Computers and Geotechnics 104 (2018) 140–151

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

A robust prediction model approach to energy geo-structure design

Nikolas Makasis[a], Guillermo A. Narsilio[a,*], Asal Bidarmaghz[b]

[a] Department of Infrastructure Engineering, The University of Melbourne, Parkville, Australia
[b] Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, United Kingdom

ARTICLE INFO

Keywords:
Geothermal
Prediction modelling
Numerical modelling
Sensitivity analysis
Ground heat exchangers (GHEs)
Energy geo-structures

ABSTRACT

Energy geo-structures, such as piles or retaining walls, provide geothermal space heating and cooling, in addition to their structural purposes. The thermal design of these structures is undertaken on a case by case basis, commonly using costly finite element simulations, especially for complex geometries. This work introduces a simple but robust prediction methodology that can be used alongside such simulations to significantly reduce computational time and resources for the analysis of any energy geo-structure. An evaluation is presented and exemplified with energy diaphragm walls, for a range of geometrical and material conditions, showing insignificant prediction errors and vast computational savings.

1. Ground source heat pump systems and energy geo-structures

Transitioning towards cleaner and more renewable sources of energy and finding ways to reduce energy consumption are considered as essential means to ensure a sustainable future. A technology that can contribute towards these goals is shallow geothermal, which uses the ground as a heat source or sink to efficiently heat and cool buildings, by utilising the fact that the ground temperature a few tens of metres below the surface is relatively constant throughout the year [1]. Shallow geothermal, or ground source heat pump (GSHP), systems incorporate High Density Polyethylene (HDPE) or cross-linked polyethylene (PEX) pipes with a circulating carrier fluid into underground trenches or structures such as boreholes, piles or retaining walls, creating ground heat exchangers (GHEs) that transfer the heat to and from the ground [2–6].

Energy geo-structures are underground GHEs for which energy provision is a secondary function, after structural stability, such as energy piles or retaining walls [7–13]. The main advantage of these structures is that the capital costs are potentially significantly reduced, mainly because drilling (which is amongst the highest associated capital costs) is not accounted as part of the geothermal design [14,15]. On the other hand, the main limitation of energy geo-structures is that a significant number of design parameters (such as their geometry) is governed by the structural design. Therefore, since the location of GHEs and internal piping geometry are some of the key parameters (aside from the thermal properties of the ground) that determine how much energy they can provide, energy geo-structures cannot be designed to provide a specified/target amount of thermal energy. Instead, the amount of energy they can provide needs to be determined and, if required, complemented using auxiliary means, forming a hybrid system [16–20].

Moreover, because of the wide range of variability in structures, configurations and conditions, establishing a standardised, analytical, fast approach to energy geo-structure design is non-trivial. Instead, the use of complex and computationally expensive numerical simulations is usually required, especially for complex geometries, which is time demanding. This study presents a prediction model approach, that can be used alongside those complex numerical simulations to significantly reduce the amount of time required to undertake energy geo-structure analysis and/or design and very quickly and accurately answer the question of how much energy can the geothermal system provide for any geometry and conditions.

2. The proposed prediction model approach

2.1. Energy geo-structures and current approaches

As explained in Section 1, an important question needed to be answered in geothermal design as well as in research of energy geo-structures is *how much energy can the system provide* [21,22], instead of *how does the system need to be designed to provide the target energy demand*, as in traditional GSHP design. Knowing how much energy the system can reliably provide is important, as it enables an evaluation of its applicability for a given project to be performed, including a cost-benefit analysis. It is also beneficial for this information to be known relatively early in the design process, to better inform the prospective

* Corresponding author at: Department of Infrastructure Engineering, The University of Melbourne, Engineering Block B 208, Parkville, VIC 3010, Australia.
E-mail address: narsilio@unimelb.edu.au (G.A. Narsilio).

https://doi.org/10.1016/j.compgeo.2018.08.012
Received 22 June 2018; Received in revised form 11 August 2018; Accepted 15 August 2018

Nomenclature

A	prediction factor for cooling (Eq. (1)), °C
B	prediction factor for heating (Eq. (1)), °C
$C_{p\ material}$	specific heat capacity of material, J/(kg·K)
L_{wall}	depth of the wall excl. toe, m
s	vertical spacing between pipe legs, m
t	time, sec
T_{fluid}	average fluid temperature of a pipe loop (average of inlet and outlet), °C
$T_{farfield}$	average annual ground temperature, °C
$T_{initial}$	initial temperature of fluid in a pipe loop, °C
$\lambda_{material}$	thermal conductivity of material, W/(m·K)
$\rho_{material}$	density of material, kg/m^3

clients and investors and aid in their decision-making process about incorporating a geothermal solution to the project or not [8].

However, there exists a lack of a standardised approach to energy geo-structure design [23]. Instead, in answering this question either analytical or numerical approaches can be adopted [7,13]. The widely used commercial software for GSHP design implement analytical design approaches, which were mostly originally developed for traditional borehole systems. Such software can be used for energy pile design (which is considered similar to boreholes), even though research advises against this approach [24]. In regards to energy pile design, design guidelines have been made available [25] and some semi-analytical approaches, adopting g-functions have been proposed [26,27]. For energy retaining walls, however, general analytical approaches may be less suitable due to the vastly different geometries and conditions compared to traditional systems, although some semi-analytical approaches have been developed [28]. Moreover, due to the large number of assumptions adopted in analytical approaches, they are unable to capture the problem in its entirety. The second and more flexible approach is using numerical models to create and run a computational simulation of the system (in this research finite elements are utilised). Numerical simulations adopt significantly fewer assumptions and constraints and can therefore be utilised for any structure, geometry and conditions. For these reasons, numerical simulations are commonly reported as used in the research of further understanding these systems as well as their thermal design with several recent examples [21,29–34]. However, the complexity behind the simulations results in them requiring significant computational resources and, very importantly, time to provide results. The proposed methodology aims to address this drawback.

2.2. The prediction model principles

In utilising a finite element numerical simulation to analyse an energy geo-structure design, the thermal demand is firstly specified and the viability of the system to provide that demand is determined by examining the resulting temperature of the fluid within the HDPE pipes. The fluid temperature range, throughout the operation of the system, determines the efficiency and viability of the design. Each numerical simulation, which can require from hours to days or weeks to compute, can be used to evaluate if the temperature of the fluid is within the operational range of the GSHP. If not, then another simulation needs to be computed, specifying a new thermal demand to be satisfied by the energy geo-structures. This iterative process can be extremely computationally expensive and time consuming. This work introduces a prediction model that can aid in speeding this iterative process by removing the need for multiple costly numerical simulations, but instead uses the results of two such simulations to more quickly and inexpensively predict the system behaviour (the fluid temperatures) for any other combination of thermal loading. The overall process can be seen in Fig. 1, noting that the two finite element simulations can be run simultaneously instead of sequentially in order to further save time.

The proposed methodology involves predicting how the fluid temperature (T_{fluid}) within the system pipes at a specific time-step (t) will change, when the system provides different amounts of thermal energy for cooling and heating (to determine how much thermal energy the geothermal system can provide and how much is required to be provided by auxiliary means). This relationship turns out to be expressed in Eq. (1) and can be used alongside numerical modelling techniques to substantially reduce the required time to undertake the design.

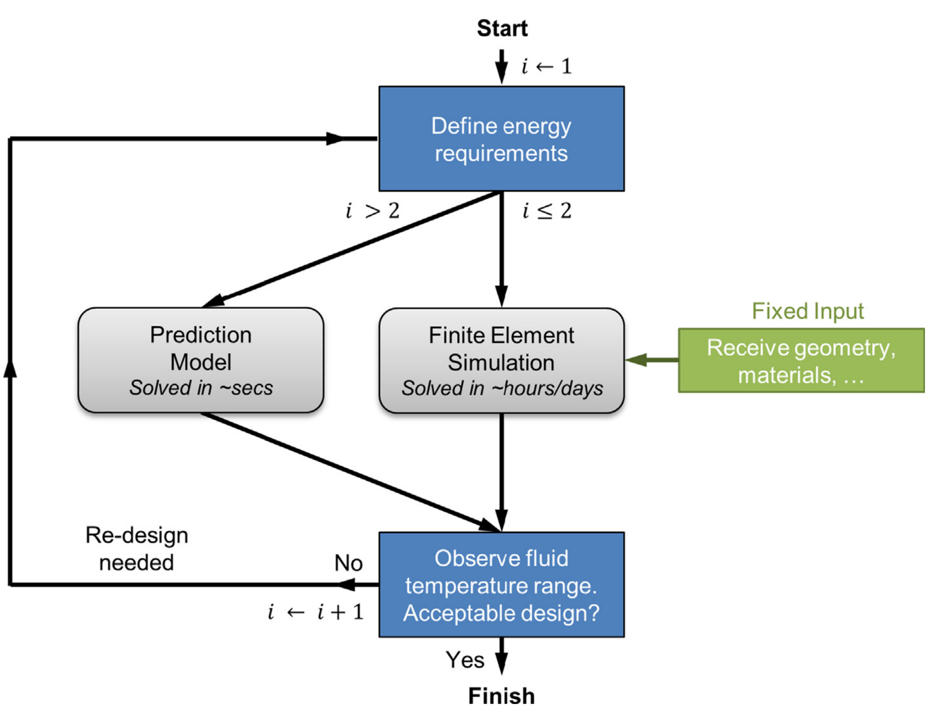

Fig. 1. Energy geo-structure design methodology with prediction model.