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On the Exploitation of Ground Heat Using Transportation Infrastructure

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Abstract
The use of shallow geothermal energy systems that employ heat-exchange loops within trenches and boreholes is well established. The use of civil engineering structures that are in contact with the ground (geo-structures) to replace the more conventional heat-exchange methods is creating great interest in many countries. Bearing piles have been used for this purpose since the mid-1980s, retaining walls since the late-1990s and the use of tunnels has been explored since the early-2000s. With regards to transportation infrastructure shallow geothermal may be used to provide renewable heating and cooling to the infrastructure itself or adjacent users, or even to enhance safety by providing e.g. heat to de-ice bridges, station platforms, airport run-ways and the like. This paper presents an overview of the potential application energy geo-structures in transportation infrastructure through case studies and numerical simulations, and then goes on to discuss some of the issues associated with the potential use of geo-structures for heat exchange, in terms of construction, thermal operation and the impact of heating and cooling on the geo-structure.

Keywords: renewable heating & cooling, shallow geothermal, thermally-activated structures, tunnels

1 Energy Geostructures in Transportation

In the upper part of the Earth's crust, the latent heat energy present in the ground derives primarily from the impact of solar radiation - the solar energy input into this zone being several orders greater than the energy flux radiating from the Earth's core. Below a shallow zone where temperatures vary in response to seasonal atmospheric cycles, the temperature remains remarkably stable, at more-or-less the average annual temperature, the temperature increasing with depth only a few degrees per 100 m.

Shallow Geothermal Energy (SGE) refers to the thermal potential of this near-surface zone, Figure 1. It should not be confused with hot-rock geothermal energy however – SGE involves temperatures at tens of degrees rather than 100s. Ground Source Heat Pump (GSHP) systems harvest this energy potential. Temperatures in the zone targeted by GSHP systems are stable and provide a

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heat sink in summer, i.e. ground temperature is lower than the air and a heat source in winter, i.e. ground temperature is higher than the air. The most efficient systems approximately balance the heating and cooling demand drawn from the ground, across the year and it is also possible to store excess heat or cold in the ground for use when needed in other parts of the year.

The use of SGE/GSHP systems that employ heat-exchange loops within trenches and boreholes is well established. Annualized growth in terms of installed capacity in this energy sector from 1995 to 2015 is about 18%, although growth rates approximately halved to around 13% annually in the last 10 years compared to the previous 10 years, presumably as a consequence of the economic crisis, data from (Lund & Boyd, 2015). The use of civil engineering structures that are in contact with the ground (geo-structures) to replace these more conventional heat-exchange methods is creating great interest in many countries. Bearing piles have been used for this purpose since the mid-1980s, retaining walls since the mid-1990s and tunnels since the early-2000s (Brandl, 2006). Many operational installations using geo-structures have now been installed in China, Europe, Japan and the United States of America (USA); however, though increasing rapidly, the total installed thermal capacity of Energy Geo-Structures (EGS) remains a tiny fraction of the total shallow geothermal energy systems installed.

Using ground energy in transportation projects is not a new concept; (Lund, 1999) describes the refurbishment of a hot water pavement snow melting system that had been operational since the late 1940s. During the late 1970s and 1980s a number of projects were undertaken across the USA to investigate the use of different snow melting systems, including the passive use of ground heat via so-called "heat-pipes", Figure 2 (Nydahl, et al., 1984) and seasonal heat storage (Pravda et al., 1978). Heat pumps have also been incorporated in a number of bridge de-icing systems (Minsk, 1999). Similar systems have been developed and used a number of different countries including Japan (Iwamoto et al., 1998), Europe (Eugster, 2007), China and Turkey (Yildirim & Hepbasli, 2015). Currently the major users of snow melting/de-icing via ground energy appear to be Iceland (c. 195 MW_t installed) and Japan (c. 147 MW_t installed) with other countries having mainly research installations or small operational systems. Cost comparisons with conventional de-icing technologies tend to show that geothermal type systems are not economic (Zhang et al., 2009). This is due to much higher capital costs, while operational costs tend to be much lower. However, life cycle analysis should also take into account the impact of e.g. salt induced damage on pavements and other structures, and environmental impacts; such analysis is not apparent in the literature.

The possibility of extracting ground heat or storing excess heat via transportation infrastructure for use in SGE systems has been developed more recently, and possibilities exist for the use of heat from tunnels and other buried infrastructure, to be used by local businesses and communities that are not too distant via e.g. hot waste water outflows (Wilhelm & Rybach, 2003) or thermal exchange with the ground (Hofinger et al., 2010; Frodl et al., 2010). The use of tunnels to provide renewable heating and

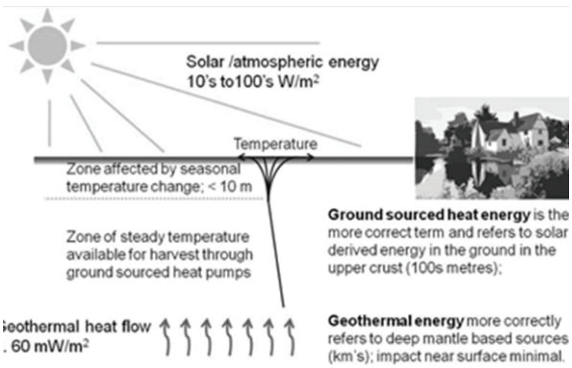

Figure 1: Shallow Geothermal Energy defined

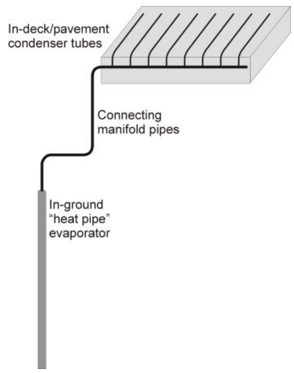

Figure 2: Schematic layout of "heat pipe" bridge/pavement de-icing system.

cooling is also not a new idea; in Iran, centuries old systems exist that utilize tunnels in combination with wind-catcher towers, to augment the cooling potential of the air-flow (Bahadori et al., 2014). Pile foundations currently represent the widest application of the EGS concept and have been used across a wide number of projects from housing to transport infrastructure (Brandl, 2006; Hofinger et al., 2010).

In this paper, some case studies of the applications identified above will be described in more detail with a focus on the use of wall technologies close to the ground surface. A numerical study where heat exchange from cut-and-cover tunnel has been modelled will then be presented and the results in terms of both heat flow and soil-structure interaction effects discussed.

2 EGS Case Studies

2.1 Integration of EGS in Transportation Projects

In this discussion only closed-system ground heat exchangers are considered. Such systems entail the embedding of plastic heat absorber pipes within structural elements in contact with the ground, e.g. bearing piles, retaining walls and tunnel linings, through which a fluid (typically a water-glycol mix) is pumped to provide a means for heat exchange with the ground.

In addition to the particulars associated with each structural form (see below) and the details of the requirements for the SGE system, there are a number of other factors that need to be taken into consideration when implementing EGS to provide ground loops within the SGE system. These primarily relate to planning, design and construction management; such issues include (Bourne-Webb, 2013):

- Definition of responsibilities – need to be well-defined for each stakeholder with a clear basis for coordination of activities and communications.
- Design management – whether undertaken within a single organization or between several specialists, design management is a key issue and review points need to be included in the process for the development of EGS from planning through to execution to ensure that all changes are implemented as planned.
- System redundancy – in addition, sufficient redundancy between the specified energy outputs of the EGS and that which is intended to be provided, needs to be agreed in order to account for possible system underperformance, due to e.g. changes in expected ground conditions, and damage or loss of ground loops.
- Awareness & skills training – raising stakeholder awareness in terms of what is involved and what impacts the inclusion of an energy geostructure within a project might have, may need to occur at several levels within the scope of a project, depending on the novelty of the concept within a particular market. This extends from the Client, through regulatory bodies, other affected groups, the design and construction teams, and end-users, especially those responsible for facilities management.

2.2 Pile Foundations

Thus far, most pile types have been adapted for use as heat exchangers, from micro-piles through to large diameter rotary bored piles constructed with support fluids, and using steel, precast and in situ and reinforced concrete sections. Additionally, so-called plunge column type piles have been constructed as heat exchangers (Amis et al., 2010); this type of pile is formed with a deep cut-off with a steel column inserted (that can eventually form part of the final structure) to allow top-down type excavation sequencing to be used in deep excavations. This technique is very useful in the construction of deep excavations associated with underground railway stations and has been used in several station developments on London´s new Crossrail route (Amis, personal communication), likewise thermally-activated bearing piles were also integrated into station developments in Vienna and Salzburg (Hofinger et al., 2010).

The issues with each pile type are largely similar, i.e. how to fix the ground loops, how to integrate the pipe work with minimal impact on the construction process and programme, and how to prevent damage during installation and follow-on works, especially where piles need to be broken down, Figure 3 (Bourne-Webb, 2013). When incorporated into plunge columns, the installation process needs to avoid the possibility for snagging of the tubes by the column while it is being lowered into place, and the pipe work above final excavation level needs protection throughout the excavation phase of the work.

2.3 Embedded Retaining Walls and Base Slabs

Embedded retaining walls are often required to support the sides of excavations, particularly in urban areas where battered unsupported excavations are not feasible due to neighbouring infrastructure and buildings. They are widely used in urban transportation projects to provide station facilities and shallow tunnels and may be formed using either reinforced concrete bored pile and diaphragm wall techniques, or steel sheet piling methods. As with piles, these elements may be thermally-activated through the inclusion of heat exchange ground loops during their installation, and a number of examples of this application exist in e.g. Vienna (Hofinger et al., 2010) and are being incorporated in the Crossrail project (Amis, personal communication).

Broadly speaking, the issues associated with the integration of ground loops in wall systems are similar to those for piles, i.e. protection of the tubes during installation and in the midst of follow-on activities (Bourne-Webb, 2013). In concrete elements, as with piles, the loops can be attached to the reinforcement, Figure 4. In steel sheet pile walls, a protective sleeve will be required. If tubular steel piles are used in the wall system, the ground loops would be able to be grouted into the space within the tube. In the construction of deep excavations, the floor slab constructed at the final excavation level is usually in contact with the ground and may also be thermally-activated. This may happen in any case, as it is at this level that pipework from piles and/or the wall are often collected together for plumbing through into the building system.

Pipework for wall systems may also be run-out through the capping beam that is used to tie the top edge of the wall system. Whether run through the base slab or the capping beam, careful detailing is required to ensure that the pipework is integrated into the structure without affecting the

Figure 3: Protection of ground loops at pile head prior to concreting, with permission Cementation Skanska Ltd.

Figure 4: Installation of wall panels & ground loops in wall panel, with permission GI Energy

constructability and function of the elements (Bourne-Webb, 2013). In particular, how pipes pass into the building envelope and whether there is a potential for leaks to develop must be addressed and suitable measures taken, i.e. the inclusion of water stops.

2.4 Deep Tunnels

While embedded walls may be used for the construction of shallow tunnels, different techniques are required when the tunnel is deep and/or passes below existing structures. Two broad methods are employed:

- mining where the ground is required to support itself either permanently or temporarily prior to the installation of support linings,
- shield tunnelling where a tunnel boring machine provides support to the ground while segmental lining elements are installed to provide permanent support.

Tunnel linings employed in both of these techniques have been modified to allow heat exchange and a number of demonstration projects have been implemented. The lining of mined tunnels tends to be formed as a primary and secondary application and may be thermally-activated via the insertion of heat exchange pipes between these two layers (Brandl, 2006). Segmental tunnel linings may also be thermally-activated through inclusion of the ground loops within the component segments when they are fabricated and such a system has been developed by Ed Züblin & Rehau (Frodl et al., 2010). While these systems involve installing ground loops around the circumference of the tunnel, it is also possible to install them in the invert only.

Tunnel based thermal exchange differs from that of piles and walls in a variety of ways (Frodl et al., 2010; Bourne-Webb, 2013). The main technical difference is that thermal exchange may occur with either the surrounding ground or the air volume within the tunnel. However, there are a number of other issues such as:

- Relationships between tunnel owner, energy supplier and end-user.
- Access and supply routes from the tunnel to the end-user.
- Ownership of the thermal resource.
- Thermal interference/pollution.

3 Effect of Heating and Cooling on EGS Walls

3.1 Observations and Analysis

Whilst a number of EGS wall systems have been constructed, to-date there has been very little in the way of evidence to demonstrate either the heat exchange potential or the impact on performance of the geostructures of imposed thermal loading.

Limited heating performance data has been published for installations in the Lainzer Tunnel and the Vienna U2 metro extension (Adam & Markiewicz, 2009; Brandl et al., 2010) and the new Shanghai Museum of Natural History (Xia et al., 2012). These results identify a number of factors affecting the heat exchange rate, including whether heat is being injected or extracted, the interval over which heating is applied, and loop configurations.

Even less information is available regarding the impact of heating and cooling on EGS Walls with the only publically available data coming from a cut-and-cover section of the Lainzer tunnel (Brandl, 2006). This data suggests however that the effect of heat exchange is largely benign and that, at least for this situation where the tunnel is near the ground surface, greater alterations in structural response were observed to follow seasonal temperature changes. This outcome has been confirmed in numerical studies as well (Bourne-Webb et al., 2015).

3.2 Heat Exchange Through an EGS Wall

In the following, the heat exchange through a piled EGS wall is examined using numerical analysis. For the purpose of the analyses a two-dimensional (2D) finite element model was created that represents a section of bored pile wall in plan, Figure 5. The thermal boundary conditions used are indicated on the figure and the convection coefficient used on the tunnel-wall boundary was assigned a value of 2.5 W/m^2K which is equivalent to a case with near-zero air flow. The initial temperature field was set to 12°C and to represent conditions in summer when heat might be injected, a tunnel air

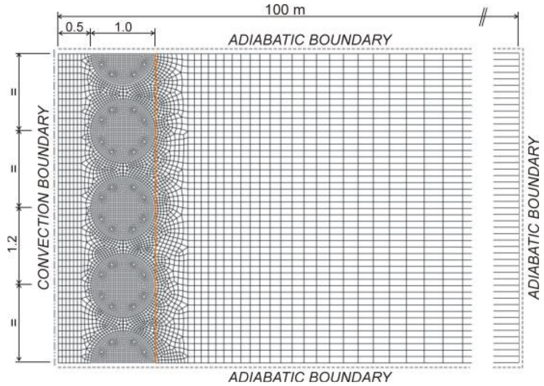

Figure 5: 2D Pile wall heat flow model

temperature of 15°C was imposed at the tunnel-wall (left) boundary in Figure 7 and at the surface of the ground loop piles (4 loops per pile) a temperature of 27°C was applied. Material properties for the wall and soil are summarised in Table 1.

Property	Wall	Soil
Thermal Conductivity, k (W/mK)	2 (or 1)	2 (or 1)
Density, ρ (kg/m^3)	2447	1835
Young's modulus, E (MPa)	20000	80
Poisson ratio	0.3	0.5
Linear CTE, α ($\mu\varepsilon$/K)	10	10 (0, 5, 20)
Undrained shear stress, c_u (kPa)	-	60

Table 1: Soil and wall material properties

Temperatures and associated heat flow on the tunnel-side (convection boundary) and soil-side (orange dashed line, Figure 5) faces of the wall are compared in Figures 8 and 9 respectively. Clearly, as more piles are thermally-activated, temperatures across the faces of the wall become more uniform.

As a consequence, heat flow across the tunnel-wall interface increases and that across the soil-wall interface decreases to nearly zero, Figure 9. Although present in both faces, interference between heat exchange pipes is especially apparent on the wall-soil interface with heat flow values dropping significantly as additional piles are thermally-activated.

Further analyses were undertaken to evaluate the effect of differing conditions in the tunnel, i.e. increasing convection, h due to higher air-flow; Figure 10 shows the temperatures across the wall interfaces and Figure 11, heat flow. At the soil-wall interface the effect on temperature is small and the changes in terms of heat flow are also small. The effect at the tunnel-wall interface is much greater and the temperature at the interface approaches that specified for the tunnel air (15°C) and at the same

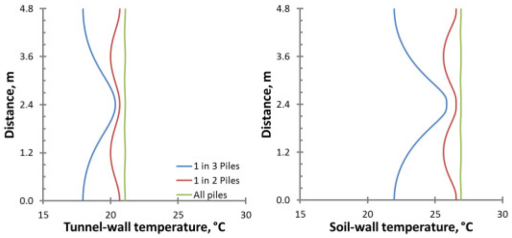

Figure 8: Temperature across wall interfaces (near-zero air flow)

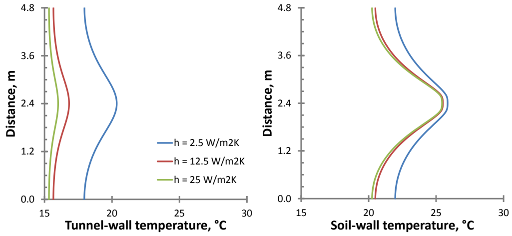

Figure 10: Temperature across wall interfaces (varying air flow)

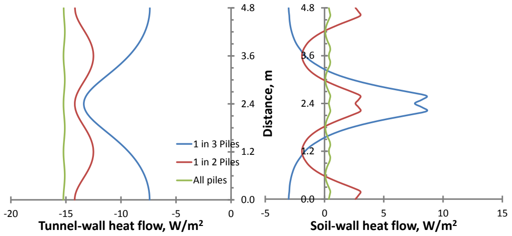

Figure 9: Heat flow across wall interfaces (near-zero air flow)

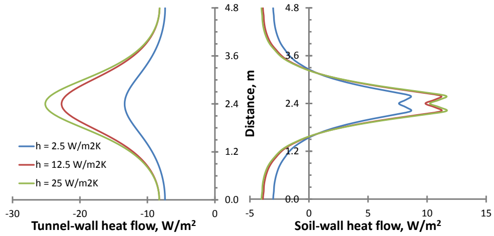

Figure 11: Heat flow across wall interfaces (varying air flow)

time heat flow to the tunnel increases. This would be expected and demonstrates the importance of having a reliable measure of the tunnel environment (air flow, humidity, etc.) in order to provide realistic heat flow predictions.

4 Conclusions

Shallow geothermal energy has demonstrated its potential to contribute to the mix of renewable energy sources in the provision of heating and cooling and it is possible to integrate the ground heat exchange loops within underground structures, thus saving on the costs of boreholes and allowing the use of SGE where space constraints might otherwise prevent its consideration. The inclusion of ground loops has been successfully demonstrated in a variety of different geostructures including a number of urban transportation projects, but requires careful planning and control measures.

Few observations of the heating potential and structural impact of heat loads on near-surface geo-structures exist however those that do exist and supporting numerical analysis highlight some of the key parameters affecting each factor:

- Heat flow is affected by the mode of operation (extraction/injection), system layouts, operational energy demand over time and the tunnel environment.
- There is a significant knowledge gap with respect to how tunnel environments develop and the potential for heat exchange between the walls of the tunnel and the tunnel air void.
- Internal load changes and deformations due to thermal loading due to heat exchange appear to be small when compared to those caused by seasonal temperature changes.

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