Factors affecting the energy efficiency of energy diaphragm walls: statistical analysis

A Short Term Scientific Mission (STSM) by Francesco Cecinato

STSM Final Report, February 2016

COST is supported by
the EU Framework Programme
Horizon 2020

COST Association
Avenue Louise 149 I 1050 Brussels, Belgium
t: +32 (0)2 533 3800 I f: +32 (0)2 533 3890
office@cost.eu I www.cost.eu

Report on Short Term Scientific Mission

1 Purpose & Aim of STSM

1.1 Background

Geothermal geostructures are an interesting and promising technology to face the increasing energy demand for heating and cooling of buildings and other infrastructures, through use of a local and sustainable source. However, a correct and optimized design is of fundamental importance to deliver an energy efficient solution.

Several authors have already studied the efficiency of energy geostructures. However, this has mainly concerned energy piles, for example see [1], [2]. Parametric analyses performed to investigate the relative influence of different parameters on the heat exchange potential of energy geostructures have also been carried out by the authors. In particular Cecinato and Loveridge [1] studied the influence of a number of engineering parameters on the energy efficiency of thermoactive piles, while Di Donna and Barla [3] studied the influence of underground conditions on the heat exchange capacity of energy tunnels. Both these aspects are of fundamental importance to define the efficiency of energy geostructures in each specific case.

However, relative little work has been carried out on the study of diaphragm walls converted to energy geostructures. Available studies have either been small (e.g [4]) or specific to certain projects (e.g [5]). Certainly there has been no rigorous parametric assessment of the capability of energy diaphragm walls, and few attempts to fully justify design choices and assumptions.

1.2 Motivation and Objective

The motivations for this STSM are to investigate the possibility of applying the rigorous statistical methods developed in the host institution for piles to the particular conditions of diaphragm walls, as well as sharing the knowledge of the three institutions on the aspects related to the optimization of the energy efficiency of energy walls more generally. The objective of this mission is to share knowledge, information and work methods for the development of coherent design procedures for a proper definition of the energy efficiency of geothermal systems using diaphragm walls.

2 Work Carried Out

The work of the STSM falls into three main parts, review of existing case studies and analyses, development and validation of numerical models and finally application of these models in parametric analysis. These topics are discussed further in the following sections.

2.1 Review

A critical task to ensure that the subsequent analysis carried out was representative was to review existing case studies and construction practices for diaphragm walls. This included constructed energy diaphragm walls, especially in London and Vienna, and typical details for diaphragm walls more generally. Also reviewed were assumptions and boundary conditions adopted in previous analyses of these energy geostructures.

2.2 Model Validation

Two numerical approaches were used in the framework of this STSM. While both of them are based on the Finite Element method, the first one was developed using the software FeFlow and the second one the software Abaqus combined with user subroutines.

Both the approaches were validated against the experimental data provided [6] and [7]. In the considered in-situ experiment a 38 m depth wall with a 19.5 m excavation was tested. The wall panel was 1.25 m wide and a single U-pipe was installed with spacing 75 cm. The heat carrier fluid velocity was set equal to 0.6 m/s, its inlet temperature was kept constant to 35 °C, the soil temperature was initially imposed equal to 21.4 °C, the external air temperature equal to 10.6 °C and the wall temperature equal to 23 °C [6], [7]. The thermal and hydraulic properties of concrete and subsoil were those indicated by [7] and are collected in Table 1. The Feflow and Abaqus models are represented in Figure 1a and b. In the first case the pipes are modelled using the 1D elements provided in the software, while in the second case bespoke 1D line elements are introduced in which the hydraulic and diffusive coupling is carried out in the user subroutines. In both cases, the pipes have an external diameter of 25 mm and thickness of 2.3 mm. In Feflow the thermal resistance of the plastic pipes is neglected, while in Abaqus it is taken into account within the calculation of the subroutines. The thermal properties are reported in Table 1.

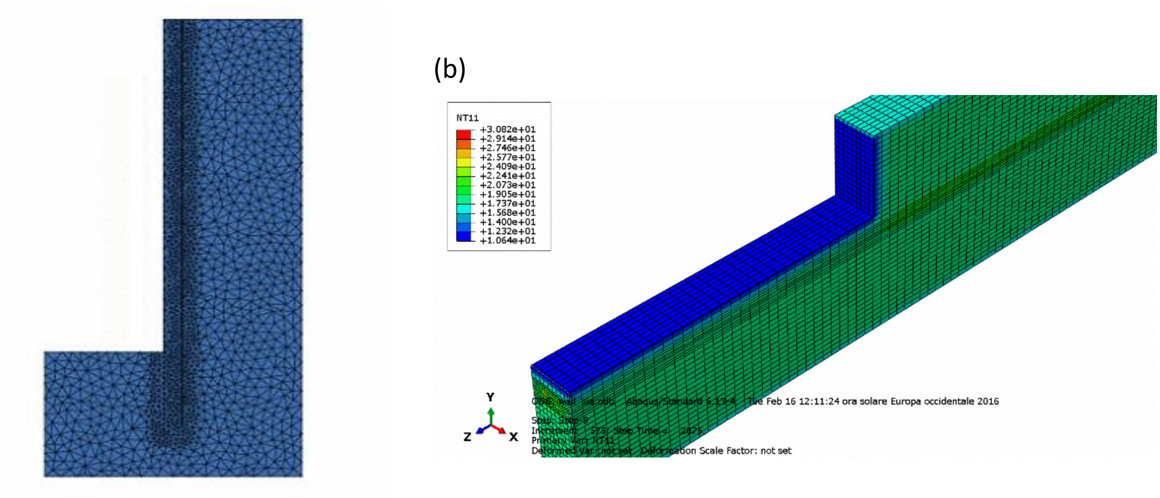
Table 1 - Thermal properties of the involved materials in the validation analysis.

Property	Concrete	Soil	Water	Pipes
Bulk thermal conductivity [W/m/K]	2.34	1.74	0.58	0.42
Bulk specific heat capacity [J/kg/K]	1046	1690	4200	2300
Density [kg/m^3]	2500	1800	1000	950
Porosity [-]	0	0.3	-	-

2.3 Parametric Study

The validated approaches were used to perform a parametrical analysis based on the Taguchi method [8], in order to identify the most influential parameters in maximising the energy performance of energy walls. An “L8” seven parameter set with two levels each was chosen to be the most suitable to the considered situation. Accordingly, the array presented in Figure 2 was employed to design the parameteric numerical analysis program. This approach led to the need of carrying out a total of eight statistically independent runs (lines in Figure 2), instead of exploring all possible parameter combinations, which would have implied to perform 2^7=128 runs. The seven parameters (columns in Figure 2) to be investigated were selected on the basis on the literature review. For each of them, the chosen two levels were reasonable upper- and lower-bound values (referred to as 1 and 2 in the array in Figure 2, respectively). The selected parameters and their levels are listed in Table 2.

(b)



(a)

Figure 1 - (a) Feflow model and (b) Abaqus model.

Experiment Number	Column 1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Figure 2 - L8 seven parameter set chosen for the parametric study.

Table 2 - Parameters investigated in the parametrical analysis.

Parameters	**Lower (1)**	**Upper (2)**
Panel width	0.8 m	1.2 m
Depth/excavation ratio	1.25 (exc. 16m)	2 (exc 10 m)
Spacing of pipes	25 cm	75 cm
Concrete cover to pipes	50 mm	100 mm
Fluid velocity	0.2 m/s	1.2 m/s
Difference in temperature between the soil and external air	2 °C (Tair=14°C)	6 °C (Tair=18 °C)
concrete conductivity	1.5 W/mK	3 W/mK

In these analyses the wall panel was considered to be 20 m high and 1.5 m long. Within the 1.5m wall length the 25cm pipe spacing implied the embedment of 6 pipes, while the 75cm spacing resulted in 2 pipes only. The pipes go down to 19.5 m depth and have a diameter of 25 mm. They are installed on the soil side of the wall only. The soil initial temperature is 12 °C and the simulations last 30 days. The inlet temperature is imposed equal to 20 °C, with an initial ramp from 12 to 20 °C lasting 5 minutes. The thermal and physical properties of concrete and soil are summarized in Table 3. Temperature is fixed to the initial soil temperature on the far field boundaries of the model. External air temperature is fixed on the excavation plane, wall side and top boundary, with a value depending on the run according to Figure 2 and Table 2. A constant temperature boundary is applied. The panel width, depth of excavation, pipes spacing, concrete cover and heat carrier fluid velocity also depend on the run according to Figure 2 and Table 2.

Table 3 - Thermal properties of the involved materials in the parametric analyses.

Property	Concrete	Soil	Water	Pipes
Bulk thermal conductivity [W/m/K]	Depends on the run	2.0	0.6	0.42
Bulk specific heat capacity [J/kg/K]	1600	1600	4200	2300
Density [kg/m^3]	2210	1900	1000	950
Porosity [-]	0	0.3	-	-

3 Key Results

3.1 Review

3.1.1 Geometry

Diaphragm walls are often used for the support of deep excavations where other techniques may be unsuitable. These include at greater depths and where cut off functions are important. A large number of case studies are presented in [6], as well as general indications of typical practice in [10]. These suggest that walls are typically 0.8m to 1.2m in width with depths typically between 10m and 40m. Previous work [1] suggests that the length of the wall will be of great influence in the energy efficiency of the geostructure. However, with diaphragm walls there is the additional consideration of how much of the wall is embedded within the soil and how much is open on one side to the excavation. These two parts of the wall would be expected to experience different rates of heat transfer due to the differing boundary conditions. Other geometric factors that may affect the energy exchanged include the number (and/or spacing) of installed heat transfer pipes, whether these are fixed to both sides of the walls and what distance they are from the wall edge (the concrete cover). Where possible constructed values for these parameters have been extracted from the literature and are summarised in Table 4 overleaf. It can be seen that typical Austrian construction includes pipes on both sides of the walls. However, the pipes on the excavation side are only included in the embedment section of the wall. This has been possible in these cases as the steel cage to which the pipes are fixed is constructed in one piece. This means that pipes can all be placed on the steel in advance. This type of construction is not possible where constraints mean that the cage must be spliced on site. In such cases the pipes are typically placed only on the soil side of the wall and are restricted to vertical arrangements.

Table 4 Geometric Information from Constructed Energy Diaphragm Walls

Case & References	Wall Depth	Embedment Depth[1]	Panel Width	Panel Length	Pipes spacing (Ground Side)	Pipes on Excavation Side?	Pipe cover	Pipe Size
U2 Taborstrasse Station, Vienna [11], [12]	31m	10.45m	0.8m		0.53m	Yes	60mm (to steel, pipes inside steel)	25mm
Shanghai Museum of Nature History [6], [7]	30 – 38m	12m – 20m	1.0m	3.7m	1 U-loop per panel	Yes	87.5mm	25mm/20.4mm
Bulgari Hotel (formerly Knightsbridge Palace Hotel) [13]	Up to 36m	11.65m	0.8m		0.84 (average)	No	75mm	
Dean Street Station, London [14]	41m	12m	1.0m					
Tottenham Court Road Station, London			1.2m	3m	0.5m	No	40mm (pipes in 75mm cover zone)	35mm
Moorgate Shaft, London	48.5m to 52.4m		1.2m		0.452m interloop, 0.603m between loops	No	62.5mm	25mm/20.5mm
Arts Centre, Bregenz, Austria [15]	Up to 28m	Up to 17m	0.5m to 1.2m		A wavy or slinky type arrangement was used			

1 including any slab thickness

3.1.2 Boundary Conditions

A key difference between diaphragm walls and more tradition types of ground heat exchanger is their exposure to the air on one side for some proportion of their depth. The space within the excavation that the wall supports may be used for a number of different functions, the most common being basements, underground car parks, metro stations or shallow light rail tunnels. Those applications where there is potentially a source of heat, e.g. rail tunnels and metro stations, may be more suitable for efficient heat extraction, but potentially less suitable for applications in heat disposal.

There are few case studies in the literature which make a thorough assessment of the internal boundary condition for energy diaphragm walls. Those where analysis of energy exchange has been carried out use either a constant temperature boundary or assume a convective heat flux (q, W/m^2) determined by a heat transfer coefficient (h, W/m^{2}K) and the temperature difference between the wall and the space:

$$q = h(T_{excavation} - T_{wall})$$

Those authors considering a constant temperature boundary condition include Kurten [16], [17], Rui [14], Soga et al [18] and Sterpi et al [19] who all conducted numerical analysis. Kurten considered basement applications, whereas Rui and Soga et al were considering metro stations. The analysis of Sterpi et al is more generic. None provide a comprehensive rationale for use of this type of boundary condition, although Kurten was validating large scale laboratory experiments so there is some justification for the approach.

Meanwhile those authors adopting a heat transfer coefficient approach are summarised in Table 5. Some justification for this approach can be found in ISO 6946 where surface heat transfer coefficients are quoted for internal and external spaces in the built environment. Depending on the direction of heat flow and the case, general values between 6 W/m^{2}K and 20 W/m^{2}K are suggested. ISO 6949 also provides guidance on linking wind speeds to heat transfer coefficients, suggesting values in excess of 50 W/m^{2}K could be achieved with speeds of 10 m/s. However, caution should be applied to using such high values. While [22] suggests that wind speeds of 10 m/s could be achieved in the London underground system, heat transfer estimates from the current Crossrail constructions [21] suggest that much lower values would be achieved in reality.

Table 5 Heat Transfer Coefficients Used in Analysis

Case & Source	Scenario	Heat Transfer Coefficient (W/m^{2}K)	Comments
Lainzer Tunnel Analysis[5]	Metro tunnels & stations	10 - 15	
General sensitivity analysis only [4]	Not specified	2.5 - 25	Depending on wind speed
Mongolian Road Tunnel [20][21]; note not diaphragm wall, but comparable analysis	Road tunnel	15	
Crossrail Tunnel [21] ; note not diaphragm wall, but comparable analysis	Rail tunnel	5	
Analytical model and laboratory experiments [17]	Basements	7.7	Based on ISO 6946

3.2 Model Validation

The results in terms of heat exchanged per meter of pipes is illustrated in Figure 3. It can be concluded that both numerical approaches provide a good fit to the experimental data. The small differences between them are caused by the fact that the Feflow approach neglects the pipe thermal resistance, resulting in a slightly higher heat exchange. Validation was thus considered successful, especially given some uncertainty with respect to input parameters in the case study.

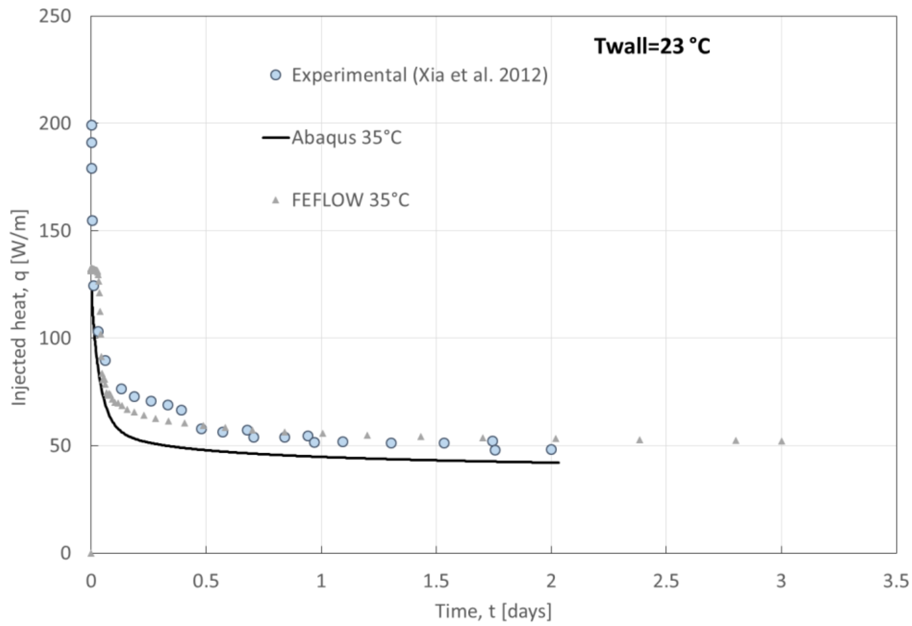
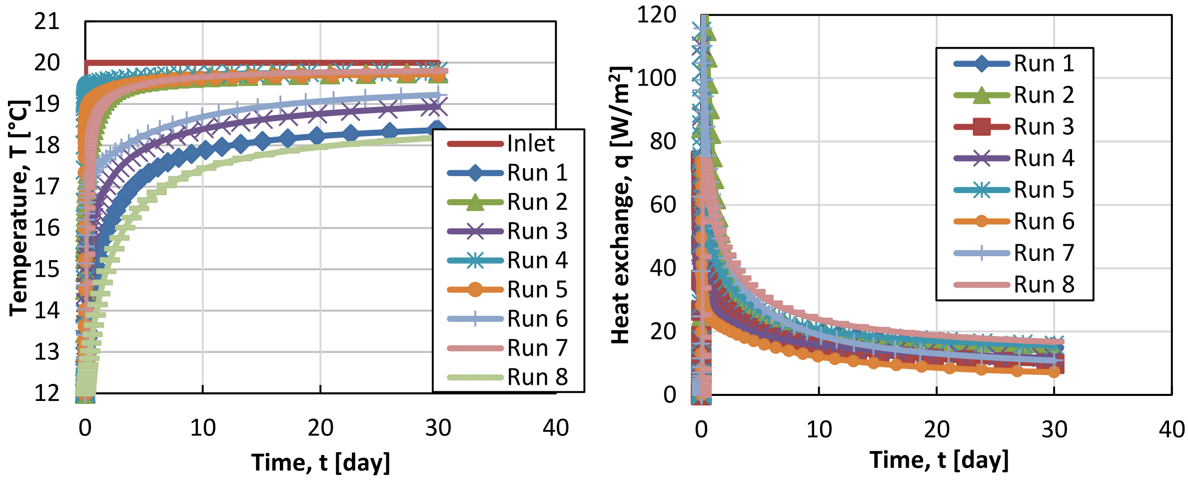


Figure 3 - Validation of the numerical approach (experimental data from Xia et al. 2012).

3.3 Parametric Study

The results of the eight runs in terms of outlet temperature and heat exchange per square meter of wall are illustrated in Figure 4.



(a) (b)

Figure 4 - Results of the parametric analyses.

The energetic efficiency of a geothermal installation can be assessed by looking at the total exchanged energy in a given time (measured in MJ). Hence, the above simulation results in terms of exchanged power vs time were further elaborated, by computing for each simulation the integral

$$E_{tot} = \int_0^{t_f} \dot{q}(t)\,dt$$

where $\dot{q}(t)$ the exchanged power during the simulations (measured in W). A response table was then created (Table 6) where the output for each simulation is reported, in terms of total exchanged energy in 30 days (last column of Table 6).

Table 6 Response table

Depth/excavation	Spacing*	Cover	Fluid velocity	DT	concrete cond	Response (MJ)
1.25 (exc 16m)	25 cm	50mm	0.2 m/s	2 °C	1.5 W/mK	1.63E+03
1.25 (exc 16m)	25 cm	100mm	1.2 m/s	6 °C	3 W/mK	1.83E+03
2 (exc 10 m)	75 cm	50mm	0.2 m/s	6 °C	3 W/mK	1.17E+03
2 (exc 10 m)	75 cm	100mm	1.2 m/s	2 °C	1.5 W/mK	1.24E+03
1.25 (exc 16m)	75 cm	50mm	1.2 m/s	2 °C	3 W/mK	1.69E+03
1.25 (exc 16m)	75 cm	100mm	0.2 m/s	6 °C	1.5 W/mK	9.19E+02
2 (exc 10 m)	25 cm	50mm	1.2 m/s	6 °C	1.5 W/mK	1.64E+03
2 (exc 10 m)	25 cm	100mm	0.2 m/s	2 °C	3 W/mK	1.93E+03

The above presented parametric study results were further processed along the lines of a level average analysis [8], consisting of (1) calculating the average simulation result for each level of each factor, (2) quantifying the effect of each factor by taking the absolute difference between the highest and lowest average results and (3) identifying the strong effects, by ranking the factors from the largest to the smallest absolute difference. Results are summarised in the response table (Table 7).

Due to the statistical nature of this type of analyses, the influence of the bottom-ranked parameters cannot be assessed with confidence, hence attention will be hereby given to the top-five properties, namely (1) the pipe spacing, (2) the concrete thermal conductivity, (3) the difference in temperature between the soil and external air, (4) the fluid velocity , (5) the panel width. It can be seen from Table 7 that energy efficiency is maximised with small values of parameters (1), (3) and large values of parameters (2), (4) and (5).

Table 7 Level average analysis

	Panel width	Depth/excavation	Spacing*	Cover	Fluid velocity	DT	concrete cond
avg result min	1.47E+03	**1.52E+03**	**1.76E+03**	**1.53E+03**	1.41E+03	**1.62E+03**	1.36E+03
avg result max	**1.55E+03**	1.50E+03	1.26E+03	1.48E+03	**1.60E+03**	1.39E+03	**1.65E+03**
Effect	77.59017431	20.15141302	502.4159	55.65995	186.9099597	233.3778447	296.007966
Ranking	5	7	1	6	4	3	2

The results indicate that in common with other ground heat exchangers increasing the number of pipes by reducing their spacing is the primary route to increasing energy efficiency. The thermal properties of the wall concrete and the temperature excess within the excavation space are also important, confirming in particular the benefits of exploiting the retaining walls installed for railway tunnels and metro stations. Further analysis is ongoing, leading to providing guidelines for the energy design of diaphragm walls.

4 Future Plans

4.1 Ongoing Work

The results presented in this report have focused on the application of a constant temperature boundary condition within the excavation space. Further analysis will be carried out to consider:-

- The use of varying values of heat transfer coefficients
- The effect of the timescale of the study
- The effect of variable heat/cool demand

4.2 Publication Plan

An abstract has been submitted for the 2017 Themed issue of Proceedings of the Institution of Civil Engineers which is titled “Geotechnics in Energy Provision”. The paper will need to be submitted by the 10th June.

5 References

[1] Cecinato F and Loveridge F. (2015) Influences on the thermal efficiency of energy piles. Energy, 82, 1021–33.

[2] Batini, N., Rotta Loria, A. F., Conti, P., Testi, D., Grassi, W. & Laloui, L. (2015) Energy and geotechnical behaviour of energy piles for different design solutons, Applied Thermal Engineering, 85, 199-213.

[3] Di Donna A and Barla M. (2015) The role of ground conditions and properties on the efficiency of energy tunnels. Environmental geotechnics, ahead of priont DOI http://dx.doi.org/10.1680/jenge.15.00030.

[4] Bourne Webb, P., Costa Goncalves, R. A. & Bodas Freitas, T. M. (2015) Retaining walls as heat exchangers: a numerical study, Proceedings of XVI ECSMGE Geotechnical Engineering for Infrastructure and Development, 2499-2504, DOI 10.1680/ecsmgr.60678.

[5] iCConsulten (2005) Wirtschaftliche optimierung von tunnelthermieabsorberanlagen, grundlagenuntersuchung und planungsleitfaden, 23.12.2005, Rev. 1, 84pp (In German).

[6] 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.

[7] Sun, M., Xia, C. & Zhang, G.(2013) Heat transfer model and design method for geothermal heat exchange tubes in diaphragm walls, Energy and Buildings, 61, 250-259.

[8] Taguchi, G., El Sayed, M., & Hsaing, C. (1989) Quality engineering and quality systems. McGraw-Hill, New York.

[9] Gaba, A. R., Simpson, B., Powrie, W. & Beadman, D. R. (2003) Embedded retaining walls – guidance for economic design, CIRIA C580, Construction Industry Research and Information Association, London, UK.

[10] Burland, J., Chapman, T., Skinner, H. & Brown, M. (2012) ICE Manual of Geotechnical Engineering, Thomas Telford, London, 2012.

[11] Brandl, H., Adam, D., Markiewicz, R., Unterberger, W. &Hofinger, H. (2010) Concrete absorber technology for earth coupled concrete structures using geothermal energy for the Vienna Undeground line U2, Osterr. Ingenieur und Architekten Zeitschrift, 155, Heft 7-9/2010 & Heft 10-12/2010. In German.

[12] Markiewicz, R. (2004) Numerical and experimental investigations for utilization of geothermal energy using earth-coupled structures and new developments for tunnels. Doctoral Thesis, Vienna University of Technology. In German.

[13] Amis,T., Robinson, C. & Wong, S (2010) Integrating geothermal loops into the diaphragm walls of Knightsbirdge Palace Hotel project, Geotechnical Challenges in Urban Regeneration, Proceedings 11th DFI./EFFC International Conference, London.

[14] Rui, Y. (2014) Finite Element Modelling of Thermal Piles and Walls, PhD Thesis, University of Cambridge.

[15] Brandl, H. (1998) Energy piles and diaphragm walls for heat transfer from and into the ground, In: Van Impe&Haegeman (Eds) Deep Foundations on Bored and Auger Piles, Rotterdam. P37-60.

[16] Kurten, S., Mottaghy, D. & Ziegler, M (2015) Design of plane energy geostructures based on laboratory tets and numerical modelling, Energy and Buildings, 107, 434-444.

[17] Kurten, S.(2014) Zur thermischen Nutzung des Untergrunds mit flächigenthermo-aktiven Bauteilen, PhD Thesis, Aachen University. In German.

[18] Soga, K., Qi, H., Rui, Y. & Nicholson, D. (2014) Some considerations for designing GSHP coupled geotechnical structures based on a case study, 7th International Congress onEnvironmental Geotechnics 2014, Melbourne, Australia, 10-14 November 2014.

[19] Sterpi, D., Angelotti, A., Corti, D. & Ramus, M. (2014)Numerical analysis of heat transfer in thermo-active diaphragm walls, In: Hicks et al (Eds) Numerical methods in geotechnical engineering, 1043-1048, Taylor & Francis Group, London.

[20] Zhang, G., Xia, C., Sun, M., Zou, Y. & 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, 59-66.

[21] Nicholson, D., Chen, Q., de Silva, M., 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, 118-134.

[22] Ampofo, F., Maidment, G. & Missenden, J. (2004) Undeground railway environment in teh UK Part 2 : Investigation of heat load, Applied Thermal Engineering, 24, 633-645.

Appendix: Host Institution Letter

UNIVERSITY OF
Southampton

26 February 2016

Subject: STSM "Factors affecting the energy efficiency of energy diaphragm walls" (8th to 12th February 2016)

To whom it may concern,

Within the framework of COST Action TU1405 - "European Network for Shallow Geothermal Energy Applications in Buildings and Infrastructure" – I was delighted to welcome Alice Di Donna (Politecnico di Torino) and Francesco Cecinato (University of Trento) to Southampton earlier this month.

The week was exceedingly fruitful and allowed knowledge sharing regarding simulation techniques and software, and statistical methods between the three institutions. The STSM also resulted in a useful review of constructed energy diaphragm walls, along with the first parts of a parametric study considering the factors most important in ensuring energy efficiency of such structures.

I am confident that our collaboration will continue beyond this STSM and we already have plans to extend the analysis carried out during the brief visit to include other pertinent factors.

Overall I am happy to confirm the successful execution of the project.

Yours faithfully

Fleur Loveridge
Royal Academy of Engineering Research Fellow & Lecturer in Geomechanics
Faculty of Engineering and the Environment