https://doi.org/10.4322/cobramseg.2022.0001
ISBN: 978-65-89463-30-6

XX Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica
IX Simpósio Brasileiro de Mecânica das Rochas
IX Simpósio Brasileiro de Engenheiros Geotécnicos Jovens
VI Conferência Sul Americana de Engenheiros Geotécnicos Jovens
15 a 18 de Setembro de 2020 – Campinas - SP

Use of Geothermal Energy Piles to in Ground Source Heat Pump systems for provision of Renewable Heating and Cooling

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RESUMO:
As emissões de gases de efeito estufa produzidas por combustíveis fósseis estão causando uma lenta mudança nas condições climáticas. Os sistemas de climatização usuais em edifícios requerem uma quantidade considerável de energias provenientes de fontes não renováveis e poluentes. O Brasil produz 1,3% da quantidade total de gases de efeito estufa no mundo. Esse valor não isenta o país do Protocolo de Quioto, que exige uma redução de 18% até 2020, possibilitando assim um enorme interesse político e uma grande demanda por soluções técnicas. Nesse sentido, muitos países europeus e alguns outros países desenvolvidos têm focado esforços no desenvolvimento da Geotermia Superficial (SGE – Shallow Geothermal Energy) como uma fonte renovável de energia digna de investimento e desenvolvimento. SGE refere-se à energia térmica, passível de exploração, presente abaixo da superfície da terra, geralmente explorada utilizando sistemas de bombas de calor de fonte geotérmicas (GSHP – Ground-Source Heat Pumps) para trocar e armazenar o calor do solo. Estes sistemas de energia conseguem fornecer aquecimento e arrefecimento (H&C – Heating and Cooling) para edifícios, ajudando a reduzir as emissões nocivas de gás.

PALAVRAS-CHAVE: alterações climáticas, energia geotermia superficial, bombas de calor, estacas energéticas

ABSTRACT:
Greenhouse gas emissions produced by fossil fuels are causing a slow change of the climate´s conditions. Air conditioning systems in engineering superstructures demand a considerably amount of the existing carbon related energy sources, which are pollutant and non-renewable. Brazil produces 1.3% of the world´s total amount of greenhouse gas. This value does not exempt the country from the Kyoto Protocol that demands a decrease in 18% up to 2020, thus enabling a huge political interest and a large demand for technical manners to do so. In this regard many European countries and some other developed countries have addressed Shallow Geothermal Energy (SGE) as a renewable source of energy worthy of investment and development. SGE refers to the exploitable thermal energy in the shallow subsurface of the earth, usually exploited using ground source heat pumps (GSHP) to exchange and store ground heat. These energy systems can provide Heating and Cooling (H&C) to buildings, helping the reduction of harmful gas emissions.

KEYWORDS: climate change, shallow geothermal energy, heat pumps, energy piles

ISBN: 978-65-89463-30-6

1 Introduction

For forest-dwellers, there's wood. For everyone else, there's heat pumps (Mackay, 2009)

Greenhouse gas (GHG) emissions produced by fossil fuel combustion are causing a gradual change in the Climate (Figure 1), and the Doha amendment to the Kyoto Protocol mandates a decrease of GHG emissions of 18% from 1990 levels, by 2020 (https://unfccc.int/kyoto_protocol). In 2016, Brazil had the 7th equal highest GHG emissions of any country (Figure 1), around 1% of the World total (https://www.ucsusa.org) and 18th per capita.

Air-conditioning systems for buildings utilise a considerable proportion of existing energy resources, which are often polluting and non-renewable. In the EU-28, around 80% of all residential energy use is for the provision of space heating and cooling and hot water, and around half this energy is derived from fossil fuels. In Brazil the same figures are 40% and 60%. In addition to the dichotomy of reducing GHG while meeting existing needs, global demand for energy services is expected to increase by as much as an order of magnitude by 2050 (Dincer, 2000).

The need to reduce harmful emissions and the pressures of future increased energy demand, justify the search for alternative ways to reduce both energy consumption and GHG emissions. One way forward is the widespread implementation of ground source heat pump (GSHP) systems to reduce this reliance on carbon intensive energy and to reduce overall energy demand. Alves & Schmid (2015) conclude that conditions in Brazil, below about 4 m depth, are suitable for providing 100% of cooling and between 40% and 100% of heating across eight climate zones from the south to the north of Brazil. There are now many examples, of operational GSHP systems as a renewable source of energy for heating and cooling. This is a mature technology and today, such systems can be found across 48 countries, totalling about 4.2 million, 12kW equivalent units, which represent about 70% of installed direct geothermal capacity (50000 MWt) or 325000 TJ/year energy provided, (Lund & Boyd, 2016).

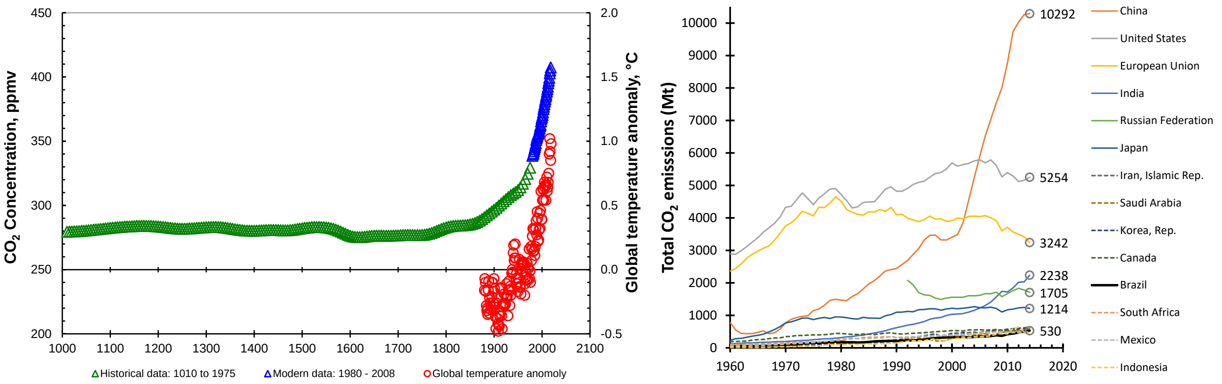

Figure 1. CO_2 concentration and temperature trends (https://data.giss.nasa.gov/gistemp) and National CO_2 emissions data (https://data.worldbank.org)

This paper introduces GSHP technology with a focus on the use of shallow geothermal energy structures (SGES) to provide heat exchange with the ground, provides an overview of the design process, and discusses some of the issues associated with the use of geothermal energy piles (GEP).

2 Shallow Geothermal Energy and GSHPs

Shallow Geothermal Energy (SGE) refers to the exploitation of geothermal resources to provide space heating and cooling (H&C) for residential, commercial and industrial buildings. Usually, SGE makes use of shallow (less than about 200 m depth) and low-enthalpy geothermal resources (typically less than 40°C) that can be economically exploited. Temperatures in the superficial layers of the Earth are determined primarily by solar radiation with geothermal heat flux from the Core playing only a minor role. Below the uppermost 10-

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15 m which are affected by seasonal changes, the ground temperature is largely stable, and is more-or-less the annual average air temperature. In Europe, this stable temperature lies between 10°C and 15°C depending on location, while in the Tropics it is around 20°C to 25°C.

GSHP systems exploit this zone where the ground temperature is stable throughout the year, providing a source of heating in winter when air temperatures are cooler than average, and a sink for cooling in summer when air temperatures are hotter. The GSHP system comprises a primary and secondary circuit and the heat pump:

- The primary circuit provides for heat exchange with the ground. Boreholes and deep foundations penetrate into the zone of stable temperature, so they an ideal means by which this heat resource may be exploited.
- The secondary circuit distributes heat to the air-conditioned structure.
- Heat exchange between the circuits is facilitated by the heat pump whose operation introduces a step change in temperature to allow rejection/extraction of heat to and from the ground, to regulate the superstructure´s internal temperature throughout the year. Importantly, for each unit of energy used to run the system, at least three times as much heat energy is produced – this compares with less than 1 for conventional heating/cooling plant, and is typically one-third higher than air-source heat pumps.

In GSHP systems, the most dominant heat transfer mechanisms are conduction (energy transfer by the movement of molecules and atoms) and convection. Convection occurs e.g. due to groundwater flow past the ground-coupled heat exchangers. Where the groundwater level is deeper and the ground is not fully saturated, the efficiency of the heat exchangers can be lower due to the soil pores containing air which has a low thermal conductivity (0.03 W/m.K), compared to water (0.6 W/m.K). Other factors can mitigate this effect, such as when soils have high thermal conductivity due to their minerology, e.g. significant proportions of metal oxides (Cunha, 2019). In soils, radiation is usually a negligible component of heat transfer; its effect in sand is less than 1% of the overall heat transfer (Rees et al., 2000).

Conventionally, ground–coupling is provided via pipe systems laid either horizontally, in shallow trenches, or vertically, in boreholes; the cost of these groundworks can represent a large proportion of the installation cost of the GSHP system. A recent development in the application of GSHP systems is the use of building elements (slabs, piles, retaining walls, tunnel linings) embedded in the ground as heat exchangers (Brandl, 2006), so-called shallow geothermal energy structures (SGES). The major advantage of this being that the cost of inserting the exchangers is substantially reduced, improving the economic viability of the GSHP system. Geothermal energy pile (GEP) systems are the most common form of SGES and act as load-bearing deep foundations while also providing for heat exchange with the ground as part of a GSHP system. GEP were first used in Austria in the 1980s but their application accelerated in the 2000s as the search for urban renewable energy sources accelerated, Figure 2.

3 Design of GSHP Systems

For the sustainable development of the technology, the need of a standard design process for GSHP projects is recognized. This standardization is important to ensure best practice procedures are followed in order to maintain a high level of installation quality and system performance (GSHP association, 2012). The deployment of GSHP systems involves a mix of complementary professional disciplines, each with different responsibilities and competencies. While no unifying standard for design of GSHP systems or GEP have been developed, several professional and standards associations have produced guidance (GSHP Association, 2011 & 2012; Geotrainet, 2011; VDI 4640, 2001; SIA D 0136, 1996).

The design process involves a trilemma between: the availability and sustainability of the heat source, the heating and/or cooling requirements of the building, and the characteristics of the heat pump system equipment:

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- Thermal capacity of the ground, or underground water, to act as heating or/and cooling source/sink for the GSHP system, is site specific due to the heterogeneity of the ground and groundwater. There are well established methods for determining the thermal performance of borehole systems, and these have been adapted for application to GEP.
- Heating and cooling (and water heating) requirements of the building need to be defined, again there are a number of methods for doing this but for GSHP system design Building Energy Simulations are required in order to provide the required hourly head loads.
- Characteristics of the heat pump system equipment determine the energy efficiency of the system and it depends on the requirements of the heat pump itself but also other equipment, such as, the circulation pumps, the diameter of the heat exchanger pipes and the equipment used to acclimatize the building.

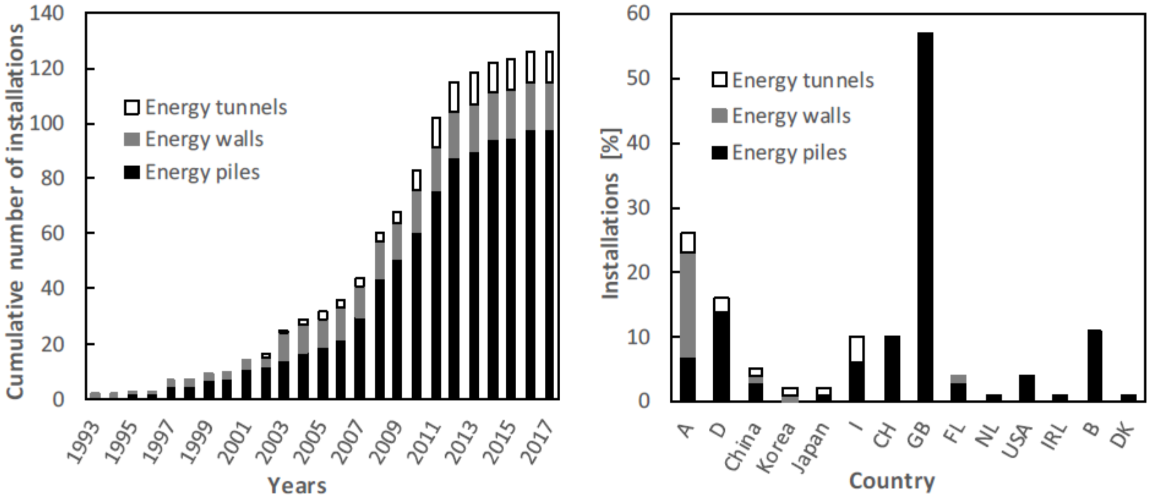

Figure 2. Uptake of SGES based GSHP systems (Di Donna et al., 2017)

The design process has to be iterative in order to arrive at the optimal system configuration that balances all the objectives and constraints of the project, this optimisation process also depends on the previous experience of the designer. As well as meeting the design objectives (building heating/cooling loads, heating/cooling capacity of the ground, thermal efficiency), which greatly depend on the context and constraints of the project itself, other decision criteria that may have to be considered include:

- Compliance with applicable regulations and energy policies regarding all the aspects of a GSHP system - environmental, technical, political, ownership;
- Long-term sustainability - Unsustainable usage of SGE, e.g. either the rate of thermal exchange is higher than the available thermal capacity, or the operation mode does not give enough time for thermal recovery, leads to a local thermal anomaly and a decrease of energy efficiency of the system over time. This local thermal anomaly can also lead to environmental issues, such as alteration of the groundwater chemistry, changing its pH or oxidising organic matter (Possemiers et al., 2014). The exploitation of SGE resources adds several political and social issues related to heat ownership, interference of neighbour SGE systems, legal documents to manage its usage, and others.

4 Behaviour of Geothermal Energy Piles

4.1 Thermo-Mechanical Response

Energy geo-structures and in particular, bearing piles have been widely used in Austria, Germany, Switzerland, the United Kingdom and the USA, and increasingly in China. After over a decade of investigations, there is increasing technical evidence regarding the impact of thermal cycles on the serviceability and safety performance of the geo-structures.

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Based on a number of field tests of GEPs, Bourne-Webb et al (2013) proposed a simple qualitative means for describing the thermo-mechanical response of GEP, which was updated by Bourne-Webb & Bodas Freitas (2020), Figure 3. This framework highlights how in response to heating or cooling, the pile will expand or contract respectively, and the imposed thermal strains provoke changes in the level of the pile head and the axial stress mobilised in the pile shaft – in a manner analogous to down drag.

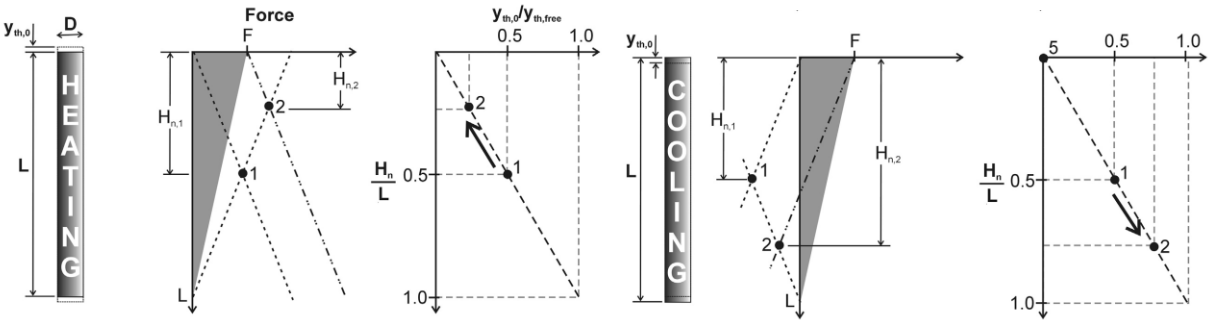

Figure 3. Effect of soil restraint during thermal loading, Bourne-Webb & Bodas Freitas (2020)

Bourne-Webb et al. (2019) and Bourne-Webb & Bodas Freitas (2020) collated a number of full-scale and small-scale tests, and numerical studies, Figure 4. Here, the pile head movement, $y_{th,0}$ and maximum axial stress, $\sigma_{th,max}$ change due to thermal action have been normalised by the free thermal expansion, $y_{th,free} = \alpha.\Delta T.L_p$ and fully-restrained thermal stress, $\sigma_{th,fixed} = \alpha.\Delta T.E_p$. The median normalised ratio $y_{th,0}/y_{th,free}$ has a value of 0.5 or 0.9 for heating or cooling respectively and $\sigma_{th,max}/\sigma_{th,fixed}$ is about 0.5, irrespective of heating mode. It is apparent that thermal stress changes are bounded by the value of $\sigma_{th,fixed}$, however it is possible for the thermal pile head movements to be greater than $y_{th,free}$. In reality, $y_{th,free}$ is unlikely to be greater than 5-10 mm for temperature changes typical of a GSHP system and pile lengths of around 30 m. It is also clear that if the thermal response leads to higher movement, then the thermal stress response will be mitigated.

There is some evidence from various full- and small-scale tests (e.g. Faizal et al., 2018; Ng et al., 2014; Nguyen et al., 2017), and numerical studies (e.g. Pastern & Santamarina, 2014; Olgen et al., 2014), that pile head deformations might also be subject to a form of cyclic thermal ratcheting. This seems to be due to both mechanical effects, especially if the pile shaft resistance is fully mobilised, and thermal effects, if there is a heat imbalance in the test/analysis. In all cases reported to-date, this effect seems to stabilise after several cycles. This remains an area of active consideration by researchers.

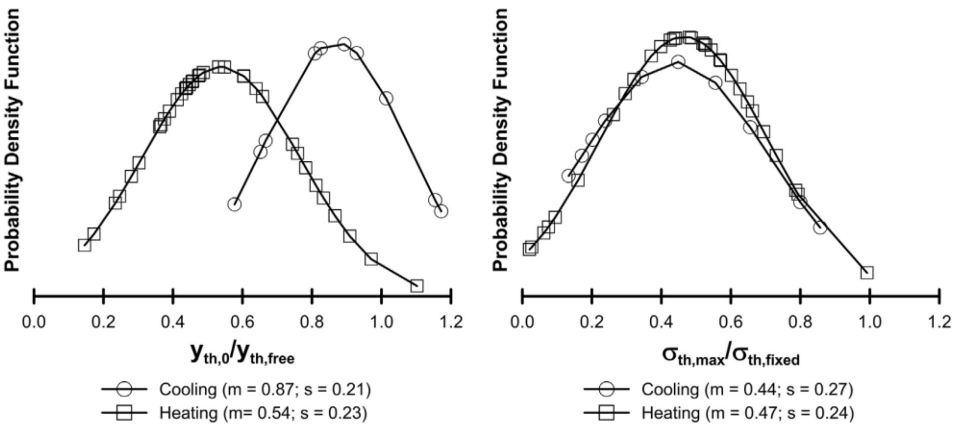

Figure 4. Normalized pile head thermal displacement and axial thermal stress response of GEP, Bourne-Webb & Bodas Freitas (2020)

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4.2 Thermal Performance

Bourne-Webb (2013) provided an overview of the observed response of GEP in terms of their reported thermal response and (Di Donna et al., 2017) updated this information with some new case studies, Figure 5. Broadly speaking the heat exchange obtained from GEP is around 50 W/m length of pile which fits with the recommendations made by (Brandl, 2006) and for boreholes. It is also apparent that heat exchange can be increased dramatically, by a factor of two or more, if the thermal loading is intermittent.

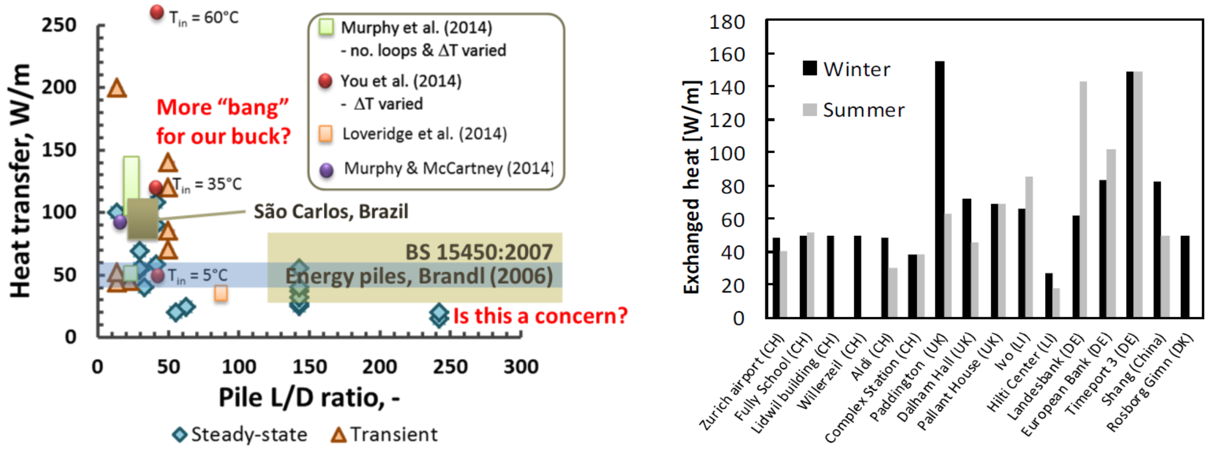

Figure 5. Heat exchange potential of GEP, (Bourne-Webb, 2013; & Di Donna et al. 2017)

5 Final remarks

The objective of this paper was to provide an introduction into GSHP technology and the use of geotechnical structures to provide heat exchange with the ground, within these systems. The technology is mature and GSHP systems may be employed to provide renewable and energy efficient heating and cooling, across most climate zones, including those that span Brazil. It will be an essential tool in the struggle to eliminate GHG emissions whilst managing future energy demand growth. Shallow geothermal energy structures (SGES), and geothermal energy piles (GEP) in particular provide low-cost and efficient ground heat exchangers, and are especially useful in urban areas where space for extensive borehole fields is not available.

Based on the main subjects described in this paper, and the already existing knowledge on the matter in technical literature, some key points related to SGE systems in Brazil can be raised:

- International standards for design, commissioning, operation, monitoring and investment of GEP-GSHP systems are necessary;
- Integration of research and investment efforts from academy, private sectors and public institutions are mandatory to further improved development of this technology in Brazil and elsewhere;
- Thermomechanical phenomena do take place in the pile and in the surrounding soil due to thermal load. Physical, biological and chemical changes should be better accounted for;
- Thermomechanical changes in the foundation system do not compromise the structural or geotechnical performance of the infrastructure f accounted for correctly. Guidelines for are required;
- The thermal efficiency of the system as a whole depends on the interplay of a number of variables and better simulation design tools are needed.

Acknowledgements

The first author is grateful for the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the post doc scholarship Process no. 204517/2018-9 that allowed him to pursue advanced studies for 6 months at the Instituto Superior Técnico (IST) from Portugal in 2019 in this particular technical field. Additionally, the work at IST was undertaken as part of the project DEEPCOOL (PTDC/ECI-EGC/29083/2017) financed by the Fundação para Ciência e a Tecnologia (FCT), Portugal.

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