Dwellings' foundation as Ground Heat Exchangers in Eastern Mediterranean conditions

Lazaros Aresti[1], Georgios A. Florides[2], Paul Christodoulides[2,*]
[1] EMERGE CoE, Cyprus University of Technology, Limassol, Cyprus
[2] Faculty of Engineering and Technology, Cyprus University of Technology, Limassol, Cyprus; paul.christodoulides@cut.ac.cy

KEYWORDS - Geothermal energy, District Heating and Cooling, Ground Source Heat Pump

ABSTRACT

The current research analyzes the feasibility of deploying Ground Source Heat Pump (GSHP) systems in a micro-scale urban context for a prospective 5th Generation (5G) district heating and cooling network (DHC) with the integration of Energy Geo-Structures (EGS). In particular, a case study is carried out to evaluate the potential usage of EGS in residential blocks on the Mediterranean island of Cyprus. The study's subject is a typical multiple multi-story residential building with nearly Zero Energy Building (nZEB) characteristics. COMSOL Multiphysics software is used to computationally investigate the influence of ground temperature and temperature gain/loss from heat distribution during cooling in the summer. The Coefficient of Performance (COP) is found to remain essentially constant at around 5.85. It follows that EGS as GSHP systems for a domestic micro-scale level have a promising future in terms of cost savings, environmental friendliness, and renewable energy use.

1 INTRODUCTION

Geothermal energy is a renewable and environmentally beneficial type of energy that harnesses the inherent heat of the Earth. In particular, the use of shallow geothermal energy (SGE) has emerged as a potential and sustainable approach for fulfilling the ever-increasing energy demands while lowering carbon emissions and minimizing climate change consequences. This renewable energy technology uses the natural heat of the Earth from shallow depths, often within the first 100 meters below the surface, to provide heating, cooling, and hot water for residential, commercial, and industrial purposes. SGE system success and efficiency are strongly reliant on a thorough grasp of the design criteria that determine their performance. External meteorological conditions on ground temperature as well as the thermal behavior of shallow and deep ground zones have an impact on the behaviour of such energy source and how one can design and implement a geothermal system.

One of the most well-known types of geothermal energy systems is ground source heat pumps (GSHPs). GSHP systems heat and cool by extracting/rejecting heat from/to the ground via the connection of an HP with Ground Heat Exchangers (GHEs). GHEs are essentially a network of underground tubes that contain a secondary circulating fluid. GSHPs can outperform traditional Air Source Heat Pumps (ASHPs), and so they have lately gained popularity [1]. However, the high initial cost and resulting long payback period as well as questions about their environmentally friendliness have been deterrents to the implementation of GSHP systems in the residential sector [2–4].

* Corresponding author

GSHPs have recently been used in building foundations as Thermo-Active Structure systems or Energy Geo-Structures (EGS), with relevant applications including energy piles, barrette piles, diaphragm walls shallow foundations, retaining walls, embankments, and tunnel linings [5–7]. For example, energy piles are reinforced concrete foundations with geothermal pipes that are used to offer space heating and cooling; that is, the dwellings' foundations act as GHE elements. This could offer a significant reduction in the cost of the system, due to the reduction of the drilling and backfill material (grout) costs [8,9]. GHE energy pile configurations are similar to vertical borehole configurations, such as the U-tube, W-tube, 3U-tube, and spiral/ helical tube [10]. Although energy piles are the most commonly used components in EGS systems, the foundation of the dwelling can be of many types based on the site features and the required support of the building [13,14].

The use of a dwelling's bed foundation [15] as a GHE instead of foundation piles gives an alternative to energy piles, particularly on the island of Cyprus, where foundation piles are rarely employed. The reinforced concrete shallow foundation bed (similar to the monolithic slab foundation) is the most often utilized foundation element on the island of Cyprus. The foundation bed is related to horizontal type GHEs with similar features since it is used as an EGS element at shallow depths. Horizontal GHEs are less expensive and easier to install, but they require longer pipes and a greater land area [11]. Weather conditions affect horizontal GHEs on a daily or seasonal basis, depending on depth. Pouloupatis and collaborators [12–14] conducted experimental research on the effect of ambient temperature on ground temperature at numerous places in Cyprus (see Figure 1) and found that daily weather fluctuations were less significant between 0.25m and 7-8 m. Other researchers have carried out experimental and computational studies on the utilization of shallow building foundations as EGS [15,16].

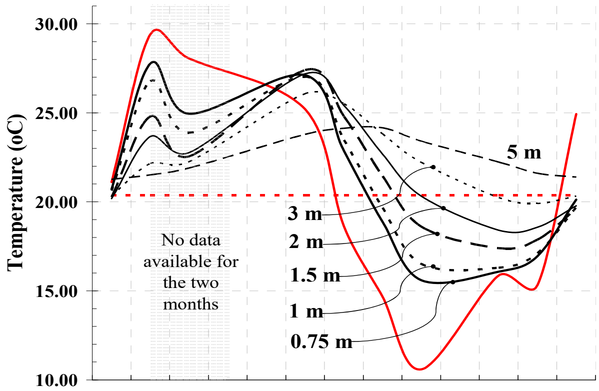


Figure 1: Mean monthly ground temperatures in the region of Athalassa, Cyprus, at shallow zone [14].

Geothermal energy has been recently used in District Heating and Cooling (DHC) networks. As a result, GSHP systems may become more viable, contributing to decreased DHC costs, maintenance, and carbon emissions [17]. The use of EGS systems in conjunction with DHC networks could give additional energy and support to the network while also reducing the requirement for larger centralized units [18]. Although such DH systems exist in central and northern Europe, where heating demand is higher than in southern Europe, the infrastructure required for a central unit and distribution makes the application difficult to implement. To overcome this, a micro-scale GSHP system could be used as an alternative to the above.

The current paper conducts such an initial investigation and preliminary assessment using the foundation bed of a multi-story dwelling as an EGS element in Eastern Mediterranean climate conditions. This preliminary assessment considers the viability of using EGS elements to support the building's heating and cooling loads, as well as perhaps providing extra energy for a 5th Generation (5G) DHC network.

2 METHODOLOGY

A computational analysis is chosen and applied in this study, with COMSOL Multiphysics serving as the computational tool. Specifically, the general three-dimensional convection diffusion equation has been used for all domains,

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot q = Q \tag{1}$$

where ρ is the density of the foundation material [kg m^{-3}], C_p is the specific heat capacity at constant pressure [J kg^{-1} K^{-1}], T is the temperature [K], t is time [s], q is given by the Fourier's law of heat conduction [W m^{-2}] and Q is the heat source [W m^{-3}].

A preliminary evaluation of the EGS systems might be made using a specific type of dwelling as a case study. Following the pattern of recent house constructions [19], the selected dwelling case here is a residential building unit in Lemesos (Limassol), Cyprus, having nine (9) housing units on 3 floors and a ground floor parking space. The dwelling has a total covered area of 198m^2 per floor/story, with the technical qualities of a nZEB. Figure 2 depicts the yearly heating and cooling story loads per month of the building under consideration. The cooling demand is obviously much higher than the heating demand, owing to the climate of Cyprus.

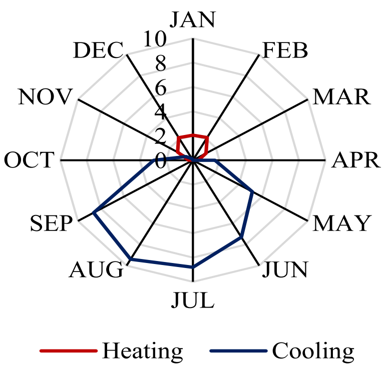


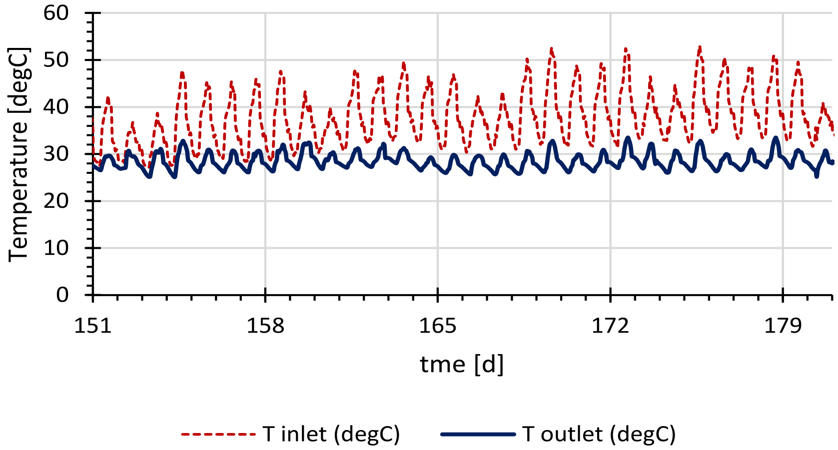
Figure 2: Left: the selected dwelling' yearly heating (red line) and cooling (blue line) demand per square meter per story; right: the dwelling's North face.

In Cyprus, the foundation bed is the most commonly utilized foundation element, with foundation piles being rarely employed. In the current study, the foundation bed is chosen to act as an EGS, but always fulfilling its primary duty (as a foundation); a thorough explanation of such hybrid systems can be found in [20].

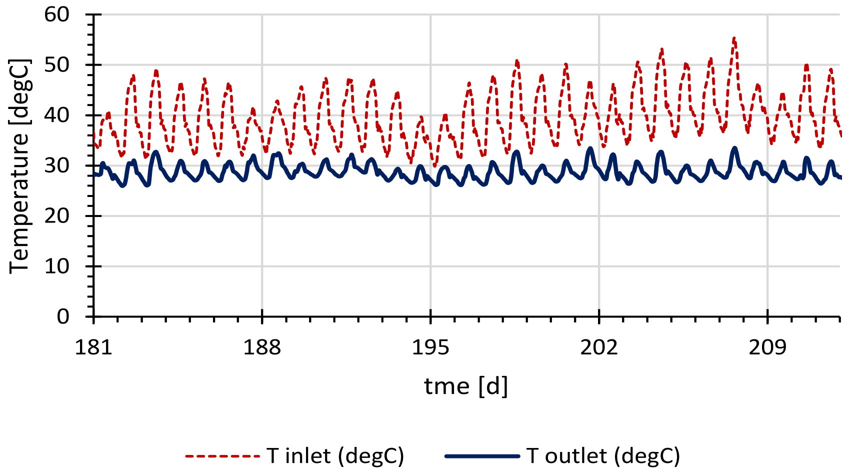
Note that equation (1) can be expanded and used accordingly in COMSOL Multiphysics for the in-foundation piping. The GHE pipe network is 350m long and made up of 32mm HDPE (high density polyethylene) pipes of 1.5mm wall thickness and 0.38 W m^{-2} K^{-1} thermal conductivity. Experimental ground temperature data from the literature (see Figure 1) were used, and ambient temperature data were treated as an inlet to the domain's top surface to act as a boundary condition (as seen in Figure 2). Finally, the COP (coefficient of performance) of the system was determined using the methodology of Mouzeviris and Papakostas [21].

3 RESULTS

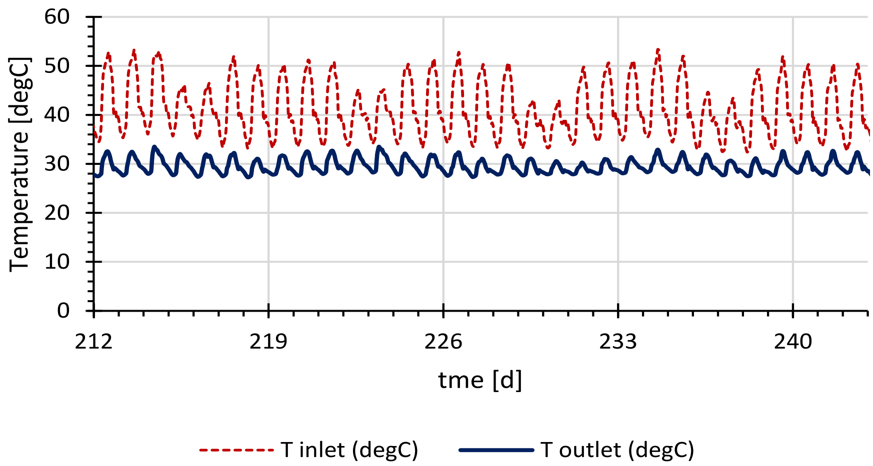
The HVAC (Heating Cooling and Ventilation) systems is customary to be designed based on the highest peak load, in this case in the summer months (see Figure 2), specifically in August, at 5586 kWh. Hence, preliminarily we investigate the foundation element temperature variation and the efficiency of the system for cooling during the summer months; we can then assess whether the investigated case study's system is viable.



(a)



(b)



(c)

Figure 1: Performance results for cooling of the proposed GSHP-EGS system with full load for the summer months of (a) June, (b) July and (c) August.

Figure 3 presents the daily fluid inlet and outlet temperatures for the months of June, July and August. The temperature from the GHEs will contribute towards a higher GSHP efficiency (COP) [22]. In cooling mode, energy rejection to the ground is substantially higher than energy absorption (see Figure 1). For the investigated summer months, it can be observed that the temperature on the outlet of the system (Toutlet) is nearly steady at monthly averages of 29°C, 29.5°C, 30°C, for June, July and August respectively. The average fluid temperature difference between inlet and outlet on the pipe network (ΔT) is at 10°C.

It turns out that COP of the GSHP using the outlet temperature as a reference values follows a similar trend (not shown here) with nearly steady values at averages of 5.9, 5.85 and 5.8 for June, July and August respectively. One can then conclude that the proposed GSHP-EGS system provides high performance, making it an acceptable EGS element, as it functions consistently for the outlet temperature.

4. DISCUSSION AND CONCLUSION

A typical residential 3-story dwelling with 9 apartments and nZEB characteristics was considered as a case study of a micro-scale 5G DHC. Specifically, the heating and cooling loads were used and directed into a pipe network installed into the foundation bed of the dwelling. In order to simulate the foundation bed system, a COMSOL Multiphysics computational model was built, taking into consideration the site's ground temperature and thermal properties as well as the surrounding ambient temperature. Based on the supplied loads, the inlet and outlet temperatures were computed hourly for the summer months. Computational simulation results have indicated that the GSHP cooling system achieves high COP values estimated at 5.8 to 5.9.

However, by performing yearly simulations, one can account for the regeneration of the foundation bed as a heat source/sink (in this example, the ground's superheating), which is the focus of future research. In addition, for a consistent performance of the EGS element, one should investigate the ground temperature and the foundation temperature, so that any possible rise in temperature only affects the parking space and not the residential area of the dwelling.

In addition, an extension of the current study would be to see if the EGS element could withstand extra load (for example, from surrounding residences). Another scenario to consider is one where the planned system is incapable of meeting a specific load (for example, greater estimated loads per apartment, increased number of apartments, insufficient foundation element area to install additional pipe length). In this situation, the produced COP values would be lower than expected, rendering the system inappropriate for usage, as the higher capital expenditure in a GSHP system would not make it preferable to an ASHP system; a possible "therapy" might be provided by partially loading of the foundation element in relation to the entire thermal load (heating and cooling) of the residence, with the employment of other geothermal components such as boreholes.

Acknowledgment: The authors greatly acknowledge the Cyprus University of Technology and the «POST-DOCTORAL» Programme for the funding support, as well as Dr. Costas Vasiliades (Vasiliades Architects, Lemesos, Cyprus) for providing the building data and plans.

REFERENCES

[1] L. Aresti, P. Christodoulides, G. Florides, A review of the design aspects of ground heat exchangers, Renew. Sustain. Energy Rev. 92 (2018) 757–773. doi:10.1016/j.rser.2018.04.053.

[2] P. Christodoulides, L. Aresti, G. Florides, Air-conditioning of a typical house in moderate climates with Ground Source Heat Pumps and cost comparison with Air Source Heat Pumps, Appl. Therm. Eng. 158 (2019) 113772.

doi:10.1016/j.applthermaleng.2019.113772.
[3] L. Aresti, G.A. Florides, A. Skaliontas, P. Christodoulides, Environmental Impact of Ground Source Heat Pump Systems: A Comparative Investigation From South to North Europe, Front. Built Environ. 8 (2022) 1–13. doi:10.3389/fbuil.2022.914227.
[4] L. Aresti, P. Christodoulides, G.A. Florides, An investigation on the environmental impact of various Ground Heat Exchangers configurations, Renew. Energy. 171 (2021) 592–605. doi:10.1016/j.renene.2021.02.120.
[5] D. Sterpi, G. Tomaselli, A. Angelotti, Energy performance of ground heat exchangers embedded in diaphragm walls: Field observations and optimization by numerical modelling, Renew. Energy. 147 (2020) 2748–2760. doi:10.1016/J.RENENE.2018.11.102.
[6] H. Brandl, Thermo-active Ground-Source Structures for Heating and Cooling, Procedia Eng. 57 (2013) 9–18. doi:10.1016/J.PROENG.2013.04.005.
[7] F. Loveridge, The Thermal Performance of Foundation Piles used as Heat Exchangers in Ground Energy Systems, Univ. Southhampt. (2012) 206. http://eprints.soton.ac.uk/348910/1.hasCoversheetVersion/F Loveridge eThesis FINAL.pdf.
[8] Y. Cui, J. Zhu, F. Meng, Techno-economic evaluation of multiple energy piles for a ground-coupled heat pump system, Energy Convers. Manag. 178 (2018) 200–216. doi:10.1016/J.ENCONMAN.2018.10.042.
[9] S. Yoon, S.-R. Lee, J. Xue, K. Zosseder, G.-H. Go, H. Park, Evaluation of the thermal efficiency and a cost analysis of different types of ground heat exchangers in energy piles, Energy Convers. Manag. 105 (2015) 393–402. doi:10.1016/J.ENCONMAN.2015.08.002.
[10] G. Tinkler, Geothermal Heat Pump Systems, 2014. doi:10.1081/e-eee2-120041653.
[11] U. Lucia, M. Simonetti, G. Chiesa, G. Grisolia, Ground-source pump system for heating and cooling: Review and thermodynamic approach, Renew. Sustain. Energy Rev. 70 (2017) 867–874. doi:10.1016/j.rser.2016.11.268.
[12] G. Florides, P.D. Pouloupatis, S. Kalogirou, V. Messaritis, I. Panayides, Z. Zomeni, G. Partasides, A. Lizides, E. Sophocleous, K. Koutsoumpas, Geothermal properties of the ground in Cyprus and their effect on the efficiency of ground coupled heat pumps, Renew. Energy. 49 (2013) 85–89. doi:10.1016/j.renene.2012.01.059.
[13] P.D. Pouloupatis, G. Florides, S. Tassou, Measurements of ground temperatures in Cyprus for ground thermal applications, Renew. Energy. 36 (2011) 804–814. doi:10.1016/j.renene.2010.07.029.
[14] P.D.. Pouloupatis, Determination of the Thermal Characteristics of the Ground in Cyprus and Their Effect on Ground Heat, Brunel University, 2014.
[15] C.E. Moon, J.M. Choi, Heating performance characteristics of the ground source heat pump system with energy-piles and energy-slabs, Energy. 81 (2015) 27–32. doi:10.1016/j.energy.2014.10.063.
[16] N. Kayaci, H. Demir, B.B. Kanbur, Ş.O. Atayilmaz, O. Agra, R.C. Acet, Z. Gemici, Experimental and numerical investigation of ground heat exchangers in the building foundation, Energy Convers. Manag. 188 (2019) 162–176. doi:10.1016/j.enconman.2019.03.032.
[17] L. Aresti, P. Christodoulides, G.P. Panayiotou, G. Florides, Residential Buildings' Foundations as a Ground Heat Exchanger and Comparison among Different Types in a Moderate Climate Country, Energies. 13 (2020) 6287. doi:10.3390/en13236287.
[18] S.S. Meibodi, F. Loveridge, The future role of energy geostructures in fifth generation district heating and cooling networks, Energy. 240 (2022) 122481. doi:10.1016/j.energy.2021.122481.

[19] CYSTAT, Bulding Permits, Annual, Repub. Cyprus, Stat. Serv. (2022). https://cystatdb.cystat.gov.cy/pxweb/en/8.CYSTAT-DB/8.CYSTAT-DB__Construction/.

[20] L. Aresti, P. Christodoulides, G.P. Panayiotou, G. Florides, The Potential of Utilizing Buildings' Foundations as Thermal Energy Storage (TES) Units from Solar Plate Collectors, Energies. 13 (2020) 2695. doi:10.3390/en13112695.

[21] G.A. Mouzeviris, K.T. Papakostas, Seasonal heat performances of air-to-water heat pumps in the Greek climate. In *IOP Conference Series: Earth and Environmental Science* (Vol. 410, No. 1, p. 012043) (2020). IOP Publishing.

[22] P.D. Pouloupatis, S.A. Tassou, P. Christodoulides, G.A. Florides, Parametric analysis of the factors affecting the efficiency of ground heat exchangers and design application aspects in Cyprus, Renew. Energy. 103 (2017) 721–728. doi:10.1016/j.renene.2016.11.006.