Energy Geostructures: Analysis from research and systems installed around the World

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Abstract

Energy geostructures are becoming an increasingly popular solution around the world for Developers looking to reduce CO_2 and system running costs. Energy geostructures are geotechnical structures that provide both the important role of structural stability while also acting as a heat exchanger with the ground, enabling the supported buildings and or infrastructure to be heated and cooled using the principle of low enthalpy geothermal systems. The main advantage of this innovative technology with respect to standard geothermal plant is the reduction of the initial installation costs and construction schedule benefits, compared to installing conventional geothermal solutions, largely due to the additional use of structures which would be constructed in any case. However, it is important with respect to energy geostructures that additional aspects need careful consideration. For this very reason, several research studies have been carried out over the last decade on this subject and a number of real case studies have been monitored and analysed. The key difference with respect to conventional shallow geothermal systems are mainly related to the geometry, which is imposed by the geotechnical project, and the need to ensure that the primary structural role is always guaranteed. Special boundary conditions, the reduced depth, the influence of atmospheric external temperature can also play an important role for energy geostructures. They can affect, both energy efficiency and, the geotechnical behaviour because of the possible thermal induced mechanical effects. This paper presents a picture of the current situation regarding energy geostructures and their peculiar features, and collects available data to provide a reference framework. Data has been collected from literature and personal communications and then processed to provide easy-to-read charts useful for practical consultation at a glance. This paper provides, an indication of the distribution of such systems worldwide, their spread in time, and a global view of their actual efficiency from the structural, energy, economic and environmental point of view.

Keywords: Energy Piles, Energy Walls, Energy Tunnels, Database

1. Introduction

Energy geostructures are becoming an increasingly popular consideration around the world. Energy geostructures are geotechnical structures with a dual role of providing structural stability and the ability to exchange heat with the ground, to provide low carbon heat and coolth to supporting and or adjacent buildings and infrastructure, using the principle of low enthalpy geothermal systems (Barla and Di Donna, 2016; Laloui and Di Donna, 2013). A closed circuit of high density polyethylene (HDPE) pipes is embedded in the concrete, and a heat carrier fluid circulates through them exchanging heat with the ground. The HDPE pipework circuit inside the geostructure is linked to one of the above buildings or infrastructure through a heat pump, which adapts the temperature of the circulating fluid to the heating (winter mode) and cooling (summer mode) needs. In this way, heat can be injected into the ground during summer and extracted from it during winter. In principle, all structures in contact with the ground can be used as energy geostructures. The first examples of energy geostructures date back to the eighties in Austria and were mainly piles and shallow foundations. A decade later, Henderson et al. (1999) reported on what would appear to be the first successful use of geothermal energy piles in the US, with loops incorporated into the foundation for a hotel in Geneva, New York. As was their use in this New

York case history, the typical geothermal energy pile application is used in conjunction with additional closed loop boreholes to provide the required energy capacity for a structure. Interestingly the report concludes that the geothermal energy piles had a better heat transfer performance than the borehole field. The first energy walls appeared slightly later, while still today only a few experimental cases of energy tunnels exist (Brandl, 2006; Franzius and Pralle, 2011; Riederer et al., 2007; SIA DO 190, 2005). However, with respect to conventional geothermal systems additional aspects need to be considered to make a proper use of this technology. Amongst these, there are those related to energy efficiency and, also, those related to the geotechnical design and structural integrity, which must be guaranteed, even in the presence of the temperature variations that will be induced by the geothermal activation. Examples are the effects of underground conditions on the heat exchange potential, the effect of temperature on the response of soils and soil-structure interaction and the possible additional thermal-induced displacements and stresses inside the structures.

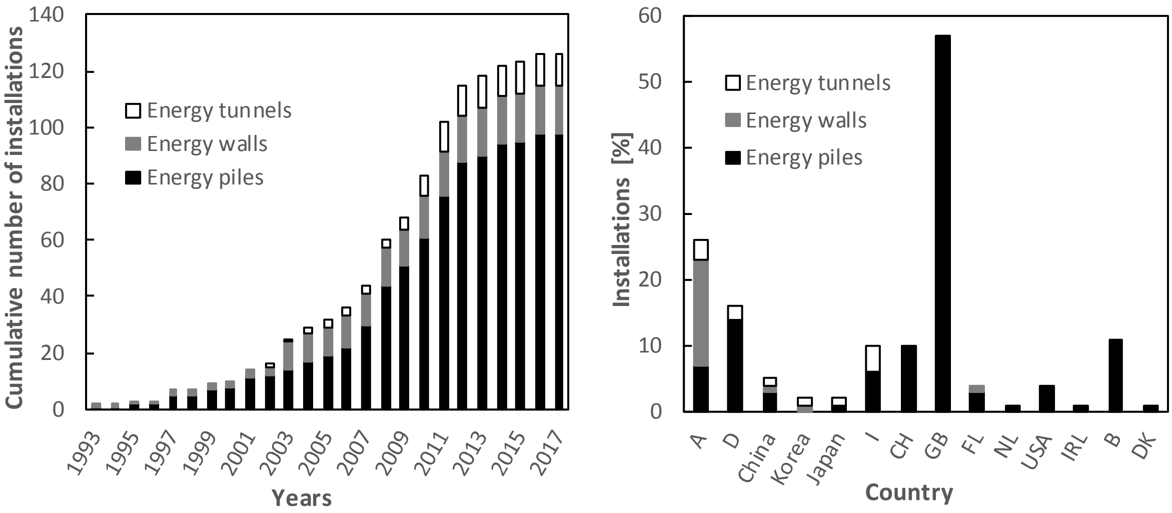
Data on operational and trial energy geostructures have been collected into a database by the Authors over the last decade, with the intent of providing an overview of the current state of diffusion, advancement, and efficiency of this technology. In the following, after an update on the current status of geoenergy structures around the world, the paper provides an introduction on the structure of the database, the observations from the analysis of the collected data are discussed in terms of (i) diffusion of the technology in time and space, (ii) energy efficiency, (iii) geotechnical aspects and (iv) economic and environmental considerations.

2. Current status of geoenergy structures around the world

The cumulative number of energy geostructures installed since 1993 is presented in Figure 1a. The graph shows a steep increase in using this type of geoenergy technology between 2005 and 2011; this is largely as a result of the UK market being driven by tighter planning requirements and also incentives associated with installing renewable technologies. In more recent years, uptake of energy geostructures has eased somewhat but known opportunities exist in France and the USA that are likely to show a revitalised trend in the coming years. As mentioned earlier, most installations are energy piles, while energy walls and tunnels have started to play a role more recently and can be considered an interesting and exciting future application of this technology. The use of tunnels as ground heat exchangers has clearly the advantage of involving much larger volumes of ground, but also some additional challenges exist associated with the identification of the owner of heat and the distribution of the resource. It is felt by the authors that this is possibly the reason why the evolution of energy tunnels has been somewhat slower with respect to other energy geostructures, however trials currently underway in Turin (Italy) are hoping to identify the best means of loop installation and heat dissemination (Barla et al., 2017). Figure 1b shows the percentage of installations per country (A=Austria, D=Germany, I=Italy, CH=Switzerland, GB=Great Britain, FL=Liechtenstein, NL=Netherlands, USA=United States of America, IRL=Ireland, B=Belgium, DK=Denmark), with respect to the total. Austria, where the technology was born, together with the United Kingdom and Germany, are the countries where most of energy geostructures have been constructed. However, data might be missing for certain countries such as France, Switzerland and others outside Europe. Known USA projects include:

- 1997 Hotel Geneva -New York 198 Piles
- 2004 Art Stable –Seattle 150 piles
- 2014 Trevor Day School New York 360 energy piles

And the USA looks like it will eclipse Europe over the next few years as more large companies look to reduce their CO_2 footprint. For example, Google’s San Francisco headquarters is currently under construction with over 3000 energy piles (not included in graph below)



(a) (b)

Figure 1. Evolution of energy geostructures installations (a) over time and (b) in different countries.

3. Structure of the data base

The database is divided into two sections, the first one is devoted to energy efficiency, costs and environmental issues, while the second to geotechnical aspects. For the first section, information on existing energy geostructures was collected from papers (Amis et al., 2010; Brandl, 2006; Franzius and Pralle, 2011; Frodl et al., 2010; Islam et al., 2006; Lee et al., 2012; Markiewicz and Adam, 2009; Schneider and Moormann, 2010; Unterberger et al., 2004; Xia et al., 2012; Zhang et al., 2013), published documents (Riederer et al., 2007), recommendations (SIA DO 190, 2005), companies or contractors web sites and personal communications. They include operational plants and trial installations. Data collected includes:

- Name of the installation;
- Country;
- Year of installation;
- Geometry (number of piles, surface of walls, length of tunnel etc.);
- Normalised extracted/injected heat in W/m of pile length and W/m2 of wall or tunnel surface;
- Heat power provided in winter and summer (in kW);
- Annual energy provided in winter and summer (in MWh/y);
- Soil-structure temperature;
- Pipes dimension and configuration;
- Inlet – outlet temperature;
- Heat carrier fluid flow rate;
- CO_2 reduction;
- Ground conditions;
- Costs and payback period;
- Contractor;
- Reference;

The second section (geotechnical aspects) includes only data related to experimental real scale energy piles, as no information on monitored energy walls and tunnels are available to date, to the author's best knowledge. The data was collected from published papers (Akrouch et al., 2014; Amatya et al., 2012; Di Donna et al., 2016; Laloui et al., 2003; McCartney and Murphy, 2012; Murphy et al., 2015; Rotta Loria and Laloui, 2017; Sutman et al., 2014; Wang et al., 2014; You et al., 2016) and include:

- Pile typology;
- Ground;
- Mechanical load applied;

- Geometry;
- Temperature range;
- Thermal induced stresses;
- Thermal induced head displacements;
- Degree of freedom;
- Reference.

For both sections, the available data is not uniform and neither complete, but provides a preliminary global view on this exciting technology. In the first section, a total of 151 records were collected: 119 energy piles, 20 energy walls and 12 energy tunnels. In the second section, data from a total of 8 energy piles was collected.

4. Energy efficiency

Compared to the conventional method of constructing closed loop geothermal systems, using purpose drilled boreholes, energy geostructures have a dual role and the structural and geotechnical design imposes the geometry and dimension of the ground heat exchanger. In this sense, the number and length of energy piles, the depth of energy walls, the diameter of an energy tunnel is not designed to satisfy the heat demand but depends on the structural constraints. Consequently, a designer will need to evaluate, how much heat such structures can effectively and sustainably exchange with the ground and, also the factors most affecting the energy efficiency. Among these are some site-specific parameters, e.g. soil thermal properties, underground temperature, degree of saturation. Other factors can be engineered, such as the number of geothermal pipes, fluid flow rate, and the concrete thermal properties. A number of research studies have been recently carried out on these aspects (Cecinato and Loveridge, 2015; Di Donna et al., 2017; Di Donna and Barla, 2016). Data collected in the database in terms of heat exchange in kW for real case studies was, when possible, normalised over the piles length or walls and tunnels surface in contact with the ground, to provide a more generalised figure. The output is presented in the following.

4.1. Energy piles

Exchanged heat in the case of energy pile installations are presented in Figure 2, in terms of W/m exploited in winter and summer. It can be seen that, for the data available, the heat exchange is generally in the range between 40 to 100 W/m, with some exceptions. The differences might depend on the pile depth and diameter, soil thermal and hydraulic properties and underground conditions, and especially where there is the presence of groundwater flow. Longer piles involve a volume of surrounding soil which is less influenced by the external atmospheric temperature changes, being consequently more efficient in terms of heat exchange. On the other hand, the bigger their diameter, the wider is the soil-structure contact surface, the higher is the heat exchange. In addition, the thermal conductivity of the ground can dramatically affect the heat exchange, which improves considerably in the case of saturated soil. The presence of groundwater flow allows for heat transfer between the soil and the pile to occur not only through conduction, but also through convection, being more favourable if the system is used for heat exchange only, while less convenient for underground heat storage.

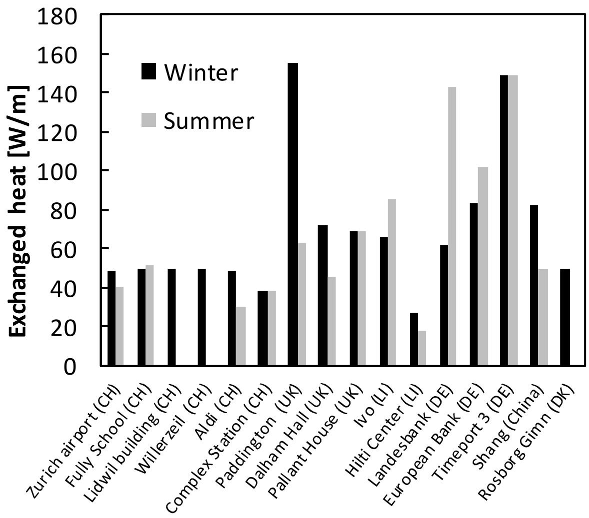
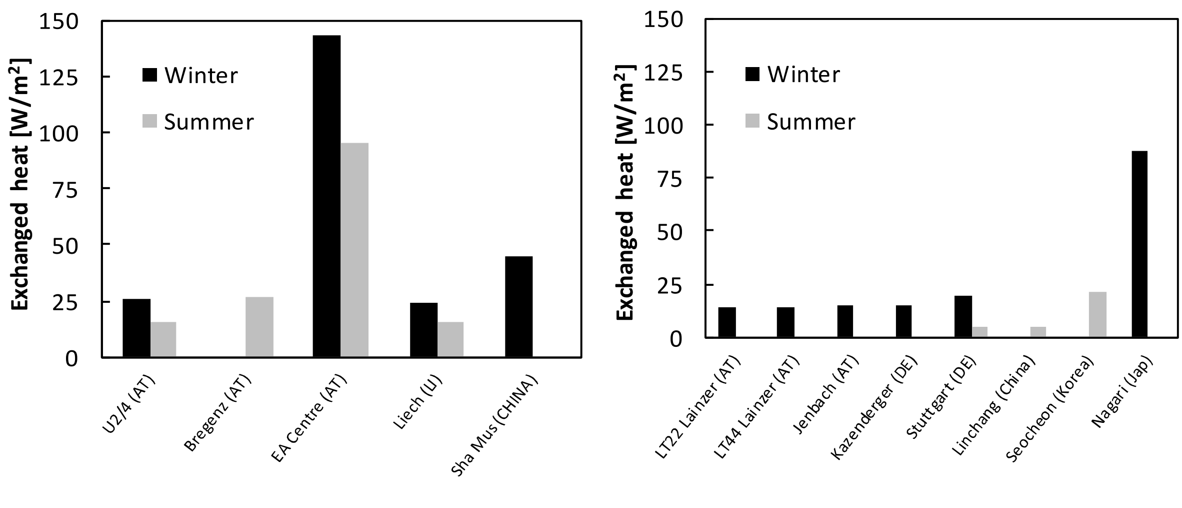


Figure 2. Heat exchange in real energy piles per meter of pile.

4.2. Energy diaphragm walls and tunnels

Figure 3a and b show respectively, the heat exchanged in winter and summer in terms of W/m[2] for the existing cases of energy walls and tunnel installations. It can be seen that the heat exchange is generally in the range between 10 to 50 W/m[2], with some exceptions. It is anticipated that the differences might depend on the depth of the installation and, as for the case of energy piles, on soil thermal and hydraulic properties and underground conditions, especially the presence of groundwater flow.

With respect to cut-and-cover tunnels, and underground tunnels in urban areas, these tunnels are more likely to be constructed in saturated soils and will be less influenced by the external air temperature variation as a result of their higher cover, this should at the same time improve their heat exchange potential. An additional aspect which must be considered specifically for energy walls and tunnels, that is not necessary with energy piles, is the effect of temperature and speed of the air inside the tunnel or underground space (Nicholson et al., 2014). These energy geostructures will exchange heat not only with the ground, but also with the air inside the underground space. In the case of hot tunnels this might represent an additional source of heat during winter, but a drawback during summer. Trials currently being undertaken in Turin will provide more detailed results which will be available in 2018.



(a) (b)

Figure 3. Heat exchange per square meter of wall in real (a) energy walls and (b) energy tunnels.

5. Geotechnical aspects

It is important that the use of geostructures as ground heat exchangers must consider that they have a primary structural role which must be preserved even in the presence of the temperature variations induced by the geothermal activation (Di Donna et al., 2013). This is considered to be one of the reasons why engineers and practitioners have not been fully confident with the technology and its diffusion has been slower in some countries. For current applications, the temperature changes are usually limited in the range of ±20°C, but they might increase in cases where geostructures are used for underground heat storage.

Generally speaking, when a structural element (concrete, steel...) is heated/cooled without any constraints, it dilates/contracts according to the material thermal elastic expansion coefficient. However, geostructures are not free to deform, as their deformation is partially prevented by the soil around and over-structures. Hence, heating/cooling will induce additional thermal stresses, which will correspond to the portion of thermal deformation which is not allowed, according to the theory of thermo-elasticity. Accordingly, Laloui et al., (2003) defined the degree of freedom of energy piles as the ratio between the observed and the free thermal deformation (i.e. the deformation that would occur if the pile was completely free to deform). The ratio is equal to zero when the pile is completely restrained (no observed deformation) and to one when it is completely free to deform under temperature changes (observed and free deformation are equal).

The same conceptual framework would apply also for tunnels and walls. Depending on the degree of freedom, thermally induced stresses and displacement might be more or less significant: the higher the restraints, the higher the thermal stresses and the lower the thermal displacements, and vice versa (Amatya et al., 2012; Laloui et al., 2003).

These aspects have been largely studied for energy piles, and are on the way to being studied in detail for tunnels and walls. However, to the author's best knowledge, monitoring data for thermal induced stresses and strains is only available for energy piles. These are also easier to assess from a theoretical point of view, considering a pile as a 1D element for the sake of simplicity.

To have an order of magnitude, considering a L=15 m long concrete pile having a linear thermal expansion coefficient β of 10^{-5} °C^{-1}, the maximum head displacement d (assuming the pile completely free to dilate and fixed at the toe) for a temperature variation of ΔT=30°C would be:

$$d = \beta \cdot \Delta T \cdot L = 10^{-5} \cdot 30 \cdot 15 \cdot 10^{3} = 4.5\,mm \tag{1}$$

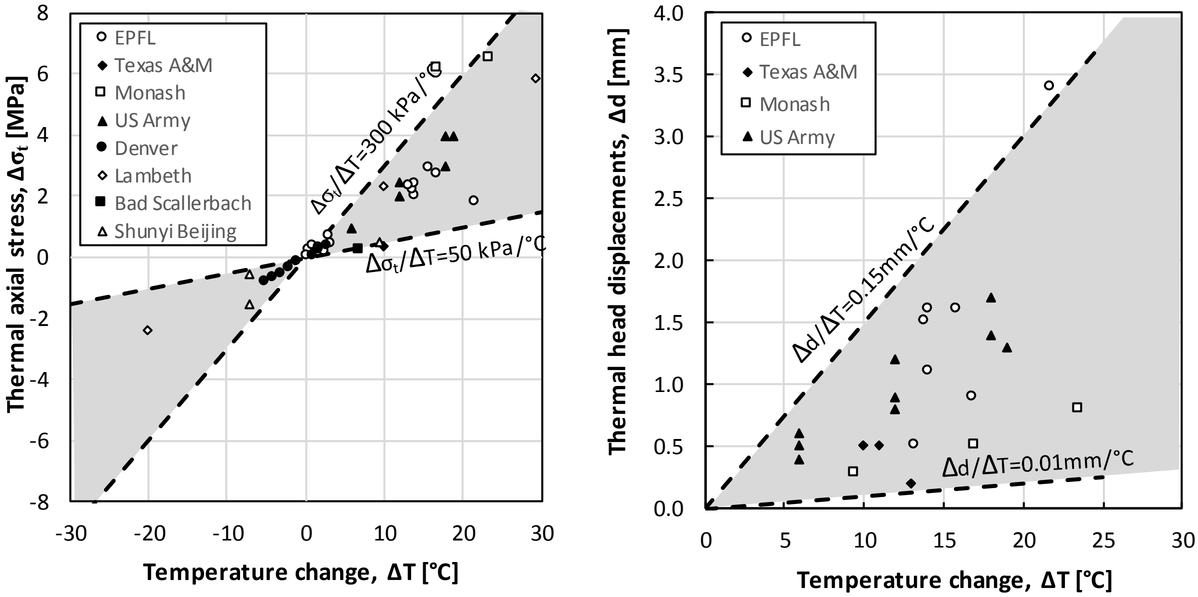
i.e. 0.15 mm/°C. Considering the same thermal loading, the same geometry and a Young's modulus for the pile equal to E=30 GPa, the maximum thermal stress (assuming the pile completely blocked) would be:

$$\Delta\sigma_t = E \cdot \beta \cdot \Delta T = 30 \cdot 10^{3} \cdot 10^{-5} \cdot 30 = 9\,MPa \tag{2}$$

i.e. 300 kPa/°C. These are clearly the theoretical upper and lower bounds; real conditions are between these two extreme cases.

Available monitoring data from experimental sites includes a single pile and a group of piles at EPFL (Switzerland) (Di Donna et al., 2016; Laloui et al., 2003; Rotta Loria and Laloui, 2017), a single pile in a piled foundation in Texas (USA) (Akrouch et al., 2014), a single pile in Monash (Australia) (Wang et al., 2014), a piled foundation for the US Army (Murphy et al., 2015), a single pile in Denver (USA) (McCartney and Murphy, 2012), a single pile at Lambeth College (UK), another in Bad Scallerbach (Austria) (Amatya et al., 2012) and a group of six piles in Shunyi in Beijing (China) (You et al., 2016).

Data was analysed and is presented below in terms of the thermally-induced axial stress in Figure 4a and thermally-induced displacement at the pile head in Figure 4b, as function of the temperature variation imposed to the pile. The results indicate that the thermally-induced axial stress is in the range between 50 to 300 kPa/°C and the thermally-induced displacement in the range of 0.01 to 0.15 mm/°C. These values are generally acceptable with respect to concrete strength and buildings requirements in terms of serviceability performance.



(a) (b)

Figure 4. Geotechnical aspects of energy piles: (a) thermally-induced axial stress and (b) thermally-induced head displacement as a function of the imposed temperature variations in real-scale tests.

6. Environmental and cost benefits

One of the main advantages and interests of using geothermal systems is that they represent local resources, which are renewable and environment-friendly, in accordance with the current energy politics. In the interest of environmental protection, the reduction of CO_2 emissions and other pollutants is increasingly becoming an important issue and a relevant cost factor. Data regarding the reduction of CO_2 emissions due to energy geostructures was collected or computed, when not directly available, assuming 320 kg of CO_2 saving for every kW of energy produced using ground sourced heat pump technology, according to the British, Building Services Research and Information Association. The result, presented in Figure 5 in terms of ton of CO_2 saved cumulated per year since 1993, shows that the contribution of energy geostructures to the pollution reduction is significant.

From an economic point of view, available data is limited. Payback periods of operative energy geostructures are set between 4 to 8 years (Riederer et al., 2007; SIA DO 190, 2005). In the case of energy tunnels, the initial investment is usually estimated around 2% of the total cost (Barla et al., 2016; Schneider and Moormann, 2010).

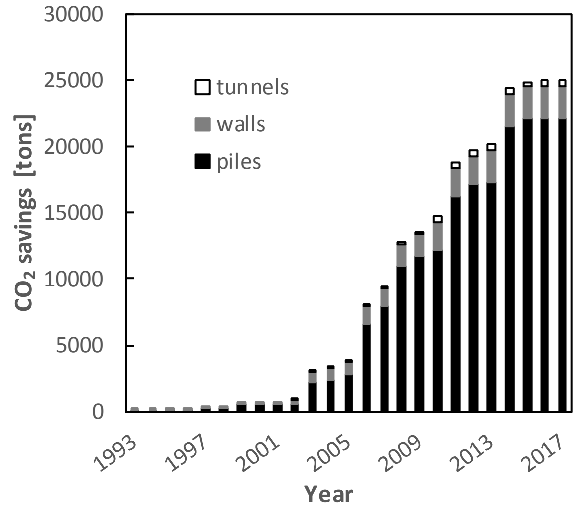


Figure 5. CO_2 savings in Europe thanks to energy geostructures.

On city center sites, economic pressures to maximise building footprint space will require a geothermal installation to be installed under the footprint of the new structure as generally there is no adjacent site to install them. This leads the geothermal designer to consider three possible solutions:

- Option 1 Open loop wells;
- Option 2 150-200 m deep purpose drilled geothermal boreholes;
- Option 3 Energy piles.

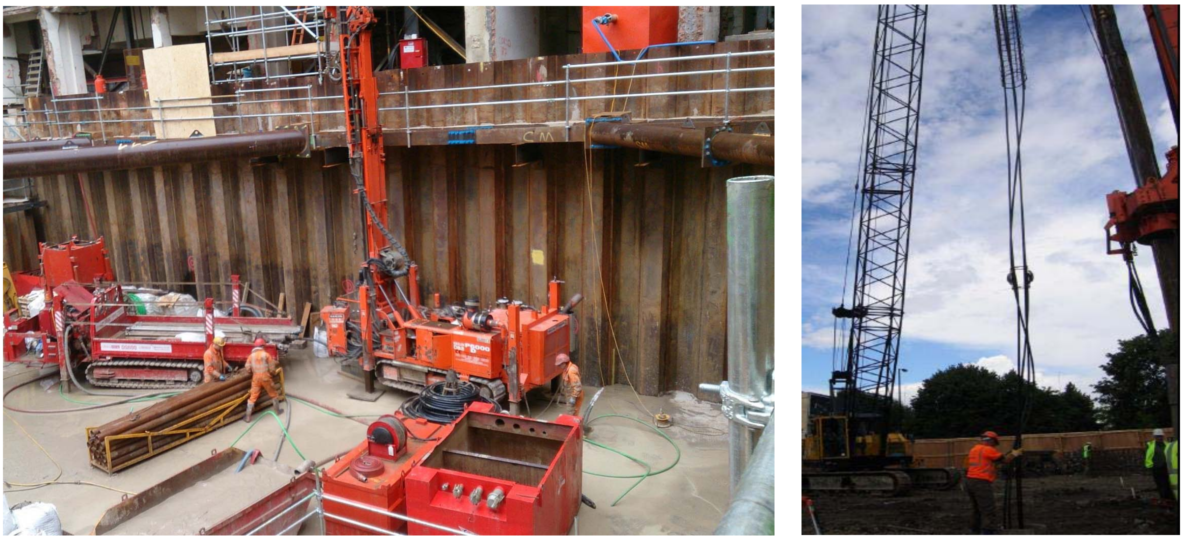
While Option 1 and 2 are likely to provide a greater heating and cooling output than option 3, there are significant additional costs associated with doing so. Both option 1 and 2 requires the supplementary use of large drilling equipment and associated plant to construct the boreholes and will generate significant additional volumes of spoil to be removed from site. On a limited city center site this will significantly impact upon a construction schedule (Fig 6), restricting other activities from commencing, resulting in geothermal work falling onto the critical path, thereby extending the overall construction period of a project.

An additional delay on a city center project can run into significant amounts of money/week. In addition to this additional time required, are the costs associated with:

- Mobilizing drilling equipment and associated plant;
- Providing suitable working platforms to ensure rig stability;
- Spoil and slurry removal, which is highly likely to be contaminated.

These are the fundamental reasons why utilizing the very foundations that are required to provide structural support to the building to also provide heating and cooling make such sense. Indeed, a recent proposed building located on a highly contaminated site in San Francisco, made using energy piles, rather than installing supplementary boreholes an easy “no brainer” of a decision.

Table 1 demonstrates the cost benefits of utilizing energy piles versus boreholes.



(a) (b)

Fig 6. (a) Constructing 25 200 m deep boreholes in basement in Central London, added 8 weeks to construction schedule, (b) Installation of Geothermal Loops into 260 25 m deep 900 mm Rotary Bored Piles at Westminster Academy, incurred no impact on construction schedule.

Table 1. Comparison between cost benefits of boreholes and energy piles.

Item	Option 2 borehole loop	Option 3 thermal pile
Diameter	0.2 m	0.6 m
Heat transfer	35 W/m	35 W/m
Number of loops	One	Two
Length	100 m (3500 W)	27 m x 2 No (1750 W)
Boring/installation cost	\$50/m x 100 = \$5000	Pile included anyway Allow 2 hours' attach loops \$270/crew time
Thermal grout	\$7/m x 100 m = \$700	N/A
Pipe – 25 mm ID	\$7/m – 1 loop = \$700	\$7 x 2 x (27 m x 2) = \$756
Spoil removal	\$1000	Nil
Total installation	**\$7400**	**\$1026**
Header pipes	\$1500/borehole +trenching	\$1100 per pile
Grand total for 3500 W	**\$8900 + trenching**	**\$4,252 (2 piles)**
Construction work	Additional construction time required if under footprint of building	On critical path. Addition of loops in piles adds no additional construction period.

7. Conclusions

Energy geostructures are a very cost effective and convenient technology which couples the structural aspects to the energy needs, providing a renewable source for heating and cooling, with respect to conventional shallow geothermal systems. Data available, shows that energy piles can exchange between 40 and 120 W/m, while energy walls and tunnels between 10 to 50 W/m^2. The thermally-induced mechanical aspects are present but usually acceptable. Data is available only for energy piles, from which results show that thermally induced stresses are in the range between 50 to 300 kPa/°C and the thermally-induced displacements are in the range of 0.01 to 0.15 mm/°C. Ultimately an energy geostructure that is designed using standard engineering procedures, ensuring design concrete stresses are not exceeded, and conventional factors of safety for skin friction and end bearing are maintained, will adequately deal with the additional stresses that will be imposed on them as a result of heating and cooling. What is also noted as being important is that the geothermal designer/installer provides a control strategy that enables the long-term management and system optimisation of the ground loop to ensure that the installed system operates within its design parameters for the life of the building.

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