constant around 20°C, with the exception of the ST - P2 test on the steel pipe backfilled with steel fibre concrete which the room temperature was maintained at 22°C due to problems in air conditioning.

## 2.2 Soil properties

In all tests, the tank was filled with medium silica sand, placed in layers to achieve a relative density of 90%. Prior to assembly, all sand was oven-dried. A series of characterization tests was performed to determine the properties of the sand, and the results are presented in Table 3. The sand used in the experiments was uniformly graded, with a coefficient of uniformity (Cu) of 3.75 and a coefficient of curvature (Cc) of 1.20.

*Table 3. Sand characteristics.*

| Properties | Unit | Sand |
|---|---|---|
| Particles Unit weight, $\gamma$ | g/cm$^3$ | 2.66 |
| Maximum dry unit weight $\gamma_d$ | g/cm$^3$ | 1.72 |
| Max. void ratio | - | 0.67 |
| Min. void ratio | - | 0.54 |

# 3 RESULTS AND DISCUSSION

The initial temperature of the sand surrounding the pile sections for all tests is summarized in Table 4.

*Table 4. Sand initial temperature results.*

| Test ID | Sand initial temperature (°C) |
|---|---|
| P1 | 19.35 |
| P2 | 22.03 |
| P3 | 20.40 |
| P4 | 19.15 |
| P5 | 19.53 |

During the tests, two PT100 temperature sensors were damaged and produced inconsistent readings, so their data were discarded. The positions of the remaining sensors for each test are presented below:

- Test P1 – sensors in positions 0.5R and 1.5R at 0°;
- Test P2 – sensors in positions 1R at 0°;
- Test P3 - sensors in positions 0.5R and 1.5R at 0°;
- Test P4 – sensors in positions 0.5 and 1.5R at 0°;
- Test P5 – sensor in position 0.5R at 0°.

Figures 6 to 9 illustrate the temperature gradients around the piles during the heating phase, measured at radial distances of 0R, 0.5R, 1R, 1.5R, and 2R, in both directions analyzed: 0° and 90°.

Comparison of the temperature gradient results for piles P1 and P2 showed that soil temperature variations around P2 were much lower than those of

P1, contrary to the expectation of similar results. This discrepancy was likely caused by a heater malfunction during the P2 test; consequently, these results were excluded from the analysis.

For the pile backfilled with water (P5), a temperature sensor was positioned at the pile center, corresponding to the same section monitored by the other sensors. The recorded temperature variations in both directions analyzed (0° and 90°) are presented in Figure 9.

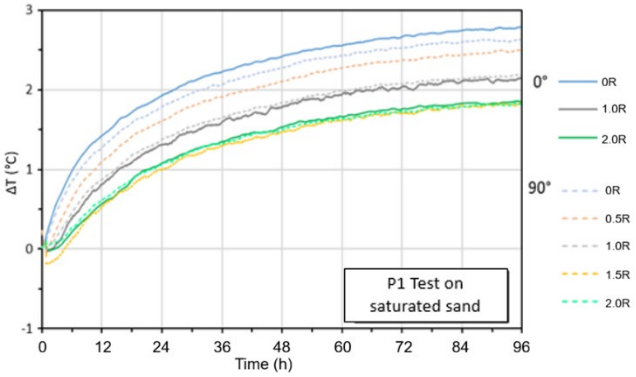


*Figure 6. Temperature variation during pile P1 heating phase (Steel pipe pile backfilled with concrete).*

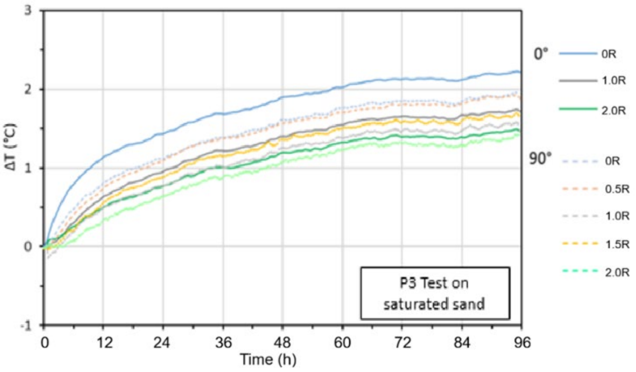


*Figure 7. Temperature variation during pile P3 heating phase (Steel pipe pile backfilled with saturated sand).*

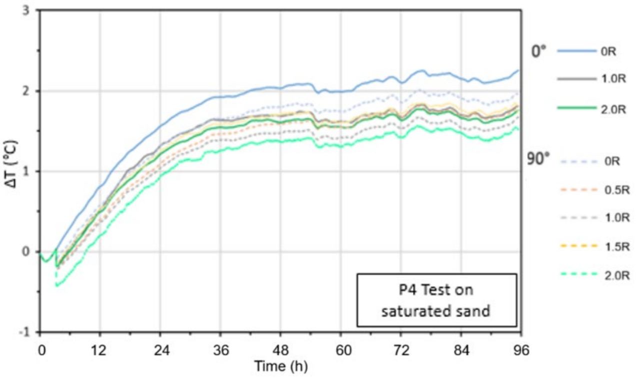


*Figure 8. Temperature variation during pile P4 heating phase (concrete pile).*

Table 5 provides a summary of the temperatures at piles interface and at 2R for both directions after 96 hours of heating.

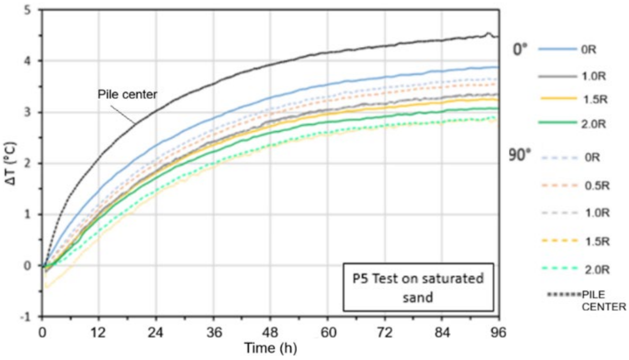


*Figure 9. Temperature variation during pile P5 heating phase (Steel pipe pile backfilled with water).*

The temperature gradients at the pile interfaces in both directions are presented in Figure 10 for all piles tested. These values qualitatively indicate the thermal resistance of the piles in the evaluated cases. Piles with lower thermal resistance exhibit better heat transfer performance.

At the end of the heating phase, the steel pipe pile backfilled with water (P5) showed the greatest temperature increase at the pile interface, reaching 3.87 °C along 0° and 3.65 °C along 90°. In comparison, pile P1 exhibited the highest temperature gradient at the pile interface among the other cases, with 2.82 °C at 0° and 2.64 °C at 90°. Additionally, as shown in Figure 10, the heat transfer performance of a steel pipe pile backfilled with saturated sand (P3) is very similar to that of a saturated concrete pile (P4).

*Table 5. Temperature variation at pile interface and at 2R tested on saturated sand in both directions 0° and 90° after 96 hours of heating*

| Pile | ΔT(°C) Interface 0º | ΔT(°C) Interface 90º | ΔT(°C) 2R 0º | ΔT(°C) 2R 90º |
|---|---|---|---|---|
| P1 | 2.82 | 2.64 | 1.85 | 1.81 |
| P3 | 2.21 | 1.87 | 1.45 | 1.37 |
| P4 | 2.27 | 1.97 | 1.76 | 1.51 |
| P5 | 3.87 | 3.65 | 3.07 | 2.87 |

Although water does not have the highest thermal conductivity, pile P5 exhibited the lowest thermal resistance. This result can be attributed to the combined effects of conduction and convection on heat transfer in this test. The convective heat transfer in water depends directly on the heat injection rate and the pile temperature gradient, making the problem inherently three-dimensional. Despite the small scale of the tests, the occurrence of natural convection in the water was observed. Field and laboratory studies by Kjellson and Hellström (1997) and Spitler et al. (2016) have shown that natural convection is influenced by scale effects, which limits the direct extrapolation of results from model tests. Nevertheless, even within the scale limitations of these experiments, the impact of convection was significant, as also observed in the thermal response of field energy piles reported by de Freitas Murari et al. (2022).

The temperature results at the pile–soil interface for piles P1 (filled with concrete) and P3 (filled with saturated sand) are similar, as shown in Figure 10. Likewise, field tests of steel pipe energy piles conducted by Freitas Murari et al. (2022) at the University of São Paulo Campus in saturated sand showed comparable thermal resistance values for piles filled with either saturated sand or grout. These findings suggest that the model tests performed in this study can serve as a useful, rapid, and efficient tool to inform decisions regarding the filling material for steel pipe energy piles.

Finally, Freitas Murari et al. (2022) showed that saturated sand and water represent cost-optimal backfill solutions with substantially lower environmental footprints than concrete or grout alternatives.

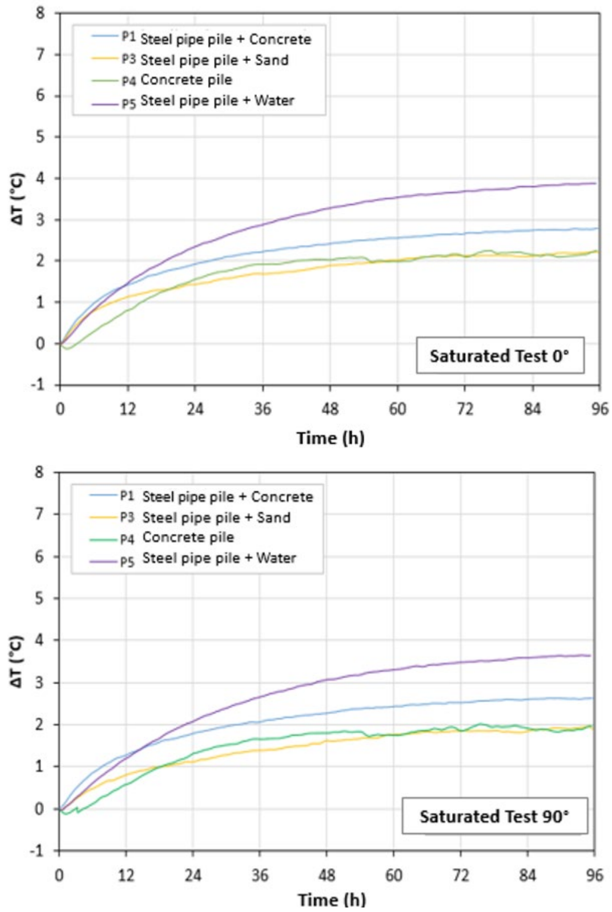


*Figure 10. Temperature variation x time at piles interface for both directions analysed (0° and 90º).*

## 4 CONCLUSIONS

This study developed a laboratory model to investigate heat transfer in steel pipe energy piles with different infill materials embedded in saturated sandy soil. The experiments generated detailed temperature data at the pile–soil interface and in the surrounding soil, showing trends consistent with field observations that indicate similar thermal resistance for piles filled with saturated sand and grout. These results demonstrate that the laboratory model can reliably replicate field behavior, offering a fast and cost-effective tool for evaluating energy pile performance. The findings provide practical guidance for selecting optimal infill materials for pipe energy piles installed below the water table.

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