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Title

Environmental impact calculations, life cycle cost analysis

Permalink

<https://escholarship.org/uc/item/59s900kc>

Journal

DFI Journal - The Journal of the Deep Foundations Institute, 8(2)

ISSN

1937-5247

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Publication Date

2014-10-01

DOI

10.1179/1937525514y.0000000009

Peer reviewed

Session 6 Report: Environmental Impact Calculations, Life Cycle Cost Analysis

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Abstract

This session explored the evaluation and characterization of the sustainability of thermo-active geotechnical systems. Thermo-active geotechnical systems take advantage of shallow geothermal energy by using the foundation of a structure as a heat source and sink for use with a ground source heat pump. Methods for their evaluation within a sustainability framework still need to be developed. This can be done within larger regulatory frameworks such as the Code for Sustainable Homes. The Life Cycle Analysis methodology has been used to examine non-thermo-active geotechnical systems using both embodied carbon and embodied energy as metrics. Life Cycle Analyses have also been performed on ground-source heat pumps and can provide valuable insight into the indirect operational environmental impacts of thermo-active geotechnical systems.

1. Introduction

Thermo-active geotechnical systems take advantage of shallow geothermal energy by using the structure's foundation to also serve as a heat source and sink for use with ground source heat pumps. They are being heralded as a more sustainable way to provide heating and cooling to buildings compared to ground source heat pump systems as they provide the energy and cost savings of shallow geothermal systems without the high initial cost of a borehole field or vertical trench installation. This session explored the evaluation and characterization of the sustainability of thermo-active geotechnical systems by using current sustainability evaluation methodologies. This report first provides a background on sustainability evaluation methods. It then explores these existing methods such as Environmental Impact Assessments and Life Cycle Analyses to characterize the sustainability of thermo-active geotechnical systems. The current evaluations of foundations and ground-source heat pumps (GSHP) within these methodologies are discussed with a goal of developing a methodological framework for the sustainability of thermo-active geotechnical systems.

2. Sustainability

The Brundtland Commission of the United Nations defined sustainable development as development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). The goals of sustainability are to meet all people’s basic needs and to promote their quality of life while ensuring that the natural systems, resources, and diversity on which they depend are maintained and enhanced for both their benefit and that of future generations (Pearce et al., 2012). Thus sustainability can be envisioned as an integration of the needs of the environment, the economy, and society for both present and future generations.

2.1. Sustainability Models

There are two primary sustainability models that offer a framework within which to integrate the needs of the environment, economy, and society. One model, “Weak Sustainability,” or substitutability, is shown in Figure 1. Under this model, the needs of the environment, economy, and society are interchangeable such that if sufficient societal gains are made by vastly depleting a natural resource, the gains made by the society will (either presently or in the future) make up for the loss experienced by the environment such that the overall return on investment is greater than zero (Neumayer, 2013). Thus, weak sustainability assumes that (Neumayer, 2013):

- Natural resources are extremely abundant;
- The ability to substitute economic or societal gain for the depletion of environmental resources can result in an overall benefit;
- Technological advancement can overcome resource constraints.

“Strong Sustainability,” or non-substitutability, holds that the needs of the environment are not interchangeable with the needs of the economy or society, and thus any use of the environment (resource extraction, pollution absorption, etc.) must be done in such a way that does not prevent the environment from adequately and fully recovering (Neumayer, 2013). This is demonstrated in Figure 2 where the economy and society exist fully within the environment, which controls and constrains their growth. If the society were to outgrow the environment, there is a net loss and the condition would be unsustainable. The assumptions associated with strong sustainability are (Neumayer, 2013):

- The maximum rate of consumption of renewable resources is their rate of regeneration.
- The environment can only be used as a sink for pollution such that its natural absorptive capacity does not deteriorate over time.

Thermo-active geotechnical systems are appealing when using either the “Weak or Strong Sustainability” models. The economic benefit is the same for the owner under both models in installation costs as compared to traditional borehole systems and in energy savings over the life of the system as compared to conventional heating/cooling systems. Environmentally, strong sustainability may hinder the use of thermo-active geotechnical systems when material use is

considered (for example, concrete is a more energy intensive material than recycled steel piles – discussed further in Section 4).

2.2. Sustainability Objectives

Chapter 11 of the ICE Manual of Geotechnical Engineering (Pantelidou et al., 2012) defines seven sustainability objectives that relate to geotechnical engineering (Table 1). Thermo-active geotechnical systems have the potential to meet all seven of the sustainability objectives, as shown in Table 2.

2.3. Sustainability Certification Tools

Although assessing the sustainability of a foundation is challenging, several tools exist that are generally used to assess the sustainability of an entire project. Applying the same methodology to thermo-active geotechnical systems provides a framework within which to assess and balance the environmental, economical, and societal needs.

2.3.1. Building Research Establishment Environmental Assessment Methodology

The Building Research Establishment Environmental Assessment Methodology (BREEAM) defines itself as “an internationally recognized measure and mark of a building’s sustainable qualities” (BRE Global, 2014). BREEAM certifies buildings on the merits of their sustainability as either pass, good, very good, excellent, or outstanding. The metrics are presented in Table 3. It has certified over 250,000 buildings and is used in more than 50 countries around the world (BRE Global, 2014). BREEAM is used on the following building types: residential, offices, industrial, retail, community, residential institutions, and public.

2.3.2. Code for Sustainable Homes

The Code for Sustainable Homes was developed in 2006 to assess the performance of new homes (citation goes here). It also considers the triple bottom line and evaluates homes according to nine categories (Table 4).

2.3.3. Civil Engineering Environmental Quality Assessment and Award Scheme

The Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL), now referred to as the ‘Sustainability Assessment and Awards for Civil Engineering, Infrastructure Landscaping and Public Realm Works’ is similar to BREEAM except that it is applicable to all civil engineering projects, not just buildings. The CEEQUAL assessments are evidence based and its methodology is available for both projects and term contracts (CEEQUAL, 2012). Within the triple bottom line of sustainability, CEEQUAL addresses all environmental and almost all societal issues plus many economic issues, as shown in Figure 3. A project’s performance is evaluated in nine categories (Table 5). Based on the performance of a project, CEEQUAL awards a score of pass, good, very good, and excellent.

2.3.4. Leadership in Energy and Environmental Design

The Leadership in Energy and Environmental Design (LEED) green certification program was developed by the U.S. Green Building Council (USGBC) to recognize a building's ability to save money, conserve energy, reduce water consumption, improve indoor air quality, and make better building material choices (USGBC, 2009). By considering the triple bottom line, the goals of LEED are to (USGBC, 2009):

- Reduce contribution to global climate change
- Enhance individual human health
- Protect and restore water resources
- Protect and enhance biodiversity and ecosystem services
- Promote sustainable and regenerative material cycles
- Build a green economy
- Enhance the community's quality of life

There are five project types LEED considers: building design and construction, interior design and construction, building operations and maintenance, neighborhood development, and homes. LEED rates buildings or projects as either certified, silver, gold, or platinum based on their accumulation of credits in several categories.

2.3.5. China Green Building (Chinagb.net)

China Green Building (ChinaGB) is a movement within China to promote green building and infrastructure and energy-efficient living and production styles. ChinaGB hosts the International Conference on Intelligent Green and Energy-Efficient Building & New Technologies and Products Expo. The organizers of ChinaGB realize that China has tremendous potential to contribute to the sustainability movement as it experiences population growth, urbanization, and an increased standard of living.

3. Environmental Impact Assessment Of Thermo-Active Geotechnical Systems

An Environmental Impact Assessment (EIA) is defined as “a process for anticipating the effects on the environment caused by a development” (CAAS Environmental Services, 2002). The process leads to the creation of an environmental impact statement (EIS). The author goes on to state that “where effects are identified that are unacceptable, these can then be avoided or reduced during the design process” (CAAS Environmental Services, 2002). It is likely that an EIA will not be carried out on a foundation alone, rather its environmental impact would be included as a contribution to the overall environmental impact of the larger project. And generally, a project's entire life cycle is included, thus EIAs and Life Cycle Analyses are mutually related.

3.1. Environmental Concerns of Thermo-Active Geotechnical Systems

Traditionally, typical geotechnical projects other than dam designs, landfills, and special cases have not required an EIA due to their rather inert presence underground. However, when considering the environmental impact of thermo-active geotechnical systems, one must consider all the additional ways in which thermo-active geotechnical systems have potential to change their environment as opposed to a non-thermo-active geotechnical system. By far the largest

direct change to the environment from thermo-active geotechnical systems is temperature change of the subsurface. Brandl (2006) notes several environmental effects of temperature change in soil:

- Changes to hydraulic properties. Lowering the groundwater temperature increases the viscosity of the fluid, which would hinder flow, and vice-versa for increasing the groundwater temperature.
- Changes to physiochemical properties. If the groundwater temperature is lowered extensively, it could result in a pH increase and a reduction of calcium solubility. Furthermore, the solubility of gaseous substances increases, which can result in increased water hardness.
- Changes to biological activity. Many microorganisms can only live in a small temperature range. The activity of bacteria-consuming microorganisms reduces significantly below 10°C and above 50°C, so heat extraction could result in a change in the populations of microorganisms in the soil.
- Freeze/thaw cycles on soil are known to weaken the shear strength, which could occur if too much energy is withdrawn from the ground.
- Another potential direct environmental impact is leakage of the circulation fluid into the groundwater, whose effect will largely depend on the quantity of fluid and type of circulation fluid used.

Thermo-active geotechnical systems can have several additional indirect environmental impacts from those of non-thermo-active geotechnical systems that stem from the extra materials required such as circulation tubing, circulation fluid, and the ground-source heat pump system (GSHP) that it is connected to. These effects largely stem from the production of materials and operation of the system and are further discussed in Section 5.

3.2. Environmental Regulations for Thermo-Active Geotechnical Systems and GSHP Systems

Subsurface ecosystems are still not well understood and very few regulations are in place, especially for closed loop systems (Haehnlein et al., 2010). There are no absolute temperature limits for the ground in closed GSHP systems, however Austria and Denmark define 35°C and 15°C, respectively, as maximum allowable temperature of the circulation fluid, and they define 5°C and 2°C, respectively, as the minimum allowable temperature of the fluid (Haehnlein et al., 2010). Germany also defines the range for the weekly mean load to be $\pm 11\text{K}$ and $\pm 17\text{K}$ for the peak load (Haehnlein et al., 2010). Haehnlein et al. (2010) state that these standards appear to exist to ensure adequate operation of the system and are not based on environmental considerations.

3.3. Working within a Larger Regulatory Framework: Code for Sustainable Homes

In England, Wales, and Northern Ireland, the Code for Sustainable Homes (CSH) addresses ground temperature changes for ground-source heat pump systems. The CSH is required for all new housing funded by the Homes and Communities Agency (Level 3), all new housing promoted or supported by the Welsh Assembly Government or their sponsored bodies is required

(Level 3), and all new self-contained social housing in Northern Ireland is required to meet CSH Level 3. Nicholson and Smith (2013) showed how a thermo-active pile system can be used to meet CSH compliance. In the study, they compare two designs for a standard terrace house, one that complies with Code 3/4 and one that complies with Code 6. The insulation requirements are given in Table 7. This was used in a building energy program to develop the hourly heat needs over an annual cycle for the house. The authors then developed a pile layout for 11 of the houses according to ground conditions given in Table 8. The pile layout was used in GLHE Pro 3D (Spitler, 2000) to determine the effect the system would have on the ground temperature. The results are given in Figures 4 and 5. Notice that the ground temperatures stabilize after 10 years above 2°C for both House 1 and House 2. In fact, the ground temperature for House 2 stabilizes above 5°C.

Nicholson and Smith (2013) also state that thermo-active geotechnical systems can be used to achieve higher code levels by their amount of CO₂ savings. For the two houses analyzed previously, using thermo-active piles and a heat pump with immersion top up results in CO₂ savings of 35% and 42% for house 1 and house 2, respectively, which qualifies as Code 3. Using thermo-active piles with a heat pump results in CO₂ savings of 48% and 55% for house 1 and house 2, respectively, which qualifies as Code 4. The authors state that it is unlikely thermo-active geotechnical systems can be used to achieve Code 5 and 6 unless renewable on-site electricity production is available to operate the heat pump.

4. Life Cycle Analysis

Life Cycle Analysis (LCA) is a cradle-to-grave approach in assessing a product or system's impact on the environment during every stage of its development, use, and disposal (FHWA, 2012). Geotechnical engineering has traditionally focused on cradle-to-site LCA analyses due to the long lives that are typical of geotechnical projects, uncertainty about the methods of future service and disposal, and because the significant majority of environmental impacts occur between raw material extraction and foundation construction (Soga et al., 2011). However, a LCA analysis for a thermo-active geotechnical system also needs to include the service/maintenance stage of the system due to the simple fact that they are now integrated with a structure's heating/cooling system. This is shown in Figure 6.

To determine the impact on the environment, a Life Cycle Inventory (LCI) is conducted where information about the unit processes of a system are gathered (Saner et al., 2010). The results of the LCI are then used in the Life Cycle Impact Assessment (LCIA), which converts the results to environmental impacts (Saner et al., 2010). Several tools exist for doing this. One such tool is ReCiPe 2008. This tool uses two levels of impact calculations, midpoint and endpoint levels. There are 18 different midpoint levels that address such areas as climate change, ozone depletion, etc. (for all 18 see Figure 13 and Table 15), and three different endpoint levels that include damage to human health, damage to ecosystem diversity, and damage to resource availability (Goedkoop et al., 2013).

There are two LCA tools that are becoming more common in geotechnical engineering; embodied carbon and embodied energy. Both can be quantified and converted to environmental impacts relatively easily. Although both have existed for quite some time in the construction

industry, these tools are relatively new to evaluation of foundations. Thus, they are still in the process of being developed and their reach has not yet extended into thermo-active geotechnical systems. However, Section 4.1.3. includes an exploration of how thermo-active geotechnical systems can be evaluated on the basis of embodied energy and/or embodied carbon.

4.1. Embodied Carbon

Carbon dioxide is a greenhouse gas that is released during the combustion of fossil fuels. Thus, its measurement is a metric of environmental impact. The terms ‘carbon footprint’ and ‘embodied carbon’ refer to carbon dioxide and its equivalents which are produced during the manufacture and transportation of materials as well as during construction, operation, and in the decommissioning of a building. If a particular process emits something in addition to or different from CO₂ such as methane which is a more potent greenhouse gas, the amount of methane produced is converted to an equivalent amount of carbon dioxide by using environmental impact as the standard. Therefore, determination of embodied carbon is essential for most LCAs.

To determine the embodied carbon of a particular foundation system, Carbon Emission Factors (CEFs) are used. A CEF is the amount of embodied carbon emitted in producing 1 unit of construction material from the point of raw material extraction to the final product. To calculate the total volume of carbon emitted for a particular material, multiply the quantity of material by the CEF. The CEFs of some common construction materials used in foundations are shown below in Table 9.

A LCA also considers transportation and installation, as shown in Figure 6. Thus, the embodied carbon of a precast concrete pile foundation, for example, also includes the carbon emissions involved in transporting the piles to the site and the carbon emitted by the pile driving equipment used to install the piles. The CEFs of various fuel types is given in Table 10.

There are several sources of error in embodied carbon calculations. The first is in the development of CEF values of materials. The CEF of a material can be heavily dependent on the standard used to develop the value, the region where the material is produced, and the availability of data from material suppliers (Hammond and Jones, 2008). In order for proper embodied carbon values to be developed and for different foundation types and projects to be compared, standardized and accurate databases of CEF values are needed (Hammond and Jones, 2008). Although the CEF of fuel types is fairly accurate, the amount of fuel consumed during installation is dependent on machine efficiency, ground conditions, operator experience, etc. Often this is not known until after the project is completed, which can make determining embodied carbon values at the beginning of a project challenging.

4.1.1. DFI/EFFC Carbon Calculator

The Deep Foundations Institute (DFI) and European Federation of Foundation Contractors (EFFC) have developed a tool engineers can use to assess the embodied carbon of various foundations. The calculator is applicable for bored piles, displacement piles, micropiles, diaphragm and slurry walls, sheet pile walls, soil mixing, grouting, bored piles, soldier pile walls, anchors, soil nails, dynamic compaction, vibro compaction, jet grouting, stone columns, vertical drains, dewatering, underpinning, and horizontal drilling.

This geotechnical carbon calculator uses several corporate standards including GHG Protocol Corporate standard (Rangathan et al., 2004), ISO 14064, ADEME Bilan Carbone, ENCORD, and European Organization Environmental Footprint (European Commission, 2013b). These standards specify how to evaluate the embodied carbon of an organization or company. The calculator also uses product standards including PAS 2050, BP-X-30-323, GHG Protocol Product Life Cycle Accounting and Reporting Standard, European Product Environmental Footprint (European Commission, 2013a), and ISO 14067, which specify how to evaluate the embodied carbon of a product. The calculator also uses several databases to develop the CEFs including Bilan Carbone v.7, Defra 2012, EcoInvent v.2.2 (Althaus and EMPA, 2010), EcoTransit, ICE v.2 (Hammond and Jones, 2011), IEA 2012, and sustainable concrete. An example output from the calculator is shown in Figure 7. The largest contribution to the total embodied carbon is in materials.

4.1.2. Embodied Carbon of Different Foundation Types

To give an example of how carbon calculation tools can be used in a project, seven different ground condition groups were assumed for a chosen 195 m² terraced house. Two types of founding stratum were considered, sand/gravel and clay, and four thicknesses of unsuitable load bearing material were specified. The ground parameters and chosen trench and pile designs are tabulated in Table 11. The amount of CO₂ emissions of the three foundation designs mentioned above is compared with respect to materials, transportation, and installation operation. As shown in Figures 8 through 10, when compared to transport and installation, material production is by far the leading emitter of CO₂. Also notice that the total carbon emissions for driven and bored piles are very similar.

4.2. Embodied Energy

Embodied energy is the total amount of energy required to bring a product to its current state (Soga et al., 2011). It is similar to calculations for embodied carbon in that it considers the same stages shown in Figure 6, but may be a more accurate representation of the efficiency of a system as it deals with total energy as opposed to just emissions. Ideally, both should be used together in assessing the environmental impact of a product. Soga et al. (2011) explain that embodied energy results can be interpreted in at least four ways:

- Give greater understanding of how much energy and raw materials are required at each stage of a product's life.
- It can potentially serve as an overall indicator of environmental impact.
- If the energy source(s) is from fossil fuels, it could give an indication as to the degree of depletion of resources.
- If the energy source(s) is from fossil fuels, it can serve as an indicator of greenhouse gas emissions.

The embodied energy value of a foundation can be determined by considering three components: materials, transportation, and installation (Soga et al., 2011). An embodied energy intensity (EEI) value is assigned to each material and to the fuel used for transportation and installation. By multiplying the quantity of material by the EEI value of the material, and doing the same for

fuel consumed during transportation and installation, a total embodied energy value can be obtained for a foundation. Thus, embodied energy calculations rely heavily on accurate and standardized databases for EEI values.

4.2.1. Embodied Energy of Retaining Wall Systems

Soga et al. (2011) present several case studies of different geotechnical engineering projects using embodied energy to differentiate between design options. One of the case studies, also shown in Chau et al. (2008), is of a basement retaining wall for a 40 story high-rise building. There are two different sites considered, as shown in Table 12. The designs for the retaining walls that are compared for each site are given Table 13. The resulting embodied energy values per meter of wall length for the designs are given in Figures 11 and 12. Notice that for each foundation type, the retaining wall material is the leading contributor to embodied energy. Also note that each design considers virgin steel and recycled steel and that the error bars for some designs are as great as 2 GJ/m per meter of wall, showing the high uncertainty in some of the calculations. In every case, using recycled steel results in less embodied energy. In fact, the authors report that for an average 200 m perimeter wall, the difference between the most efficient and least efficient design is 50 TJ. The authors also note that for both sites, cantilever wall systems result in more embodied energy than the other systems due to the fact that they require significantly more manufactured material.

4.3. Embodied Carbon and Embodied Energy for Thermo-Active Geotechnical Systems

There is no current literature of embodied carbon or embodied energy calculations for thermo-active geotechnical systems. Thus, the following considerations are proposed:

- The calculation of embodied carbon and/or embodied energy for the materials and installation of thermo-active geotechnical systems will differ little from that of typical geotechnical systems. The circulation tubes must also be included in the materials calculations, however it is likely to make little difference due to the proportionally small volumetric amount of tubing as compared to concrete or steel. The transportation of the tubing must also be considered.
- Because human labor is generally not included in embodied carbon or embodied energy calculations (Soga et al., 2011), the added embodied carbon/energy from installing the circulation tubes is likely to be minimal.
- In comparing thermo-active geotechnical systems, it is best to consider the service/maintenance stage as suggested in Figure 6. For example, a concrete thermo-active piling system contains 30MJ more embodied energy than a recycled steel piling system. However, the thermo-active system is expected to save 50MJ of energy over a traditional electrical HVAC system during its lifetime, resulting in a net savings of embodied energy.
- As the aforementioned point may be difficult for geotechnical engineers to assess, it would be of great benefit to develop correlations of CEFs and EEIs for the service life portion of a thermo-active geotechnical system based on its climatic location, size and use of the structure, ground condition, etc. This is obviously an extensive undertaking but will be made more realistic as a database of case histories is developed.

4.4. Case Study of the Maintenance Phase of a LCA

For thermo-active geotechnical systems, the service/maintenance phase of heat pump systems is one of the most difficult phases to predict; and, it has not traditionally been included in LCAs for non-thermo-active geotechnical systems. The Sloane Robinson building at Keble College in Oxford was completed in 2002 and is the first energy wall project in the UK. Therefore, much can be learned about the service/maintenance phase of a LCA for thermo-active geotechnical systems by examining its performance.

In this project, 61 thermo-active piles (450mm dia.) were bored and 29 non-thermo-active secant piles (750mm dia.) were driven. The annual heating and cooling load was predicted to be 74MWh and 55MWh, respectively. Between February 2007 and February 2009 the fluid temperature in the pipes, heat pump flow rate, and outside temperature data was recorded using 52 monitoring points. The heating requirements of the building have been as expected but the cooling energy requirements have been higher than what was originally predicted during spring and autumn, requiring additional cooling systems to be installed. Annually, the system rejects 17,000kWh to the ground resulting in a 2°C temperature increase of the ground in 2008. It is still unknown whether this is a long term trend, which would affect the efficiency of the system, or if it is just a function of an abnormal climate during that year (Kefford, 2010).

In October 2009, an electrical meter was installed to determine the coefficient of performance (COP) of the heat pump and the running costs of the system. It is considered economical to have a $COP \geq 4$. During 2010, the values of COP equaled 5.83 for cooling and 3.89 for heating, demonstrating the economic advantage of this system over traditional heating/cooling methods for cooling, but not so much for heating (Nicholson and Smith, 2013). However, by using this system, 40 tons of CO₂ emissions have been saved annually (Smith, 2010).

5. LCA and Environmental Impacts of Ground-Source Heat Pump Systems

Though LCA methodology is not standardized for thermo-active geotechnical systems, it is becoming more so for ground-source heat pump (GSHP) systems. Saner et al. (2010) took a LCA approach in evaluating the environmental impacts of a GSHP system. A thermo-active geotechnical system is generally with a GSHP, thus this study offers valuable insights into the potential environmental impacts of thermo-active geotechnical systems. The authors defined a base case, a warm case, and cool case so that the results could be extrapolated to different climatic regions. The different cases are shown in Table 14.

Saner et al. (2010) then performed an LCI on all components of the GSHP system including electricity, heat pump refrigerant, the heat pump, heat carrier fluid, borehole heat exchanger, borehole, and transport. A standardized method presented in ReCiPe 2008 was used to determine the LCIA for 18 impact categories. The impact categories and the respective contribution of each component are shown in Figure 13, and in Tables 15 and 16.

Notice that for every impact category except ozone depletion, electricity is the leading contributor. Thus, the way the electricity is produced becomes extremely important in a GSHP

system's environmental impact. In this study, the authors used a representative electricity profile of continental Europe where 30.4% is produced from coal, 4.4% is produced from oil, 16.1% is produced by natural gas, and 30.8% is produced from nuclear energy, among other sources.

At this point, Saner et al. (2010) asked two questions. The first is if a GHG (greenhouse gas) based assessment is adequate when compared to a full LCA analysis and the second is if GSHP systems result in a net CO₂ savings. To answer the first question, a correlation was made between the overall environmental impact (the ReCiPe 2008 single score) and the GHG emissions (IPCC global warming potential) of a GSHP system for 29 European countries. The correlation coefficient was 0.95, which indicates it (embodied carbon) is probably a suitable indicator of overall environmental impact for GSHP systems (Saner et al., 2010).

To answer the second question, Saner et al. (2010) compared the savings in CO₂ emissions of a GSHP vs heating with an oil boiler and a gas furnace for 29 different European countries. They found that for countries with a high proportion of electric energy coming from renewable sources, the savings were as high as 87% (in Norway where 86% of the electric energy is produced using hydropower) when compared with oil boilers, and as high as 83% when compared with gas furnaces. However, when a large proportion of the country's electricity is produced with fossil fuels (or imported from countries where that is true), GSHP systems could potentially produce more CO₂ than oil boilers and gas furnaces. Such is true in Macedonia where the CO₂ savings of GSHP systems when compared with oil boilers and gas furnaces is -5% and -14%, respectively. However, when using the GSHP for passive cooling as well as heating, the savings increase to 2% and -6% for oil boilers and gas furnaces, respectively. The median values are given in Table 16. When also used for passive cooling, the savings are greater, especially for the warmer cases. When not also used for passive cooling, the savings are greatest for the cool case.

6. Conclusions

It is apparent that thermo-active geotechnical systems have tremendous potential to lead the way in creating holistic structures by integrating two previously separate building components into one sustainable dual-purpose system. There is a great deal of uncertainty about the direct effects of thermo-active geotechnical systems on the environment. However, from a life cycle perspective, using thermo-active geotechnical system instead of conventional geotechnical systems contributes little to the embodied carbon and embodied energy of a structure. In fact, by possibly reducing the amount of carbon that would otherwise be used by a conventional heating/cooling system, thermo-active geotechnical systems have the potential to minimize a structure's overall environmental impact. But from analyzing the environmental impacts from a LCA of a GSHP system, the degree of reduction in environmental impact is largely dependent on how the electricity to operate the GSHP is produced. Unfortunately, the operational phase of the LCA for thermo-active geotechnical systems is not very well understood due to a lack of case histories. From the case histories that do exist, there appears to be slight differences between the expected performance and actual performance of a system, but these systems are capable of achieving a COP $\geq$ 4.

7. Acknowledgments

The paper is an overview of the technical session presented at the International Workshop on Thermo-active Geotechnical Systems for Near-Surface Geothermal Energy, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland, March 2013. Support from NSF grant CMMI 1249656 is greatly appreciated for the organization of the workshop. The session was chaired by Duncan Nicholson and reported by Peter Smith. Lauren Meyer was the scribe of the session. The views in this paper are those of the authors alone.

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LIST OF ABBREVIATIONS

ADEME	Agence de l'Environnement et de la Maîtrise de l'Énergie
BREEAM	Building Research Establishment Environmental Assessment Methodology
BRE	Building Research Establishment
CAAS	Conservation and Amenity Advice Service
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme
CEF	Carbon Emission Factors
ChinaGB	China Green Building
COP	Coefficient of Performance
CSH	Code for Sustainable Homes
EEI	Embodied Energy Intensity
EFFC	European Federation of Foundation Contractors
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
ENCORD	European Network for of Construction Companies for Research and Development
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GLHEPro	Ground Loop Heat Exchange Program
GSHP	Ground-Source Heat Pump System
ICE	Institution of Civil Engineers
LCA	Life Cycle Analysis

LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
USGBC	U.S. Green Building Council

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Table 1. Sustainability objectives for geotechnical engineers (Pantelidou et al., 2012)

Objective	Environment	Economy	Society
1. Energy efficiency and carbon reduction	X	X	X
2. Materials and waste reduction	X	X	X
3. Maintained natural water cycle and enhanced aquatic environment	X	X	X
4. Climate change adaptation and resilience		X	X
5. Effective land use and management	X	X	X
6. Economic viability and whole-life cost		X	X
7. Positive contribution to society			X

Table 2. Ways in which thermo-active geotechnical systems meet the sustainability objectives for geotechnical engineers listed in Table 1

Objective	How Objective is Met
1. Energy efficiency and carbon reduction	Ground source heat pumps provide more energy efficient heating/cooling systems and a reduction in fossil fuel use compared to electrical HVAC systems
2. Materials and waste reduction	Allow for the foundation to serve a dual purpose, rendering a borehole field unnecessary
3. Maintained natural water cycle and enhanced aquatic environment	Closed systems have no direct interaction with the groundwater
4. Climate change adaptation and resilience	Offer the potential for thermal energy storage, serving to buffer HVAC systems for changing temperatures
5. Effective land use and management	Only access the footprint of the building (no additional borehole field required)
6. Economic viability and whole-life cost	Potential for significant savings in heating/cooling costs compared to electric HVAC systems
7. Positive contribution to society	Under optimal conditions, it is infinitely sustainable

Table 3. BREEAM sustainability assessment criteria (BRE Global, 2014)

Category	Assessment criteria	Section weighting
Energy	<ul style="list-style-type: none"> • Level of CO₂ emissions • Sub-metering of substantial energy uses • Renewable and low emission energy (built in) • Sub-metering of areas/tenancy 	26.5 %
Water	<ul style="list-style-type: none"> • Water consumption • Water meter • Leak detection systems • Water recycling (use of rainwater / recycled water) 	8.0 %
Health & Well-being	<ul style="list-style-type: none"> • Natural and artificial lighting (quality; levels; control) • Drinking water provision (plumbed in water coolers) • Thermal control • Indoor air quality (ventilation rates; microbial contamination) • Acoustic performance • Outdoor space 	17 %
Transport	<ul style="list-style-type: none"> • Proximity of amenities • Accessibility/availability of public transport • Pedestrian/cyclist safety • Cyclist facilities 	11.5 %
Materials	<ul style="list-style-type: none"> • Robustness (impact protection / durability / longevity) • Quality of asset • Security (quality and maintenance status of systems) • Fire protection (Remotely monitored fire alarm systems) 	8.5 %
Waste	<ul style="list-style-type: none"> • Storage of recyclable waste 	5 %
Land Use & Technology	<ul style="list-style-type: none"> • Ecological value 	9.5 %
Pollution	<ul style="list-style-type: none"> • Ground/water pollution control measures • Refrigerant type and leakage detection/control • Land contamination • Emissions to air (including NO_x) • Flood risk • Flood management facilities 	14 %

Table 4. Code for Sustainable Homes sustainability criteria (Communities, 2010)

Sustainability Criteria	Considerations	Weightings
Energy and CO ₂ Emissions	Dwelling emission rate; fabric energy efficiency; energy display services; drying space; energy labelled white goods; external lighting; low and zero carbon technologies, cycle storage; home office	36.4%
Water	Indoor water use; external water use	9%
Materials	Environmental impact of materials; responsible sourcing of materials – basic building elements; responsible sourcing of materials – finished elements	7.2%
Surface Water Run-off	Management of surface water run-off from developments; flood risk	2.2%
Waste	Storage of non-recyclable waste and recyclable household waste; construction site waste management; composting	6.4%
Pollution	Global warming potential of insulants; NO _x emissions	2.8%
Health and Well-Being	Daylighting; sound insulation; private space; lifetime homes	14%
Management	Home user guide; considerate constructors scheme; construction site impacts; security	10%
Ecology	Ecological value of site; ecological enhancement; protection of ecological features; change in ecological value of site; building footprint	12%

Table 5. Assessment criteria for CEEQUAL (CEEQUAL, 2012)

Category	Description
Project/Contact Strategy (optional)	The performance of project team/client to the contributions to the sustainable development
Project/Contact Management	Environmental risk assessment, active environmental management, training, the influence of contractual and procurement processes, delivering environmental and social performance, construction issues, minimizing emissions.
People and Communities	The positive and negative impacts on people affected by the project such as legal requirement, nuisance from construction noise and vibration, and from air and light pollution, and visual impact.
Land Use and Landscape	Design for optimum land-take, legal requirements, and flood risk, previous use of the site, land contamination and remediation measures, loss and compensation or mitigation of landscape features, implementation and management.
The Historic Environment	Baseline studies and surveys, conservation and enhancement measures to be taken if features are found, and information and public access.
Ecology and Biodiversity	Impacts on sites of high ecological value, protected species, surveys conservation & enhancement, habitat creation measures, monitoring and maintenance.
Water Environment (fresh and marine)	Control of a project's impacts on and protection of, the water environment, legal requirements, and enhancement of the water environment.
Physical Resources Use and Management	Life cycle energy, and carbon analysis, energy and carbon emissions in use, and energy and carbon performance on site, minimizing environmental impact of materials used, using re-used and/or recycled material.
Transport	Location of a project in relation to transport infrastructure, minimizing traffic impacts of a project, construction transport, and minimizing workforce travel.

Table 6. LEED credit categories (USGBC, 2009)

Credit Category		Description
Integrative Process		Technically not a credit category, but encourages interdisciplinary teams during the pre-design period.
Location and Transportation		Assesses the project's proximity to diverse areas with access to a variety of transportation options.
Materials and Resources		Assesses how well a building incorporates sustainable building materials and reduces waste.
Water Efficiency		Assesses how well the water is used and controlled, and if the building can reduce potable water consumption.
Energy and Atmosphere		Assesses the building's ability to save, conserve, and/or optimize energy use.
Sustainable Sites		Assesses the building's direct impact on ecosystems and water resources.
Indoor Environmental Quality		Assesses the building's ability to maintain a quality indoor space, for both air and ergonomics.
Innovation		Assesses any sustainable measures taken by the project that are not covered in the other categories.
Regional Priority Credits		Assesses the project's ability to meet regional environmental priorities for building in different geographic regions.
	Smart Location & Linkage	Assesses the 'walkability' of a neighbourhood and the efficient transportation options and open space.
	Neighbourhood Pattern & Design	Assesses how well a neighbourhood is connected to nearby communities as how mixed-use it is.
	Green Infrastructure and Buildings	Assesses the project's ability to reduce environmental consequences during construction and operation.

Table 7. Insulation requirements of the two houses used to develop the annual heating load (Nicholson and Smith, 2013)

	House 1 (Code 3/4)	House 2 (Code 6)
Ventilation type	Naturally ventilated	Naturally ventilated
Window U value (W/m ² K)	1.20	0.70
Wall U value (W/m ² K)	0.20	0.11
Roof U value (W/m ² K)	0.20	0.11
Floor U value (W/m ² K)	0.20	0.11
Air tightness (m ³ /m ² h at 50Pa)	5.00	3.00

Heat loss parameter (W/m ² K)	1.05	0.70
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Table 8. Pile and ground characteristics (Nicholson and Smith, 2013)

Parameter	Value
Pile length	13.0 m
Pile radius	0.1 m
Initial temperature of the ground	12 °C
Thermal resistance of the pile	0.145 K-m/W
Thermal conductivity of the ground	1.6 W/(m-K)
Volumetric heat capacity of the ground	2400 kJ/(m ³ K)
Specific heat capacity of water	4200 J/(kg-K)

Table 9. CEFs of common construction materials (Hammond and Jones, 2008)

Material	CEF (kg _{CO2} /kg _{Material})
Concrete – In-situ	0.035
Concrete – Precast	0.059
Steel (primary)	0.749
Steel (recycled)	0.117
Backfill (soil)	0.023

Table 10. CEFs of common fuels used during construction (Shillaber et al., 2014)

Fuel	CEF	Unit
Diesel	3.248	kg _{CO2} /L
Electricity	0.627	kg _{CO2} /kWh
Motor Gasoline	2.826	kg _{CO2} /L
CNG	2.870	kg _{CO2} /L

Table 11. Ground condition and foundation type specifications (Nicholson and Smith, 2013)

Ground Condition		GC 0	GC 1	GC 3	GC 5	GC 2	GC 4	GC 6
Founding Stratum		Clay $C_U = 75 + 10z$ [kN/m ²]				Sand SPT N = 25		
Made Ground Thickness		0	1	2.5	4	1	2.5	4
Deep Trench (length = 97m)	Trench Width	0.75	0.75	0.75	n/a	0.6	0.6	n/a
	Trench Depth	1	2	3	n/a	2	3	n/a
Bored Piles (diameter = 0.3m)		11.3	12.3	13.8	15.3	12.6	12.8	13.1

Driven Piles (diameter = 0.2m)	-	13.5	15	16.5	14.5	14.5	15
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Table 12. Ground conditions and profile of the two sites used in an embodied energy analysis (redrawn after Chau et al., 2008)

Soil Type	Bulk Unit Weight [kN/m ³]	Phi [°]	Key
Made Ground	19	25
Soft Alluvium	16	24
Terrace Gravel	20	36
Lambeth Clay	20	30
Lambeth Sand	20	36
Thanet Sand	21	36

Table 13. Retaining wall designs for site 1 (top) and site 2 (bottom) (Chau et al., 2008)

	Sheetpile AZ48	Secant pile	Steel tubular piles	Combi wall

Toe level	-12m	-12m	-12m	-12m
Volume of materials/m [m3]	Steel: 0.57m3	Steel: 0.16m3 Concrete: 17.9m3	Steel: 0.42m3	Steel: 0.62m3
1 level anchors	971.4kN @+1m	-	-	-
2 levels anchors	384kN@+3m 320kN@-3m	470kN@+1m 320kN@-2.5m	420kN@2.25m 605kN@-3m	348kN@2.25m 640kN@-3m

	Sheetpile AZ34	Propped Diaphragm 1	Propped Diaphragm 2	Cantilever Diaphragm

Toe level (length)	-12m (17.4m)	-12m (17.4m)	-12m (17.4m)	-18m (23.4m)
Sizing (width)	AZ34	800mm	1000mm	1500mm
Volume of materials/m [m3]	Steel: 0.42m3	Steel: 0.13m3 Concrete: 13.8m3	Steel: 0.13m3 Concrete: 17.3m3	Steel: 0.30m3 Concrete: 34.8m3
Strut load	239kN @+1m	239kN @+1m	260kN @+1m	-

Table 14. Values used in an LCA of a GSHP system (Saner et al., 2010)

Parameter	Unit	Base Case	Warm Case	Cool Case
Average annual air temperature	°C	8.3	14.2	6.4
Heating capacity	kW	10.0	7.2	11.0
Cooling capacity	kW	6.0	7.6	6.0
Energy demand for heating	MWh/a	18	6.8	22.8
Energy demand for cooling	MWh/a	0.9	4.3	0.5
Operating hours of the heat pump per year	h/a	1800	940	2070
Total duration of the passive cooling per year	h/a	250	570	85
Number and length of the borehole heat exchanger	s	2 x 85m	1 x 100m	2 x 112m

Table 15. The environmental impact of a GSHP system using ReCiPe 2008 and a European electricity mix (Saner et al., 2010)

Midpoint Categories	Technological Elements							
	Electricity	Heat Pump Refrigerant	Heat Pump	Heat Carrier Fluid	Borehole Heat Exchanger	Borehole	Transport	Total
Climate Change [t CO ₂ eq]	53.5	6.8	0.4	0.5	0.6	1.2	0.5	63.5
Ozone Depletion [g CFC-11 eq]	2.63	69.57	0.04	0.01	0.05	0.16	0.08	72.5
Terrestrial Acidification [kg SO ₂ eq]	228.3	0.7	4.0	0.7	2.6	10.1	2.8	249.2
Freshwater Eutrophication [kg P eq]	0.93	0.00	0.08	0.01	0.04	0.02	0.01	1.1
Marine Eutrophication [kg N eq]	12.72	0.03	0.19	0.09	0.21	1.89	0.5	15.6
Human Toxicity [kg 1,4-DB eq]	4139.9	14.5	590.5	13.9	30.1	27.9	25.6	4842.4
Photochemical Oxidation Formation [kg NMVOC]	113.5	0.3	1.8	0.7	2.8	17.2	4.8	141.1
Particulate Matter Formation [kg PM10 eq]	71.6	0.2	1.9	0.3	0.9	5.1	1.2	81.2
Terrestrial Ecotoxicity [kg 1,4-DB eq]	5.5	0.0	0.1	0.0	0.1	0.1	0.1	5.9
Freshwater Ecotoxicity [kg 1,4-DB eq]	55.7	0.1	3.5	0.3	2.2	1	0.7	63.5
Marine Ecotoxicity [kg 1,4-DB eq]	85.2	0.1	9.7	0.4	0.8	1.3	0.9	98.4
Ionizing Radiation [t U235 eq]	41.94	0.01	0.11	0.09	0.04	0.04	0.07	42.3
Agricultural Land Occupation [m ² a]	770.6	0.7	9.5	3.7	5.2	1.7	2.0	793.4
Urban Land Occupation [m ² a]	216.3	0.2	19.1	1.0	10.5	2.6	9.2	258.9
Natural Land Occupation [m ² a]	6.0	0.0	0.1	0.0	0.3	0.6	0.2	7.2

Water Depletion [m ³]	435.9	14.5	4.4	2.0	6.0	1.9	1.9	466.6
Metal Depletion [t Fe eq]	2.41	0.00	0.93	0.02	0.01	0.05	0.03	3.5
Fossil Depletion [t Oil eq]	15.5	0.02	0.17	0.14	0.43	0.44	0.19	16.9

Table 16. Median values of CO₂ equivalent savings when compared with oil boilers and gas furnaces for European countries (Saner et al., 2010)

	Oil boiler (and air conditioning)			Gas furnace (and air conditioning)		
	Base Case	Warm Case	Cool Case	Base Case	Warm Case	Cool Case
% CO ₂ savings	38 (41)	30 (55)	39 (40)	22 (26)	11 (48)	23 (25)

Figure 1. Weak sustainability where the needs of the environment, the economy, and society are considered equal and can substituted one for another (redrawn after Adams, 2006)

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