GROUND SOURCE HEAT PUMPS AND THEIR INTERACTIONS WITH UNDERGROUND RAILWAY TUNNELS IN AN URBAN ENVIRONMENT-A REVIEW

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ABSTRACT

Ground source heat pumps (GSHPs) can provide an efficient way of heating and cooling buildings due to their high operating efficiencies. The implementation of these systems in urban environments could have further benefits. In such locations the ground source heat is potentially more accessible through alternative sources such as through underground railways (URs). The heat from the ground surrounding an UR tunnel could be exploited to enhance the operation of GSHPs operating in heating mode. To achieve this, the interactions of GSHPs with neighbouring URs must be fully understood but there is little exploration of these in current literature. This paper focuses on the potential benefit of understanding such interactions. It starts with a summary of typical and alternative heat sources for heat pumps and then it highlights the reasons why URs can be regarded as one of the most attractive ones. Then the paper reviews the current approaches used to model GSHPs and URs. Based on that review the paper suggests a method for the combined analysis of GSHPs and URs. The reasons why London is a sensible choice for a case study are also described. Summary of results from a preliminary investigation are also presented.

Keywords: Ground Source Heat Pumps, Underground Railways, Thermal Interactions, Mathematical Modelling, Heat Recovery, London

1. INTRODUCTION

In March 2007, the European Council made a commitment to reduce greenhouse gas emissions by 20% by 2020 (European Commission, 2009a). The British Government went further and established a target to reduce the nation’s carbon dioxide emissions overall by 80% by 2050 in comparison to a 1990 reference point (The Stationery Office, 2008). Shortly after that the Renewable Energy Directive (European Commission, 2009b) set a target for the UK that 15% of its energy demand would be supplied from renewable sources by 2020. As part of The Renewable Energy Strategy (Secretary of State for Energy and Climate Change, 2009) the UK Government indicated that the target could be achieved with 12% of heat energy demand being satisfied by renewable sources. Financial incentives such as the Renewable Heat Incentive (DECC, 2011) designed to encourage the uptake of renewable heat technologies in the UK started to appear at that time. Heat pumps are one of the technologies to become incentivised.

1.1. Heat Pumps – Typical And Alternative Heat Sources

Typically heat pumps use electricity to raise the temperature of low grade heat to high grade. The Coefficient of Performance (CoP), which indicates the efficiency, depends largely on the temperature difference between the heat source and the heat supplied: The greater the difference, the less efficient the heat pump. Common sources of heat for heat pumps include ground, air and water. GSHPs have higher operating efficiencies compared to air source heat pumps. This is because the ground usually has a lower temperature than the outdoor air during the cooling season, and a higher temperature than the outdoor air in the heating season. GSHPs systems typically require between 0.22 - 0.35 kWh of electricity for each kWh of heating or cooling output. This can be 30 - 50% less than the seasonal power consumption of air-to-air heat pumps (Lund *et al.*, 2004). Therefore implementing GSHPs is an increasingly common practice. The schematics of the two common types of GSHP system configuration i.e. open and closed loop systems are illustrated in Figure 1. In urban settings heat is potentially more easily accessible through alternative sources. It was shown that the total heat that could be delivered from secondary sources in London is of the order of 71 TWh/yr (The Greater London Authority and Buro Happold, 2013). This was estimated by using heat pumps that delivered heat at 70°C. This was more than the city's total heat demand of 66 TWh/yr in 2010. Of this 71 TWh/yr, around 50 TWh/yr (70%) would be from the secondary heat source itself and the remaining 21 TWh/yr (30%) would be attributed to the heat pump energy requirements. Some of these secondary heat sources are summarized in Table 1. The focus of this paper is on UR as an alternative source of heat.

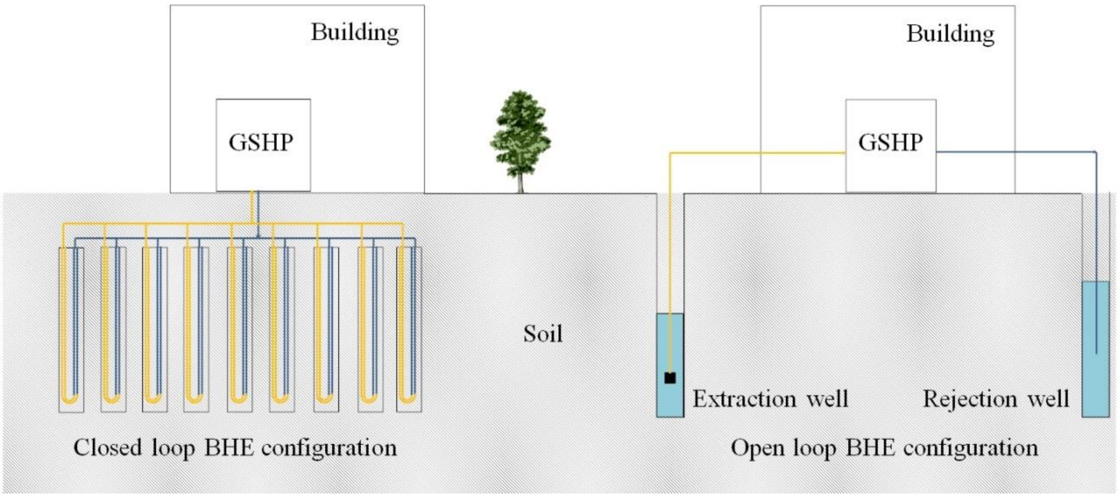

Figure 1 Schematic of the closed and open loop type GSHP configurations

Table 1 Alternative heat sources for heat pumps (Adapted from: The Greater London Authority, 2013)

Heat Source	**Description**	**Typical source temperature**
Power station rejection	Power stations that burn fuel to generate electricity generally operate at electrical efficiencies of around 30-50% depending on fuel type and technology. Considerable energy is lost in the form of waste heat that is generally rejected to the atmosphere.	35°C (in some cases much higher)
Building cooling system heat rejection	Buildings use a range of different cooling systems which typically operate more during summer months and use air or water cooled chillers to reject heat at low temperatures.	28°C
Industrial sources	A number of industrial processes e.g. chemical industries, clinical waste incinerators and food producers lead to the rejection of waste heat.	35-70°C Highly variable
Commercial buildings non-HVAC	Some buildings reject heat from equipment other than building cooling systems (e.g. from food refrigeration, IT equipment). Two key commercial operations are supermarkets and data centres.	32-40°C
Underground Railways (Direct)	There is a substantial amount of heat generated through the operation of URs. Recovering that heat through heat exchangers directly linked to the tunnel body is viable.	Can be high as 35°C

Underground Railways (Indirect)	The ground surrounding a typical urban UR tunnel contains a substantial amount of heat energy, which might be extracted with nearby GSHPs.	Typically between 20 and 30°C depending on the distance from the tunnel.
Electricity substations	Electricity substations in both the transmission and distribution networks contain transformers to convert power from one voltage to another. Transformer coils are usually cooled and insulated by being immersed in insulating oil.	50°C
Sewer heat mining	Sewage in underground sewers contains heat which can be 'tapped' or 'mined' in a similar way to the extraction of heat from the ground or rivers.	14-22°C
Roads / Car parks	The exploitation of heat stored in roads and car parks can be recovered through asphalt solar collectors.	25°C

1.2. Underground Railways – A Continuous Heat Source

In many capital and large cities internationally, a UR is a major public transport system and serves millions of passengers every day. In 2012 the Paris Metro carried nearly 1.5 billion passengers, the London Underground Metro system approximately 1.1 billion, and the Madrid Metro nearly 700 million passengers (ERRAC and UITP, 2012). Commuters are demanding more frequent and faster trains that are likely to result in a rising energy consumption, a large proportion of which will ultimately be rejected into the tunnel as heat. Often a large quantity of kinetic energy is generated when the trains brake. A good proportion of this energy can be regenerated, but the remainder still presents a great thermal stress on the tunnel environment. This was evidenced by Ampofo *et al.* (2004) who demonstrated that the major contributor of heat to the tunnel is the braking mechanism and that to the train carriage is the passengers. This is illustrated in Figure 2. Another contributing factor to rising temperatures is the climate change. Railway infrastructure has a lifespan of over 100 years and over this period climate change could potentially cause several degrees Celsius of warming. Over time, in addition to the changes that occur due to the operation of trains, the in-tunnel environment would experience change similar to the outside environment. The soil surrounding a typical deep UR tunnel also contains a large amount of heat energy due to the heat sink effect that the ground provides the tunnel. Ampofo *et al.* (2004) have shown that the heat absorbed by the earth surrounding an UR accounts for 30% of the total heat release, and contains approximately 4,500 GJ of heat energy per km of tunnel. This energy is low-grade and ranges in temperature from approximately 20 to 30°C (Thompson *et al.*, 2008). It is important to note that Ampofo *et al.* (2004) only used steady state calculations with a constant convective heat transfer coefficient. The transient balance is somewhat different and would depend on the air volume being moved within the tunnel, and so the percentage of the heat absorbed by the ground can vary significantly depending on the prevailing circumstances. Failure to manage increasing temperatures in tunnels can drive up operating costs by increasing the amount of energy required to cool the trains and stations. Energy efficiency is the first and foremost measure that can be employed to take on the challenges. This tackles the heat release at its source. Optimizing rolling stock and traction power specifications, train speed operating profiles, and maximizing regenerative braking all play a major role in reducing temperatures as well as reducing energy use. Efficient energy utilization may be further improved by heat recovery.

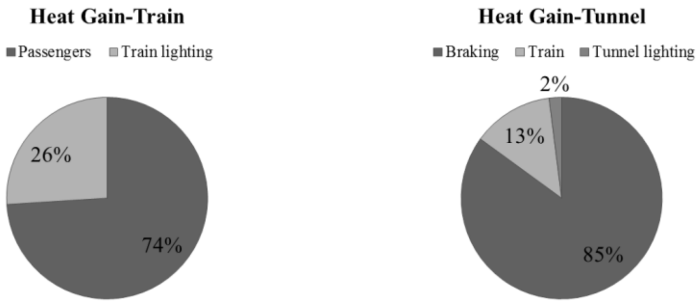

Figure 2 Heat gains in a typical underground railway environment

1.3. Heat recovery from URs

The heat energy provided by URs could potentially be captured, transferred and utilised by nearby users of heat. For example, a heat exchanger in the tunnel may capture the heat and a water circuit then transfer it to a heat pump. The heat pump may be connected to a third party's building or small-scale district heating system. The work of Thompson and Maidment (2010) showed that air source recovery through the ventilation system of a UR was viable (Figure 3 left). This was further supported by Gilbey *et al.* (2011). However neither Thompson and Maidment nor Gilbey *et al*. reported on the opportunity of heat recovery via an external ground loop (Figure 3 right). This is the subject of this paper. Conventional GSHPs in London typically extract heat from earth which is at about 13-14°C (The Greater London Authority, 2013). Utilizing source temperatures of 20-30°C which exist in the earth surrounding the deep bored tunnels of the LU network (Thompson *et al.*, 2008) could substantially enhance the performance of GSHPs. An operating characteristics rule of thumb for GSHPs is that the heating CoP is improved by approximately 3% for each degree Celsius that the evaporating temperate is raised (Cengel and Boles, 2001). Improved CoP figures would result in savings in running costs of the heat pumps, smaller heat pumps and reductions in heating related carbon emissions.

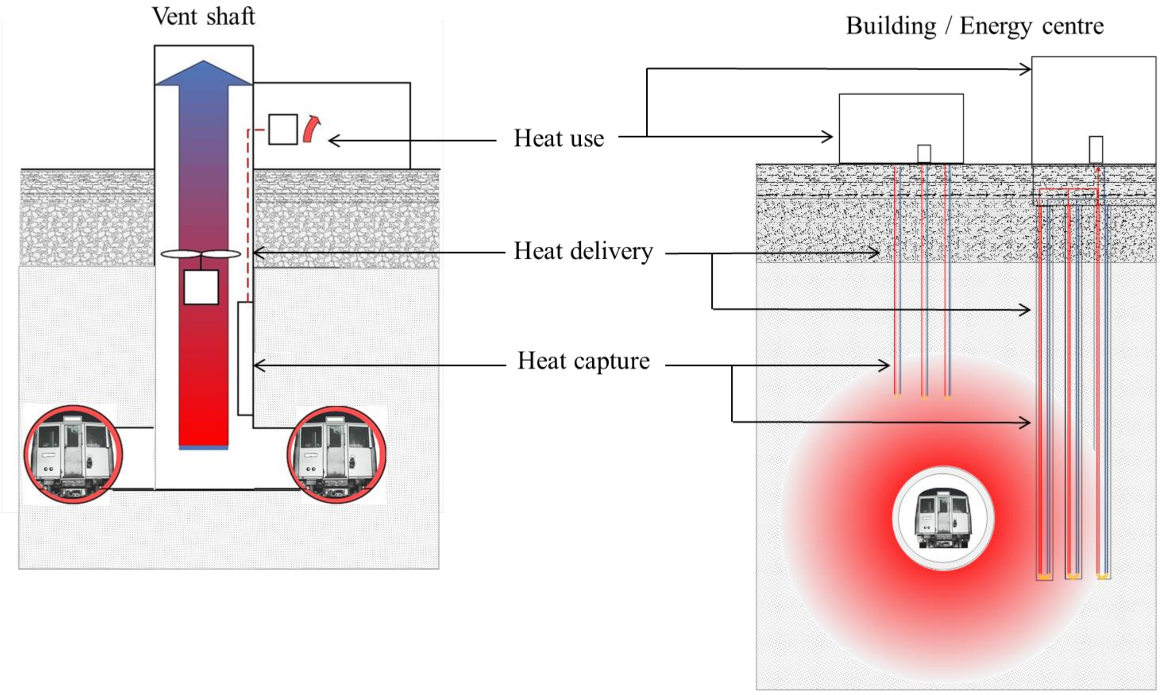

Figure 3 Heat recovery from tunnels and platforms (left) and heat recovery from the ground through BHEs (right)

2. MODELLING URs AND GSHPs

A wide range of models for both GSHPs and URs have been developed, with different capabilities depending on the modelling objectives and methodology which were adopted during the development phase. Mathematical models of URs are either custom models (i.e. small models for specific sections of railway) or developed to provide a complete thermo-fluid analysis of an underground railway environment (Thompson, 2006). GSHP models can also be divided into different categories. Some models focus only on the processes within and in the surroundings of the ground heat exchangers. Other models are of integrated building simulations, whereby the entire GSHP system is coupled to HVAC and building thermal models to study overall system performance. A common feature of GSHP and UR models is that their level of detail and complexity mostly depends on the modelling objectives that are set and the timescales under consideration. The two main types of modelling approaches are numerical and analytical methodologies. Numerical methods solve the fundamental engineering equations using an established numerical differential-equation solving technique, such as a finite-difference (FD), finite-element (FE) or finite-volume (FV) method. These numerical solution methodologies are particularly useful when modelling URs and BHEs. This is because there are complex, transient, three-dimensional transport phenomena and extreme geometrical aspect ratios involved within both schemes. Numerical approaches, if designed correctly, can provide solutions for phenomena with very different time scales (e.g. the system response of coupled low and high inertia systems) and also consider a variety of transient boundary conditions. Accounting for moisture migration in the soil and ground stratification, is also typically less complicated in numerical models because they can operate with larger degrees of freedom than analytical solutions.

A common disadvantage of fully discretized 3D numerical models is that even when using modern and powerful computers, extensive computation times can result. To combat excessive runtimes, theoretical and computational assumptions and approximations have been developed. The work of Al-Khoury *et al.*, (2005) presented a simplification for the analysis of heat flow in BHEs. The model was formulated such that it allows for the utilization of relatively large elements, alleviating thus the need for extremely fine meshes that are typically required in modelling such systems. The method of simplification to the modelling process included a specific mathematical model for the BHE. The model had an inclusion of thermal interactions among the different components of the BHE. This inclusion has lessened the need for finite element discretization of the component geometry and allowed a spatial discretization using a line element. On the other hand the use of a sequential numerical algorithm for solving the resulting system of non-linear equations has also contributed in reducing the required number of finite elements necessary for describing the involved systems. The number of elements can be decreased further using other approaches. One example is when the 3D discretization of the borehole is retained while the soil is described by a 2D axis-symmetrical mesh. If only heat conduction considered in the horizontal cross section, the only assumption that has to be accepted is that the borehole wall has a uniform temperature in circumferential direction. Hellström, (1991) showed that the error caused by this assumption is marginal thus can be neglected.

Although analytical models that can readily be solved do have limitations, they are often used to provide data for validation purposes of numerical modelling results for both URs and BHEs. The main reason for this is that it is difficult to gather experimental data of sufficient quality and reliability in deep ground.

2.1. Analytical UR and BHE models

One of the earliest analytical approaches to modelling BHEs is the Line Source (LS) method where the BHE is assumed to be a line source of constant heat output surrounded by an infinite homogeneous medium. This method relies on the principle of superposition where a line consists of a combination of sequentially positioned points. First the temperature change is calculated at a specific location within an infinite homogeneous medium based on the formula of point heat source. Then integration is performed to account for the effect of the point sources positioned along the line. In the Infinite Line Source (ILS) model, which was developed by Ingersoll and Plass (1948), the integral of the point source formula is performed on a line with an infinite length. Another approach based on Fourier's law of heat conduction is the Infinite Cylindrical Source (ICS) method developed by Carslaw and Jaeger (1946). This method can be used to model both BHEs and UR tunnels. This method is based on a cylinder with infinite length, surrounded by a homogeneous medium with constant properties and considers heat transfers only by conduction. Also it only considers a single cross-section of a cylinder and neglects axial heat conduction effects. The first method accounting for the finite length of the BHE was developed by Eskilson (1987). The approach was based on a combination of analytical and numerical solution techniques and it is called the Finite Line Source (FLS) model. Based on Eskilson's model, Zeng *et al.* (2002) presented an full analytical solution to the FLS problem considering the soil as a homogeneous semi-infinite medium with constant thermo-physical properties. The ground surface was presented as a boundary with constant temperature throughout the time period considered. The heat flow rate per unit length of the borehole is assumed to be constant along the borehole. Table 2 categorises some of the work and improvements made on analytical BHE models. Enhancement of the ICS model used to model UR tunnels was initiated by several researchers including Brown *et al.* (2005), Brown and Vardy (2006), Sadokierski and Thiffeault (2008) and (Thompson *et al.*, 2009).

Table 2 Improvements on analytical BHE models

Varying heat rate of the BHE	**Groundwater movement**	**Ground surface temp changes**	**Multi-layered soil profile**
Deerman and Kavanaugh, (1991) [ICS] Bernier, (2001) [ICS] Weibo *et al.*, (2009) [ILS] Ozudogru *et al.*, (2014) [FLS]	Diao *et al.*, (2004) [ILS] Molina-Giraldo *et al.*, (2011) [FLS]	Bandos *et al.*, (2009) [FLS]	Abdelaziz et al., (2014) [FLS]

2.2. Numerical UR and BHE models

A number of numerical BHEs models with different features have been developed. One of the earliest is the Duct Storage model (DST), which is a two-dimensional FD scheme. The DST model was first described by Hellström (1991) and further developed by Thornton *et al.* (1997). The DST code was built in as a component in a simulation environment called TRNSYS. The TRNSYS is a modular system simulation package where users can describe the components that compose the system and the manner in which these components are interconnected. Other important efforts include the work of Lei (1993) and Muraya *et al.* (1996), who studied the thermal interference which occurs between adjacent legs of a BHE field. Most of the early numerical models were associated with low computational efficiency. In order to overcome this barrier Al-Khoury *et al.* (2005) developed an FE model for the analysis of three-dimensional steady state heat flow. Shortly after that a transient version of the model was presented in Al-Khoury and Bonnier (2006). More recently a three-dimensional numerical approach was developed by Rees and He (2013). The Al-Khoury and Bonnier's as well as Rees and He's approaches are suitable for the investigation of three-dimensional dynamic heat transfer and fluid flow physical phenomena. A number of design tools for BHEs based on some typical heat transfer models have been developed over the past decades.

On the other hand, numerical models aiming to study heat transfers in and around URs have also been developed. A few examples include the work of Hu *et al.* (2008), Ting *et al.* (2009), Mimouni *et al.* (2013) and Barla and Perino (2014). The descriptions of the implemented numerical strategies detailed within these studies however are somewhat lacking in explanation of the selected validation methodology. The most common simulation tool used in the railway industry is called the Subway Environment Simulation (SES), which was developed in the 1970s. SES is an industry standard tool in the field of tunnel ventilation. It allows engineers to mathematically model aspects of a subway environment. A supplement to the SES has been developed by Parsons Brinckerhoff to enhance the capabilities of SES. This supplement is called Dynamo, which is a one-dimensional FD model of a single length of tunnel. It uses an energy balance approach to determine the thermofluid interactions. The tool can be used for the analysis of recovery of waste heat from railway tunnels (Thompson, 2014). There are several tools available for designing GSHP/BHE systems such as EED, GLHEPRO, GLD, and CLGS. Typically the user must input the building loads, design area, heat exchanger configuration, pipe size and type, and heat pump capacities. In response the software usually calculates the required length of the BHEs and system CoPs, sometimes even energy consumptions and running costs of the heat pump. To date there are no models reported that allow the combined analysis of URs and nearby heat sources/heat sinks e.g. GSHPs.

2.3. Simulation platforms for the combined analysis of URs and GSHPs

At present a number of simulation tools are available commercially and through open source. Those that are capable of simulating heat and mass transports in the ground include FEFLOW, ANSYS and COMSOL Multiphysics, amongst others. Most of these simulation tools offer a user-programmable interface, allow the input of user-defined equations and enable linkage with other software such as CAD tools or Matlab. These tools allow the building of geometries within either a one, two or three-dimensional modelling domain, thus allowing the complex geometrical aspects of URs and GSHPs to be easily represented. These platforms usually also allow the use of a wide variety of boundary and initial conditions that would typically exist during the operation of URs and GSHPs. Thus the above-mentioned simulation platforms would allow the detailed investigation of the interactions of URs and BHEs within the same simulation environment. For building a model using such a tool it is essential to become familiar first with the parameters, variables, properties and operating conditions involved. This paper considers London and its Metro system the London Underground (LU) as a case study.

3. LONDON – THE LINKAGE BETWEEN URs AND GSHPs

London, the capital city of the United Kingdom, has grown to become one of the most significant financial and cultural capitals of the world. Due to this position, more people than ever are using the LU. Simultaneously, GSHP installations are becoming increasingly common in the city and thus BHEs eventually could get closer in proximity to the running tunnels. Investigating the viability of the heat recovery from the ground surrounding the tunnels through these ground loops will therefore become increasingly important. Following a brief introduction to London's geology, this section reviews the infrastructure of the LU railway and its thermal environment. The potential benefits of the interactions between the tunnels and nearby ground heat exchangers are also summarised.

3.1. London Basin

The centre of the city of London is part of the London Basin. Of all the lithology of the Basin, the London clay formation hosts many types of subterranean structures including the majority of the LU railway. A typical geology and a section of the LU railway network are illustrated in Figure 4. The London clay's generally low permeability and good load-bearing characteristics are some of the principal reasons for the comparatively early development of the LU (Paul, 2009). The major aquifer of the London Basin is the chalk aquifer (Environmental Agency, 2014). In the early nineteenth century, heavy water abstractions led to a fall in groundwater levels, increasing the strength of the London Clay. Legislation from the 1960s led to the slow recharge of groundwater levels. Since then, increased pumping has been required in some areas of the LU network as old tunnels are threatened by the changes in the pore water pressure in the London Clay, which will lead to increased leakage of water into the tunnel. It is also possible that such pressures would cause the tunnel linings to change shape. The shallower tunnels, often called "sub-surface" lines, are typically at a depth consistent with location in the River Terrace Gravel strata. These are known to be a porous strata often containing ground water flowing to the nearby River Thames basin. Some sections of the tunnels are run through the less well-consolidated sands of the Bagshot formation or the Lambeth Group. These formations mainly comprise highly permeable sands.

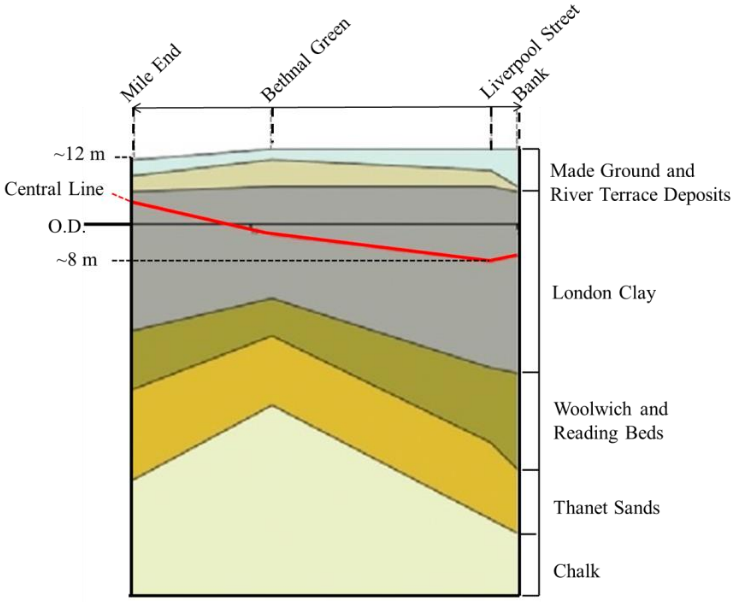

Figure 4 A short geological section following the path of the Central line of the LU railway

3.2. The LU railway tunnels and nearby GSHPs

The Metropolitan Railway was the first section of the LU railway. It was constructed from Paddington to Farringdon in 1860-1862 using the cut and cover technique. The railway was a great success from the beginning, attracting 11.8 million passengers in the first year. The railway was soon extended to South Kensington in the west and Tower Hill in the east. The "full circle" (today known as the Circle Line) was completed in 1884. The first two "deep tube" lines on the LU were the "City and South London Railway" and the "Central London Railway". Since then the LU network has broadly extended and currently contains approximately 35 km of the "sub surface lines" and about 136 km of the deeper tube tunnels. The average depth of the bored deep tube tunnels is 24 m with a maximum of 67 m (Thompson *et al.*, 2008). The extension of the Northern line was recently announced that will add an extra 5 km to the tunnel network (Constructionenquirer, 2014). Simultaneously, GSHP installations are becoming increasingly common in the city and thus BHEs could eventually get closer in proximity to the running tunnels. A great example of a GSHP installation in close proximity to LU tunnels is the building called One New Change. The building consists in 52,000 m^2 of offices and retail space on eight floors. The geothermal scheme includes 219 energy piles of up to 38 m deep and 2.5 m in diameter. To complete the hybrid GSHP system there are a pair of deep water wells to 140 m into the chalk. The GSHP system's total heating and cooling capacity is respectively 1.6 MW and 1.7 MW. The nearby LU Central Line tunnels run parallel to the northern boundary of the site. The tunnels run approximately 20-25 m below ground level. The piles are located at least 7 m clear distance from the south of the tunnel closer to the site boundary.

3.3. The thermal environment of the LU railway

Since 2005 LU has used temperature sensors and data loggers to record the air temperatures at numerous platforms and stations. The recorded data showed that during summer peak-hour operation temperatures can reach as high as 26 and 32°C. On the other hand on a cold winter day the platforms could still be relatively warm as 20°C (Thompson *et al*., 2008). The work of Gilbey *et al.* (2011) showed that there is a linear relationship between platform and outside air temperatures and it can be expressed as $T_{platform}= 0.36 \times T_{outside} + 19.5$. The authors work also showed that tunnel temperatures are typically 2-3°C cooler than platform air temperatures. This was explained as being a result of the heat produced by the braking mechanism concentrating at the platforms.

3.4. Exploitation of the low grade energy from the earth surrounding the tunnels

The soil surrounding a typical deep level UR tunnel also contains a large amount of heat energy due to the heat sink effect that the ground provides the tunnel. This low grade energy could potentially be extracted by nearby BHEs. As these ground loops will eventually get closer in proximity to the tunnels the potential for heat recovery will become greater. However, there is a limit to how close structures can be constructed to the tunnels. The minimum proximity that LU allows is about 3 m in horizontal and 6 m in vertical directions (Transport for London, 2013) Researchers have reported different values within the literature, in terms of the distance of the thermal effects from the wall of an UR railway to the soil. Cockram and Birnie, (1976) measured the changes in soil temperature adjacent to running tunnels prior to opening the passenger traffic of the Victoria Line in London. Four years after the commencement of traffic, stable temperature conditions have not yet been reached and 9.1 m from the tunnel the clay temperature continued to rise. The work of HU et al.,(2008) suggests that thermal effect from the wall of an UR tunnel built in silty clay could be up to 20 m. This means that the 136 km long deep bored tunnel sections with a diameter of 3.7 m, could potentially provide significant volume of earth, perhaps over 200 million m^3, containing a significant amount of low grade energy for potential exploitation by nearby BHEs connected to a heat pump. The heat pump may be connected to a third party's building or small-scale district heating system. Figure 5 illustrates the schematics of such heat capture, transfer and use.

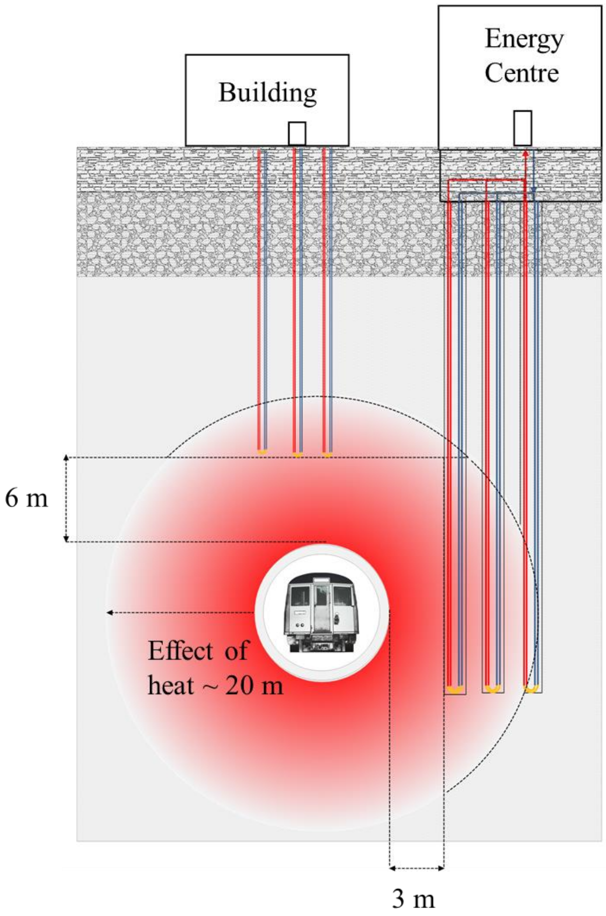

Figure 5 Heat removal from the ground surrounding the tunnels

4. INDENTIFIED GAPS

A number of models related to URs and GSHPs have been previously reported. Also several tools exist that allow engineers to mathematically model aspects of the subway environment or the operation of a GSHP system. However the literature lacks a combined analysis of the two schemes. Implementing previously developed modelling approaches for GSHPs and URs within the same simulation environment would make it possible to study the interactions of the two systems. Once a better understanding of such interactions is achieved, a detailed investigation and characterization of the most viable energy capturing and supplying solutions will be required. Additionally, identification of the key parameters that influence the interactions and the development of rules-of-thumb and designer aids are also needed to provide guidance to engineers working in fields where these interactions occur.

5. INITIAL INVESTIGATION

Given the limited exploration of the interactions of GSHPs and URs in current literature, a numerical investigation was conducted by the authors. The objective of the preliminary investigations was to establish key phenomena for more comprehensive research. The time dependent FE model was built with the software package COMSOL Multiphysics (*COMSOL Muliphysics*, 2015). The model was built in two dimensions with a simulation period of 6 years. London was chosen as a case study, thus the geometrical parameters, material properties, initial, boundary and working conditions implemented within the model were based on typical conditions for the UK capital city. Summary of the preliminary model conditions is shown in **Table 3.** Further details of the model development, validations and simulation results are explained in Revesz *et al.*, (2015).

Table 3 Initial, boundary and operating conditions of the preliminary model

Soil	The initial ground temperature within the soil domain was set based on the average UK geothermal gradient.
	A time dependent temperature boundary was applied on the surface of the soil domain based on London’s monthly average air temperatures.
	The lateral boundary of the soil domain was assumed to be adiabatic.
BHE	The fluid flow within the pipes of the BHE was ignored and instead a time periodic heat flux boundary was applied on the entire wall surface of the BHE. The maximum heat load per unit BHE length is taken to be 20 W/m. This value matched the operational performance the central London GSHP installation site at London South Bank University.
Tunnel	A time dependent temperature boundary was applied to the wall of the tunnel. This was based upon the work of Gilbey *et al.*, (2011).

The initial model was used to investigate the temperature variation at a point on the wall of the BHE in response to changes in the proximity of the tunnel. The horizontal distance between the tunnel and the BHE wall was varied between 50 and 3 m. The results of the BHE wall temperatures are plotted in Figure 6. The figure shows as the tunnel gets closer to the BHE the temperature changes at the wall of the BHE are more significant. A maximum temperature, 34°C at the BHE wall, was achieved when the proximity between the tunnel and the BHE was reduced to 3 m. Increased BHE wall temperatures improve the heat pump CoP for heating applications. In contrast, high BHE wall temperatures are likely to reduce the efficacy of the GHSP operating in cooling mode. The main outcome of this preliminary investigation was that interaction between GSHPs and URs is a genuine phenomenon. It is therefore worth further research to promote energy efficiency in GSHP installations. It is reasonable to conclude that there are other significant parameters which impact the interactions and identifying these will be the initial objective of our further research.

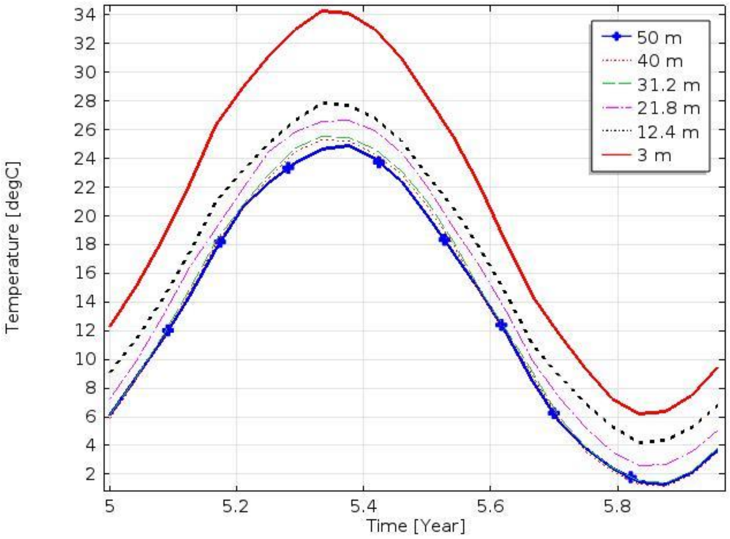

Figure 6 BHE wall temperatures versus tunnel proximity

6. CONCLUSIONS

Due to their high operating efficiencies, concerns about carbon emissions, and the highly incentivised nature of GSHPs, the technology has become an increasingly common choice for heating and cooling many types of buildings. In addition to the conventional heat sources, there are alternative options, such as the low- grade heat generated by URs. The soil that surrounds the railway tunnels also contains significant quantities of heat energy. This low grade energy could give an opportunity for a year-round heat supply for nearby users of heat. There is a comprehensive literature available regarding how to extract heat directly from URs, for example by placing heat exchangers within existing ventilation shafts. The literature however lacks exploration of the potential for recovering heat through the ground surrounding the tunnels via nearby ground heat exchangers. In order to explore this potential in detail, the interactions of GSHPs with neighbouring UR tunnels must first be fully understood. Investigation of such interactions requires mathematical modelling. A number of modelling approaches have been developed separately for schemes with a different level of complexity. These approaches could potentially be used for the combined analysis of the two systems. Since both URs and BHEs modelling involves complex geometrical aspect ratios and transient phenomena, the use of numerical solution methodologies are preferable. A number of numerical simulation platforms exist that would be suitable for such combined analysis. Investigating the interactions using London as a case study is a practical choice since the tunnels of the LU railway are running beneath a significant part of the central area of the city. Simultaneously, GSHP installations are becoming increasingly common in the city, thus ground heat exchangers will eventually get closer in proximity to the tunnels. Understanding the interactions between URs and nearby GSHPs would help to identify how the energy generated and eventually dissipated to the ground by urban railway systems could contribute to sustainable city planning. Key outcomes from a preliminary investigations demonstrated that interaction occurs between GSHPs and URs and therefore this field is worth further research to promote energy efficiency in GSHP installations.

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