Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190363

Utilising Soldier Pile Retaining Walls as Energy Geo-Structures

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Abstract. Energy geo-structures implement shallow geothermal technologies in sub-surface structures, such as piles, retaining walls, slabs and tunnels, resulting in a dual-purpose use of these elements: structural stability and thermal energy provision. This approach to shallow geothermal energy can result in lower capital costs compared to traditional ground source heat pump systems where trenching or drilling is required, and thus have received significant attention recently. Most of the existing research has so far focused on energy piles, likely due to their geometrical similarities to the traditional vertical borehole ground heat exchangers, while less information exists on the relatively more complex energy retaining walls. This research focuses on the thermal performance and design of energy soldier pile retaining walls, utilising detailed finite element techniques. A case study is adopted, modelling an underground train station with conditions and requirements typical for Melbourne, Australia (temperate climate). The thermal provision potential for these structures is investigated, noting the importance of the thermal load on the design and suggesting that a close to balanced thermal load might be crucial for the design of a well performing system, even if its incorporation might introduce logistic complexities. Moreover, important design parameters that can affect the thermal performance (as well as costs) of the system are investigated, enabling recommendations to minimising costs without significantly impacting the thermal performance of the system.

Keywords. Energy geo-structures, soldier pile walls, numerical modelling.

1. Introduction

Energy geo-structures have been receiving increasing attention by the scientific community in recent years [1]. Using shallow geothermal energy principles, pipes with a circulating carrier fluid are incorporated in underground structures mainly designed for stability (such as piles, retaining walls, slabs and tunnels), to also facilitate the secondary function of energy provision. Thus, these structures are turned into ground heat exchangers (GHE) which transfer heat to/from the ground and structural elements. The piping is connected to a ground-source heat pump (GSHP), similar to traditional shallow geothermal design, which upgrades and transfers the heat from/to the building(s). Unlike traditional GSHP systems, however, utilising energy geo-structures does not require purpose-built boreholes as GHEs and therefore can have lower capital costs. For example, in designing energy piles the drilling for the piles is accounted by the structural design (their primary function of stability) and would have been undertaken regardless. On the other hand, since factors such as the geometry are determined by the structural (and not

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geothermal) design, the amount of thermal energy that can be provided is not solely based on the geothermal design and therefore cannot guarantee to satisfy the entirety of the building needs. Therefore, energy geo-structures are commonly designed as part of a hybrid heating and cooling system, where the geothermal energy provides a base load and auxiliary means (for example solar) can provide additional energy when needed, which can lead to new innovative approaches to heating and cooling [2, 3].

Despite this growing attention, there are still several knowledge gaps in our understanding of how to best utilise and design these systems. Since energy geo-structures can have various geometries and configurations, based on the type of structure and conditions, energy geo-structure design can be a complex undertaking, currently lacking standardised design approaches [4]. A noteworthy amount of research has been undertaken for energy piles, with some design guidelines and techniques been made available [5–7]. However, less information is currently available on the prospective of energy retaining walls and their thermal performance. Even so, most the available work centres around diaphragm retaining walls [8]. This work utilises complex numerical modelling to provide insights and knowledge regarding the thermal performance and potential of energy soldier pile walls and to investigate the effect of important design parameters such as the amount of pipe per soldier pile and the pile spacing.

2. Methodology

The finite element methodology adopted in this research, to investigate the thermal performance of energy soldier pile walls, has been developed within the University of Melbourne and is based on the coupling of heat transfer and fluid flow physics, more details on which can be found in [9,10]. For the presented work, a case study of a typical underground train station (a common use for retaining walls in cut and cover construction) is adopted, with material properties and conditions representative of Melbourne, Australia (Silurian mudstone in the subsurface), shown in Table 1.

Table 1. Material parameters.

Parameter	Value	Unit	Description
λ_{ground}	2.7	W/(m*K)	Thermal conductivity of ground
ρ_{ground}	2400.0	kg/m3	Density of ground
$C_{p\ ground}$	830.0	J/(kg*K)	Specific heat capacity of ground
$T_{farfield}$	19.5	°C	Average annual ground temperature
$\lambda_{concrete}$	2.1	W/(m*K)	Thermal conductivity of concrete
$\rho_{concrete}$	2250.0	kg/m3	Density of concrete
$C_{p\ concrete}$	890.0	J/(kg*K)	Specific heat capacity of concrete
λ_{fluid}	0.6	W/(m*K)	Thermal conductivity of carrier fluid
ρ_{fluid}	1000.0	kg/m3	Density of carrier fluid
$C_{p\ fluid}$	4185.5	J/(kg*K)	Specific heat capacity of carrier fluid

The geometry and boundary conditions adopted can be seen in Figure 1. Symmetry is used along the ZX plane, to account for the retaining wall on the other side of the station, as well as along the ZY planes to represent an infinitely long wall along the y-direction, which is a (marginally) conservative approach. The average annual ground temperature is applied as the farfield temperature, where the conditions are unaffected by the activation of the geothermal system. Thermal insulation is also applied at the top and bottom surfaces as well as the inner surfaces of the station, such that the heat will be transferred to the ground and the structural elements instead of leaking into/from the station directly.

The soldier pile retaining wall is about 30 metres deep, including a 2 m depth of embedment, having a diameter of 750 mm. The piping in each soldier pile consists of 4 U-loops (lower bend) joined in series at the top of the pile (upper bend), comprising approximately 220 m per pile. The flow rate of the carrier fluid within the HDPE pipes (DN25, SDR 11) is set at 5.5 L/min, to allow time for the thermal transfer to take effect and to minimise pressure losses impacting on the size of the circulations pumps.

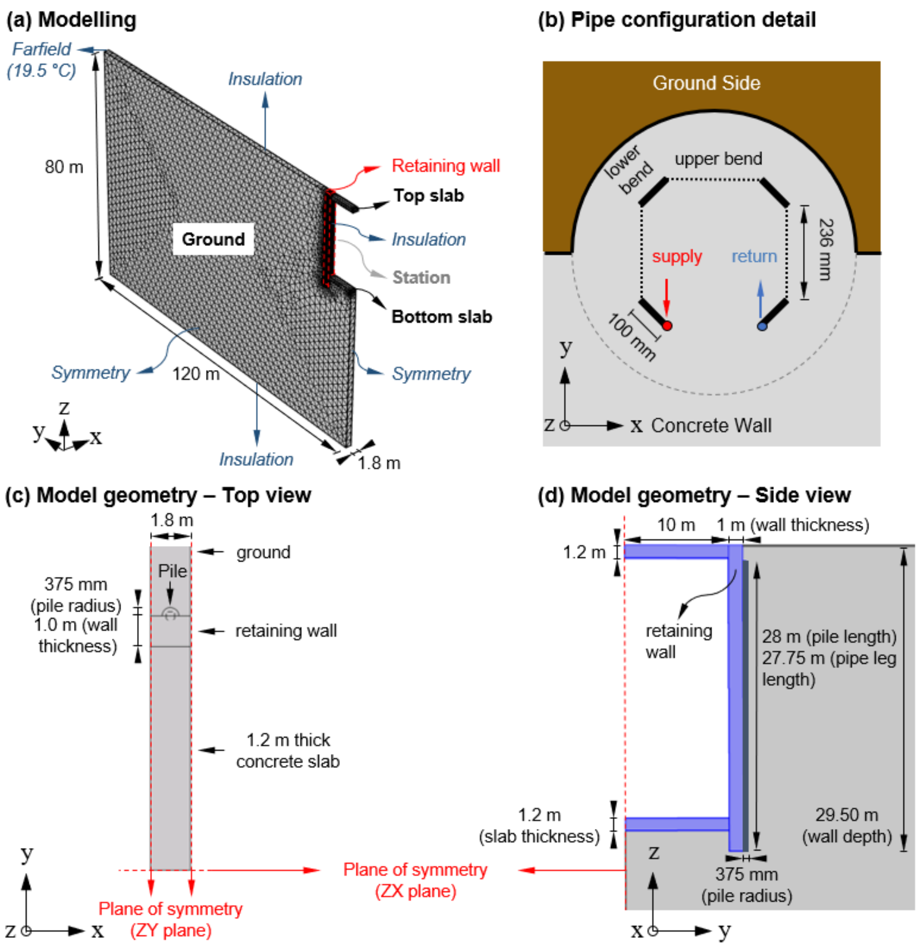

Figure 1. Soldier pile wall modelling and geometry.

An important design parameter in energy geo-structure design is the thermal load distribution, the amount of thermal energy the system is expected to be providing. Underground train stations typically have mostly cooling demands, due to train breaks, machinery and people all generating heat. However, it is widely known that a geothermal system operates most beneficially when close to equal amounts of heating and cooling are provided, to prevent accumulative thermal effects. In the case of a train station, a more balanced thermal load can be achieved by providing heating to nearby surface buildings, that can have heating demand throughout the year, in addition to the cooling demand of the station. This approach provides overall more thermal energy (cooling plus heating) and is also expected to provide better thermal performance results, compared to a cooling dominant thermal load. However, it can require the cooperation of different entities and buildings, adding to the system's complexity. For this case study, the two thermal load distributions adopted can be seen in Figure 2.

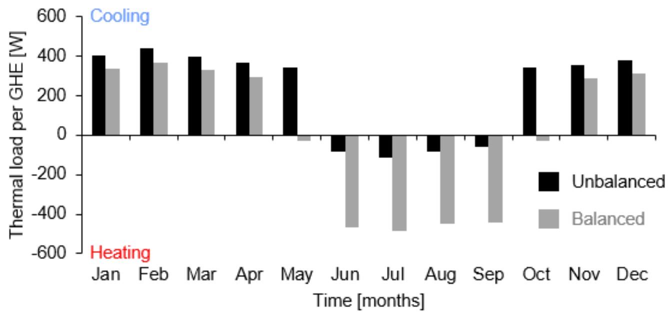

Figure 2. Thermal load distributions per soldier pile ground heat exchanger (GHE) under study.

3. Thermal performance of energy soldier pile walls

This section presents three analyses on the thermal performance of soldier pile energy walls, each investigating a different design parameter and its influence on the performance. Firstly, the effect of the thermal load is demonstrated, showing the severity that an unbalanced load can have on the thermal performance of energy geo-structures. Following, the amount of pipe within each soldier pile circuit is varied to explore the widely accepted assumption that the longer the length of pipe can be placed the better the performance. Finally, the pile spacing is investigated two-fold, both in terms of the piles being designed with different spacing as well as in terms of increasing the spacing of activated energy soldier piles by reducing their overall number. The thermal performance is evaluated in terms of the temperature of the circulating carrier fluid, which is critical to the operation of the system as these temperatures need to avoid extremes and be within the GSHP operating range, typically between 0 °C and 40 °C. Moreover, all simulations have a duration of 25 years to account for potential effects of thermal accumulation and ΔT , the temperature differential between inlet/outlet (supply/return), is between 1-3 °C.

3.1. The effect of the thermal load

As discussed in section 2, the thermal load distribution can be a very important parameter for shallow geothermal design, in particular for energy retaining walls which can be more sensitive to it due to the limited amount of ground surrounding them. In this analysis two different thermal load distributions are adopted, a cooling dominant *unbalanced* thermal load distribution and a *balanced* thermal load distribution, where close to equal amounts of heating and cooling are provided (Figure 2). The resulting fluid temperatures are shown in Figure 3 for both cases, along with indicative operational temperature limits, where applicable. Moreover, variations of the two distribution are also adopted to further emphasise the amount of thermal energy that can be provided in each case.

As it can be seen in Figure 3(a), adopting the unbalanced thermal load results in an undesirable thermal performance, with the temperatures in the carrier fluid (and therefore the structure and ground) drastically rising over the years. While for the first five years the fluid temperatures are within the acceptable limits, soon after they exceed those, for both cases where 100% (red line) and 75% (dark yellow line) of the cooling energy is provided. Only when 50% of the specified cooling energy is provided (green line) the temperatures stay within acceptable limits throughout the simulation. Figure 3(b), however, shows very different results. When the balanced distribution is adopted, the system can comfortably provide the requested 100% of heating and cooling and can even provide close to double that amount of thermal energy. Due to the balance of the load, the thermal accumulation effects are minimised, increasing how much thermal energy can be provided and extending the life of the system. Despite potential logistic complexities, a more balanced thermal load is likely usually the more favourable approach to shallow geothermal energy design.

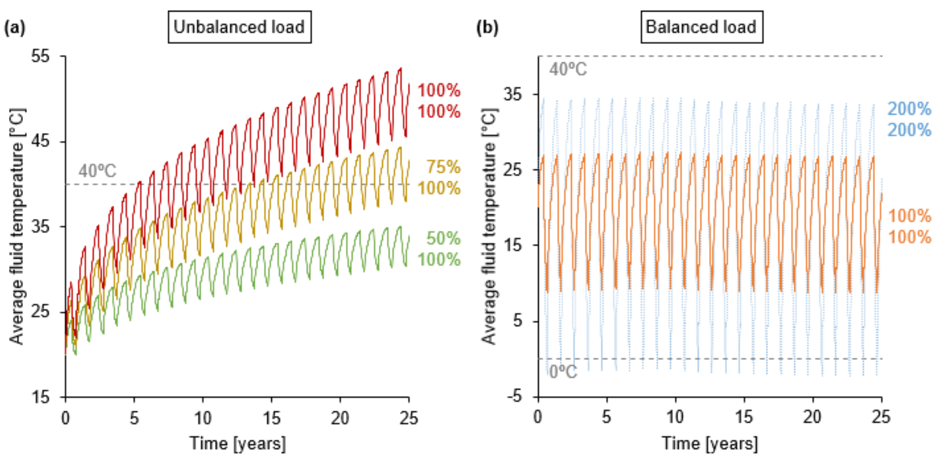

Figure 3. Thermal performance – average fluid temperature values – for (a) unbalanced and (b) balanced thermal load distributions (as well as variations of these) over 25 years of numerical simulation. The shown percentages indicate the amount of cooling (upper value) and heating (lower value) provided in each case.

3.2. The effect of the pipe length and number of U-loops

An important parameter determined by the geothermal design team is the configuration and amount of pipe that is placed into each soldier pile. Typically, in shallow geothermal systems, it is expected that the longer the pipe circuit in a GHE the better the performance will be. This investigation varies the number of U-loops placed within each soldier pile GHE (and connected in series - thus the circuit's overall pipe length), investigating the effect on its thermal performance. The number of U-loops vary from 1 to 6 following similar configurations to Figure 2(b) with the pipes placed close to the ground side where possible. Figure 4 displays the results of this investigation, utilising the maximum and minimum fluid temperatures achieved over the 25-year simulation, T_{max} and T_{min} respectively. For the unbalanced thermal load case only the first is displayed, as the thermal accumulation makes T_{max} the dominant factor and T_{min} relatively insignificant.

The results show that, as expected, the thermal performance of the GHE increases with a longer pipe length (as T_{max} decreases and T_{min} increases). However, there exist a point, around 3-4 U-loops, after which the magnitude of the increase of the performance is relatively minor and increasing the pipe length beyond this point would only be increasing the costs without much benefit. This is likely because of the finite available heat storage that exists around the energy geo-structure, especially considering that an energy retaining wall is only fully surrounded by ground on one side while the other comprises the inside of the underground structure. Moreover, interestingly, the pattern is relatively consistent between the two thermal load cases, as well as between different timelines (25 or 5 years) for Figure 4(a). This suggests that even though the magnitude of the results for the unbalanced case (providing 100% of cooling) are unrealistically high, they are still insightful since similar patterns can be expected for lower temperature values resulting from similarly unbalanced thermal loads. Overall, by understanding what the optimal amount of length that can be inserted in an energy geo-structure is, the geothermal design can achieve the most cost-effective thermal performance.

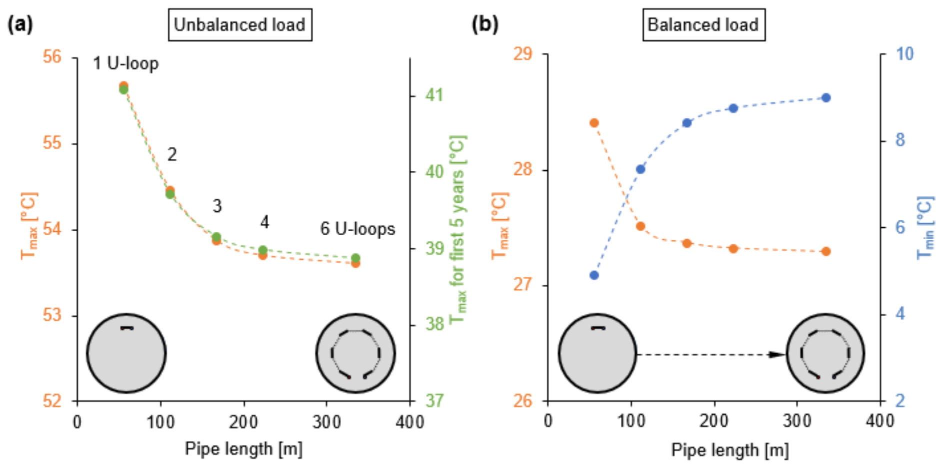

Figure 4. Thermal performance variation with pipe length – maximum and minimum fluid temperature values – for (a) unbalanced and (b) balanced thermal load distributions over 25 years of numerical simulation.

3.3. The effect of the pile spacing

The spacing between the soldier piles is another factor that can affect the thermal performance of the energy retaining wall. Therefore, the spacing of the geometry presented in Figure 2 was varied from 1.8 m to up to four times as much to investigate this effect. The results are presented in Figure 5 for both thermal load distributions. As it can be seen, the (geothermally activated soldier pile) spacing can have an immense effect on the fluid temperatures with a decrease of over 15 °C when changing the spacing from 1.8 m to 3.6 m. This suggests that the soldier piles are likely thermally interacting with each other, therefore negatively affecting the overall thermal performance when too close. In general, a spacing of about 4-5 m seems to be ideal, which agrees with guidelines for boreholes/energy piles [11], rendering even the unbalanced load case feasible (T_{max}< 40°C).

It is very important, however, to note that this parameter is determined by the structural design of the retaining wall and therefore unlikely to be influenced by the geothermal design. What is determined by the geothermal design, though, is the number of soldier piles that will be geothermally activated. For example, by choosing to only activate every second soldier pile (half of them), the spacing of the activated soldier piles is increased. However, in this case the thermal load per soldier pile GHE is also doubled to provide the same overall amount of thermal energy. The results of choosing to activate every second or every third pile (thus increasing their spacing but also the thermal load per GHE) can be seen in Figure 6. In this case, the thermal performance decreases as less soldier piles are activated, suggesting that the performance loss due to the thermal load increase dominates the benefit from increasing the effective soldier pile spacing. However, it is worth noting that, in certain cases, reducing the number of GHEs still results in acceptable limits and could be well worth the reduced capital costs. For example, looking at the balanced thermal load case, if every second or every third soldier pile is geothermally activated, the maximum and minimum temperatures still fall within the acceptable temperature range meaning the thermal energy could still be provided at a lower cost to install the system (since there are lower overall number of GHEs). Moreover, the higher the thermal load each GHE is providing, the higher the ΔT between inlet and outlet, which can be beneficial to the operation of the ground source heat pump.

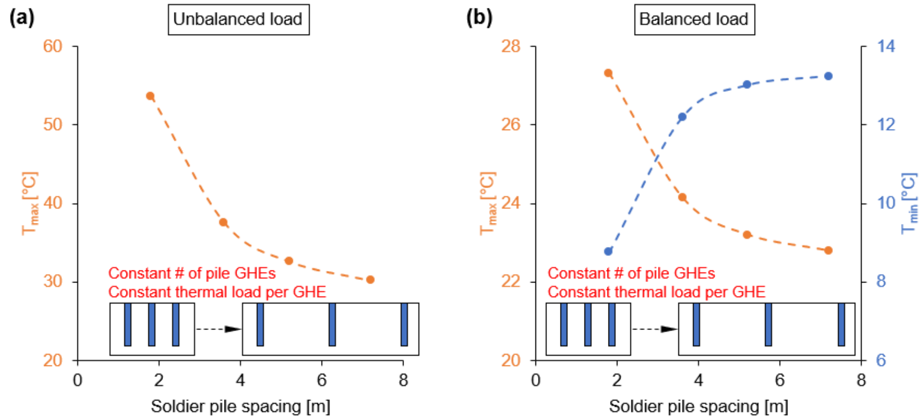

Figure 5. Thermal performance when varying the soldier pile spacing (all other parameters remain constant).

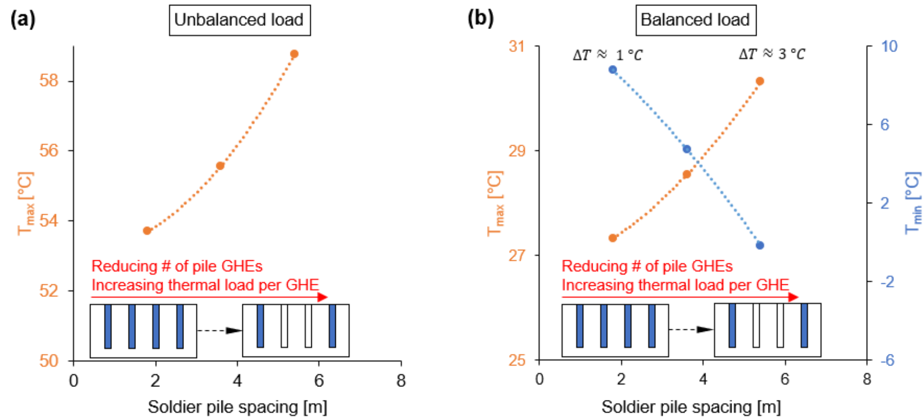

Figure 6. Thermal performance when varying the number of soldier piles activated (the less piles activated the larger the spacing between two activated GHEs and the higher the thermal load per GHE).

4. Conclusions

This work has presented a brief study on the thermal performance of energy soldier pile retaining walls, for which little information is currently available. Numerical modelling techniques were undertaken, utilising finite elements and allowing for three separate investigations on the effect of different design parameters on the thermal performance of these energy geo-structures. From these analyses the importance of the thermal load distribution was firstly showcased, suggesting that a close to *balanced* load should be adopted whenever possible, even if it might add complexity to the system, since the benefits are significant. The second parameter investigated related to the *amount of pipe* inserted in each soldier pile GHE and showed that there exists a limit after which adding more pipe in the GHE results in *insignificant further benefits* while increasing costs. For this case, about 3 to 4 U-loops connected in series were deemed a good solution. Lastly, an investigation on the *spacing* of the soldier piles showed that this can be a *very significant* factor on the thermal performance, especially when the soldier piles are placed close together. Even though the spacing is not determined by the geothermal design, it was noted that the *number* of geothermally activated piles could be used to increase the spacing between *activated* soldier piles/GHEs. This approach decreases the total number of GHEs and therefore increases the thermal load per GHE, however, it was demonstrated that in certain cases it can be a suitable option that can decrease costs and increase ΔT between inlet and outlet, which can be desirable for the operation of the ground source heat pump. Overall, this study shows the potential of energy soldier pile walls, demonstrates the importance of relevant design parameters and indicates that a good understanding of these is crucial for the geothermal design to achieve cost-effective and well-designed solutions.

References

[1] K. Soga, Y. Rui, Energy geostructures, in: S. Rees (Ed.), *Adv. Ground-Source Heat Pump Syst.*, 1st ed., Woodhead Publishing 2016: pp. 185–221.
[2] G.R. Aditya, O. Mikhaylova, G.A. Narsilio, J.I. W., Financial assessment of ground source heat pump systems against other selected heating and cooling systems for Australian conditions, in: Proc. *IGSHPA Res. Track 2018*, IGSHPA Research Track, Stocholm, (2018).
[3] M. Alavy, H. V. Nguyen, W.H. Leong, S.B. Dworkin, A methodology and computerized approach for optimizing hybrid ground source heat pump system design, *Renew. Energy*. **57** (2013) 404–412.
[4] G.A. Narsilio, L. Aye, Shallow Geothermal Energy: An Emerging Technology, in: A. Sharma, A. Shukla, L. Aye (Eds.), *Low Carbon Energy Supply. Green Energy Technol.*, Springer, Singapore, 2018: pp. 387–411.
[5] F. Loveridge, W. Powrie, G-Functions for multiple interacting pile heat exchangers, *Energy*. 64 (2014) 747–757.
[6] F. Cecinato, F. Loveridge, Influences on the thermal efficiency of energy piles, *Energy*. **82** (2015) 1021–1033.
[7] N. Makasis, G.A. Narsilio, A. Bidarmaghz, A machine learning approach to energy pile design, *Computers and Geotechnics*. **97** (2018) 189–203.
[8] D. Sterpi, G. Tomaselli, A. Angelotti, Energy performance of ground heat exchangers embedded in diaphragm walls: Field observations and optimization by numerical modelling, *Renewable Energy*. (2018).
[9] A. Bidarmaghz, *3D Numerical Modelling of Vertical Ground Heat Exchangers*, Ph.D Thesis, The University of Melbourne, 2014.
[10] N. Makasis, Further understanding ground-source heat pump system design using finite element methods and machine learning techniques, Ph.D Thesis, The University of Melbourne, 2019.
[11] C. Remund, R. Carda, Ground Source Heat Pump Residential and Light Commercial Design and Installation Guide, International Ground Source Heat Pump Association, 2009.