Energy driven piles in Australia: Design and construction lessons from a trial at Fishermans Bend

C. Price[1], G. A. Narsilio[2], Y. Zhong[2], N. Makasis[2], Y. Motamedi[2], E Smith[2], J. Li[2], and A. Tonkin-Hill[1]
[1]Wagstaff Piling Pty Ltd, Port Melbourne, Victoria 3207; PH (03) 9646-7500; FAX (03) 9646-7799; email(s): c.price@wagstaffpiling.com.au, a.tonkin-hill@wagstaffpiling.com.au
[2]The University of Melbourne, Parkville, Victoria 3010; PH (03) 8344-4659; email(s): narsilio@unimelb.edu.au, yu.zhong@, nikolas.makasis@, yaser.motamedi@, edwards1@student.unimelb.edu.au, jingzhoul@student.unimelb.edu.au

ABSTRACT

About 50% of the energy bill of buildings arises from space heating and cooling (air conditioning). The associated greenhouse gas (GHG) emissions of the sector account for between 14% and 25% (or higher, particularly overseas) of the total emissions. Geotechnical engineering designers and contractors have an opportunity to contribute to a more sustainable future. Shallow geothermal technology for efficient heating and cooling represents one such opportunity. Through a partnership between Wagstaff Pilling and The University of Melbourne, the design and construction of the first energy driven piles in Australia was undertaken in 2019, with the last field thermal performance testing completed in January 2020. These energy piles can be connected to a geothermal system. This paper discusses the construction and installation of this small-scale field trial at Fishermans Bend (Victoria), comprising three different energy driven pile configurations. An investigation into the thermo-mechanical efficiency of driven energy piles to evaluate their capacity to provide heating and cooling for buildings is undertaken. Peer-reviewed literature already exists discussing shallow geothermal energy systems and bored energy piles. However, there is a significant gap in the literature considering driven energy piles specifically, and no public guidance about construction; thus, we aim to start redressing these issues herein. Experimental data collected by running Thermal Response Tests (TRTs) on selected energy driven piles at Fishermans Bend are presented. The information collected from the fieldwork will be used to validate detailed Finite Element Method (FEM) models and to optimise construction, minimising costs and to demonstrate none or minimal program delays.

Keywords: Geothermal energy, driven piles, innovation in construction, energy foundations

1 INTRODUCTION

The need to create and continually develop sustainable energy solutions has never been more important. Shallow geothermal energy technology provides an opportunity for small to large scale developments to lower greenhouse gas (GHG) emissions by supplementing their demand from the electricity grid. Shallow geothermal or ground source heat pump (GSHP) systems use the ground as a heat source or sink to efficiently heat and cool buildings, given that the ground temperature a few tens of metres below the surface is relatively constant throughout the year (Johnston et al. 2011).

The systems typically consist of a GSHP connected to ground heat exchangers (GHEs) and a heating and cooling distribution system in the building that they condition. Under most Australian climatic conditions, plain water is circulated through the High-Density Polyethylene (HDPE) or cross-linked polyethylene (PEX) piping to exchange heat with the ground (i.e., ground heat exchanger or GHEs). In winter, relatively cold water circulated in the geothermal pipes extracts heat from the ground. The GSHP extracts and upgrades this heat to deliver space heating (and in some cases hot water) to the building. The water cooled down by the GSHP is then reinjected to the GHEs to repeat the cycle. In summer, the system is reversed, with heat rejected to ground to provide air conditioning to buildings. For every kWh used to drive the GSHP compressor, between 4 and 6 kWh of thermal energy is delivered to the building throughout the year. This highly efficient system renders flattened and lower energy use and GHG emissions associated to the sources of energy that otherwise would be used (Aditya & Narsilio, 2020).

One way of harnessing geothermal energy is by the use of *Energy Piles* rather than purposely used borehole ground heat exchangers in vertical systems (or trenches in horizontal systems) to significantly lower capital costs of GSHP systems (Lu & Narsilio, 2019; Makasis, Narsilio, Bidarmaghz, Johnston, & Zhong, 2020). These piles can be constructed in a variety of ways in either precast piles or bored piles. Prior to casting concrete, a series of HDPE closed circuit pipes are installed and fixed to the cage. The pipes provide a path for a heat transfer fluid to circulate and capture heat energy from the surrounding ground.

This paper specifically looks at the construction and installation of conventional jointed precast piles with embedded HDPE pipe loops. Three different configurations of precast energy piles were trialled to identify heating/cooling capacity and cost/programming implications. The field trials were conducted at a site located in Fishermans Bend, Victoria. Thermal Response Tests (TRTs) results to indicate the effective thermal conductivity of the site and thermal performance of various pipe and pile configurations are also presented.

2 SITE DESCRIPTION

The trial site is located within Fishermans Bend, the largest urban redevelopment district in the country. Ground conditions at the field trial site comprise 1.5 m of Fill, 4 m of Port Melbourne Sand, 3 m of Coode Island Silt, 13 to 14 m of Fishermans Bend Silt, 15 m of Moray Street Gravels underlain by

Werribee Formation clays (Figure 1). The groundwater table is relatively shallow and encountered around 2 to 3 metres below ground surface. Precast piles were driven at this site, details of the pile configurations are included in Section 3.

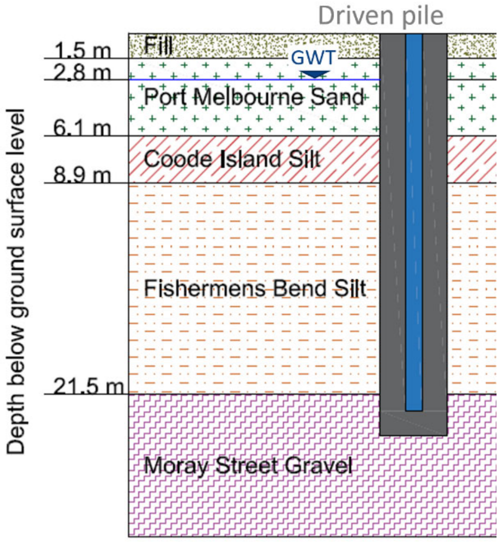


Figure 1. Soil profile (pile width not to scale)

3 PRECAST PILE CONFIGURATIONS

Precast reinforced concrete pile segments of 12 m in length and square cross section of 350 mm x 350 mm were used in this trial. Two segments were driven to form a floating pile primarily to test constructability, speed of installation, and thermal performance. Note that for structural stability, three segments rather than two would have been typically utilised in this site to reach and embed part of the pile in the firmer deeper formation. Similar results, for structural stability, may be achieved by utilising two longer precast segments (max 14-15 m). The trial precast piles were installed at this site using a Banut 700 driving rig equipped with a 6t hydraulic drop hammer.

The precast energy pile trial consisted of two pile types, namely Pile A and Pile B, and tested three geothermal pipe configurations, as schematically depicted in Figure 2. In all cases, High-Density Polyethylene (HDPE) pipe with an outer diameter of 25 mm and SDR of at least 11 has been used to form geothermal U-loops. Each U-loop was manufactured by using electro-fused fittings joining straight pipes at the bottom of the pile.

Pile A configurations include two geothermal U-loops placed inside the hollow pile segments, a cylindrical 100 mm diameter void at the centre of the pile typically used to reduce weight for transport and concrete (ultimately costs) while maintaining strength and structural functionality. Given the high groundwater table, the void is naturally filled with (ground) water ensuring no air gaps between the HDPE pipes and the surrounding concrete and soil, this is important for heat transfer.

Pile B configurations are “solid” piles with reinforcing steel cage and bars. In Pile B type, two HDPE pipe configurations were tested. The bottom precast pile segment in the pile, the one driven into the soil first, contains U-loops cast within the pile. In one pipe configuration, the U-loop pipe length extends to the surface from the side, near the top of this bottommost installed segment. This pipe excess length is rolled in the workshop to then being unrolled on site as the second segment is driving into the ground (solid pipe lines in the schematic in Figure 2). In the other pipe configuration tested, straight pipes are embedded in the second segment with chick pipe connectors on the splicing ends of the pipe segments, such that when the dynamic splicing of the pile segments takes place, the splicing of the pipes does so as well. This pipe configuration in Pile B type requires careful placement of pipes and connectors in the segment pile heads and segment pile splicing joints while precasting and installing. Once driven, the geothermal pipes run within the bottom pile segment and then run along the outside of the top pile segment (dashed pipelines in the schematic of Figure 2).

The various pile and pipe configurations allow testing different geothermal pipe circuitry (e.g., a single pile with a single U-loop of ~40m total pipe length, or pipes from adjacent piles to be connected in series, significantly increasing total pipe length between each inlet and outlet). The centre-to-centre spacing between the two piles is approximately 2 m.

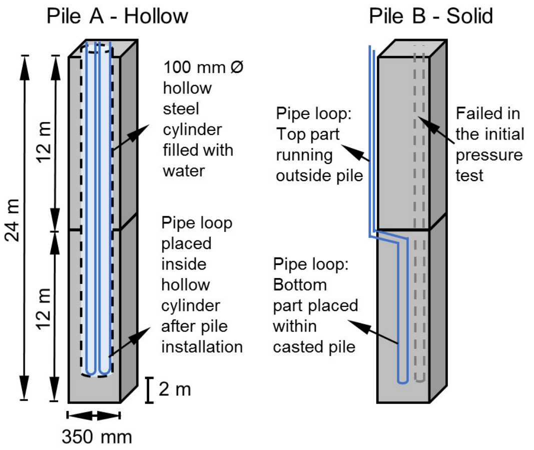


Figure 2. Schematics of the precast piles

4 THERMAL RESPONSE TESTS

4.1 In situ thermal test analysis methods

A critical parameter in designing ground heat exchangers (GHEs) of GSHP systems is the ground thermal conductivity, λ_g. The confidence in this parameter substantially influences the sizing of the GHEs and the thermal performance of the GSHP system (Mikhaylova, Johnston, & Narsilio, 2016). In-situ Thermal Response Test (TRT) is considered as the most reliable approach to obtain the site-specific ground thermal conductivity. TRTs were initially developed for traditional borehole GHEs and have been subsequently extended to the analysis in energy piles (Jensen-Page, Loveridge, & Narsilio, 2019; Spitler & Gehlin, 2015). A TRT involves heating a fluid at a constant rate of heat injection and circulating the fluid in the ground loops in a prototype GHE for around 48 hours. The inlet and outlet temperatures are constantly monitored over time, as well as the flow rate and power injection. There are several commonly adopted analytical models available to evaluate the effective λ_g from the measured TRT fluid temperatures including the Infinite Line Source Model (ILSM) (Ingersoll & Zobel, 1913; Jaeger & Carslaw, 1959), the Infinite Cylindrical Source Model (ICSM) (Yener & Kakac, 2018) and the Finite Line Source Model (FLSM) (Claesson & Javed, 2011; Lamarche & Beauchamp, 2007). Among these models, the ILSM is the most popular approach which assumes an infinite homogeneous ground subjected to a constant radial heat flow from a linear heat source. This is a close approximation to borehole GHEs, where the ratio of length (depth) to diameter is large but may require adjustment for less slender energy piles (see for example, Jensen-Page et al., 2019).

The average fluid temperature T (the average of inlet and outlet temperatures) over time can be simplified to a linear-log relationship as:

$$T(t) = \frac{Q}{H} R_b + \frac{Q}{4\pi\lambda_g H} \cdot \left[\ln\left(\frac{4\alpha_g t}{r_b^2}\right) - \gamma\right] + T_0 \qquad (1)$$

where t is time [sec], Q is the applied heat power [W], H is the buried depth of GHE in [m], R_b is the GHE thermal resistance [m·K/W], α_g is the thermal diffusivity (a function of thermal conductivity, heat capacity and density) [m^2/sec,], r_b is the radius of GHE [m], T_o is a farfield reference temperature and γ is Euler's constant (0.5772). Then the effective λ_g can be estimated from the gradient m of the semi-log plot of the linear relationship between the average fluid temperature T and time t as:

$$\lambda_g = Q/(4\pi m H) \qquad (2)$$

Prior to commencing the TRTs, a few preliminary tasks must be performed. The individual ground loops must be firstly flushed and purged ensuring a minimum fluid velocity of 0.6 m/s (2 ft/s) through all piping for at least 20 minutes and until no air bubbles are detected, to remove any debris and air pockets. Pressure tests are conducted to ensure there was no leakage in the loops prior and after installation as well.

4.2 TRT tests in this trial

For this particular trial, a manifold with manual valves and quick clamp fittings were introduced to allow a variety of different loop combinations to be tested. A total of eight tests were performed, four of which are reported in this work. The in-situ tests were undertaken using a Precision Geothermal GeoCube unit, as shown in Figure 3. The pipes and fittings were well insulated and covered to minimise (thermal) disturbance from the environment.

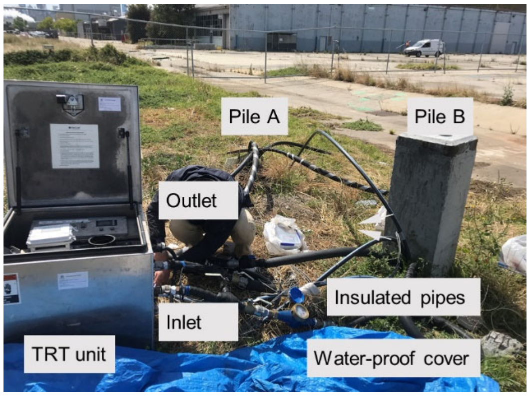


Figure 3. In-situ TRTs set up

The four different piping configurations considered in this study are shown in Figure 4. TRT1 was conducted on a single U-loop embedded within one Pile A, TRT2 was conducted on two U-loops connected in series within Pile A, TRT3 was conducted on one U-loop within Pile B. In TRT4, one U-loop in Pile A with another U-loop in Pile B were connected in series, resulting a common joint inlet and outlet to be connected to the TRT unit. During the TRTs, a completed testing cycle consisted of 3-4 days of a heating phase (rejecting heat to the ground, emulating air conditioning a building) and an equivalent amount of time in a recovery phase. During the heating phase, a 1.5 kW heating element was used for TRT1 through TRT3, and a larger heating power of 3.5 kW was used for the TRT4 considering the circuit went through two different piles. During the recovery phase, the heating elements were switched off and only the circulation pump was left running to help the ground to restore to its undisturbed equilibrium temperature.

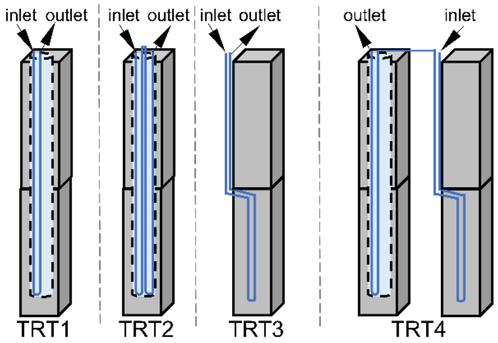


Figure 4. Pipe configurations tested with TRTs

5 NUMERICAL SIMULATION

The long-term thermal potential of the precast energy piles can be assessed through simulations. While specialist shallow geothermal commercial software like GLD or GLHEPro or more generic TRNSYS models may be used for concept design, they are unable to capture in detail the energy pile thermal behaviour. To redress this shortcoming, detailed 3D finite element models built in COMSOL Multiphysics and developed by The University of Melbourne's Porous Media Research Laboratory are used herein to explore some few cases (Bidarmaghz, 2014;

Makasis, 2018). The model couples the governing equations of the heat transfer and fluid flow. The thermal analyses consider a combination of the conductive heat transfer in the pipe wall, pile concrete and surrounding ground and the convective heat transfer in the flowing fluid (water) within the pipes. A geo-mechanical model is not included in this work. For piles driven to the firmer underlying layer, thermo-mechanical effects are known to be negligible (this may not the case for floating piles in normally consolidated clays though). Relevant material properties used in the models are summarised in Table 1.

Table 1: Material properties adopted in the numerical simulation

Description	Value
Thermal conductivity of ground (W/(m·K) λ_g	2.4[a]
Density of ground (kg/m^3) ρ_g	1,940
Specific heat capacity ground (J/(kg·K)) $C_{p,g}$	1,500
Annual average ground temp (°C) $T_{farfield}$	18
Thermal conduct. of concrete (W/(m·K)) λ_c	2.0
Density of concrete (kg/m^3) ρ_c	2,400
Specific heat cap. of concrete (J/(kg·K)) $C_{p,c}$	1,000
Thermal conductivity of water (W/(m·K)) λ_w	0.58
Density of water (kg/m^3) ρ_w	998
Specific heat cap. of water (J/(kg·K)) $C_{p,w}$	4,185
Pipe flow rate (L/min) m_w	6

[a] from TRT results shown later in Table 2

One pile group is modelled, consisting of 24 and 36-metre-deep precast piles, 2 metres apart, i.e., floating and embedded piles. Symmetry boundary conditions are prescribed on the far boundaries of the model to allow the modelling of only one pile group and save computational time. The undisturbed ground temperature of 18°C is applied on the bottom surface of the model while thermal insulation is applied on the top surface of the model to render zero thermal flux through the surface considering the ground is covered by the building.

The thermal heating and cooling load distribution is a critical factor for the GSHP system performance. For simplicity, a constant cooling load (-ve) is applied to the energy pile group for half year (October to March) and the same amount of heating load (+ve) is prescribed for the rest of the year (April to September). The thermal potential of the system is determined as that corresponding to the resulting maximum or minimum average fluid temperature reaching the design operational limits of the GSHP system. Typical lower and upper design limits, 0 °C and 35 °C respectively, are adopted in this work while noting that these limits may change depending on the selected GSHP model type and design.

6 RESULTS AND DISCUSSION

Both pile types were installed without issues. In a full scale roll out, the pilot test showed that Pile A type execution falls outside the critical path but may require a separate crew for piping installation after protruding pile heads are cut on the surface, while Pile B type may add between 5 to 15 minutes per complete pile installed (3 segments to firm layer), with minimal impact on daily number of piles installed and using the same pile installation crew as per normal (non-energy) pile driving, but requires pre-casting of pipes and careful transport to site. Results from the in situ thermal testing and from the long term simulations (under an exemplary given thermal load distribution) are summarised below.

6.1 TRT: Effective thermal conductivity

The various tests were conducted between October 2019 and January 2020. TRT tests were not performed on the connecting straight pipes embedded in the precast pile segments as they did not pass the pressure test after installation (dashed lines in Figure 2-B). This is likely due to leaks in the splicing. Figure 5 shows the measured average fluid temperature, T_{avg} during testing. These temperature response curves are like typical borehole TRTs, with the temperature increasing dramatically for the first few hours and reaching a steady state at a later stage. It is found that the fluid temperature was influenced by the ambient temperature, shown by the fluctuating record seen particularly in TRT1 and TRT2. These were particularly hot days.

In this work, the TRT data were simply interpreted by the application of ILSM and the use of Equation (2) to evaluate thermal conductivity. The actual heat exchanged within the ground, rather than the nominal 1.5 and 3.5 kW, Q, was evaluated as $Q = \dot{m}C_p(T_{inlet} - T_{outlet})$, where $\dot{m}$ is the fluid mass flow rate (kg/s), C_p is the specific heat capacity of water taken as a constant value of 4,186 J/kg/K and T_{inlet} and T_{outlet} represent the measured inlet and outlet fluid temperatures (K). It should be noted that the power disruption period in TRT1 was excluded for the thermal conductivity evaluation. The resulting effective thermal conductivities from each TRT and key testing conditions, including the measured Q are summarised in Table 2.

It is interesting to observe that the average actual heat exchange rate of TRT1 and TRT2 was slightly higher than the expected power from the heating elements. This is most likely due to the tests were conducted over hot summer days thus additional heat energy from the ambient environment may be added into the system.

It is found that the effective thermal conductivity of the ground evaluated from these four tests and configurations is relatively close to each other. The average actual heat exchange Q was computed for each test and used in Equation (2) to evaluate the effective thermal conductivities λ_g.

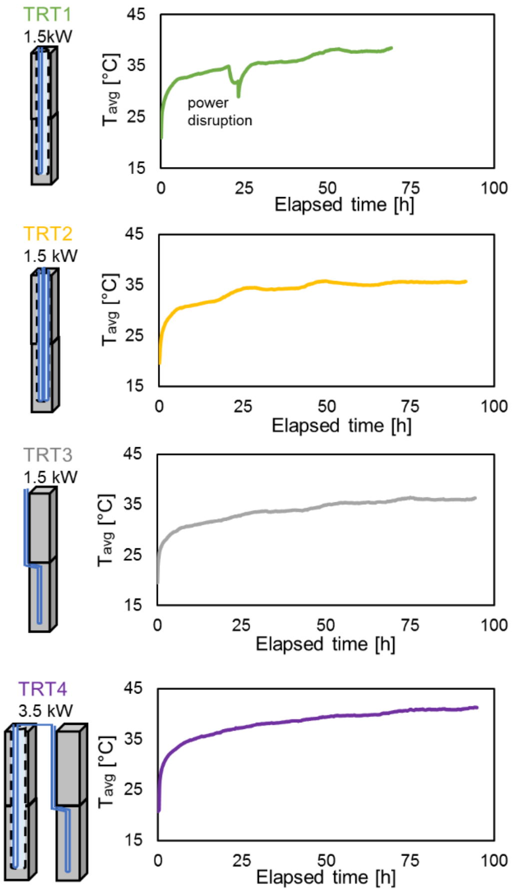


Figure 5. TRTs results expressed in terms of average fluid temperature

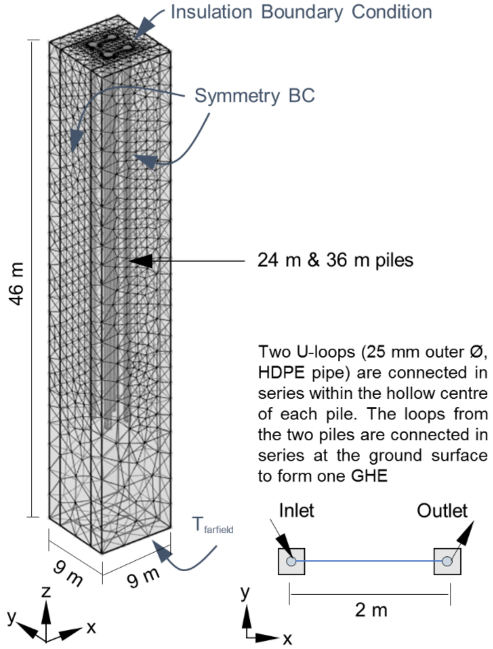
Results in Table 2 shows that the highest effective thermal conductivity of the ground is found to be 2.6 W/m·K in TRT2 and the lowest, 2.1 W/m·K in TRT2.

This is higher than the values of thermal conductivity for this geology obtained from small scale laboratory testing (Barry-Macaulay, Bouazza, Singh, Wang, & Ranjith, 2013). This is somehow expected and may be due to the presence of groundwater flow in the project site, which enhances the thermal conductivity of the ground. This condition is not covered in the laboratory tests. There are no other known in situ measurements available to compare.

6.2 Long-term performance simulations

To get an indication of the long-term thermal performance of these energy driven piles, a detailed FEM model was built (as per Section 5) assuming pile groups in which Pile A type piles are 2 metres apart. Piles of 24 m (two segments) and of 36 m (three segments) were modelled. Figure 6 summarises the model and includes key boundary conditions. Connecting adjacent piles in series increases total pipe length between inlet and outlet of each GHE to render adequate fluid temperature coming in and out of the GSHP in the geothermal plant. An effective λ_g of 2.4 W/(m·K) is used in the models. This was evaluated using the TRT4 data which is considered as the most stable thermal response and the result of also modelling the TRTs, thus it is considered the most reliable value. Note that TRT2, with double U-loops, resulted in a higher λ_g of 2.6 W/(m·K) than the one used in the models.

Long-term thermal performance is highly sensitive to thermal load distribution and operation of the system as described in Section 5. A balanced load, with six months of cooling and six months of heating operating 12 hours day for 50 years is modelled. Peak heating and cooling loads were varied successively to render the design water temperature limits (0-35°C). Figure 7 summarises the results of these analyses. A pair of 36 m deep energy driven piles, which result in a single inlet and outlet with a total GHE pipe length of approximately 275 m, can deliver 2.2 kW peak thermal capacity in heating and in cooling.



Two U-loops (25 mm outer Ø, HDPE pipe) are connected in series within the hollow centre of each pile. The loops from the two piles are connected in series at the ground surface to form one GHE

Figure 6. FEM model and key boundary conditions

Table 2: Testing conditions and in-situ TRT results

TRT No.	Heating element (kW)	Average actual heating power (kW)	Flow rate (L/min)	Power/active pile length (W/m)	Gradient *m*	Effective thermal conductivity (W/m·K)
1	1.5	1.63	28.8	74.1	2.8	2.1
2	1.5	1.58	21.0	70.5	2.2	2.6
3	1.5	1.49	28.2	67.7	2.2	2.5
4	3.5	3.49	21.0	79.3	2.7	2.4

A floating 24 m deep energy driven pile pair, with approximately 180 m of total pipe length, shows a potential thermal yield of 1.5 kW (Figure 7-top); in both cases resulting in a long term annual fluid temperature in the piles within the design limits (Figure 7-bottom).

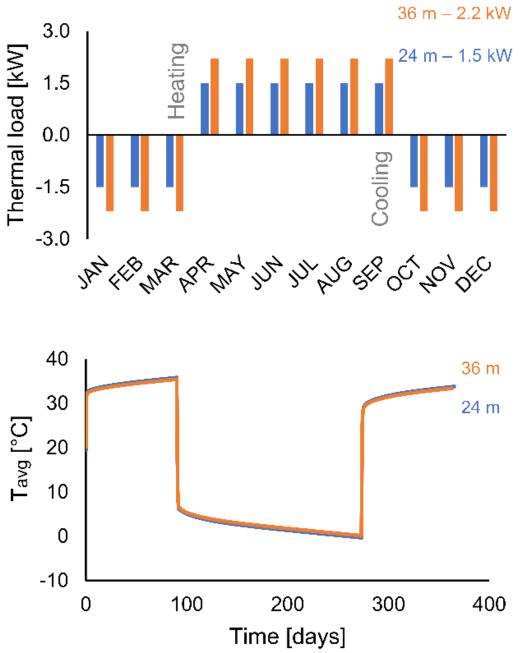


Figure 7. FEM model results showing thermal yield per pair of energy piles (top) and resulting long-term annual fluid temperature (bottom)

At the Fishermans Bend site, this means that all or a large portion of the space heating and cooling demand of a 4 story residential building, for example, could be satisfied with a shallow geothermal system that uses its piled foundations as ground heat exchangers. Any remaining balance can be provided by additional borehole or pushed-in U-loops integrated into the geothermal system or by means of traditional auxiliary HVAC (heating, ventilation, and air conditioning) systems, of much smaller capacity than needed otherwise without geothermal energy. Given the average overall higher efficiency of GSHP systems over traditional HVAC systems, lower GHG emissions are to be expected as well as a cost reduction in providing energy infrastructure to the new district if widely adopted.

7 CONCLUSION

A small-scale field trial was conducted at Fishermans Bend to test constructability and speed of installation of the first energy driven piles in Australia. Three different configurations were trialled and their long-term thermal yield investigated numerically, based on the effective thermal conductivity obtained from various in-situ Thermal Response Tests (TRTs). Connecting pipes embedded into the pre-cast pile segments proves promising but difficult. Embedding pipe in the bottom-most segment and rolling it out on site as the pile segments are driven into the ground proved effective, fast and safe (Pile B type), adding between 5 and 15 minutes per 36 m deep pile, with low impact on pile production and using the same pile installation crew as per usual installations. Pre-casting of pipes off site is cost effective. Installing geothermal pipes in hollow driven piles (Pile A type) proved to also be effective, fast and safe, with no additional time added to a construction program, but requiring a potentially different crew to add pipes once pile heads on the surface are cut off. In both configurations, the use of piles rather than purposely built boreholes as ground heat exchangers reduces installation costs significantly, estimated in up to 90%. Results from the in-situ TRT show consistent effective ground thermal conductivities (upper ~24 metres), rendering values between 2.1 and 2.6 W/(m·K). Pile A type with double U-loops connected in series in pairs show a long-term energy yield of 2.2 kW peak for a 36 m deep piles and an assumed balanced annual thermal load. This figure is highly dependent on the thermal load distribution designed for and operation the geothermal system, but does indicate the high potential to utilise energy piles on site to satisfy all or part of the heating and cooling required for buildings in Fishermans Bend and thus contribute to a more sustainable future.

8 ACKNOWLEDGEMENTS

Ground Source Systems and Melbourne University's Industry collaboration grant are duly acknowledged.

REFERENCES

Aditya, G., & Narsilio, G. (2020). Environmental assessment of hybrid GSHP ground source heat pump systems. *Geothermics, 87*, 101868.

Barry-Macaulay, D., Bouazza, A., Singh, R., Wang, B., & Ranjith, P. (2013). Thermal conductivity of soils and rocks from the Melbourne (Australia) region. *Engineering Geology, 164*, 131-138.

Bidarmaghz, A. (2014). *3D numerical modelling of vertical ground heat exchangers.*

Claesson, J., & Javed, S. (2011). *An analytical method to calculate borehole fluid temperatures. ASHRAE transactions.*

Ingersoll, L., & Zobel, O.(1913). *An introduction to the mathematical theory of heat conduction: with eng. and geological applications*: Ginn.

Jaeger, J. C., & Carslaw, H. S. (1959). *Conduction of heat in solids*: Clarendon P.

Jensen-Page, L., Loveridge, F., & Narsilio, G. (2019). Thermal response testing of large diameter energy piles. *Energies, 12*(14).

Lamarche, L., & Beauchamp, B. (2007). A new contribution to the FLSM model for geothermal boreholes. *Energy & Buildings, 39*(2), 188-198.

Lu, Q., & Narsilio, G. A. (2019). Cost Effectiveness of Energy Piles in Residential Dwellings in Australia. *Current Trends - CTCSE, 3*(3), 1-6.

Makasis, N., Narsilio, G., et al. (2020). The importance of BC on the modelling of energy walls. *Computers & Geotechnics, 120*, 103399.

Mikhaylova, O., Johnston, I. W., & Narsilio, G. A. (2016). Uncertainties in the design of GHEs. *Environmental Geotechnics, 3*(4), 253-264.

Spitler, J. D., & Gehlin, S. (2015). Thermal response testing for GSHP systemsreview. *Renewable & Sustainable Energy Reviews, 50*, 1125-1137.

Yener, Y., & Kakac, S. (2018). *Heat conduction*: CRC Press.