INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

SIMSG ISSMGE

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3
© The authors and IGS: All rights reserved, 2019
doi: 10.32075/17ECSMGE-2019-0592

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Long-term thermal performance of a thermo-active retaining wall

Performance thermique à long terme d'un mur de soutènement thermoactif

E. Sailer
Imperial College London, London, UK

D.M.G. Taborda, L. Zdravkovic, D.M. Potts, M. H. Pang
Imperial College London, London, UK

ABSTRACT: Thermo-active retaining walls have a great potential for providing low-carbon heating and cooling due to their large contact area with the ground. However, analysing their energy efficiency is complex, as they are not completely surrounded by soil, but partially exposed to the environment, the thermal characteristics of which depend on the function of the underground space. This paper investigates the long-term thermal performance of a thermo-active wall by performing finite element (FE) analyses using the Imperial College Finite Element Program (ICFEP). A first set of analyses assesses the effect of modelling the heat exchange in a 2D plane strain analysis compared to a full 3D simulation. Secondly, the influence of different characteristics of the studied problem, such as the thermal conductivity of the materials and the operation mode, on the long-term thermal performance of the system are analysed. Furthermore, for all considered scenarios, the impact of varying the conditions along the exposed part of the wall is investigated.

RÉSUMÉ: Les murs de soutènement thermoactifs offrent un grand potentiel de chauffage et de refroidissement à faible émission de carbone grâce à leur grande surface de contact avec le sol. Cependant, l'analyse de leur efficacité énergétique est complexe, car ils ne sont pas complètement entourés par le sol, mais partiellement exposés à un environnement dont les caractéristiques thermiques dépendent de la fonction de l'espace souterrain. Cet article examine les performances thermiques à long terme d'un mur thermoactif en réalisant des analyses par éléments finis (FE) à l'aide du programme ICFEP (Imperial College Finite Element Program). En premiere lieu, on évalue l'effet de la modélisation de l'échange de chaleur dans une analyse de bidimensionelle en deformations plans par rapport à une simulation tridimensionelle. En deuxièmeme lieu, on analyse l'influence de la conductivité thermique des matériaux et le mode de fonctionnement sur les performances thermiques à long terme du système. En outre, on étudie l'impact de la variation des conditions le long de la partie exposée du mur pour tous les scénarios considérés.

Keywords: ground source energy; thermal performance; retaining walls.

1 INTRODUCTION

Retaining walls forming underground basements, train stations or tunnels, can be employed as heat exchangers in the context of shallow geothermal energy exploitation. This can be achieved by incorporating pipes within the structure, through which a fluid circulates, exchanging heat with the ground. In comparison to thermo-active piles, geothermal walls have a larger heat exchange area. However, these structures are more complex from the perspective of energy performance, as they are not fully surrounded by soil. Indeed, part of the structure is exposed to an environment, which is generally difficult to characterise, as it depends on the use of the underground space and the climatic conditions at the location of the structure.

To date, limited field studies on the thermal performance of thermo-active retaining walls have been carried out. Xia et al. (2012) presented a field test conducted on thermo-active diaphragm wall panels within the Shanghai Natural History Museum. However, the tests lasted only for 48h, hence the long-term response is unknown. Sterpi et al. (2018) reported a field study carried out on a diaphragm wall forming a basement of a residential building in Italy. The monitoring data suggest that the conditions within the basement affect the registered wall temperatures, which may impact the thermal performance.

Several numerical studies have been performed to assess the effect of different parameters on the energy efficiency of thermo-active walls. Bourne-Webb et al. (2016) analysed the effect of concrete and soil conductivity as well as the boundary condition on the exposed part of the wall, where this was varied from a constant temperature to surfaces with different convective heat transfer coefficients. It was shown that the boundary condition on the exposed face of the wall controls the heat flux towards the excavation, which is also largely affected by the concrete conductivity. However, it should be noted that the performed analyses did not consider the advective heat transfer within the pipes, nor the transient nature of the problem. Di Donna et al. (2017) performed a parametric study on the thermal performance of a wall over a period of 60 days through 3D finite element analyses, where pipes were modelled as one-dimensional elements with simulation of water flow. They concluded that the factors that have the greatest influence on the thermal performance of the wall during the considered time period are the concrete conductivity and the temperature difference between the pipe inlet temperature and the constant temperature imposed at the excavated face of the wall. In addition, they computed that increasing the number of pipes within a wall panel has a beneficial effect in terms of thermal performance. Sterpi et al. (2017) investigated the impact of different pipe configurations. The results showed that the efficiency of thermo-active walls is related to the layout of the pipes, rather than the pipe length, where certain pipe layouts increased the heat flux by 50%.

Considering the lack of long-term transient analyses focusing on determining the energy efficiency of thermo-active retaining walls, this study aims at identifying the energy potential of a hypothetical thermo-active retaining wall. While the long-term sustainability of these systems generally improves if heating and cooling loads are balanced, the analyses carried out in this paper focus only on the first 6 months of operation. A first set of analyses outlines the procedures to model thermo-active wall problems, which are inherently three-dimensional in nature due to the existence of the heat exchange pipes, in two-dimensional plane strain analyses. Secondly, a parametric study is carried out to evaluate the effects of different parameters on the thermal performance of such structures. All simulations highlight the impact of the conditions along the excavated section of the wall, where two extreme scenarios were analysed: a perfectly insulated wall and one exposed to an environment at constant temperature.

The analyses are carried out using the Imperial College Finite Element Program (ICFEP, Potts & Zdravkovic 1999), which is capable of performing fully coupled THM simulations. The THM finite element formulation, its implementation and validation are fully described in Cui et al. (2018a).

2 NUMERICAL ANALYSIS

2.1 Problem description

This study analyses a hypothetical thermo-active diaphragm wall installed in the London ground profile, which retains an excavation of 11.0 m, at the bottom of which a 1.5m thick base slab is constructed. Each wall panel is 18.0 m long, 0.8 m thick and 1.5 m wide. Within each panel, two vertical pipes (inner diameter of 20.4 mm) are installed with a pipe-to-pipe spacing of 0.75 m at a distance of 0.1 m from the concrete edge on the soil side. These reach a depth of 17.5 m and are connected at the bottom by a horizontal pipe segment, forming a U-shaped loop. The wall is embedded within Made Ground (4.8 m thick), Terrace Gravels (2.0 m thick) and London Clay. The water table is located 4.0 m below the ground surface and the initial ground temperature was 13°C (Loveridge et al., 2013). The thermal parameters used in the reference analyses are reported in Table 1.

Table 1. Material properties for reference analyses

Material	**Thermal conductivity λ (W/mK)**	**Volumetric specific heat capacity ρc (kJ/m^{3}K)**
Concrete	1.60	2615
Made Ground	1.40	1900
Terrace Gravel	1.40	1900
London Clay	1.79	1820
Water	0.60	4200

2.2 Modelling procedure

The finite element model, depicted in Fig. 1, extends 15.0 m either side of the wall – detailed studies were performed to check that this distance was sufficient to prevent any boundary effects on the results. Soil and concrete structures were modelled with eight-noded solid elements in 3D and four-noded solid elements in 2D, where each node has temperature degrees of freedom. The use of lower-order elements was possible as the focus of this study was solely the thermal performance of the wall (i.e. no mechanical effects were considered). For the heat exchanger pipes, special one-dimensional elements were employed, both in the 2D analyses (Cui et al., 2018b) and in the 3D analyses (Gawecka et al., 2018), where at each node both temperature and pore pressure degrees of freedom exist, enabling the simulation of conductive-advective heat transfer within the pipes. For this purpose, and given the large velocities simulated, the Petrov-Galerkin finite element method (Cui et al., 2018c) was adopted to guarantee numerical stability.

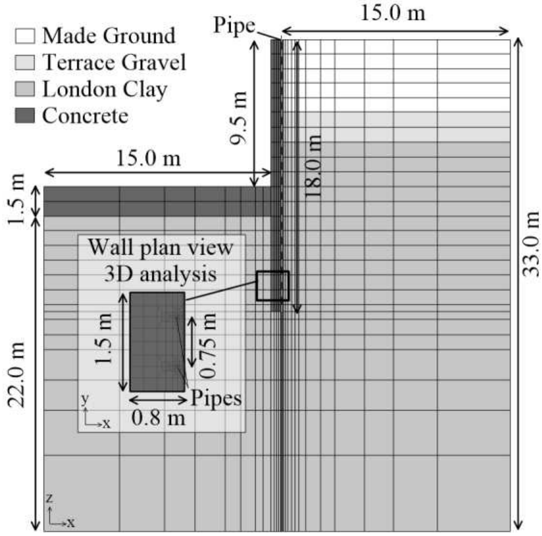

Figure 1. Finite element mesh

The heat exchange is simulated by imposing a constant temperature of 28°C at the inlet node of the pipe loop, within which water flows at a constant velocity of 0.5m/s. At the outlet node, the coupled thermo-hydraulic boundary condition (see Cui et al., 2016a for details on this nonlinear boundary condition) was applied. All the analyses were run for six months with a continuous operation mode and appropriate time-steps were adopted to avoid oscillations (Cui et al., 2016b). The ground surface was kept at a constant temperature equal to the initial temperature of 13°C. No heat flux was allowed across the other boundaries of the domain, with the exception of the exposed part of the wall, where the conditions were varied, as discussed in subsequent sections.

2.3 *Performed analyses*

Different analyses were performed to assess the influence of various factors on the thermal performance of the simulated thermo-active retaining wall.

Firstly, the procedures to model this type of problems in two-dimensional plane strain analyses, which reduce considerably the required computational effort, are presented and the results are compared to the equivalent 3D analyses.

Subsequently, further analyses are carried out evaluating the effect on the thermal performance (assessed in terms of heat flux) of:

(1) the boundary condition on the exposed part of the wall, where two extreme conditions were considered, i.e. applying either a no heat flux (NF) boundary condition (completely insulated wall) or a constant temperature (CT) boundary condition (equal to the initial temperature, T_0, of 13°C). These would be equivalent to using a convective heat transfer coefficient (W/m^{2}K) of zero and infinity, respectively;

(2) the conductivity of the concrete and soil, where these were varied between half and double the value of the reference analysis (Table 1);

(3) the operation mode, where 6h of heat injection were alternated with 6h of idling.

3 MODELLING HEAT EXCHANGE IN 2D PLANE STRAIN ANALYSIS

3.1 *Modelling approach*

While in a 3D analysis there is a finite number of pipes within a panel, a 2D plane strain analysis simulates the presence of a continuous “sheet” of water flowing through the wall where the pipes are located. Hence, when using pipe elements in a 2D plane strain analysis, a conversion is required in order to take into account the geometric configuration of the pipes in the out-of-plane direction of the simulated 3D problem. This can be achieved by modelling the same water flow rate per unit meter in both 3D and 2D analyses:

$$\frac{Q_w^{3D}}{B} = \frac{A_p v_{3D} n_p}{B} = \frac{Q_w^{2D}}{1.0m} = \frac{v_{2D} A_p}{1.0m} \tag{1}$$

where Q_w^{3D} is the water flow in 3D (m^3/s), B is the width of the panel (m), A_p is the area of the pipe (m^2), v_{3D} is the water flow velocity in 3D (m/s), n_p is the number of pipes in 3D (-), Q_w^{2D} is the water flow in 2D (m^3/s) and v_{2D} is the water flow velocity in 2D (m/s).

Rearranging Eq. 1 and considering A_p in the 3D analysis to be the thickness of the pipe in 2D, the water flow velocity to be applied in the 2D plane-strain analysis can be determined using:

$$v_{2D} = \frac{v_{3D} n_p}{B} \tag{2}$$

A further correction is required when a constant temperature is simulated on the exposed face of the wall, due to the larger contact area between the pipe and the wall-ambient interface simulated in the 2D analysis, which enhances the heat exchange through this boundary. Conversely, this effect is less relevant when an insulated wall is simulated, as heat flux takes place predominantly through the interface with the soil. Hence, for a wall exposed to an ambient at constant temperature, the temperature difference at the inlet in the 2D analysis, ΔT_{2D} (i.e. $T_{in,2D} - T_0$), is calculated using:

$$\Delta T_{2D,CT} = \frac{exp}{L}\left(1 - \frac{\overline{A_p^{2D}}}{\overline{A_p^{3D}}}\right)\Delta T_{3D} + \frac{emb}{L}\Delta T_{3D} \tag{3}$$

where $\overline{A_p^{2D}}$ (m^2/m) is the area of pipes per metre in the 2D model (assumed in the present case for simplicity to be given by the area of a single pipe, i.e. $\overline{A_p^{2D}} = A_p/1.0m$), $\overline{A_p^{3D}}$ (m^2/m) is the area of pipes per metre in the 3D model (i.e. $A_p \cdot n_p/B$), "exp" and "emb" are, respectively, the exposed and embedded lengths of the wall (m), L is the total length of the wall (m) and ΔT_{3D} (°C) is the temperature difference applied in the 3D analysis (i.e. $T_{in,3D} - T_0$). Eq. 3 can be rewritten in a simpler form as:

$$\Delta T_{2D,CT} = \frac{exp}{L}\left(1 - \frac{B}{n_p 1.0m}\right)\Delta T_{3D} + \frac{emb}{L}\Delta T_{3D} \tag{4}$$

Clearly, as the number of pipes in the 3D problem increases, the correction factor applied to the temperature drop along the exposed face approaches unity, suggesting that the 2D representation of the problem is more accurate. It should be noted that this correction is limited to cases where $\overline{A_p^{2D}} < \overline{A_p^{3D}}$ or, equivalently, to values of spacing between the pipes (i.e. B/n_p) below 1.0 m.

The heat flux per unit area q (W/m^2) is then calculated through the following equation:

$$q = \frac{(\rho c)_w A_p v (T_{in} - T_{out})}{A_{wall}} \tag{5}$$

where $(\rho c)_w$ is the volumetric heat capacity of water (kJ/m^{3}K), v is the water flow velocity (which is calculated using Eq. 2 for 2D analyses), T_{in} and T_{out} are the inlet and outlet temperatures (°C), where T_{in} for a 2D analysis with a CT condition is given by Eq. 3, and A_{wall} is the area of the wall (m^2). Clearly, the latter is different for 3D and 2D analyses, since in the first it is calculated considering the actual width of the panel in the out-of-plane direction (B), whereas in 2D analyses this is equal to 1.0 m. It should be noted that both T_{in} and v are input parameters, while T_{out} is a quantity calculated during the simulation.

3.2 Comparison between 3D and 2D

The applicability of the proposed 3D to 2D conversion procedures was verified for numerous values of exp/L, ΔT_{3D}, n_p and other thermal parameters, obtaining a very good agreement for all cases. For the problem described in section 2.1, the calculated water flow velocity (see Eq. 2) for the 2D analyses is 0.6667 m/s and the inlet temperature for the constant temperature (CT) case calculated with Eq. 3 is 22°C. The results of the 3D and 2D analyses, for both boundary conditions on the exposed face (i.e. no heat flux (NF) and constant temperature (CT)), are shown in Fig. 2. For both cases, the 2D approach overestimates the heat flux at the beginning of the analysis. This is because the plane strain assumptions (i.e. larger contact area between pipe and concrete) lead to a much faster heat transfer in the short term, hence a lower outlet temperature. After 20 days, an excellent agreement between the 3D and 2D analyses is obtained for both cases, with a difference after 6 months of operation of 1 W/m^2 (13%) for the NF case and of 0.2 W/m^2 (1%) for the CT case. This demonstrates the possibility of simulating this type of problem using a 2D plane strain approach, thus reducing considerably the required computational effort.

Regarding the effect of the boundary condition along the exposed face, the assumption of a constant temperature leads to a larger heat injection rate (16 W/m^2 compared to 8 W/m^2 for the NF case), reflecting the additional heat exchange taking place through this boundary. As previously mentioned, this simulates a surface with a heat transfer coefficient (W/m^{2}K) equal to infinity, typical of a large air-flow velocity at the wall-ambient interface (forced convection).

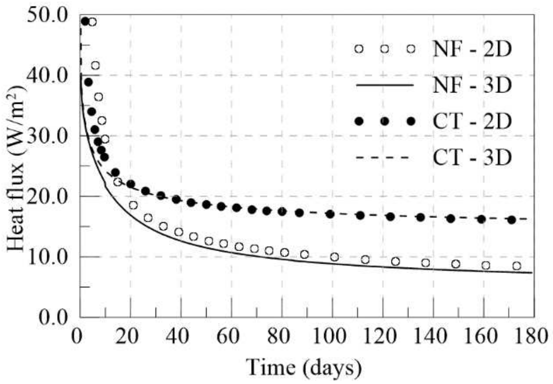

Figure 2: Heat flux with time – comparison between 3D and 2D analyses with NF and CT boundary condition on the exposed face of the wall

4 PARAMETRIC STUDY

In this section, results obtained in 2D plane strain analyses are presented to provide insight into the impact of some factors on the thermal performance of the thermo-active retaining wall shown in Fig. 1. The effect of each parameter, as outlined in the previous section, is analysed for two different boundary conditions on the exposed face of the wall, i.e. no heat flux (NF) and constant temperature (CT) equal to 13°C.

4.1 Thermal conductivity of concrete

As shown in Fig. 3, varying the thermal conductivity of the concrete has clearly a large effect for the CT case, whereas almost no difference is computed for the NF case. This is due to the heat transfer in the former case taking place mainly within the excavated part of the structure towards the exposed face, and, hence, through the concrete. Conversely, in the latter case, the heat transfer occurs towards the soil, therefore the conductivity of the concrete has a limited effect on the observed thermal behaviour (the difference in heat injection rate is limited to ±3% of the one computed for the reference case).

Doubling the concrete conductivity in the CT case results in a heat flux after 6 months of 27.0 W/m^2 (68% above that calculated in the reference case), whereas halving the concrete conductivity leads to a heat flux of 10.0 W/m^2 (35% less than in the reference case).

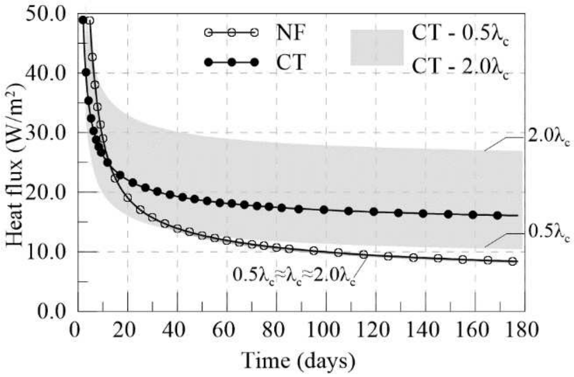

Figure 3: Heat flux with time for different concrete thermal conductivity

4.2 Thermal conductivity of soil

As previously observed, in the NF case the heat transfer takes mainly place towards the soil. Hence, as depicted in Fig. 4, varying the soil conductivity has a major effect on the heat flux computed for the NF case, where halving or doubling the soil's conductivity leads to differences in heat flux after 6 months of -37% and 63%, respectively, when compared to the reference analysis. As expected, a smaller, albeit still relevant, difference is calculated for the CT case, where a 20% larger heat flux is calculated when a higher thermal conductivity is assumed for the soil. However, it should be noted that in absolute terms, the divergence of the heat flux from the reference analysis are similar in both cases and limited to a maximum of 5.0 W/m^2.

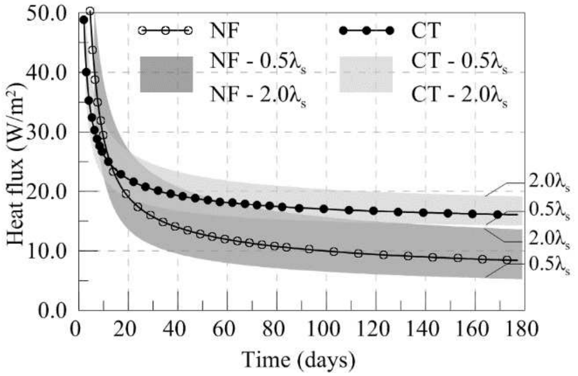

Figure 4: Heat flux with time for different soil thermal conductivity

4.3 Operation mode

The analyses presented so far simulated heat exchange with a continuous operation mode, i.e. the heat pump was constantly operating for 24h a day. In real applications, this is unlikely to be the case, with the exception perhaps of periods corresponding to the peak heating/cooling load. Indeed, heat pumps usually operate following an intermittent pattern, meaning the heat pump is likely to be switched off for substantial periods of time.

The results for the reference analyses adopting a continuous operation mode are compared in Fig. 5 to those obtained when simulating an intermittent operation mode (IOM) (alternating between 6h operation and 6h idling). Clearly, the simulation of an intermittent operation mode leads to a noticeable increase in the heat injection rate. Indeed, on average, the modelled rate is 50% larger than the one computed with a constant operation mode, for both NF and CT boundary conditions. This increase in heat flux is due to the fact that during the resting periods (i.e. when the heat pump is switched off) the temperature in the concrete and surrounding ground is allowed to recover (in this case, a reduction is observed, with the opposite being expected in case of heat extraction). Therefore, when the heat pump resumes its operation, the gradient between the geothermal fluid and the surrounding medium is higher, enhancing heat transfer from the former to the latter. Moreover, it is important to note that the total energy extracted over 6 months using the two different operation modes is approximately the same, i.e. 1100 kWh/m for NF and 1450 kWh/m for CT. This suggests that the intermittent operation mode is more efficient, since the same energy is exchanged in half the operation time, reducing the costs associated with system operation.

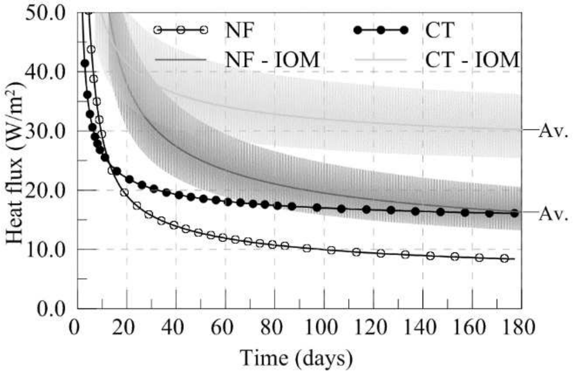

Figure 5: Heat flux with time – comparison between continuous and intermittent operation mode

5 CONCLUSIONS

A series of finite element analyses on the energy performance (over 6 months) of a hypothetical thermo-active wall constructed in the London ground profile were presented. Particular focus was given to characterising the impact of the boundary condition assumed on the exposed part of wall, namely a perfectly insulated wall and one exposed to an ambient at constant temperature. Furthermore, a possible procedure to model this type of problems in 2D plane strain analyses was presented, with an excellent agreement between 3D and 2D results being observed. Therefore, it can be concluded that 2D plane strain analyses can be used without sacrificing accuracy while reducing the computational effort associated with the solution of these complex problems.

A parametric study on the effect of the thermal conductivity of soil and concrete was carried out and the influence of simulating an intermittent operation mode in contrast to a continuous operation was investigated. The findings of the study can be summarised as follows:

- the wall exposed to a constant temperature is characterised by a greater thermal performance (50% higher when compared to an insulated wall).
- the effect of the different boundary condition on the exposed face demonstrates the importance of characterising the environment in which the wall is located;
- when a concrete with high thermal conductivity is employed, the impact of assumed boundary condition on the exposed face is greater;
- the soil's thermal conductivity has a limited effect on the thermal performance of the thermo-active retaining wall;
- an increase in efficiency of 50% is computed when an intermittent operation mode consisting of 6h of heat injection alternating with 6h of idling is considered.

6 ACKNOWLEDGEMENTS

The PhD programme of the first author is sponsored by the Department of Civil and Environmental Engineering, Imperial College London, through a Skempton Scholarship.

7 REFERENCES

Bourne-Webb, P. J., Bodas Freitas, T. M. & Da Costa Gonçalves, R. A. 2016. Thermal and mechanical aspects of the response of embedded retaining walls used as shallow geothermal heat exchangers. *Energy and Buildings* 125: 130-141.

Cui, W., Gawecka, K. A., Potts, D. M., Taborda, D. M. G. & Zdravković, L. 2016a. Numerical analysis of coupled thermo-hydraulic problems in geotechnical engineering. *Geomechanics for Energy and the Environment,* 6: 22-34.

Cui, W., Gawecka, K.A., Taborda D.M.G., Potts, D.M., & Zdravković, L. 2016b. Time-step constraints in transient coupled finite element analysis. *International Journal for Numerical Methods in Engineering* 106(12), 953-971.

Cui, W., Potts, D.M., Zdravković, L., Gawecka, K.A., Taborda, D.M.G. 2018a. An alternative coupled thermo-hydro-mechanical finite element formulation for fully saturated soils, *Computers and Geotechnics*, 94: 22-30.

Cui, W., Potts, D., Zdravković, L., Gawecka, K.A., Taborda, D.M.G. & Tsiampousi, A. 2018b. A coupled thermo-hydro-mechanical finite element formulation for curved beams in two-dimensions. *Computers and Geotechnics*, 103, 103-114.

Cui, W., Gawecka, K.A., Potts, D.M., Taborda, D.M.G. & Zdravković, L. 2018c. A Petrov-Galerkin finite element method for 2D transient and steady state highly advective flows in porous media. Computers and Geotechnics, 100, 158-173.

Di Donna, A., Cecinato, F., Loveridge, F., & Barla, M. 2017. Energy performance of diaphragm walls used as heat exchangers. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, 170(3), 232-245.

Gawecka, K.A., Potts, D.M., Cui, W., Taborda, D.M.G., & Zdravković, L. 2018. A coupled thermo-hydro-mechanical finite element formulation of one-dimensional beam elements for three-dimensional analysis. *Computers and Geotechnics*, 104, 29-41.

Loveridge, F., Holmes, G., Powrie, W., & Roberts, T. 2013. Thermal response testing through the Chalk aquifer in London, UK. *Proceedings of the Institution of Civil Engineers. Geotechnical Engineering* 166(2): 197-210.

Potts, D. M. & Zdravković, L. (1999) *Finite element analysis in geotechnical engineering. theory*. London: Thomas Telford.

Sterpi, D., Coletto, A., & Mauri, L. 2017. Investigation on the behaviour of a thermo-active diaphragm wall by thermo-mechanical analyses. *Geomechanics for Energy and the Environment* 9: 1-20.

Sterpi D., Angelotti A., Bigdarvish O.H. & Jalili D. 2018. Assessment of thermal behaviour of thermo-active diaphragm walls based on monitoring data, *Journal of Rock Mechanics and Geotechnical Engineering.*

Xia, C., Sun, M., Zhang, G., Xiao, S. & Zou, Y. 2012. Experimental study on geothermal heat exchangers buried in diaphragm walls. *Energy and Buildings*, 52, 50-55.