Using buildings' foundation as a GHE in moderate climates

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Rationale and Summary

Shallow Geothermal Energy, a Renewable Energy Source, finds application through Ground Source Heat Pumps (GSHPs) for space heating/cooling via tubes directed into the ground. There are two main categories of Ground Heat Exchanger (GHE) types: the horizontal and the vertical types. Ground Heat Exchangers (GHEs) of various configurations, extract or reject heat into the ground. Even though GSHP have higher performance in comparison to the Air Source Heat Pumps (ASHPs), the systems high initial costs and long payback period have made it unattractive as an investment. GSHP systems can also be utilized in the buildings foundation in the form of Thermo-Active Structure (TAS) systems or Energy Geo-Structures (EGS), with applications such as energy piles, barrette piles, diaphragm walls, shallow foundations, retaining walls, embankments, and tunnel linings. Energy piles are reinforced concrete foundations with geothermal pipes, whereby the buildings foundations are utilized to provide space heating and cooling. Apart from energy piles, another EGS system can be achieved by the incorporation of the building's foundation bed as a GHE. Foundation piles are not required in all constructions, but a building's foundation bed is mandatory. This configuration is still based on the principles of the energy pile.
The potential of the GSHP systems by utilizing the building's foundation is considered here for a nearly Zero Energy Building, in moderate climate conditions such as Cyprus. The current study deals with the case of a typical house thermal load in moderate climate, through computational modelling, based on the convection-diffusion equation and transient time analysis. Water inlet temperatures are examined for summer/winter. The power rejected to the ground is discussed with regard to system efficiency, affected by the fluid temperature entering the HP. A basic initial capital comparison is also done.

Introduction and Set-up

- The GSHPs, compared to ASHPs, exhibit significantly higher performance but with greater initial cost.
- In order to evaluate and compare the cost effectiveness of a GSHP system, a typical house in moderate climate in Cyprus is considered.
- From a sample of 500 residential buildings arises that most of the houses are between 51 to 200m^2 with a mean area of 173 m^2 and an average of 57 m^2/occupant, while the primary energy per total area is between 51 and 150 kWh/m^2 [1].
- The selected typical house is a three-bedroom two storey house, with a total useful floor area of 190 m². In one side, the house is attached to another house, and there is available land space of at least 4 m in the other three sides. The house is made of reinforced concrete foundation bed, pillars and beams, while the walls are made of red and sandy clay bricks. All parts of the house are thermally insulated with extruded polystyrene, while double glazed aluminium framed windows are used. The layout of the house is illustrated in Figure 1.
- Thermal characteristics of nearly Zero Energy Building; U-values of 0.4 W/m^2/K on all walls and ceiling and 2.25 W/m^2/K on all doors and windows, respectively.

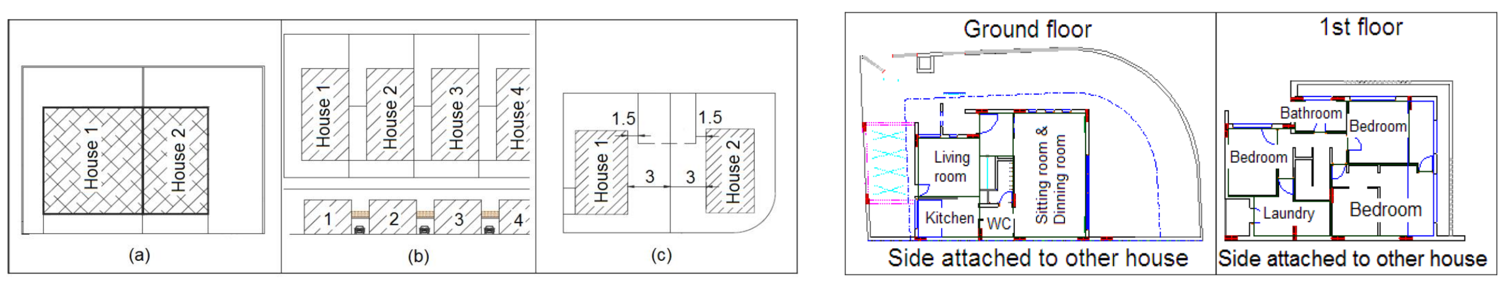

Figure 1. Left: Typical positioning of houses in plots; units in meters,(a) semi-detached, (b) linked detached and (c) detached, Right: Plan views of the typical house used for the estimation of the heating and cooling load

Heating and Cooling Loads Results

- TRNSYS software is used to calculate the heating and cooling loads, model set-up illustrated in Figure 2.
- Set Temperatures for the building are fixed at 21°C and 27°C for Winter and Summer respectively.

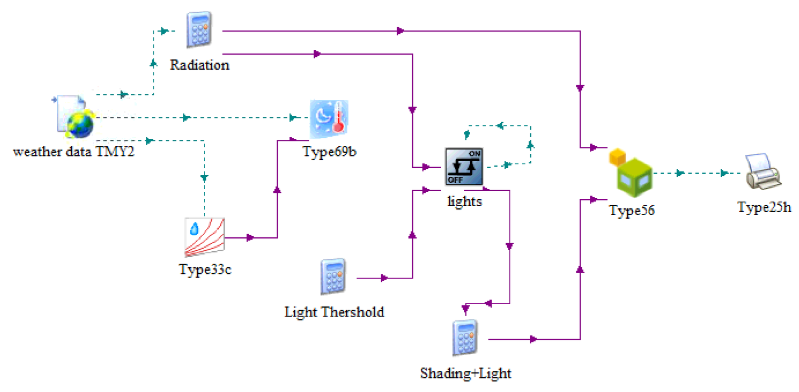

Figure 2. TRNSYS model set-up for heating and cooling load calculations for the investigated residential building

- The following TRNSYS types are used for the computations: Type 109 – TMY2 (weather data processing model), Type 33 – Psychrometrics, Type 69 – Effective sky temperature for long-wave radiation exchange, Type 2 – ON/OFF Differential controller, Type 65 – Online graphical plotter, Type 25 – Printer – TRNSYS – supplied units printed to output file, Type 56 – Multi-Zone Building.
- The results illustrated in Figure 3 show that the heating load peak is nearly half the cooling load, with peak cooling load being 15.4 kW and peak heating load being 7.9 kW. Additionally, the cooling load is required for a longer period (more months).
- An existing commercial GSHP is selected and the COP values versus input fluid temperatures are used to calculate the condenser load a shown in Figure 4.

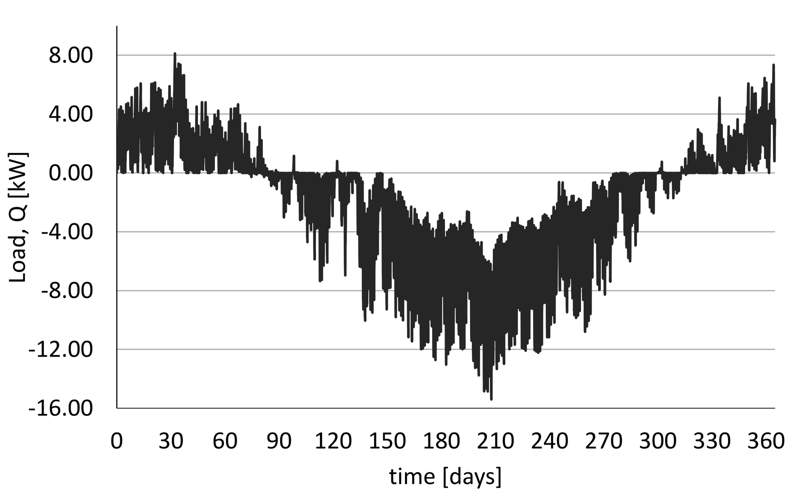

Figure 3. Simulated Heating and Cooling loads of the investigated residential building

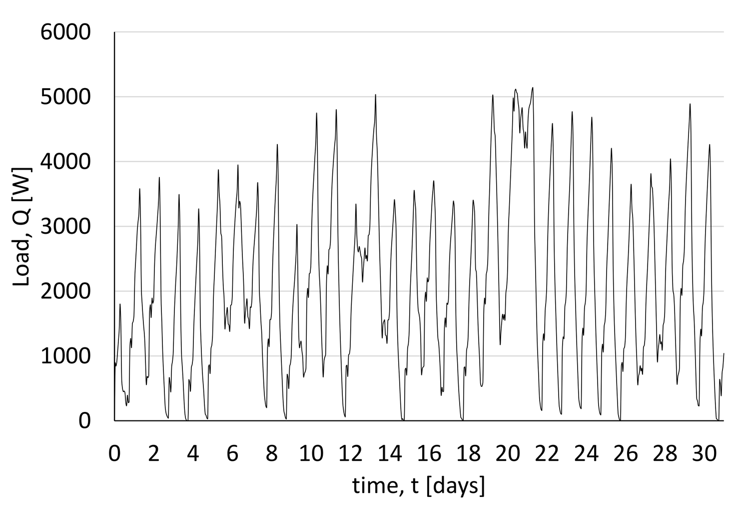

Figure 4. Condenser heating loads of the investigated building for the month of January

GHE Computational Modelling Results

- The basic equation governing the convective and conductive heat transfer in the system under investigation is [2]

$$\rho c_p \frac{\partial T}{\partial t} + \rho_f c_{pf} u_f \nabla T + \rho_w c_{pw} u_w \nabla T + \nabla\cdot(-\kappa\nabla T) = Q$$

where t denotes time [s], ρ denotes the density [kg m^{-3}], u the velocity [m s^{-1}], T the temperature [K], c_p the specific heat capacity [J kg^{-1} K^{-1}], κ the thermal conductivity [W m^{-1} K^{-1}], Q the power density of the heat source [W m^{-3}]. Subscript f denotes the GHE fluid, while w denotes underground water.

- COMSOL Multiphysics software is used for the investigated GHE using the convection-diffusion equation above with transient time analysis. Geometry model illustrated in Figure 5. The model consists of two domains, the ground and the foundation bed, where a network of pipes in included.
- Note that at the boundary between the fluid and the tubes the convective heat flux is hΔT, where h is the convective heat transfer coefficient of the process [W m^{-2} K^{-1}] and ΔT is the temperature difference at the boundary. The convective heat transfer coefficient h depends on the Nusselt number Nu, the Prandtl number Pr, and the Reynolds number Re, all of which can be estimated as

$$h = \kappa\frac{Nu}{D}, \qquad Nu = 0.023Re^{0.8}Pr^{n}, \qquad Pr=\frac{\mu c_p}{\kappa}, \qquad Re=\frac{\rho c_p d}{\mu}$$

where μ is the dynamic viscosity, d is the inside tube diameter (m), D is the hydraulic diameter.

- Inlet temperatures are computed based on the estimated condenser load.
- Calculated values for one month in Winter are illustrated in Figure 6, where the GHE inlet and outlet fluid temperatures are plotted against time. These show that the greater the difference between the input water temperature and the ground temperature, the greater the rejected heat to the ground. A temperature difference of approximately 2°C is observed. The resulting outlet temperature exhibits a nearly constant output, which is favorable for the heat pump to operate efficiently.

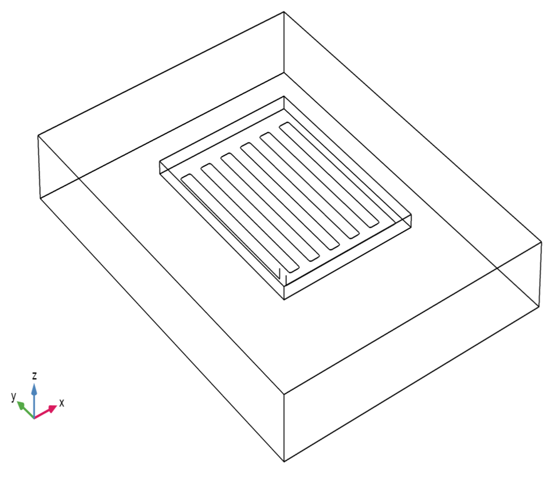

Figure 5. Buildings foundation as a GHE, with a network of pipes

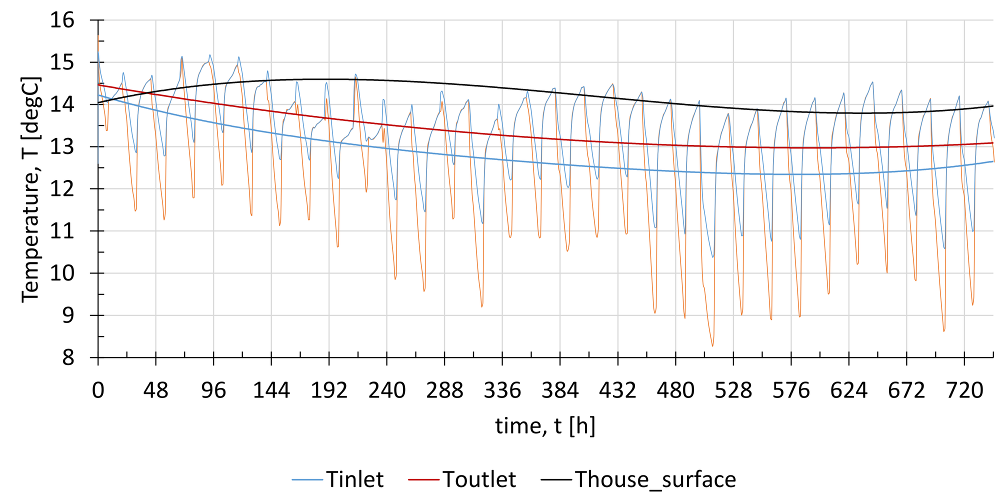

Figure 6. Initial investigation for one month in Winter

GHE Initial Capital Comparison

- The difference in the cost between a GHSP coupled with a borehole GHE, and a GSHP system coupled with a foundation bed as a GHE, lays in the GHE and the associated equipment [3], such as the borehole extraction, U-tube GHE, grout material, ground loop installation, header-flowmeter valves, horizontal pipe circuits, and other general expenses. In order to examine and compare the difference, typical extra cost values for the installation of a GHE to satisfy the building load are illustrated in Table1.

Table 1. Typical cost values for the installation of a GSHP

Item	Current Cost	400 m GHE Cost (€)	800m GHE Cost (€)	Foundation bed GHE Cost (€)
Borehole extraction	13 €/m	5200	10400	0
pipe GHE Φ 32 mm	6 €/m	2400	4800	1320 (220m)
Grout material	7.5 €/m	3000	6000	0
Header-flowmeters-valves	-	900	900	900
Horizontal pipe circuits	-	600	1000	600
General expenses	-	500	700	500
Total		12600	23800	3320

- The cost of grout material and the extraction is not calculated since it is mandatory in any building. Therefore only the extra cost factors are included. It can be seen that the cost of the foundation GHE covers only one fourth of the convectional U-tube borehole GHE with 400m pipe (4 boreholes if each borehole has 100m depth)

Conclusions

- The TRNSYS software was used to examine the heating and cooling loads of a typical residential building in moderate Mediterranean climate conditions. The three bedroom house of 190 m² has a peak cooling load of 15.4 kW and a peak heating load of 7.9 kW.
- The COMSOL Multiphysics software was used to investigate the building's foundation bed as a GHE using the convection-diffusion equation with transient time analysis.
- The model appears to have a nearly steady outlet temperature, without a great variation between day load and night load.
- Initial capital cost comparison shows that the GSHP system with foundation bed as GHE is an economical alternative, with savings of 75% over convectional GSHP coupled with a U-tube borehole GHE.
- The preliminary results, although promising, indicate there is a need for further investigation and to expand the system analysis in the more demanding months of summer, where the load is greater.
- Moreover, a parametric analysis of the GHE design aspects should also be carried out.

Selected References

[1] G.P. Panayiotou, S.A. Kalogirou, G.A. Florides, C.N. Maxoulis, A.M. Papadopoulos, M. Neophytou, P. Fokaides, G. Georgiou, A. Symeou, G. Georgakis, The characteristics and the energy behaviour of the residential building stock of Cyprus in view of Directive 2002/91/EC, Energy Build. 42 (2010) 2083–2089.

[2] L. Aresti, P. Christodoulides, G.A. Florides, A review of the design aspects of ground heat exchangers, Renewable and Sustainable Energy Reviews. 92 (2018) 757-773.

[3] P. Christodoulides, L. Aresti, G.A. Florides, Air-conditioning of a typical house in moderate climates with Ground Source Heat Pumps and cost comparison with Air Source Heat Pumps, Applied Thermal Engineering. 158 (2019) 113772.