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Session 3 Report: New Technologies and Applications; Materials and Equipment in Near Surface Geothermal Systems

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ABSTRACT: This paper presents an overview of new technologies and applications on thermo-active geotechnical structures. A discussion session on issues involved with near surface geothermal systems is presented, focusing on opportunities for developing new technologies to address these issues. In addition, opportunities for new applications of geothermal heat exchange in geotechnical engineering were discussed. Progress on the development of new materials and equipment that may be used to enhance the rate of heat transfer or heat storage capacity were discussed.

KEYWORDS: Geothermal, heat exchange, materials, equipment, bridge deck deicing

1. Introduction

Near surface geothermal systems present an increasingly common method of taking advantage of the thermal storage capacity of the ground, exploiting the ground's capacity to collect heat energy, and provide geothermal energy for heating of associated structures. The use of these systems leads to a reduction in carbon-based energy use, carbon emissions, and operational costs. As near surface geothermal systems have become more common, new technologies and applications have emerged. These applications make use of the high thermal storage capacity of both concrete and the ground. In addition, most of these systems are already needed for structural

purposes, which make them economically more appealing. The main objectives of the session were to identify existing and new technologies related to near surface geothermal systems and to discuss the new materials and equipment used in these systems.

2. Seasonal Thermal Storage

Geothermal energy use from near surface geothermal systems is commonly used in two modes: heat extraction only, or alternating seasonal operation with heating and cooling requiring both extraction and injection. Heat-extraction-only systems are commonly used for residential systems in cold climates and rely on the heat extracted during the winter being replaced by heat conducted from the surrounding ground and from the earth's surface. This is possible because these systems typically use sparsely-spaced ground heat exchangers. Alternating-seasonal-operation systems are used to provide both heating and cooling for residential and commercial buildings. In these systems, some degree of energy equilibrium is attained through the seasonally alternating heat rejection and extraction (Adam and Markiewicz, 2009). However, if the imbalance between heat rejection and extraction is too large the system performance can be impaired by ground temperatures rising or falling year after year. System imbalances can be ameliorated in some cases by spreading out the ground heat exchangers or managing the load by, for example, utilizing excess heat to serve another load such as heating domestic hot water.

For systems operating in the alternating seasonal operation mode, the ground is used as a heat sink in the cooling season. The thermal energy is stored in the ground as shown in Figure 1(a). Depending on internal heat gains and solar heat gains, some buildings may require heating during the spring and fall shoulder seasons; others may not, as illustrated in Figure 1(b). Buildings requiring heating during the shoulder seasons will start drawing on the thermal energy stored in the ground. Finally, during winter the thermal energy that was stored during summer is used to heat the buildings. In case the heating energy demand is higher than the amount that was stored, the additional need will be met by heat conducted from the surrounding ground, thereby lowering the ground temperature as shown in Figure 1(c). Conversely, if the summer heat rejection is higher than the winter heat extraction, excess heat will be conducted into the surrounding ground, thereby raising the ground temperature.

3. Near-Surface Geothermal Energy Applications

In many countries, especially Germany, Austria and Switzerland, near-surface geothermal energy applications have expanded from thermo-active piles to many other types of near-surface and deep foundation systems. These applications include piles, diaphragm walls, tunnel linings, anchors, sewers, basement walls, and basement slabs. Further, opportunities to investigate phase change materials are being considered. Some of these systems (such as thermo-active piles) are not necessarily new technologies, but are included below for both completion and to show how this technology has evolved over time.

3.1. Thermo-active piles

Thermo-active piles were the first type of thermoactive geotechnical technology due to the ease with which circulation tubes can be added and their resemblance to typical borehole heat exchangers (BHEs). Their popularity is continuing to increase, as shown in Figure 2, which

displays the number of thermo-active pile installations in Austria since 1984 (Brandl, 2006). Because of this trend and the age of thermo-active pile technology, there is a significant amount of literature on thermo-active piles. Several projects involving full-scale thermo-active piles have been performed, as summarized in Table 1, focusing on thermo-mechanical effects, thermal effects, and numerical modeling.

A descriptive framework on thermo-mechanical aspects of thermo-active piles are presented in Amatya et al. (2012) and Bourne-Webb et al. (2012) where an idealized soil with uniform strength, a linear elastic pile with constant cross sectional area, and uniform temperature change along the pile are assumed. Various end-restraint conditions are considered in these papers, one of which is shown in Figure 3. It represents the case of a pile with no significant tip resistance subject to heating. The first part of the figure shows the case with only an imposed structural load, which results in upward skin friction and compressive axial forces along the pile. As the temperature in the pile increases (due to heating), it tends to expand about its neutral point in proportion to its coefficient of thermal expansion and amount of temperature increase. The neutral point is the depth where no displacement occurs. For a pile free at both ends and embedded in a soil with uniform stiffness, the neutral point is found at the mid-depth. The portion of the pile above the neutral point moves upward and the portion of the pile below the neutral point moves downward. Due to the relative movement of the pile with respect to the surrounding soil, downward shaft friction above the neutral point is mobilized. In addition, part of the pile expansion is restricted by the surrounding soil or by the structural load on top, which induces axial compressive stresses along the pile. The combined effects of structural and thermal loads is shown at the far right in Figure 3. It can be seen that a temperature increase in the pile causes a decrease in the shaft resistance in the upper portion of the pile and an increase in the lower portion. The compressive axial load along the pile then increases due to the restricted expansion of the pile.

3.1.1. Field Tests

Two pioneering thermo-mechanical field tests on thermo-active piles were performed in Switzerland and in the UK. In Switzerland, a field test was implemented during the construction of a new building at École Polytechnique Fédérale de Lausanne (EPFL). Thermal loads were applied to an thermo-active pile under a four-story building at the end of the construction of each story to couple the mechanical and thermal loads (Laloui et al., 2006). During these tests a maximum temperature increase of 22°C was applied to the pile after which the pile was left to cool naturally. Thermo-elastic linear strains during heating, an increase in axial load (the thermo-mechanical load being double that of the mechanical load), and shaft friction mobilization due to thermal load are reported by the authors.

In the UK, heating-cooling cycles were applied to an thermo-active pile under a maintained mechanical load for a period of seven weeks (Bourne-Webb et al., 2009; Amatya et al., 2012). The results are presented for both the test pile and the heat sink pile which had opposite heating-cooling episodes. At the end of the cooling cycle, a temperature decrease of 20°C in the test pile and a temperature increase of 29.4°C in the heat sink pile was observed. After the heating cycle, the temperature in the test pile increased 10°C. The authors reported that an increase in compressive axial forces during the temperature increase was also observed and should be

accounted for in design if the resulting forces are too close to the structural limits imposed by design codes. Temperature changes along the test pile also resulted in changes to the mobilized shaft resistance, which was not expected to cause a significant, permanent displacement of the test pile. However, the authors added that closer examination is required to determine if the factor of safety with respect to the mobilized shaft resistance is too low.

Amatya et al. (2012) synthesized the results from the EPFL and Lambeth College sites and examined the effect of temperature changes on the axial stresses and mobilized shaft resistance. The variation of thermally induced axial stresses during heating for the Lambeth College heat sink pile and the EPFL test pile during Test 1 are shown in Figure 4. In both of these tests, the piles were unrestrained at the head, and did not have a structural load applied from the surface. For comparison, the thermally induced axial stresses for a fully restrained pile are also presented. The maximum induced axial stresses are at a depth of 17 m (55.7 ft) for the Lambeth College pile and at a depth of 21.5 m (70.5 ft) for the EPFL pile. The maximum induced axial stresses are less than the ones for fully restrained piles, which shows that some expansion in both piles occurred. The variation of mobilized average shaft resistance during heating for the same piles are shown in Figure 5. For the Lambeth College heat sink pile, negative (downwards) shaft resistance is observed until a depth of 17 m (55.7 ft), after which the mobilized shaft resistance is upwards. For the EPFL test pile, negative shaft friction is observed to a depth of 21.5 m.

In addition to these pioneering studies, field tests focusing on the characterization of the thermo-mechanical behavior of thermo-active foundations in different climates and soil profiles have been performed in the United States (Olgun et al. 2012; Murphy et al. 2014a, 2014b; Akrouch et al. 2014) and Australia (Wang et al. 2012). These studies provide additional information on end restraint boundary conditions and the role of different soil stratigraphies that can be used to calibrate numerical models in the future.

3.1.2. Numerical Modelling

Numerical modelling of thermo-mechanical behaviour of thermo-active piles was performed in several studies. Laloui and Nuth (2006) developed a thermo-hydro-mechanical model for saturated porous media to model the behaviour of thermo-active piles and the surrounding soil. The authors validated the model by using the results of the thermo-mechanical field test performed at EPFL, which was mentioned before. A method for the analysis of thermo-active piles based on the load-transfer approach was then developed by Knellwolf et al. (2011) and was validated by using the results of the thermo-mechanical field tests at EPFL and Lambeth College. Ouyang et al. (2011) also developed a model using existing hybrid load transfer approaches and modifying them to couple the thermal response. The Lambeth College test results were simulated by using the developed model. Wang et al. (2014) developed a fully-coupled finite element model to evaluate the role of thermally-induced water flow in unsaturated soils surrounding thermo-active foundations during heating.

3.1.3. Case Studies of Challenging Applications of Thermo-active piles

This section provides examples of full-scale energy-pile installations that addressed interesting challenges on a full-scale basis. In the project PalaisQuartier located in Frankfurt, Germany, 262

of the 302 foundation piles and 130 of 543 retaining wall piles were thermo-active piles (Katzenbach, 2013). The foundation piles were a maximum of 1.86 m (6.1 ft) in diameter and 27 m (88.6 ft) in length. The retaining wall piles were a maximum of 1.5 m (4.9 ft) in diameter and 38 m (124.7 ft) in length. Figure 6 shows the plan of the project. The piles marked in red show the thermo-active piles and the blue lines show the groundwater flow direction which is from northwest to southeast.

The temperature contours along a horizontal cross-section of Frankfurt Limestone during winter operations are shown in Figure 7. As can be seen in the figure, the areas with high thermo-active pile density have the highest thermal influence. Heat extraction during the winter resulted in the lowest temperature in the area where there is an abundance of thermo-active piles. It can also be seen in Figure 7 that the greatest migration of the thermal influence was in the groundwater direction.

The temperature variations along axis-B (which is marked in Figure 7) for summer and winter operations in the Frankfurt Clay and Frankfurt Limestone are plotted in Figure 8. Axis-B cuts through the retaining wall where some of the piles were used as heat exchangers. During summer operation, due to thermal energy storage in the ground, the ground temperature in the vicinity of the retaining wall increases up to 24°C. On the other hand, for winter operation, the temperature of the ground decreases to 14°C as a result of thermal energy extraction. The effect of heat exchange operations diminishes with distance from the retaining wall as shown in the plot.

Another case study is reported by Brandl (2006) where thermo-active piles were used to heat and cool a rehabilitation centre at Bad Schallerbach, Austria. 143 out of 175 retaining and foundation piles with depths ranging from 9 m (29.5 ft) to 18 m (59.1 ft) were equipped with absorber pipes to be used as thermo-active piles. One of the foundation piles was fitted with various sensors (pressure cells on the pile toe and head, fissuremeters, temperature sensors) to monitor the effect of temperature changes during operation of the heat pump system. The authors reported that the thermo-active piles have been in operation since 1997 and long-term monitoring of the temperature shows typical seasonal fluctuations, with maximum temperatures during summer and minimum temperatures during winter. In addition, it is observed that operational temperatures between -2 to -3°C caused the formation of ice lenses in the ground with a maximum frost depth of 15 cm (5.9 in). Other projects in Vienna where thermo-active piles were used are reported as being Strabag Office Center (2002), Columbus Centre (2002), Lainzer Tunnel (2002), and Vienna Metro U2 (2003) in Brandl (2006).

There have been several studies on the thermal behavior of thermo-active piles. Gao et al. (2008) described the characteristics of thermo-active piles that will be applied in an architectural complex in Shanghai. Thermo-active piles with different absorber pipe types (U and W-shaped) and flow rates are being experimentally and numerically evaluated. They reported that although the W-shaped absorber pipes have a higher cost, they are the most efficient type for practical applications. Wood et al. (2010) presented a case study of a residential building where 16 out of 21 foundation piles were used for heat exchange purposes. The thermo-active piles were 10 m (32.8 ft) in depth with a diameter of 30 cm (11.8 in) and were equipped with single U-type absorber pipes at the centre. Temperature changes in the thermo-active piles and the surrounding soil were monitored during the operation. It was observed that at 1 m (3.28 ft) distance from the

piles, the ground temperature decreases 2.5°C and at 2.5 m (8.2 ft) distance, the decrease was 1°C, due to heat extraction. At a distance of 5 m (16.4 ft), no temperature change in the ground was recorded. In addition, it is reported that when the heat extraction decreased, temperatures in the ground recovered quickly, probably as a result of potential water movement. Olgun et al. (2014) performed a finite element analysis on the long-term temperature distribution surrounding thermo-active foundations, and provided insight on how to maintain efficient heat exchange conditions in different climatic settings. Murphy and McCartney (2014) describe the thermal and thermo-mechanical behavior of a pair of thermo-active foundations evaluated over the course of two years of building operation, and found that the foundations provide sustainable heat exchange over time. However, the results indicate that thermo-plastic strains may be occurring due to thermal effects on the claystone bedrock at the site.

3.2. Diaphragm Walls

Diaphragm walls may be easier to convert to a dual purpose use than piles. There are no limitations for the depth of a diaphragm wall in terms of the absorber system installation and it is known that the energy potential increases with depth. This makes the deeper diaphragm walls more advantageous, which also holds true for the other thermo-active systems (Brandl, 2006). There are already various applications of thermo-active diaphragm walls in Austria. Brandl (2006) summarizes some of these applications as shown in Table 2.

The Arts Centre in Bregenz consists of perimeter diaphragm walls with a maximum depth of 28 m. The Uniqa Tower in Vienna is founded on diaphragm walls with a maximum depth of 35 m (114.8 ft). In this project, 7800 m² of thermo-active diaphragm walls were used for wall and floor heating, as well as cooling (Adam and Markiewicz, 2009). Another example of thermo-active diaphragm walls is the Viennese Metro line U2, where the stations are constructed by the cut and cover method. The absorber pipes are installed in diaphragm walls, which comprise an area of 11200 m². A feasibility analysis showed that the geothermal energy extraction/storage only had an influence on the surrounding soil within a few meters. The first thermo-active diaphragm wall in the UK was constructed in 2010, at Bulgari Hotel, Knightsbridge. The panels were up to a depth of 36 m (118.1 ft) and were equipped with two geothermal loops placed on the side of the surrounding soil (Laloui and Di Donna, 2013). Other applications of diaphragm walls are 6000 m² and 12400 m² of thermo-active diaphragm walls in the Generali Office Tower and Columbus Centre, respectively. (Brandl, 2006). As seen in the above examples, although there have been practical case studies, there has been less research for thermo-active diaphragm walls than thermo-active piles.

3.3. Tunnel Linings, Metros and Metro Stations

Tunnels have tremendous heat exchange potential due to their large surface interface with the surrounding ground. They represent a unique opportunity to access shallow geothermal energy, however, there are also many related challenges. The advantages of thermo-active tunnels are listed as follows (Brandl, 2006):

- The seasonal ground temperature is widely constant where the tunnels are constructed.

- Tunnels have large surface interface with the surrounding soil which favours the extraction and storage of geothermal energy.
- Geothermal energy utilization from tunnels is environmental friendly and economical.

For cut and cover tunnels, the methods that are already established for thermoactive bored piles, diaphragm walls, and base slabs can be employed. For tunnels that are bored with tunnel boring machines (TBM), tunnel linings present a relatively easy and efficient way of installing a geothermal system as many linings are prefabricated and the loops can easily be integrated. For bored tunnels that are constructed by the New Austrian Tunnelling Method (NATM), energy geosynthetics are being used. A list of thermo-active tunnels is presented in Table 3. The Lainzer Tunnel in Vienna represents a case using both cut and cover and NATM techniques. For the LT24 testing plant, 59 thermo-active piles were used for the cut and cover portion. NATM was used to excavate the LT22 testing plant, where a new technology had to be developed for the thermo-active linings. Absorber pipes were first attached to a non-woven geosynthetics off site and then placed between the primary and secondary linings of the tunnel (Adam and Markiewicz, 2009). Demonstrator project in Jenbach, Austria is an example of thermo-active tunnels where tunnel boring machine (TBM) was used for construction. In this project, 54 m length of the 12 m diameter twin-track, high-speed railway tunnel was converted to be used as geothermal heat exchanger system. The 20 mm diameter heat exchanger loops were attached to the reinforcement cage of the prefabricated concrete segments to supply 40 kW heat energy to the municipal building above the tunnel (Franzius and Pralle, 2011).

As mentioned in Brandl (2006), underground metro tunnels can be a significant source of heat due to the waste heat from transportation. By accessing this heat, not only does it provide efficient heating elsewhere, it reduces the heat in the tunnel making travel more comfortable for passengers and requiring less energy for air-conditioning. A case study is presented in Unterberger et al. 2004, where an extension of Viennese Metro Line U2 was designed for heat exchange purposes. Diaphragm walls, base slabs, and piles were used for this purpose and the details of each separate element are already/will be given in the corresponding sections of this document.

Although tunnels and metro stations represent an innovative way of accessing the geothermal energy, there are still pending questions on their thermo-mechanical behaviour. In conventional tunnels, the linings are already under intense stress, especially at the joints. In thermo-active tunnels, the temperature increase resulting from accessing geothermal energy causes additional stress on tunnel sections and joints which must be considered by the structural engineers. Equilibrating the temperature between outside and inside of tunnel to reduce stresses is a possible solution to this problem however, more research is necessary.

3.4. Anchors

Anchors extending deeply into the surrounding ground represent favourable conditions in terms of heat exchange operations. However, they can be difficult to convert to a dual purpose use because of the high stresses involved. Vienna University of Technology conducted research for developing energy anchors to be used in conjunction with tunnels and retaining walls. Energy anchor prototypes were produced and tested in the laboratory (Adam and Markiewicz, 2009).

Mimouni et al (2014) used a 2D finite element analysis to explore the potential of using heat-exchange anchors with a cut-and-cover tunnel. The advantage to using heat exchange anchors with a cut-and-cover tunnel as opposed to a bored tunnel is that the heat exchange operations will not begin until after the anchors are no longer needed structurally. The analysis considered several cases including anchors in saturated and unsaturated SP soil, saturated NP soil, and different heat extraction cycles. Table 4 summarizes the results.

Based on the results above, the authors also determined the efficiency of incorporating seasonal heat storage by taking the difference of extracted heat from the heat injection/extraction and extraction only cases and dividing by the amount of heat injected. Those values are given in the Table 5 below.

3.5. Sewers

The experience of thermo-active tunnel systems can be applied to sewer tunnels and fresh water lines to equip them with absorber pipes from which heat can be extracted. One of Vienna's main sewer lines, with a diameter of 1.6 m (5.2 ft), was equipped with heat exchanger technology to be used to heat and cool an adjacent plant building (Adam and Markiewicz, 2009).

3.6. Basement Walls and Slabs

Basement walls and slabs are less effective in terms of heat exchange compared to other geothermal structures like tunnels, piles, and diaphragm walls. However, they are advantageous in terms of low cost and ease of application especially when they are situated in temperate environments. Brandl (2006) defined the construction sequence for base slabs as follows:

- First lean concrete layer is poured on the ground
- Wire mesh is placed to facilitate fixing of the absorber pipes
- Absorber pipes are installed
- Second lean concrete layer is poured to protect the absorber pipes
- Reinforcement is placed followed by the casting concrete

The U2 Viennese metro line in Vienna is an example where absorber pipes have been installed in base slabs (Unterberger et al., 2004). The base slabs of the four stations are being used as heat exchangers to heat the lounges and salesrooms in the stations as well as cool the transformer and engine compartments. The absorber pipes, which are already installed in the piles and diaphragm walls for the excavations, are placed below the base slabs.

Thermo-active basement walls have been used in small houses in the United States for the last 4-5 years. However there are still questions on their construction, including the insulation scheme required to prevent heat loss through the wall into the building. Dr. Spitler's experience on basement walls that are being used in Tennessee, USA shows that the heat loss to the inside is a few percent of the heat exchanged with the soil. In this case, the absorber pipes were placed about 100 mm (3.9 in) from the outside of the wall.

Similar to the other near surface geothermal systems, heating and cooling operations will result in additional stresses along the base slabs and basement walls, which should be taken into

consideration when designing them for heat exchange. In addition, it is reported by Brandl (2006) that excessive heat extraction may result in soil freezing and can cause heave in the base slabs.

A proper design should also consider the insulation of the base slabs and basement walls depending on the application. A numerical simulation was performed at EPFL to investigate the necessity of insulating the slabs. It was concluded that the influence depth of the slab is 4 m (13.1 ft) and the impact of insulation is significant.

4. Areas of Research

4.1. Improving Soil-Heat Exchanger Interaction

- Reduction in circulation pipes : Spiral loops perform measurably better than U-tubes. This can also be as a result of the reduced number of connections. PEX pipe (REHAU everlock) has permanent mechanical connection compared to electrofusion of HDPE. However bending radius is an issue with PEX pipes.
- Increasing thermal conductivity of concrete : This is an important area of research on new materials such as using alternative aggregates – Flint (silicate) aggregates can increase thermal conductivity of concrete possibly allowing reduced number of loops or heat exchanger length.

4.2. CO₂ Geothermal Heat Exchangers

CO₂ geothermal heat exchangers use CO₂ as the heat carrier fluid in a closed system. The system requires steel or copper pipes along with corrosion protection but provides a major advantage for heat-extraction-only systems in that no circulation pump is necessary as the entire system is driven by convection within the pipe. A disadvantage to this system is that it does require additional equipment, which can become burdensome. The size of these systems is typically small, so unless further developments are investigated, these systems may also not provide the full heat exchange capacity needed for a building.

5. Alternative Uses

There are applications beyond the traditional heating and cooling of buildings that near-surface geothermal systems may be especially suited for.

5.1. Bridge Deck Deicing and Temperature Control

Bridge decks are prone to freeze before the rest of the road resulting in potentially dangerous driving conditions for motorists. Additionally, as a way of preventing accumulation of frozen precipitation on bridge decks, transportation authorities often use deicing salts and other harmful chemical agents that lead to accelerated bridge deck deterioration and environmental pollution. Thus, near-surface geothermal systems that utilize the bridge's foundation and/or approach embankment could be used to regulate the bridge deck's temperature during the winter.

Near-surface geothermal energy has been used in bridge deck deicing, though not on a large scale and not using thermoactive foundations. Rather they have used the traditional BHEs. Minsk (1999) reports of a bridge in Texas (U.S.A.) using BHEs and Liu et al. (2007a) developed an experimental bridge deck that was heated using geothermal energy. The SERSO bridge in Switzerland used BHEs to access a rock mass of 46,000 m³ for thermal storage and heating (Dupray et al., 2014).

There are two kinds of geothermal bridge deck deicing systems, active and passive (Olgun and Bowers, 2013). Active systems incorporate the use of a heat pump and use the geothermal energy to more efficiently heat the circulating fluid. Passive systems, however, rely on the geothermal energy from the ground alone to heat the fluid, thus the circulating fluid temperature is close to the ground temperature. Passive systems are ideal in that they are simpler and require considerably less energy to operate by requiring electricity only for operation of the fluid circulation pumps as opposed to heat pumps as well (active systems).

The research questions related to bridge deck deicing using energy foundations are:

- Is the foundation able to access enough thermal energy to facilitate efficient operation of the system? This is especially critical for passive systems.
- Does the heating/cooling of the foundation compromise its load carrying ability?
- Can enough energy be collected during the summer to recharge the ground and allow for balanced operation of the system? Or could the ground temperature possibly be raised and allow for more efficient operation of the system?

5.1.1. Experimental investigation

Bowers and Olgun (2015) have experimentally studied bridge deck deicing using thermo-active piles under a passive system. They report results from several tests that occurred during the 2013-14 winter. The experimental setup consists of a 3.1 m x 2.4 m bridge deck connected to four 33 m thermo-active piles. Half of the deck contains circulation tubes spaced 20 cm apart and the other half of the deck contains circulation tubes spaced 30 cm apart. However, only the 20 cm side was operated using one of the four thermo-active piles during the experiments. The other side of the slab was left alone to be used as a control.

One experiment occurred during a period of extremely cold weather where the temperature dropped to as low as -20°C at night, which is much colder than typical for Blacksburg, VA (USA). Figure 9 shows the temperatures in the bridge deck slab during this time. There is an obvious difference as great as 15°C between the surface temperatures in the heated and unheated slabs, indicating the system works. However, at no point does the surface temperature of the heated slab reach 0°C or higher, meaning that if any precipitation were to accompany this cold weather, it would accumulate on the surface. Thus there are clear operational limitations to these systems.

The pile and ground's response at various depths is shown in Figure 10. Notice that the temperatures in the pile reach near steady state despite the extremely cold weather. The reason the temperatures are different at different depths is explained in Bowers and Olgun (2015).

Additionally, after operation, the temperatures in the pile recover and approach the initial temperature. The temperatures in the ground at a location of 1.7 m from the pile (at the same depths) show a delayed decrease, but also begin to recover after operation of the system. The net temperature difference in the pile is only 6°C, which would not accumulate significant thermal stresses.

The system performed well in another test during more moderate weather conditions. On January 21, 2014 beginning around 11AM and continuing until 4PM, approximately 6.6 cm (2.6 in) of snow fell. The system was turned on in advance of the storm at 7AM. Figure 11 shows a comparison of the surface temperatures of the heated and unheated bridge deck slabs during a moderate winter storm. The system was turned on when both the heated and unheated surfaces of the deck were decreasing. After beginning operation, the heated deck surface temperature increased to approximately 4°C by the time the snow started to fall and maintained a temperature above 4°C for the duration of the event. The unheated deck maintained a temperature around 0°C. The system was able to keep the deck completely snow free for the entire duration of the experiment, whereas snow accumulated on the unheated side of the slab and the control slab (Figure 11).

5.1.2. Numerical investigation

Bridge deck deicing using geothermal energy has been explored numerically by several authors. Olgun and Bowers (2013), Liu et al. (2007b), and Chiasson and Spitler (2001) have explored bridge deck deicing using 2D and 3D models. The studies from Liu et al. (2007b) and Chiasson and Spitler (2001) have examined it in connection with a ground-source heat pump and have developed an elaborate, yet efficient, snow melting algorithm that can be used in these models.

Olgun and Bowers (2013) examined the operational limitations of ground source bridge deck deicing systems by assuming a constant inlet fluid temperature. They then used a 3D finite element model to determine how long it would take the average surface temperature of the bridge deck to reach 0°C under different atmospheric conditions and using different design scenarios. Some of the results are shown in Figures 12 and 13.

Dupray et al. (2014) have looked at bridge deck deicing using thermo-active piles from the foundation's standpoint considering both thermal recharge and ground water flow. The modelled foundation is for a 129 m bridge with a deck surface area of 1,350 m². Five of the six foundation pile groups consist of eight piles. The simulated foundation (which differs slightly from the actual foundation) consists of eight piles spaced 3.6 m apart with a 1 m diameter and an average length of 48 m. Dupray et al. (2014) used a thermo-hydro-mechanical finite element model to simulate several years of operation. They report both the temperature response and the mechanical response. If only groundwater flow is considered as the means by which the ground is thermally recharged, a design power of 37 W/m can be used without freezing the piles. The temperatures in the ground do not fully recover between operations in the finer-grained layers that have a lower permeability. The temperature change in the pile induces a positive change in vertical effective stress in the pile, with the central piles experiencing a larger change in stress than the lateral piles which is shown in Figure 14. When neglecting the effect of groundwater flow and considering only solar recharge, a design power of 53 W/m could be used, which is

higher than that of recharge by groundwater flow. Because the pile is being both heated and cooled, it experiences positive and negative changes in induced vertical stresses, which is shown in Figure 15. Most of the increases and decreases in stress occur at the onset of heat injection or extraction when the temperature gradients are the highest.

5.1.3. Thermal recharge and controlling bridge deck strain

Another factor leading to accelerated bridge deck deterioration is the cyclic expansion and contraction of the bridge decks during the summer as the temperature changes significantly from day to night. In this instance, near-surface geothermal systems can be used to keep the deck from experiencing temperature extremes while at the same time collecting heat energy to store in the ground for use in the winter. Spitler and Ramamoorthy (2000) have shown the cost benefits of using summer recharge in bridge deck deicing.

A question regarding the applicability of this technology is if the existing piles will access enough geothermal mass to heat the deck. The answer to that question seems to be dependent on location, for instance in Switzerland the number of piles generally is sufficient. But if they are not, the problem can be solved by installing additional borehole heat exchangers and taking advantage of seasonal thermal energy storage.

5.2. Airport Runways and Aprons

Near-surface geothermal energy would be especially applicable to airport runways for many of the same reasons mentioned in the bridge deck deicing section. Keeping the runways clear of snow and ice can be a very expensive and time consuming task for airports. Runways also provide a very large surface area for energy harvesting during months that it does not require snow melting. The energy could be potentially stored in the ground for use when it is required to increase the efficiency of the system.

Boris et al. (2009) developed a geothermal heating design for an airport as part of an undergraduate design competition. The system, which was implemented at the Greater Binghamton Airport in New York, USA heated a concrete apron. In this system, for every acre of heated pavement, 23,300 m of geothermal trenching was required to supply geothermally heated fluid to 18 heat pumps. The cost per acre was determined to be \$1.6 million with an annual cost of \$32,000. Over a 20 year life cycle, this is comparable to the cost of snow removal. However, what is not included in the cost of manual snow removal is all the money lost due to flight delays and cancellations (McCartney, 2014).

Some items to consider when applying near-surface geothermal energy to runways is that it may be a technology more suited for new runways or airports that are renovating due to the invasive nature. Also, the imperative to keep a runway free from snow or ice is much greater than the need to keep a rural bridge free from snow or ice, thus these systems must be robustly designed with backups in place.

5.3. Clay Thermal Consolidation

The thermal effects on clay is something that is becoming increasingly understood and is discussed further in the Session 4 report. Given the tendency of normally consolidated clay to contract under thermal loading, it is possible to extend near-surface geothermal energy technology to soil improvement with thermal consolidation.

5.4. Agriculture

5.4.1. Grain and Crop Drying

There are agricultural applications that are particularly suited to near-surface geothermal energy. Grain drying is a common process that increases the storage life of grains. However, it is also a process that requires considerable amounts of energy that is usually supplied by natural gas (Hansen et al., 2009). Several studies have demonstrated the efficiency and effectiveness of using heat pump systems to dry grain and other agricultural products (Wang and Chang, 2001; Kuzgunkaya and Hepbasli, 2007). However, the overwhelming majority of these systems are air heat pump systems (Goh et al., 2011; Colak and Hepbasli, 2009).

Wang and Chang (2001) studied the efficiency of GSHP grain drying systems and found the coefficient of performance (COP) to be 6.4 for the GSHP and 4.7 for the entire systems. Kuzgunkaya and Hepbasli (2007) also studied a GSHP drying system and determined the COP to be between 1.63–2.88 for the GSHP and 1.45–2.65 for the entire system. This is contrasted with a COP of 1.86 for an air-source heat pump drying system (Ceylan et al., 2006). The authors also reported that the performance of the system is highly dependent on the ground temperature, indicating that thermal storage is likely to benefit these systems. Also because of the unbalanced nature of these systems, there is potential to couple them with systems that are using the ground primarily as a heat sink and need to dissipate excess thermal energy to remain efficient. Such systems include metro tunnels and buildings constructed in cooling-dominated climates.

5.4.2. Greenhouse Heating

Another agricultural application is using near-surface geothermal energy to control greenhouse temperatures. By creating a controlled environment, greenhouses allow production of temperature dependent crops year-round. Several studies have reported successfully using geothermal energy to heat their greenhouses (Bakos et al., 2009; Wang et al., 2006). Bakos et al. (2009) considered several different geothermal systems for heating a greenhouse used to raise tulips. In one option geothermal fluid (in this case high temperature geothermal fluid of 100°C) was circulated directly through metal coils where the fluid transferred the heat energy to the air through forced convection with the use of fans. In the second option, the geothermal fluid was circulated in pipes that laid directly on top of the soil, thereby heating the soil and ensuring that the plants would not freeze. Although this application dealt with high temperature geothermal fluid, a GSHP could easily be used in connection with near-surface geothermal systems, which is still likely to be more economical than traditional fuel based heating systems.

6. Future Research

Although some of the near surface geothermal systems (thermo-active piles, diaphragm walls) have been used successfully for years, there is still room for further improvements in these

existing systems. Moreover, there is a great opportunity for developing new technologies and materials. The presentations and discussion sessions highlighted the following issues in this area:

- Further research is required to determine the interface heat transfer coefficient for tunnel linings. Furthermore, structural engineers should be involved in this area for determining and taking into account the additional stresses that develop at tunnel linings during heat exchange operations.
- There are still pending questions on the use of basement walls and slabs for the heat exchange operations including where to place the insulation in these elements and how to account for the additional stresses in their design.
- Several concerns also need to be addressed in relation to near-surface geothermal energy. The main one is groundwater safety. The burden is on geotechnical engineers, designers, and contractors to ensure and prove to the public and government agencies that these systems will not negatively impact the groundwater quality. Additionally, careful design, long-term monitoring, and innovation are required to ensure that these systems will not negatively affect the ground temperature. If loads are unbalanced there is a potential to significantly change the temperature of the ground, which is prohibited in some localities.
- Developing new materials for better interaction in near surface geothermal systems is another important topic that requires further research. Increasing thermal conductivity of concrete by changing aggregate type (e.g. flint aggregates) can result in reduced number of pipes and/or piles, hence easier installation. In addition, the use of new heat exchange materials, such as CO₂, should be considered an alternative to the water-antifreeze mixtures even though CO₂ can only be used for heating operations.
- The integration of near surface geothermal systems into alternative uses (e.g. bridge deck or runway deicing, clay thermal consolidation, grain drying) is already being investigated by several researchers. However, more emphasis should be placed on fundamental aspects of energy geostructure behavior to further increase the understanding of these new areas.

7. Acknowledgements

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Table 1: Various Studies on Thermo-Active Piles

Topic	Reference(s)
Field Tests on Thermo-Mechanical Aspects	Brandl, 2006; Laloui et al., 2006; Bourne-Webb et al., 2009; Amatya et al., 2012; Suryatriyastuti et al., 2012, Amatya et al., 2012; Murphy et al. 2014a
Case Studies involving Thermal Characterization	Brandl, 2006; Gao et al., 2008; Wood et al., 2010; Wang et al. 2012; Katzenbach, 2013; Murphy and McCartney 2014; Murphy et al. 2014b Olgun et al. 2012
Numerical Modelling	Laloui and Nuth, 2006; Knellwolf et al., 2011; Ouyang et al., 2011; Olgun et al. 2014; Wang et al. 2014

Table 2: Thermo-Active Diaphragm Wall Applications in Austria

Application	Location	Resource
Heating and Cooling. Used in conjunction with thermo-active piles.	Arts Centre, Bregenz, Austria	Brandl, 1998
Heating and Cooling	Generali Office Tower, Vienna, Austria	Brandl, 2006
Heating and Cooling	Uniqa Tower, Vienna, Austria	Brandl, 2006
Heating and Cooling. Used in conjunction with thermo-active piles.	Columbus Centre, Vienna, Austria	Brandl, 2006
Heating and Cooling. Used in conjunction with thermo-active piles.	Viennese Metro, Austria	Brandl, 2006
Heating and Cooling. Used in conjunction with thermo-active piles.	Bulgari Hotel, London, UK	Laloui and Di Donna, 2013

Table 3: Thermo-Active Tunnel Lining and Metro Applications in Austria

Application	Location	Resource
Connected to an energy plant	Lainzer Tunnel, Vienna	Brandl, 2006
Heating and cooling of the metro stations	Viennese Metro Line, Vienna	Unterberger et al., 2004
Heating municipal building above the tunnel	Twintack high-speed railway tunnel in Austria	Franzius and Pralle, 2011

Table 4: Finite Element Analysis Results of Heat-Exchange Anchors

Soil Type	Heat Extraction or Injection	Water Table Depth	Extracted Heat (kWh/y/m of anchor)	Injected Heat (kWh/y/m of anchor)
SP	Extraction Only	Surface	9.63	0
SP	Extraction Only	Below Anchors	7.41	0
SP	Extraction/Injection	Surface	14.46	8.41
SP	Extraction/Injection	Below Anchors	12.02	8.41
NP	Extraction Only	Surface	7.41	0
NP	Extraction/Injection	Surface	14.46	8.41

Table 5: Efficiency of Incorporating Seasonal Heat Storage

	SP – WT at surface	SP – WT below anchors	NP – WT at surface
Efficiency	55%	57%	84%

Figure 1. Solar thermal storage system (adapted from Katzenbach, 2013): (a) Charging during summer; (b) Partial discharge during autumn; (c) Energy subtraction during winter

Figure 2. Number of thermo-active pile installations in Austria since 1984 (redrawn after Brandl, 2006)

Figure 3. Thermal response of thermo-active pile during heating

Figure 4. Variation of pile axial stress when heated (redrawn after Amatya et al., 2012)

Figure 5. Variation of mobilized shaft friction during heating (redrawn after Amatya et al., 2012)

Figure 6. Plan view of PalaisQuartier (Katzenbach, 2013)

Figure 7. Numerical simulations of heat transport on the horizontal cross-section of Frankfurt Limestone (Katzenbach, 2013)

Figure 8. Temperature variations on axis-B (Katzenbach, 2013)

Figure 9. Comparison of the surface temperatures of the heated and unheated bridge deck slabs during a period with very low ambient temperatures (Bowers and Olgun, 2015)

Figure 10. Temperatures over time (a) at different depths in the thermo-active pile and (b) in the ground at a radial distance of 1.7 m from the pile during and after bridge deck heating (Bowers and Olgun, 2015)

Figure 11. Comparison of the surface temperatures of the heated and unheated bridge deck slabs during a moderate winter storm (Bowers and Olgun, 2015)

Figure 12. Effect of wind speed on the amount of time it takes the average temperature of the bridge deck surface to reach >0°C (Olgun and Bowers, 2013)

Figure 13. Effect of concrete cover thickness on the amount of time it takes the average temperature of the bridge deck surface to reach >0 °C (Olgun and Bowers, 2013)

Figure 14. Changes in vertical effective stress at different depths for a lateral pile (left) and a central pile (right) (Dupray et al., 2014)

Figure 15. Changes in vertical effective stress at different depths for a lateral pile (left) and a central pile (right) (Dupray et al., 2014)