Turning geostructures into sources of renewable energy

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ABSTRACT:

Incorporation of heat exchangers into ground embedded structures (Geostructures) such as shallow foundations, pile foundations, diaphragm walls, tunnel cut-and-cover walls, tunnel linings and anchors, is a relatively novel sustainable technology for the intermittent storage of energy in the ground with a view of utilizing it for heating and cooling by means of suitable systems integrated into the geostructures. This innovative technology can provide not only substantial long-term cost savings in relation to conventional energy systems but also can make an important contribution to environmental protection by reducing fossil energy use and minimizing the carbon footprint of built structures.

Keywords: Heating, Cooling, Heat pumps, Pile foundations, Tunnels, Diaphragm walls.

1 INTRODUCTION

The adverse effects of greenhouse gases and rapidly declining natural energy resources have changed the way we think about energy – how we consume and produce it. More and more, governments, businesses and individuals are seeking ways of reducing the amount of carbon they use. One way of doing this is by switching to power generated from renewable energy sources.

A wide range of low or zero carbon (LZC) technologies is available to provide some or all of the energy for built structures. Ground source heat pump systems represent one subset of these technologies. These systems have been used for many years as an energy efficient strategy since they often require less energy to heat and cool buildings than conventional heating and cooling systems (Lund et al., 2011). They combine a heat pump with ground heat exchangers in either closed or open loop configurations and use the soil under our feet as heat storage medium. However, in the last decade heat exchanger systems have been increasingly incorporated into ground embedded structures (Geostructures) such as shallow foundations, pile foundations, diaphragm walls, tunnel cut-and-cover walls, tunnel linings and anchors. This is a relatively novel sustainable technology for the intermittent storage of energy in the ground with a view of utilizing it for heating and cooling by means of suitable systems integrated into the geostructures. This innovative technology can provide not only substantial long-term cost savings in relation to conventional energy systems but also can make an important contribution to environmental protection by reducing fossil energy use and minimizing the carbon footprint of built structures. This paper presents a number of cases in which this technology has been implemented, the cases include pile foundation, diaphragm walls and tunnels.

2 HEAT EXCHANGER GEOSTRUCTURE BASIC CONCEPT

To efficiently operate a heat exchanger geostructure, the ground temperature needs to be warmer than the air temperature in winter and cooler than the air temperature during summer. This requires a relatively constant ground temperature and knowledge of the magnitude of ground temperature changes for this system to operate efficiently. In-situ temperature profiling conducted in South East Melbourne indicated that beyond 8 m depth temperatures are relatively constant (16-18^{o}C) and are unaffected by seasonal temperatures changes (Bouazza et al., 2011). In most European climate zones, this temperature varies between 10 to 15°C and remains constant up beyond 10 m to a depth of approximately 50 m (Adam and Markiewicz, 2009).

The principle of heat exchanger geostructures is based on the use of ground source heat pump systems. In this case heat pumps and/or cooling machines are connected to absorber pipes within the concrete elements (primary circuit) and the heating/cooling systems of the built structure (secondary circuit) which adapt the temperature to a suitable level for HVAC applications (around 6 to 50°C). Modern heat pumps have an efficiency (coefficient of performance, COP) of at least 4, meaning that ¼ of electric energy and ¾ of geothermal energy can be added up to 4/4 directly usable energy (for heating operation). Two different operation schemes for the use of geothermal energy from geostructures are possible: **i)** Exclusive geothermal energy extraction or energy input, **ii)** Alternating seasonal operation with heating and cooling storage. For exclusive geothermal energy extraction the energy flow takes place only in one direction, e.g. for heating purposes during winter. Whereas, the seasonal operation uses the thermodynamic inertia of the soil to store thermal energy for a later operation with reversed energy flow. Consequently, the seasonal operation can produce energy equilibrium in the ground over a complete heating/cooling period of a year. A geothermal cooling system extracts heat energy from the built structure (for example a building) either via an air-cooling system or a water-based cooling system, which can be integrated in ceilings and walls. The cooling machine acts like a "reverse" heat pump and the thermal energy can be stored in the ground. Geothermal energy applications which need a very low service temperature can also be operated in “free heating” or “free cooling” mode. The necessary energy input then is limited to the electricity required to operate a circulation pump, because no heat pump is needed to raise the temperature level.

3 DESIGN BASICS OF GEOTHERMAL ENERGY SYSTEMS

As indicated earlier geothermal energy systems are based on the physical principle of heat exchange between an energy consumer (built structure) and an energy supply system (absorber system, groundwater, subsoil). In the design process, the energy exploitation system needs to be adapted to the needs of the user. This can be determined according to current standards using input data such as building type and size, usage, heat distribution system, meteorological conditions and geographical location information. The energy supply system should be able to meet the requirements of the energy distribution system at the defined place and time (Figure 1). The essential difference between geothermal energy systems and conventional energy sources such as fossil fuels has to be taken into account: With conventional systems, the entire deployable quantity of energy during a supply period depends only on the quantity of fuel consumed (at a defined and constant peak output). Geothermal energy systems, however, show more or less dynamic system behaviour, as the temperature of the source of heat in the soil, and therefore the performance of the plant, generally varies depending on the above-mentioned heat exchange cycle. If, however, the parameters of the absorber configuration are known, then reliable and low maintenance energy supply systems can be constructed just as with conventional energy sources, and also have the distinguishing benefits of zero emissions and cheaper operating costs.

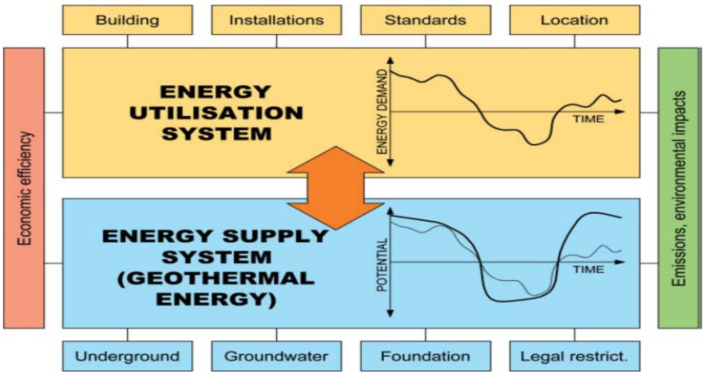

Figure 1. Overview of the most important influence factors for energy utilisation and absorber system

3.1 User Requirements

The use of geothermal energy should be taken into account and investigated as early as possible at the design stage since the heat distribution system has to be designed to operate constantly at a relatively low feed temperature. This is important so that the necessary heat pumps or chillers can operate in a reasonable range of efficiency.

3.1.1 Types of usage

Geothermal energy can be used for the provision of both heating and cooling energy. For heating purposes, the installation of a heat pump is generally required, which raises the temperature of the primary energy (geothermal heat) to a usable level for the secondary system (heating medium). For refrigeration purposes, a “free cooling” is often used, as this only requires the energy for pumping the heat distribution medium cooled by the subsoil. If the subsoil temperature If the subsoil temperature is not sufficient (anymore), a chiller can be interposed.

3.1.2 Consumption characteristics

Different buildings and types of usages also have different consumption characteristics. Generally, residential buildings such as apartment blocks may need heating and cooling energy or just heating/ or cooling energy depending on the geographical locations. On the other hand, in office buildings there may be a large demand for cooling energy only. For a geothermal energy plant, it is beneficial if the heating and cooling energy are balanced over the course of a year. This leads to longer operational periods for the plant and consequently to improved economic efficiency as well as to largely unchanged temperature conditions in the subsoil, even after many years of operation (thermal regeneration). For the reliable prediction of system behaviour, exact data are generally necessary about the energy requirements of the consumer (at least average monthly values of energy demand as well as peak heating and cooling capacities). To increase the efficiency of a geothermal energy plant, it is sometimes useful to cover only the base load of the energy requirement with geothermal energy and to install additional conventional energy sources (if available) for the peak demand, the bivalent system concept. This results in a higher utilisation efficiency of the geothermal energy plant, since the base loads occur over longer periods.

3.2 Subsoil and Ground Water Conditions

The subsoil and ground water conditions have a decisive influence on the choice of distribution system and the performance of an absorber system. Basically, there is a distinction between open and closed geothermal systems. Open systems, where the energy content of the ground water can be used directly without interposing a heat transfer medium, are usually less expensive. This, however, requires suitable aquifers in the subsoil. If these are not available or insufficient, or if there are other obstacles to direct usage (e.g. water law restrictions, chemical composition of the ground water), then closed systems (geothermal probes, massive absorber systems) can be used. The presence of ground water in the subsoil always results in increased performance of geothermal energy systems in comparison to drier soils. However, ground water flow can also have a negative effect if subsoil thermal energy storage is intended during system operation, as the stored heat is then carried away. Other subsoil characteristics, which must be known for the plant design, include the average thermal conductivity of the soil, its density and specific heat capacity. For larger systems from about 50 kW upwards, the use of thermal-response tests has become conventional. These tests can determine the average thermal conductivity of the soil as well as the average soil temperature at the location of the plant by using specially made geothermal probes, which can later also be used during operation (see Bouazza et al. 2011).

3.3 Foundation Concept and Building Structure

When using the massive absorber technology, the type of foundation primarily determines the choice of system. If the building has a deep foundation, the use of energy piles or energy diaphragm walls is possible whereas an energy slab can be used for buildings with shallow foundations. The size of the building and the plot area determine the arrangement of absorber elements for closed systems and the arrangement of extraction and recharging wells for open systems. The insertion of the building into the subsoil also has to be taken into account as this could change the natural flow of the groundwater. Finally, especially with massive absorber systems, possible thermal short circuit effects have to be considered between the inner side of a structural component and the massive absorber system.

3.4 Technical Requirements

The design and implementation of geothermal energy systems are by nature subject to technical limitations. These are mainly defined by maximal temperatures within the absorber system (structural effects on the absorber building elements) or by the minimum temperatures required at structural elements (avoidance of ice lenses). Additional problems, which may limit the application, are loss of heat due to the main collection lines being too long or loss of pressure due to absorber circuits being too long. The selection of the heat transfer medium is also crucial. A frost-resisting heat transfer medium (glycol-water mixture) is mostly used. If, however, the system is designed in such a way that water without anti-freeze can be used for the heat transfer medium, this has the following advantages:

1) Minimal costs for filling the system, as the cost of the anti-freeze (glycol or equivalent) can be saved,2) Lower operating costs, as the viscosity of water is lower while its heat capacity is higher than a glycol-water mixture, which leads to lower pump capacity being required,3) Better heat transmission within the absorber system compared to the glycol-water mixture, 4) For structural reasons, the outer surface of structural components of foundations cannot have a lower temperature than 0 °C in order to prevent the formation of ice lenses, 5) No environmental hazard in case of pipe leakages.

4 APPLICATIONS

4.1 Buildings

The utilisation of geothermal heat by using earth-coupled elements is pretty well established in Europe. Adam and Markiewicz (2009) indicated that more than 1000 new high-rise and other types of buildings located in different European cities have been equipped with geothermal energy systems. For example, the Uniqa Tower, located in the centre of Vienna is founded on diaphragm walls that reach down to 35 m below surface. At this depth, a high groundwater table and surrounding earth are ideal conditions for geothermal energy utilisation, where 7800 m^2 of diaphragm walls are used to absorb energy from the ground to produce a heating capacity of 420 kW and a cooling capacity of 240 kW. The annual heating output reaches up to 818 MWh and the annual cooling output up to 646 MWh. Simulations of this energy system result in a minimum brine entry (into the diaphragm walls) temperature of -2.8^{o}C in January (winter) and a maximum entry temperature of 31.8^{o}C in August (summer). The geothermal energy is used in combination with low-temperature heating systems such as wall and floor heating, and free cooling is used to support a conventional cooling system. More recently a massive heat exchanger system was implemented at the Vienna Main Station using energy piles and energy foundation slabs to exploit geothermal energy. For the tender design, it was necessary to simulate the projected geothermal energy plant to verify the functional capability and also to enable optimisation of the plant. In order to consider the complex shapes of the main station including its foundation elements, a three-dimensional simulation model was generated in which all massive absorber components were modelled, including the basement floors. The thermal characteristics of the subsoil (undisturbed soil temperature, thermal conductivity) had previously been determined with thermal response tests on two thermal probes and had been included in the calculation model. The heating and cooling requirements, which basically constitute the thermal “load” of the structural foundation components/absorber components, had been determined using a comprehensive building simulation. This building simulation covered the whole structure of the station including all thermal boundary conditions such as solar radiation, indoor temperatures, outside temperatures, lost heat and a simplified soil model in order to demonstrate the interaction between energy demand (within the building) and the energy supply (from the geothermal energy plant and district heating), taking the heat pump of the plant into account. The seasonally varied heat flows at the absorber surfaces (bored piles, diaphragm walls, foundation slabs) as well as thermal conditions in the garage car park represented the energetic input data for the numerical simulation of the geothermal energy plant. Figure 2 shows a section of the three-dimensional finite element model with the arrangement of energy piles and energy diaphragm walls.

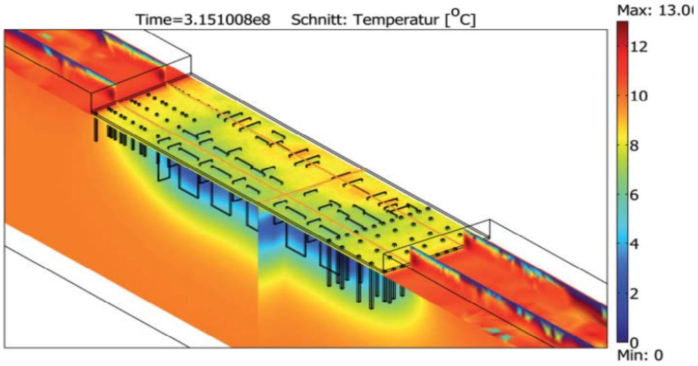

Figure 2. Results of the temperature distribution (section) on a 3D-model for Vienna Main Station

Schroder and Hanschke (2003**)** presented the case of a large geothermal heating and cooling system using prefabricated reinforced concrete energy pile piping installed in Rostock, Germany for the newly constructed Rostock business centre. The geothermal heat pump system consisted of an earth temperature probe and energy piles connected to a geothermal heat processing centre that operated at a low temperature level of about 28-35^{o}C. Costs for the reinforced concrete energy piles were 40-50% lower than standard geothermal heat exchangers. The system used 264 reinforced concrete piles connected to a reversible heat pump and provided economical heating and cooling of the business centre. The installation of thermo active pile foundations has grown exponentially in the UK where there were approximately ten times more thermo-active foundations installed in 2008 than in 2005 (Bouazza et al., 2011). The reason for this rise in production is mainly driven by the code for sustainable buildings that requires the construction of zero-carbon buildings by 2019. Switzerland has had several decades of experience with ground-source heat pumps. Two notable examples of projects, which have employed the use of energy piles are at the Swiss Federal Institute of Technology in Lausanne and Dock Midfield Terminal Airport at Zurich Airport. The Lausanne project has also been part of an extensive performance monitoring program, in particular the investigation of the thermo-hydro-mechanical behaviour of surrounding soil (Laloui et al., 2006). The implementation of the thermo active pile technology in the USA is very limited by comparison to Europe. The only well documented case involving energy pile foundations is reported by Henderson et al. (1999) for 149 room hotel located in New York, USA. It included 198 piles, 26 m deep, combined with 120 borehole heat exchangers, 42 m deep, located in the car park of the hotel. Henderson et al. (1999) reported that the piles had a better heat transfer performance than the borehole heat exchangers due to the shielding effect of the building. A decade later, the USA is experiencing a renewed interest in the use of energy piles as they have been identified as being a more cost effective solution compared to the use of GSPHs systems (McCartney et al., 2010). In Australia, the application of this technology to buildings is still in its infancy. Currently, a large research programme is being carried out at Monash University on direct geothermal energy piles (Bouazza, et al. 2011, Wang et al. 2012). The research programme consists of detailed laboratory investigations and field study of geothermal pile foundations installed in the Brighton Group (fine to coarse very dense clayey sands and sands). The study involves evaluation of the thermo-mechanical behaviour of soils, the thermal capacity of the pile, the built structure heat balance, soil thermal properties and influence of heat transfer on pile load capacity and shaft resistance. The study at Monash will shed more light on the field performance of geothermal energy piles under local conditions.

4.2 Tunnels

More recently, the application of the above technology has been extended to tunnels. In comparison with foundations of buildings, a substantially larger ground volume can be activated for geothermal heat exchange. Additionally, tunnels with a high overburden can have a significantly higher temperature of the surrounding ground, thus resulting in a better performance of the geothermal system. However, shallow tunnels (i.e. underground/subway tunnels) can also be used profitably for geothermal heat extraction due to their urban location. The installation of absorber pipes in the concrete structure of a tunnel is different for cut-and-cover tunnels and mined/bored tunnels. For cut-and-cover tunnels, installation of absorber pipes, similar to the methods used in bored piles, diaphragm walls and in or under base slabs, could be used. However, for the case of excavated tunnels the use of heat exchanger elements has been a new challenge for engineers. While the existing methods can be applied for the installation of absorber systems in the tunnel invert, a completely new technology need to be developed for the lining of the tunnel.

The first application of heat exchangers to tunnels was carried out at the Lainzer tunnel (Vienna) on a section referred to as Testing Plant LT24. It was applied to bored piles of a cut and cover tunnel. It comprised 59 energy piles with a diameter of 1.2 m and an average pile length of 17.1 m. The energy piles were equipped with absorber pipes which were connected to collection pipes, through a service room, leading to 6 heat pump units in an adjacent school building for its heating. The initial operation of the energy plant started in February 2004 with a first testing period. About 70 MWh of heating energy could be extracted from the energy piles during the first months of operation. Since autumn 2004 the energy system provides the adjacent school with geothermal heat. During the second heating period in winter 2004/05 a total amount of 186.2 MWh of geothermal heat was extracted, while in 2005/06 an amount of 193.9 MWh was gained. This amount of geothermal energy corresponded closely to the predicted maximum performance per heating season. Work on another testing plant (LT22) where the tunnel was excavated using the “New Austrian Tunneling Method” (NATM) required the development of special absorber elements (Markiewicz & Adam 2003). Energy geotextiles were developed to thermally activate the concrete lining. In this case absorber pipes were attached to non-woven geotextiles to form a geocomposite material with an upper and lower geotextiles with the pipes in the centre. Then the energy geocomposite material was placed between the primary and secondary lining of the tunnel as indicated in Figures 3 and 4.

Figure 3. Detail of the four absorber loops with collection pipe (Adam & Markiewicz, 2009).

Figure 4. Energy geotextile at lot LT22 of the Lainzer tunnel (Adam & Markiewicz, 2009).

This technology makes prefabrication possible and provides for an easier installation method on site. Similarly to the testing plant LT24, sophisticated measurement instrumentation (temperature sensors, heat carrier flow measurement, etc.) has been installed for detailed investigation. The initial operation of the energy plant started in February 2004 with a first heat extraction. However, the testing plant can be run in both heating and cooling operation. The knowledge gained from the earlier work on the Lainzer tunnel subsequently led to further major applications on infrastructure projects, like for example the four new stations in the Vienna Underground U2/1 to U2/4, which became operational in July 2008. Tunnels constructed using full-face TBMs can also make use of the heat exchanger concept. The lining of such tunnels usually consists of prefabricated concrete segments which form rings typically 1–2 m wide. Incorporating a heat-exchanger system into these segments has been implemented recently for a large tunnel project in Germany (Frodl et al., 2010).

5 CONCLUSIONS

Ground embedded structures incorporating heat exchangers have great potential as an aid in tackling climate challenges and meeting legislation requirements for greenhouse gas emissions. There are numerous possibilities for their utilization for heating and cooling purposes. Foundation elements of buildings in particular and also urban or inner city tunnels can provide clean, regenerative energy when used as heat exchangers. The large number of applications on several international projects indicates that the technical challenges can be solved during the design stage and that the implementation can be integrated in the normal construction sequence. The benefits and opportunities gained from these experiences can be adapted and applied to the Australian environment.

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