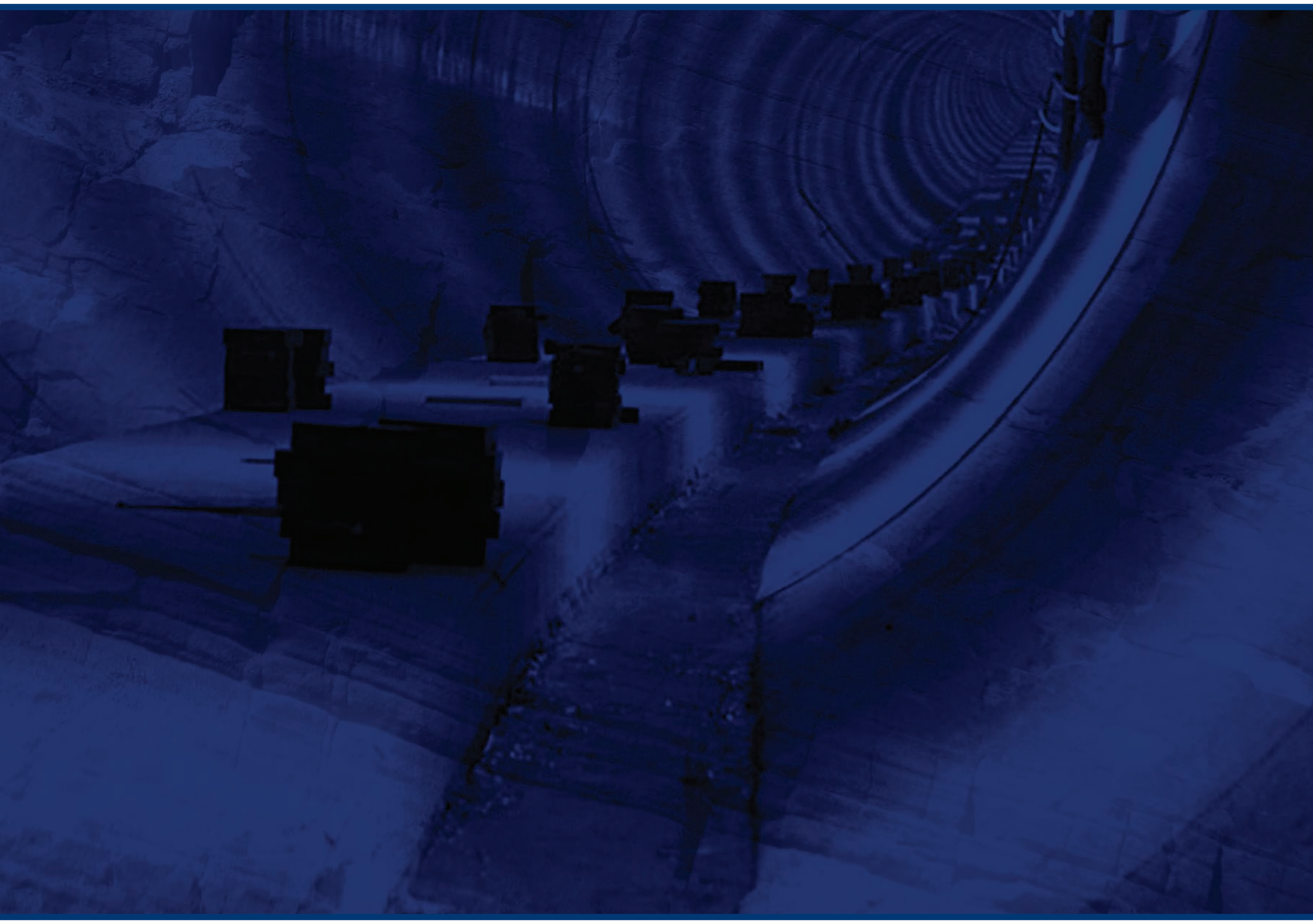
PROCEEDINGS

2018 AUSTRALIAN GEOMECHANICS SOCIETY VICTORIAN SYMPOSIUM

Geotechnics and transport infrastructure

Wednesday, 24 October 2018, 8:00am – 6:00pm
Rydges Hotel, 186 Exhibition Street, Melbourne



AUSTRALIAN GEOMECHANICS SOCIETY
VICTORIA CHAPTER

Global Synthetics

PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2018 Australian Geomechanics Society Victorian Symposium on 'Geotechnics and transport infrastructure' held on 24 October 2018.

In recent years Victoria has seen significant investment in transport infrastructure as part of a plan to manage the demands of a growing population and expanding urban fringe. The construction of Melbourne Metro, a second crossing of the Yarra River, rail and freeway upgrades as well as numerous level crossing removal projects are just some of the major transport projects currently underway in Melbourne and regional Victoria. Many of these projects carry numerous complex geotechnical challenges.

The 2018 Australian Geomechanics Society Victorian Symposium covers a variety of geotechnical challenges associated with transport geotechnics and present overviews of current infrastructure challenges, state of the-art practices, innovation, new research results and case studies demonstrating applications of advanced techniques and cost effective solutions in the construction and design of local transport infrastructure. The Symposium brought together professional engineers, researchers, specialist contractors, regulators, educators and students to share and discuss their experiences on the topic of transport infrastructure and associated geotechnical challenges and applications.

ORGANISING COMMITTEE*

Vladimir Lopez Suarez (Chair)

Daniel King

Richa Shukla Potdar

Erin Lee

David Glover

*a sub-committee of the AGS Victoria committee

SPONSORS

Platinum

Global Synthetics Pty Ltd

Gold

Chadwicks Geotechnics

Acciona Geotech

Silver

Geotesta

Foundation Specialists Group

TECHNICAL REVIEWERS

All technical papers in these proceedings, excluding the keynote addresses, were peer reviewed. The reviewers are acknowledged and listed below:

Daniel King (Editor)
Chris Coulson
Joel Gniel
Jay Lee
Jie Li
Nimal Nilaweera
Bhavikh Riyat
Ben Shannon
Sri Srithar
Manh Tran

Energy geo-structures in transport infrastructure: Are they feasible?

G. A. Narsilio[1], N. Makasis[1], A. Bidarmaghz[2], and M.M. Disfani[1]

[1]Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC 3010, Australia; PH (03) 8344 4659; FAX (03) 8344 4616; emails: narsilio@unimelb.edu.au, nikolas.makasis@unimelb.edu.au, and mahdi.miri@unimelb.edu.au
[2]Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ, United Kingdom; email: ab2492@cam.ac.uk

ABSTRACT

Ground source heat pump (GSHP) systems use the ground as a source of sustainable thermal energy. This shallow geothermal energy technology has proven to efficiently provide renewable energy for space heating and cooling. While the use of purposely built boreholes is widespread, it is becoming increasingly common to attempt to use any geo-structure in contact with the ground as the ground heat exchangers (GHEs) of GSHP systems. In this way, major capital cost savings are potentially achieved since the highest additional costs associated with geothermal technology are drilling and trenching, already required for structural purposes. In transport infrastructure, sub-surface structures designed for stability are abundant. They can be used to also exchange heat with the surrounding ground, converting them into energy geo-structures. This paper summarises the potential of applying this technology to piles, soldier pile retaining walls, diaphragm retaining walls, slabs, road bases and tunnel linings. These are geo-structures that are commonly found in rail and highway projects such as the Melbourne and Sydney Metro Projects, and the West Gate Tunnel Project to name a few. Detailed 3D finite element models have been developed to investigate the thermal performance of these systems, exemplified herein on an energy wall. The applicability of this technology is discussed for different thermal load scenarios, showing the importance of the thermal load distribution balance. Barriers to adoption are also briefly discussed.

Keywords: geothermal, energy foundations, piles, retaining walls, roads, modelling

1 INTRODUCTION

To ensure a sustainable future, it is essential that society transitions toward cleaner and renewable sources of energy, while reducing energy consumption at the same time. Ground source heat pump (GSHP) or shallow geothermal is one such technology that can be considered in transport infrastructure projects and that can contribute towards these goals. GSHP systems uses 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). Traditionally, these technologies use boreholes or trenches, incorporating High Density Polyethylene (HDPE) or cross-linked polyethylene (PEX) piping with a circulating carrier fluid (usually water), to form ground heat exchangers (GHEs). However, traditional GHEs usually lead to high capital costs due to drilling and trenching. To overcome this drawback, a relatively recent alternative approach incorporates the geothermal pipe loops into underground structures that are primarily designed for stability, such as tunnel linings, pile foundations, road bases or retaining walls (Brandl 2006 and 2016, Bidarmaghz and Narsilio 2018), effectively converting them into GHEs known as "energy geo-structures".

Transport infrastructure projects present an excellent opportunity to consider such approach given the geo-structures that are commonly found in, for example, rail and highway projects such as the Melbourne and Sydney Metro Projects, the West Gate Tunnel Project, the Melbourne Metro 2 proposal, the M80 Ring Road upgrade, and the North East Link project to name a few. The provision of 100% of the required energy demands cannot be guaranteed with the sole use of energy geo-structures, leading to the use of hybrid systems (Mikhaylova et al. 2016; Aditya et al., 2018), that incorporates energy structures with other auxiliary (conventional) heating and cooling systems (and/or the addition of traditional GHEs).

There exists now a large body of research on energy piles around the world (see e.g., Loveridge et al. 2018), most likely due to the similarities with traditional borehole GHEs. However, little research exists on the applicability and use of energy retaining walls (Bourne-Webb et al. 2016), which introduce an important difference with respect to energy piles: walls are not all surrounded by soil, but only one side, with the other facing the interior of the underground building (such as an underground train station). There is currently limited information regarding how energy retaining walls can be best utilised, especially regarding long-term thermal performance. Therefore, this paper focuses on the technical suitability of an energy wall, exemplifying such study on diaphragm retaining walls for an underground train station in Melbourne (Victoria). The study presents a novel analysis focusing on the thermal performance for two different geometrical configurations over an operating period of 100 years.

2 DESIGNING AN ENERGY D-WALL

The geothermal design basically consists on analysing how much (thermal) energy a wall can provide. We will show the importance of the thermal load distribution, and the effects of adding geothermal piping to the bottom slab as well as the retaining walls. To perform this technical feasibility study, 3D finite element modelling has been developed and used, adopting an experimentally validated methodology developed at the University of Melbourne (Bidarmaghz, 2014). This approach is implemented using the software package COMSOL Multiphysics and couples the governing equations of heat transfer (energy balance) and fluid flow (momentum and continuity), modelling the heat transfer primarily by *conduction* (ground, concrete, pipe walls) and *convection* (circulating fluid). This methodology has been experimentally validated with both traditional systems, as well as energy structures (Bidarmaghz and Narsilio, 2018).

The modelling, geometry and parameters used have been summarised in Figure 1 and in Table 1.

A meandering HDPE pipe is attached to the reinforcement cage of the D-wall. Symmetry boundary conditions have been used to reduce the computational expense. A constant undisturbed ground temperature of 18.5°C is used at the far boundary. The bottom surface is modelled as a no heat flux boundary (i.e., thermal insulation), assuming negligible bedrock heat flux. To avoid thermal leaking in/out of the station, thermal insulation is required (at a cost) on the surfaces of the wall and slabs inside the station, and accordingly modelled. The pipes in the wall have a 275 mm cover on the ground side while the ones in the slab have 156 mm cover on the bottom.

The amount of thermal energy the system needs to provide is known as the thermal load distribution and is an important model input. Figure 2 shows two thermal load distributions adopted for this work. The first one (herein called 'original', in black) represents typical requirements for an underground train station in Melbourne (cooling dominant due to the large amounts of heat generated by the trains, plants and commuters).

It should be noted that this distribution represents 100% of the heating demand for the entire station and 20% of the cooling demand, with the rest being supplemented using auxiliary means (such as chillers and cooling towers). The second one is a modified balanced version of the first (equal amounts of cooling and heating, in grey) where additional heating is supplied. This additional heating is assumed to be supplied to nearby buildings, such as schools, hospitals or apartment blocks amongst others. In all cases, the thermal load is equally distributed over 67 diaphragm wall pipe loops and (if applicable) 33 slab loops of the entire train station (about 200 m long).

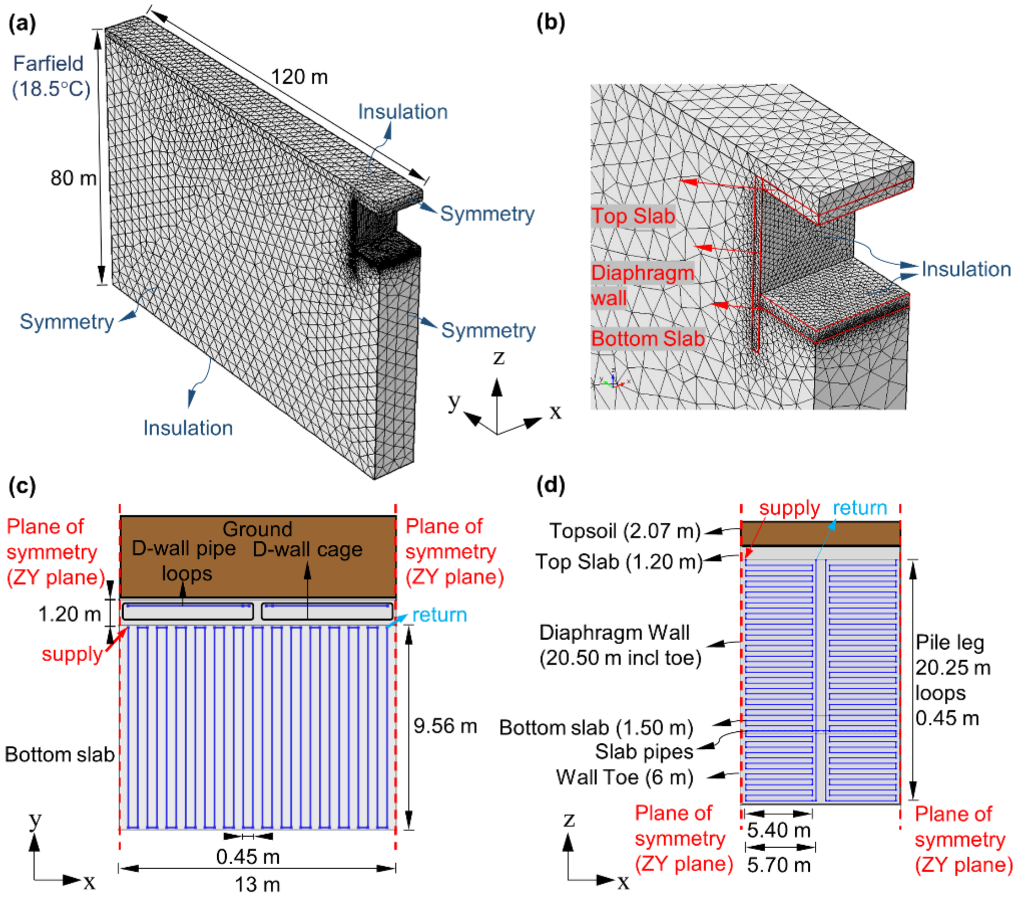


Figure 1. Finite element modelling: overview (a), detail (b), model geometry in the XY (c) and ZX (d) planes showing two D-wall geothermal pipe loops and one slab geothermal loop in blue

Table 1: Modelling parameters

Parameter	Value	Unit	Description
λ_{ground}	3.4	W/(mK)	Effective thermal conductivity of ground
ρ_{ground}	2,400	kg/m^3	Density of ground
$C_{p\ ground}$	830	J/(kgK)	Specific heat capacity of ground
$T_{farfield}$	18.5	°C	Average annual ground temperature
$\lambda_{concrete}$	2.1	W/(mK)	Thermal conductivity of concrete
$\rho_{concrete}$	2,250	kg/m^3	Density of concrete
$C_{p\ concrete}$	890	J/(kgK)	Specific heat capacity of concrete
λ_{fluid}	0.58	W/(mK)	Thermal conductivity of carrier fluid
ρ_{fluid}	1,000	kg/m^3	Density of carrier fluid (water)
$C_{p\ fluid}$	4,180	J/(kgK)	Specific heat capacity of carrier fluid

3 RESULTS AND DISCUSSION: ARE ENERGY D-WALLS TECHNICALLY FEASIBLE?

The average fluid temperature within the pipes (average of inlet and outlet of header pipes) over time that results from the numerical simulations are summarised in Figure 3. In transport infrastructure projects, lifespans of 100 years are not uncommon, but one can already extract useful conclusions from the first operating period of 25 years. In the geothermal design of these systems, it is crucial that this temperature range is within the acceptable operating limits of the ground source heat pump. In addition, one must ensure that the fluid does not prompt wall and ground freezing. For Melbourne conditions, and following recommendations by the International Ground Source Heat Pump Association (IGSHPA), carrier fluid temperature should be targeted to between about 2-4 °C and 33-36 °C to ensure a high efficiency design. In the figures, an upper limit of 40 °C is included for reference, as this is a typical cut off limit of many GSHPs.

Figure 3(a) the results when geothermal piping is included only in the diaphragm walls while Figure 3(b), when geothermal piping is included in both the diaphragm walls as well as the bottom slab. Figure 3 shows the relative improvement on the system performance, by the addition of the slab, with an average lowering of about 1 °C in the maximum mean fluid temperature. Finally, each figure shows the results for both thermal load distributions presented in Figure 2, as well as variations of the *original*, where the cooling load provided is reduced to make the design technically feasible (since providing 100% of the *original* thermal load results in temperatures over 40 °C).

In Figure 3(a), only about 80% of the *original* (cooling) thermal demand can be satisfied, assuming that the GSHP system will stop operating after 25 years to restore the thermal balance to the ground, which in the absence of groundwater flow, can take another 20 years or so, before resuming the GSHP operation for a further 25 years. This increasing fluid (and ground) temperature over time is due to the cooling dominant nature of the *original* thermal load, with heat being continuously extracted from the station and rejected to the ground, where it keeps accumulating, increasing the ground temperatures. This heat accumulation will make the operation of the geothermal system to lose efficiency over the years as the temperatures of its sink (the ground) increases.

On the other hand, under a *balanced* thermal load, the geothermal system performance greatly improves, with the carrier fluid temperatures kept stable (over 100 years), at approximately between 7 °C and 25 °C.

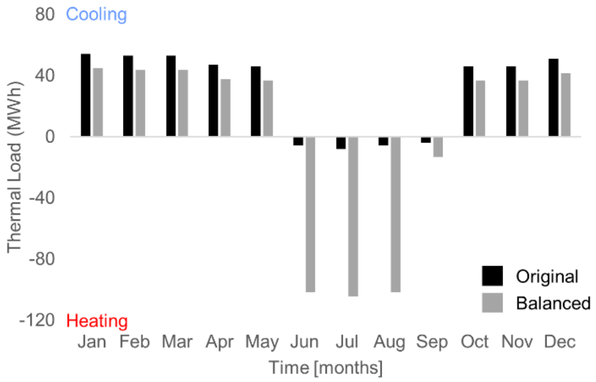


Figure 2. Annual thermal load distribution scenarios

Since equal amounts of heat are injected to and extracted from the ground, thermal equilibrium is preserved each year and there are no thermal drift effects in the long term. Due to these reasons, a system adopting the *balanced* thermal load would also comfortably run for much longer periods of time. Moreover, given the resulting narrow range of average carrier fluid temperature, the amount of thermal load able to be delivered by the energy D-wall could be doubled with respect to the one shown in Figure 2. The resulting fluid temperature would range between -2 °C and 36 °C (an anti-freeze solution shall be used in this case instead of just plain water).

Figure 3(b) shows similar results, with only about 85% of cooling being comfortably provided when the *original* thermal load is considered – although likely less in the long term; while using the *balanced* thermal load results in a stable performance with the fluid temperatures fluctuating approximately between 10 °C and 24 °C. This simulation shows that the geothermal activation of the slab improves the overall performance of the system, by shifting the fluid temperatures away from the upper and lower limits (reducing the max and increases the min). In this particular case, it would allow the system to provide about 5% more cooling energy for the *original* load case. However, in the case where the extra heating could be supplied to balance the load, adding geothermal pipping in the slab would not result in significant improvements. Even though the fluid temperature extremes are reduced/increased by 1 to 3 °C, the temperature range without the slab piping is already acceptable and therefore the improvement would only be in terms of the coefficient of performance (COP), meaning that less electricity would be required to run the system, and

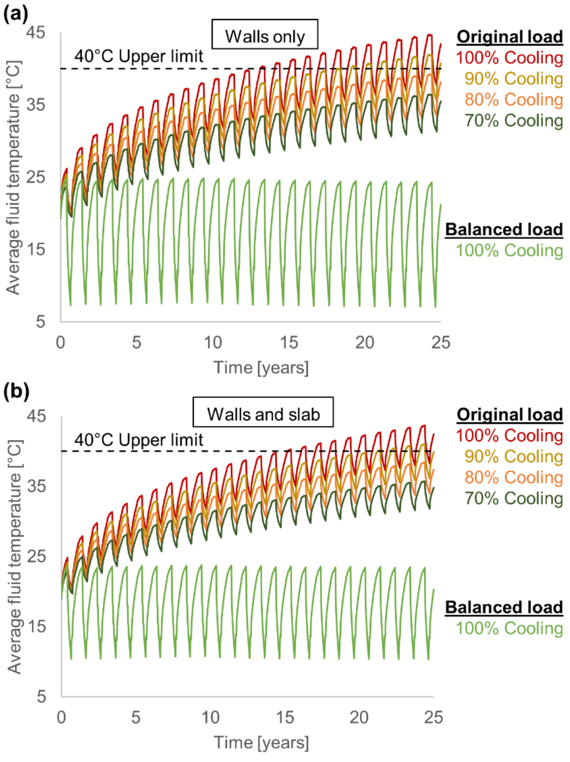


Figure 3(a) Resulting average fluid temperature over time when geothermal piping is used in the D-walls only and (b) in D-walls and bottom slab.

therefore resulting in a small reduction in the operational costs. To properly quantify the benefits of adding the piping in the slab, a thorough analysis of the relevant cost is required, considering the relative novelty of this concept and therefore the associated risks, as well as the benefits, both monetary and environmental (such as providing more renewable energy).

The exemplary investigation shows that a large portion (80-85%) of its target cooling demand (or 16-17% of total station demand) can be provided by the energy walls (and slabs). However, the fluid temperatures keep rising, indicating that the system can only run for a finite amount of time, before requiring shutting down for some time, to restore the thermal state of the ground. On the other hand, balancing the thermal load not only results in a much better running system, but also would be less costly to operate and would be able to run for much longer. Moreover, the resulting fluid temperature ranges suggest that if even more heating demand existed for the surrounding structures, the system could be able to provide even more amounts of cooling, reducing the energy dependencies on auxiliary systems (for example 200% of the target cooling, or 40% of the total station cooling demand).

4 OTHER ENERGY GEO-STRUCTURES AND BARRIERS TO IMPLEMENTATION

The use of *energy piles* is more widespread overseas and while research continues, there exists a consensus on their sound technical feasibility. However, there are only a handful of examples of their use in Victoria, with the first documented implementation as pilot tests in The University of Melbourne (Parkville) and Monash University (Clayton)'s campuses, and other projects in Monbulk (No. 17, 7-metre-deep piles, residential), and in Narre Warren (No. 48, 9.5-metre-deep screw piles, commercial).

Energy tunnels, that is, tunnel linings with embedded geothermal pipe loops are relatively rare around the world, and none exists in Australia, thus there is no routine design and analysis practice yet. Numerical simulation is the most common approach to assess temperature changes and heat transfer rates. Studies have been conducted in both two (Franzius and Pralle 2011) and three dimensions (Nicholson et al. 2014, Bidarmaghz and Narsilio 2018, DiDonna and Barla 2016). The structure internal boundary condition is very important, as the air inside the tunnel can be used as a heat source together with the ground (Zhang et al., 2014), as well as the effect of groundwater impacting on the energy efficiency of energy tunnels (DiDonna and Barla, 2016, Bidarmaghz and Narsilio, 2018). Analytical solutions have also been proposed (e.g. Zhang et al., 2013).

There are no examples of *geothermal roads* (yet) in Australia, but like well-established horizontal (trenched) GSHP systems, there is no reason to doubt of its thermal technical feasibility. Research is underway in Victoria for the incorporation of geothermal piping (HDPE and metal) and the use of recycled materials, with the two-fold objectifies of increasing thermal conductivity and of reducing recycled material stockpiles, into the bases and sub-bases of pavements (Arulrajah et al. 2018).

Nevertheless, there are several barriers to adoption and implementation of energy geo-structures in transport infrastructure projects. These include: i) lack of a standardised design approach and limited local design (and construct) knowledge base; ii) lack of policies mandating consideration of geothermal technologies in infrastructure projects; iii) lack of government incentives or rebates (although ISCA ratings may play a role here); and iv) perceived risk in project implementation and potential delays to construction programs. To overcome these (and other) barriers, the Victorian and Federal governments have been investing in R&D and (small) demonstration projects over the past five years or so. As a result, and perhaps also motivated by achieving ISCA ratings, some developers and construction companies are trailing energy geo-structures (notably, energy soldier pile walls – see Figure 4). After the initial steep learning curve, there is general consensus that much of the perceived risk was unfounded and that implementation was simpler than thought. There is still the need to program the installation of the GSHP system in stages. The first stage, concurrently with the foundations/geo-structures/earthworks, requiring coordination between drilling, piling and geothermal (plumbers) contractors. The second stage, coordinated with the fitting of the HVAC (Heating, Ventilation and Air Conditioning) plants. Traditionally, HVAC works do not come into play but much later than the foundation stages, thus, this 'new' staggered construction sequence requires a coordination not previously needed between subcontractors.

A *realistic* economic feasibility analysis is required to completely answer the question of feasibility of energy geo-structures in transport infrastructure projects. From the technical point of view, there is ample evidence of being feasible.

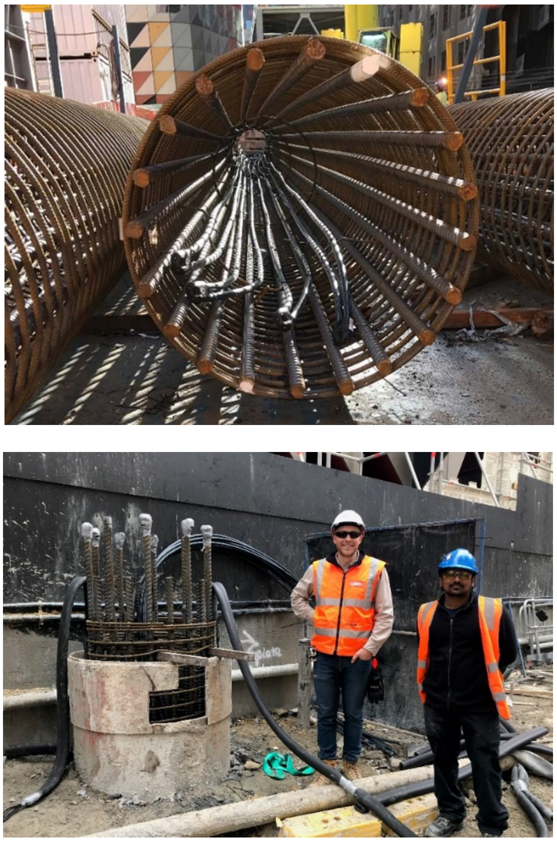


Figure 4. An energy soldier pile wall trial in Melbourne helps learning by doing and helps quantifying real (as opposed to perceived) risks associated with the technology.

5 CONCLUSION

This work briefly exemplified an investigation on the use of diaphragm retaining walls as energy geo-structures. They can be used to provide geothermal energy for space heating and cooling purposes. An underground station in Melbourne was adopted as a case study and the investigation focused on the importance of the thermal load distribution as well as two potential designs, one incorporating the technology only in the diaphragm walls and the second also adding it to the bottom slab of the station.

The thermal load investigation showed that this is a crucial parameter to energy retaining walls, likely more significant than for traditional boreholes or energy piles, due to the more limited available ground. An evaluation of the maximum feasible amount of thermal energy that can be provided for a typical under-ground station in Melbourne, showed that the system could only provide 80-85% of its initial target cooling demand (16-17% of the total cooling of the station) eventually overheating the ground, due to the heavily cooling dominant nature of the thermal load. On the other hand, balancing the thermal load by providing equal amounts of heating, transferred to nearby buildings, resulted in a much better running system that would be less costly to operate, be able to run for much longer and could almost certainly exceed the initial target demands, given that sufficient heating demand is also present. Thermally activating the bottom slab marginally improves the system performance. However, these benefits may not outweigh the additional capital costs associated and a cost-benefit analysis should be undertaken for a definite position.

A summary of the barriers to market implementation was presented, most notably given the limited local knowledge and expertise. Steps are being taken through detailed modelling and small-scale trials and demonstrations, to overcome this barrier. These works also allow more widespread adoption (or at least serious consideration) of the technology in transport infrastructure projects, given the abundance of opportunities to convert geo-structures on GHEs and/or use earthworks already required by the project to embed geothermal piping at marginally low additional costs.

6 ACKNOWLEDGEMENTS

Funding from the Australian Research Council (ARC) FT140100227, The University of Melbourne and the Victorian Government is much appreciated. A number of collaborators (notably Prof I.W. Johnston), industry partners (notably John Holland, MMRA) and Master and PhD students (notably Q. Lu, G.R. Aditya, L. Jensen-Page, Y. Zhou, Z. Li, and Y. Zhong) have helped shaping this work.

REFERENCES

Arulrajah, A., Narsilio, G., Horpibulsuk, S. (2018) 'Harnessing renewable energy from low-carbon geothermal pavements. ARC LP (2018-2020).

Bidarmaghz, A. (2014). '3D Numerical Modelling of Vertical GHEs. PhD Thesis. The University of Melbourne.

Bidarmaghz, A., and Narsilio G., (2018). "Heat exchange mechanisms in energy tunnel systems." Geomech. for Energy and the Environment, 16(Dec), 83-95.

Bourne-Webb, P. et al. (2016) 'Analysis and design methods for energy geostructures', Renewable and Sust. Energy Reviews. Elsevier, 65, pp. 402–419.

Brandl, H. (2006) 'Energy foundations and other thermo-active ground structures', Géotechnique, 56(2), pp. 81–122.

Brandl, H. (2016) 'Geothermal Geotechnics for Urban Undergrounds', Procedia Engineering. Elsevier B.V., 165, pp. 747–764.

DiDonna, A, and Barla, M. (2016). 'The role of ground conditions on energy tunnels' heat exchange'. Environmental Geotechnics 3(4), pp. 214-224.

Franzius, J. N. & Pralle, N. (2011). 'Turning segmental tunnels into sources of renewable energy.' Proceedings of the Institution of Civil Engineers - Civil Engineering 164(1), pp. 35-40.

Johnston, I. W., Narsilio, G. A. and Colls, S. (2011) 'Emerging geothermal energy technologies', KSCE Journal of Civil Engineering, 15(4), pp. 643–653.

Nicholson, D. P., Chen, Q., Silva, M. D., Winter, A. & Winterling, R. (2014). 'The design of thermal tunnel energy segments for Crossrail, UK'. Proceedings of the Institution of Civil Engineers - Engineering Sustainability 167(3):118-134.

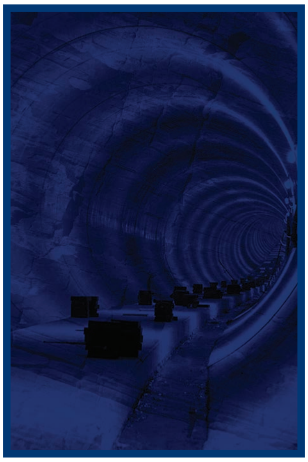
Loveridge, F., McCartney, J., Narsilio, G., Sanchez, M. (2018). 'Energy geostructures: a review of analysis approaches, in situ testing and model scale experiments', Geomechanics for Energy and the Environment, under review.

Zhang, G., Xia, C., Sun, M., Zou, Y. and Xiao, S. (2013). 'A new model and analytical solution for the heat conduction of tunnel lining ground heat exchangers.' Cold Regions Science and Technology 88, pp. 59-66.

Zhang, G., Xia, C., Yang, Y., Sun, M. and Zou, Y. (2014). 'Experimental study on the thermal performance of tunnel lining ground heat exchangers.' Energy and Buildings 77, pp. 149-157.

2018 AUSTRALIAN GEOMECHANICS SOCIETY
VICTORIAN SYMPOSIUM

Geotechnics and transport infrastructure



AUSTRALIAN GEOMECHANICS SOCIETY
VICTORIA CHAPTER