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Thermal and mechanical aspects of the response of embedded retaining walls used as shallow geothermal heat exchangers

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ABSTRACT

Engineering structures embedded in the ground can be utilised as the heat exchange circuit in shallow geothermal energy systems. Thermally-activated retaining walls supporting the sides of tunnels and basements have been completed in a small number of projects but limited operational information has been published. Such information that is available suggests that in tunnels, climatic temperature changes may dominate the thermo-mechanical response of the wall system. This article first presents an overview of thermally-activated retaining wall behaviour and observations of tunnel environments generally, which points to the importance of the tunnel/air void characteristics in the thermal performance of such systems. In a numerical study it is shown that the main mechanism for heat exchange is between the air-void and the wall rather than the ground and that the thermal characterisation of the boundary between the wall and the air void requires greater scrutiny, to ensure realistic predictions of energy performance. The numerical study also shows that changes to the wall mechanical response are dominated by seasonal temperature changes, and using the wall for heat exchange has a rather small effect. It is apparent that these seasonal changes are not insignificant and their magnitude is also a function of the ratio of the coefficient of thermal expansion of the structural elements and that of the surrounding ground, and should be considered in design.

1. Introduction

The use of shallow geothermal energy systems that employ heat-exchange loops within trenches and boreholes is well established. Annualized growth in this energy sector from 1995 to 2010 has been estimated to be 20% [28]. However, as a consequence of the economic crisis, growth rates reduced to around 13% annually in the period from 2005 to 2015, data from Lund and Boyd [29]. 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 and since the mid-1990s, retaining walls also [12]. Energy geo-structures are now common in Austria, Germany and the UK. However, the uptake of these alternative means for facilitating heat exchange with the ground has been impeded by a lack of technical evidence regarding the impact of the thermal cycles on the serviceability and safety performance of the geostructures.

1.1. Embedded walls as heat exchangers

A number of cases now exist where embedded retaining walls have been used as energy geostructures (EGS), here termed EGS walls. Brandl [12] described the use of EGS walls at a rehabilitation centre in Austria and Section LT24 of the Lainzer tunnel near Vienna, both of which involved the use of piled retaining walls, and underground stations on the Vienna Metro U2 line that used diaphragm walls. Suckling and Smith [41] describe the first use of EGS walls in the United Kingdom where an installation at Keble College, Oxford included a thermally-activated, bored pile retaining wall in addition to thermally-activated bearing piles. A bored pile type wall was also used in a shallow geothermal energy system installed in the Palais Quartier development in Frankfurt, Germany [24]. Amis et al. [3] describe the UKs first thermally-activated diaphragm wall system that was constructed for the new Bulgari Hotel in Knightsbridge, London. Diaphragm walls and bearing piles formed as part of the construction for the new Shanghai Museum of Natural History have been thermally-activated to provide heating and cooling to the museum [44]. Several underground stations along the route of the new underground railway line being built in London have

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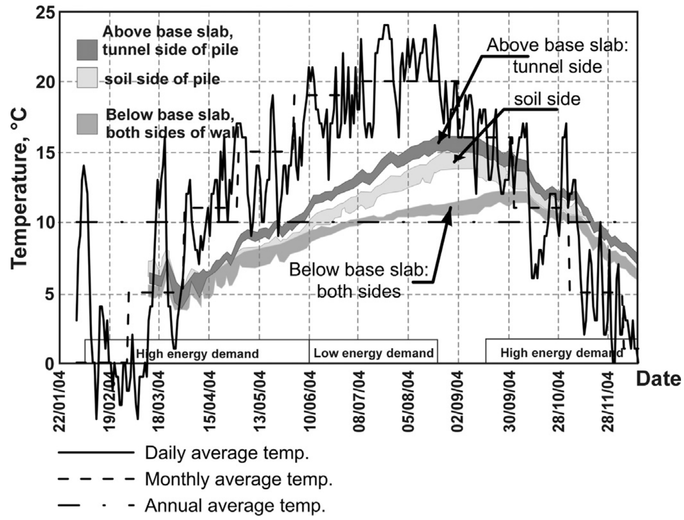

Fig. 1. Temperature variations observed in EGS wall of LT24, Lainzer tunnel, after Brandl [12] and www.wunderground.com/history/airport/LOWW/.

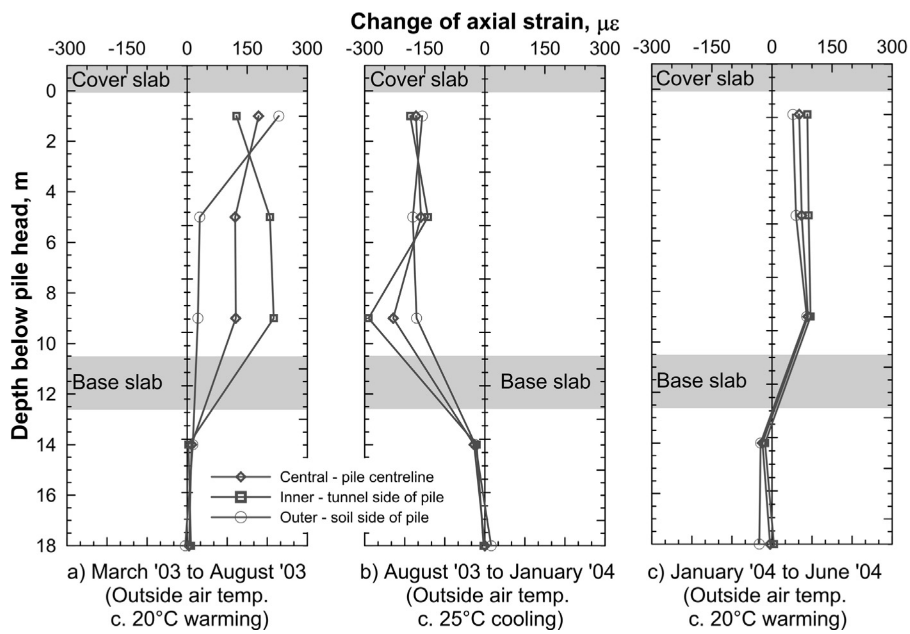

Fig. 2. Variations in wall axial strain prior to and during heat pump operation (started Feb. 2004), Bourne-Webb [10] adapted from Brandl [12]. Note: tension strain is positive.

thermally-activated retaining walls (and bearing piles) to provide heating to future over-site developments [4].

Heat exchange between the pipes embedded in EGS and the ground (and adjacent air voids in the case of tunnels and basements) is influenced by a variety of factors, not least of which is the temperature gradient between the heat exchange loops and the surrounding soil/air, and the time interval over which the heat exchange occurs. For diaphragm and piled walls used as heat exchangers, a value of 30 W/m^2 for the potential heat flow has been suggested for feasibility studies, Brandl [12]. However, observations from the Lainzer tunnel suggest that this is achievable only for short time periods and/or when the temperature differential is high [22]. In winter (heat extraction), the heat exchange potential fell to 10–15 W/m^2 for intervals greater than 1 day while in summer (heat injection), the temperature differential was higher and heat transfer in excess of 30 W/m^2 were reported for intervals out to 2 months. Clearly, when undertaking an initial assessment of the use of embedded walls as heat exchangers, the potential heat exchange must be assessed carefully and there is a need for more substantive evidence to provide guidance in this decision.

As with the thermal performance data, little data relating to the thermo-mechanical performance of EGS walls have been published. Temperature and axial strain data from overlapping periods around the start of the heat pump system in Section LT24 of the Lainzer tunnel in February 2004 were presented by Brandl [12] and form the only known data set in the public domain. The installed demonstration system was used to provide heat to an adjacent school; however, despite continuous operation with a “high energy demand” (70 MWh between February and June 2004, Adam and Markiewicz (2009)), temperatures within the wall piles rose in line with seasonal changes when cooling might be expected, Fig. 1. The observations also show that during periods of high energy demand, the temperatures across the wall section and over the height of the wall were relatively uniform, whereas in periods of low or no energy demand (June to September 2004), there were differences of about 2 °C across the wall section, less below the base slab, Fig. 1. Tunnel-side wall temperature observations are up to about