APPLICATION OF SHALLOW ENERGY PILES FOR THE PURPOSE OF HEATING AND COOLING OF BUILDINGS

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ABSTRACT

Shallow energy piles are these days internationally being implemented for serving as heat exchanging media between the ground and the building in addition to supporting structural loads. This research aims at providing the basic concepts for the application of energy piles for a portion of the total demands of high-rise buildings in Ethiopia, specifically heating and cooling demands. Preliminary estimation of the number of energy piles to cover a certain portion of the total heating and cooling demands of a selected building in Addis Ababa showed the potential for its application in the future. Investigation of the behaviour of energy piles due to the action of cycling heating and cooling loads by using finite element software TOCHNOG were also performed by employing the appropriate hypo-plasticity constitutive model for the soil layers. The measured values of the thermo-mechanically loaded pile were reasonably simulated by the finite element model. The coupled thermo-mechanical cyclic thermal and mechanical loads were found to reduce the settlements of the foundation significantly, which can be considered as an additional advantage of this foundation technique for high rise buildings.

Key words: energy piles, finite element analysis, HVAC, hypo plasticity.

INTRODUCTION

In this world of increasing development activities due to urbanization, the energy demand is growing rapidly. Since most of the traditional sources of energy are associated with environment pollution, it is desirable to seek for more modern and renewable energy sources. Geothermal energy is among such sources, which is capable of minimizing the carbon-dioxide (CO_2) emission and promotes compliance with international environment obligations such as the Kyoto and Toronto targets [1, 2].

There are two common types of applications of geothermal energy, namely deep geothermal and near surface geothermal technologies. While deep geothermal technologies exploit deep reservoirs with temperatures higher than 100^{o}C, near surface geothermal technologies exploit heat energy stored at shallow depth, i.e. commonly not deeper than approximately 200 m. Down to a depth of approximately 5 m, thermal energy absorbed from solar radiation energy plays a significant role. Since the groundwater and soil particles have high heat storage capacities, it is nowadays common practice to use the shallow sources for a certain portion of the energy demand of buildings through structural elements such as energy piles and retaining walls [3]. The good thermal storage and conductivity of concrete makes these structures ideal heat exchange media.

High density polyethylene pipes, in which a heat carrier fluid circulates, installed within the concrete structures extract the geothermal energy from the ground [4].

According to [4, 5], the ground temperature tends to be constant below approximately 10 - 15 m with the magnitude depending on the location (10 – 15^{o}C in Europe and 20 - 25^{o}C in Africa). These temperature ranges are sufficient to allow heating and cooling of buildings in winter and summer respectively. Thermal structures like energy piles are frequently incorporated in to buildings in Austria, Germany and Switzerland [1, 6]. The technology is presently attaining more practical application all over the world [8 - 10]. Some of the successful applications of energy piles for covering the heating, ventilation and air conditioning system (HVAC) demands of buildings have been summarized in Table 1.

Table 1. Worldwide energy pile applications for covering the HVAC demands of buildings

Building	Location	Total no. of piles	Energy piles	Dimension	Serving
Lainzer tunnel	Vienna	59	1/3 of total	1.2 m diam. 17.1 m length	Heating/cooling (214 MWh)
SFIT	Lausanne	440	300	0.9-1.5 m diam. 30 m length	85% of HVAC demand
HochVier	Frankfurt	302	212	1.86m diam. 27 m length	HVAC
Keble building	Oxford	61	all	0.45 m diam. 12 m length	full HVAC demand

Application of the energy piles at Swiss Federal Institute of Technology in Lausanne and Dock Midfield Airport in Switzerland showed that the additional cost of implementing energy piles has already been compensated with the energy savings only within eight years [11]. Based on these and other experiences, a preliminary analysis has been performed regarding the application of shallow energy piles in Addis Ababa based on the demand analysis of a selected high-rise building, to cover a certain portion of its heating and cooling demands.

Understanding the effects of temperature variations on the mechanical behaviour of the foundation and the ground is a key factor for an optimized application of energy piles in any parts of the world. To that effect, many in-situ tests have been performed on different ground conditions to reveal the behaviour of energy piles [12, 13]. Even if there have been research activities to model the behaviour of energy piles using numerical tools, there are still gaps to acquire material models which represent the cyclic loading scenario with close proximity to real behaviour depicted during in-situ measurements. This research further addresses the behaviour of a thermo-mechanically loaded pile in layered soils, due to cyclic thermal loading using finite element method by applying appropriate constitutive model for the soil by validating the experimental results of Laloui et al. [11].

Energy Demands in Ethiopia and introduction of energy piles for HVAC demands

The Ethiopian energy sector faces the dual challenges of limited access to modern energy and heavy reliance on traditional biomass energy sources to meet the ever-growing demands, which is associated with environment pollution [14]. In recent years, despite the fact that the country has been in continuous economic growth, there is a challenge to get the required energy supply to sustain this growth into the future.

According to Mondal et al. [14], more than 80% of the energy in Ethiopia remains to be consumed by rural and urban households until 2030 as shown in Fig. 1, dominantly meant for cooking and heating purposes. However this will be associated with environment pollution due to the tremendous CO_2 emission. It is thus important to look for sustainable renewable energy sources targeted to cover a significant portion of this demand.

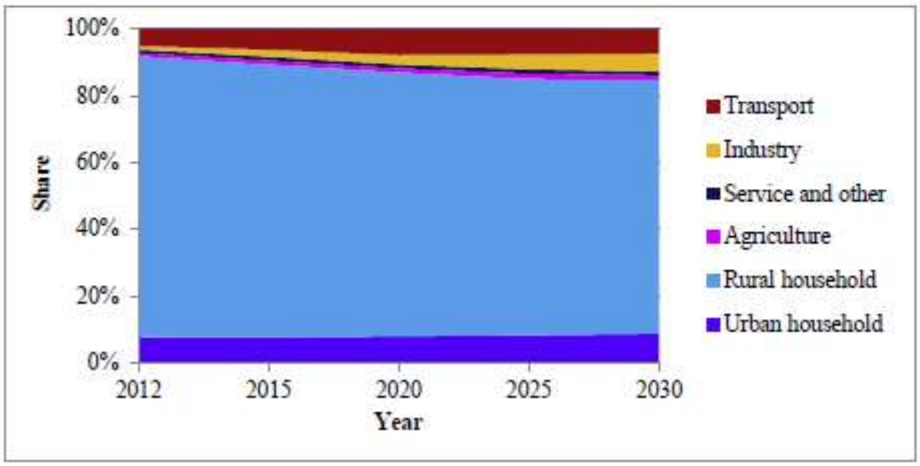


Fig. 1 Sector-wise percentage share of energy consumption in Ethiopia [14]

The percentage shares of urban household, transport and industry sectors show gradual increase with time while that of rural household decreases, due to development activities and increased urbanization. These sectors have heating and cooling demands in addition to the basic energy needs.

As experienced in the other parts of the world, shallow geothermal energy can be considered as a viable renewable energy source forth industry as well as household purpose, which can be associated with the foundation elements. If piles are accompanied by energy accessories from the ground, the energy production doesn't depend on the building area in contrary to solar energy, rather on the pile contact area with the ground, which is entirely dependent on the pile geometry.

Even if the energy extracted from the pile foundation shall be calculated based on detailed three - dimensional analyses, Brandl [15] provided design guidelines for general feasibility studies which can show the potential of using energy piles. Accordingly, the energy volume that can be extracted from thermo active energy piles can be estimated as a function of the pile diameter, D, as follows:

- pile foundations, with piles D = 0.3 - 0.5 m: 40 - 60 W per meter run,
- pile foundations, with piles D > 0.6 m: 35 W per m^2 earth-contact area

In the design and analysis of energy foundation, one of the first important tasks is analysing the energy demands of the building for HVAC demands. This value is considered when deciding the dimension of the foundation. Spacing, diameter & length as well as the number of piles with assigned dimensions will be evaluated if the energy extracted fulfils the cooling and heating requirement of the building.

According to [16], the heating and cooling demands of residential and commercial buildings in Africa accounts for about 20 % and 52 % of their total energy demands, respectively. Although detailed analyses need to be performed, the Author of this research estimates the HVAC demand of buildings in Addis Ababa to be 20 – 30 % of the total energy demands. This research is aimed at demonstrating the possibility of covering this amount of energy demands by the use of energy piles. The already constructed 4B+G+32 United Bank Head Quarter building was chosen for the preliminary demand and supply analysis of energy from shallow geothermal sources in Addis Ababa. The structure was built on 3,338 m^2 area of land and the main tower of the building was supported by 282 cast in-situ reinforced concrete piles of 28 m length and 0.8 m diameter spaced at 2.4 m. The contact area of a single pile with the soil is thus found to be 70.37 m^2, which is used for the estimation of the required number of piles. The total energy demands of the building was assessed to be 2,698 KVA; among which, 761.44 KVA or 609.15 kW, is required for heating and cooling (HVAC) of the building, which accounts for 28.22 % of the total demands. The number of energy pile required for fulfilling the cooling and heating demands of the building are determined according to the aforementioned pre-design method of Brandl [15] as illustrated in Table 2.

Table 2: Comparison of the amount of energy extracted from different number of energy piles

No. of Energy Piles	**% Energy Pile/ Total No. Piles**	**Total Contact Area(m^2)**	**Amount of energy extracted (kW)**	**Energy required for HVAC system(kW)**	**%Extracted/Required**
50	17.73	3518.58	123.15	609.15	20.22
75	26.60	5277.87	184.73	609.15	30.33
150	53.19	10555.74	369.45	609.15	60.65
200	70.92	14074.32	492.60	609.15	80.87
249	88.30	17522.53	613.29	609.15	100.68

It can be observed that the total HVAC demand of the building can be covered by using 249 energy piles, i.e., 88.3 % of the total number of structural piles. It is also possible to produce a portion of the total HVAC demand of the building by reducing the piles. Consequently, half and a quarter number of the total number of piles could produce about 60 % and 30 % of the total HVAC demand, respectively.

1 . Predicting settlements of energy piles due to coupled cyclic thermo-mechanical actions

Understanding the behaviour of energy piles due to the combined actions of mechanical and cyclic thermal loads in layered soils is the key for the successful application of the technology. Numerical methods are among the approved methods of analysis for such type of complex structures in the European code [17]. Owing to its layered formation the in-situ measurements of [11], performed on one of the piles of a four-story building at Ecole Polytechnique Federal de Lausanne (EPFL), has been considered for further analysis.

The building with a ground area of 100 m x 30 m is founded on 97 bored piles with a pile length of L_p = 25.8 m and a diameter of d_p = 0.88 m. The groundwater level is located close to the ground surface. The mechanical load acting on the test pile corresponds to the dead weight of the building under construction. The thermal load was induced by a heating device controlling the temperature of the water used as heat carrier fluid in the PE tubes. The two types of loads were applied separately and alternately in order to identify thermal and mechanical effects. As shown in Fig. 1, the thermo mechanical loading was depicted in seven cycles, excluding Test0 which represents the measurements made during the casting of the pile. During the first phase (Test1), the temperature is increased to a maximum value of 21.8 ^{o}C beyond which unloading follows to the minimum value. The mechanical load of Q =1300 kN was applied linearly beginning from the end of the first step to the end of the 6thcycle. At the end of the construction of each story, a thermal loading cycle was applied to a maximum of ΔT = 15 ^{o}C as schematized in Fig. 1.

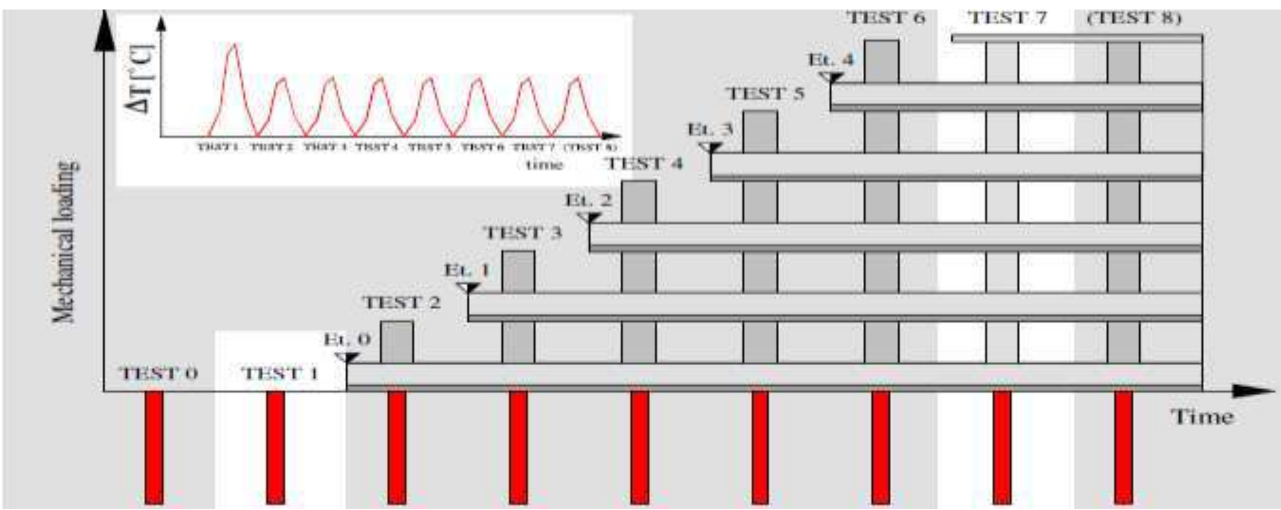


Fig. 2 Thermo-mechanical loading history (after [11]).

The results of the measurements have been compared with those of an axis-symmetric finite element model employed in TOCHNOG software [18]. The finite element mesh presented in Fig. 3 comprises approximately of 4900 quadrilateral elements, together with appropriate boundary conditions in the model for all loading conditions.

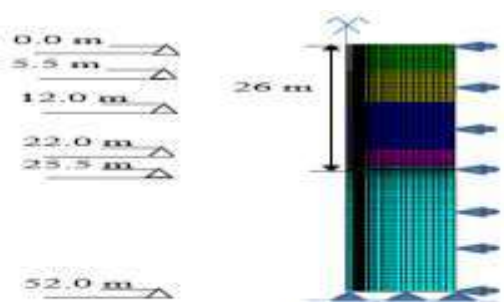


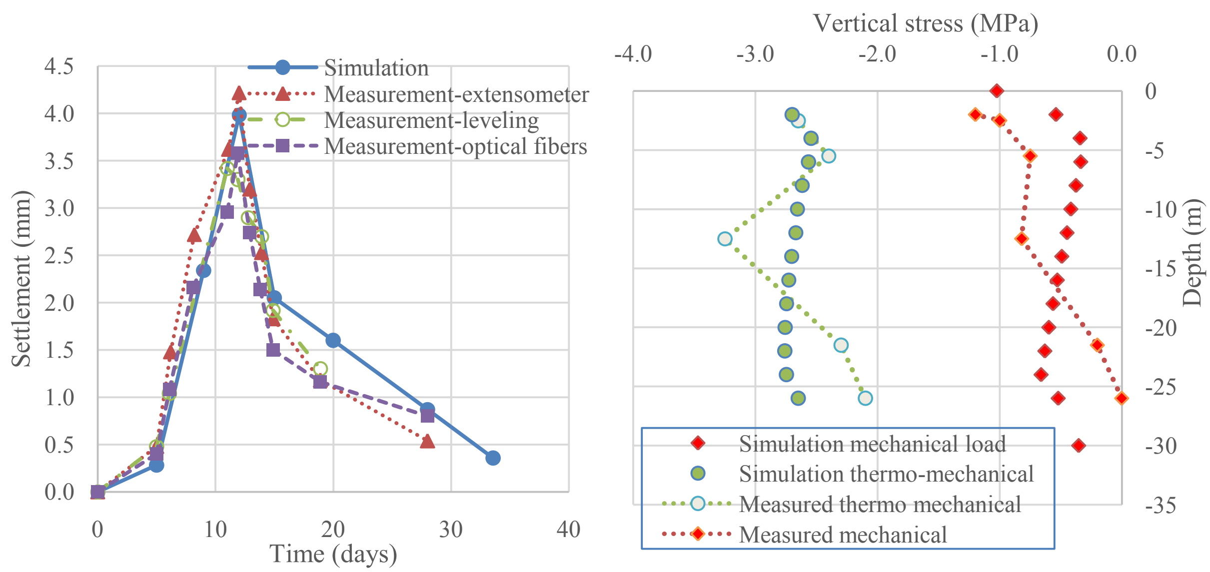
Fig. 3 Finite element mesh

Based on the results of a preliminary study comparing various constitutive models, the hypo plastic model by Masin [19] has been adopted for the predominantly cohesive soil layers. Masin's model incorporates the concept of intergranular strains first proposed by Niemun is and Herle [20], which considers the small strain stiffness allowing simulation of some effects of cyclic soil behaviour. The parameters for the selected constitutive model have been derived from the reports of [14, 21, 22] and the concrete pile is assigned linear-elastic parameters with Young's modulus, E of 29.2 MPa and Poisson's ratio, ν of 0.25. The basic soil parameters used in the analyses are summarized in Table 3.

Table 3 **.**Basic material parameters for the soil layers

Material parameters for the respective layers	**A1 Alluvial soil**	**A2 Alluvial soil**	**B Sandy gravelly moraine**	**C Bottom moraine**	**D Molasse**
Poisson's ratio υ **[-]**	0.2	0.2	0.4	0.4	0.3
Elastic modulus E [MPa]	190	190	84	90	3000
Friction angle ϕ' [°]	30	27	25	27	35
Cohesion c' [kPa]	5	3	6	20	2000
Thermal conductivityλ [W/m °C]	3.38	3.38	4.17	4.17	2.38
Specific heat capacity C_s [Joules/m^3 °C]	2463.7	2463.7	2434.2	2438.6	2359.2
Thermal expansion coefficient of solid state, β_s [per °C]	3.3×10^{-6}	3.3×10^{-6}	3.3×10^{-6}	3.3×10^{-6}	3.3×10^{-5}
Thermal expansion coefficient of liquid state β_w [per °C]	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}
Ground flow capacity C_w[Joules/m^3 °C]	4186	4186	4186	4186	4186
Permeability k [m/s]	$2x10^{-6}$	$7x10^{-7}$	$1x10^{-6}$	$1x10^{-6}$	-

The thermo-mechanical loading scheme of the in-situ test has been analyzed by considering the step-by-step procedure of the practical condition as presented in Fig. 1. Two sets of measured data (at the 1st and 7thcycles) have been used for validating the numerical model. Fig. 4 a) and b) present the comparative results of the measured and computed values for the displacements of the pile head in the first cycle and the vertical stress at pile shaft in the 7th cycle respectively.



a) Settlement versus time(1st cycle) b) vertical stress with depth (7th cycle)

Fig. 4Comparison of measured and numerically computed values

Since both simulations of the mechanical load and the thermo - mechanical load are in close agreement with the measured values, further analyses regarding the effects of cyclic loading on the settlements of an energy pile have been performed by employing the proposed constitutive model for the soil layers. The assumptions and analyses phases used for the validation purpose have been adopted for the analyses. The influence of cyclic heating and cooling on the pile head displacement is depicted in Fig. 5.

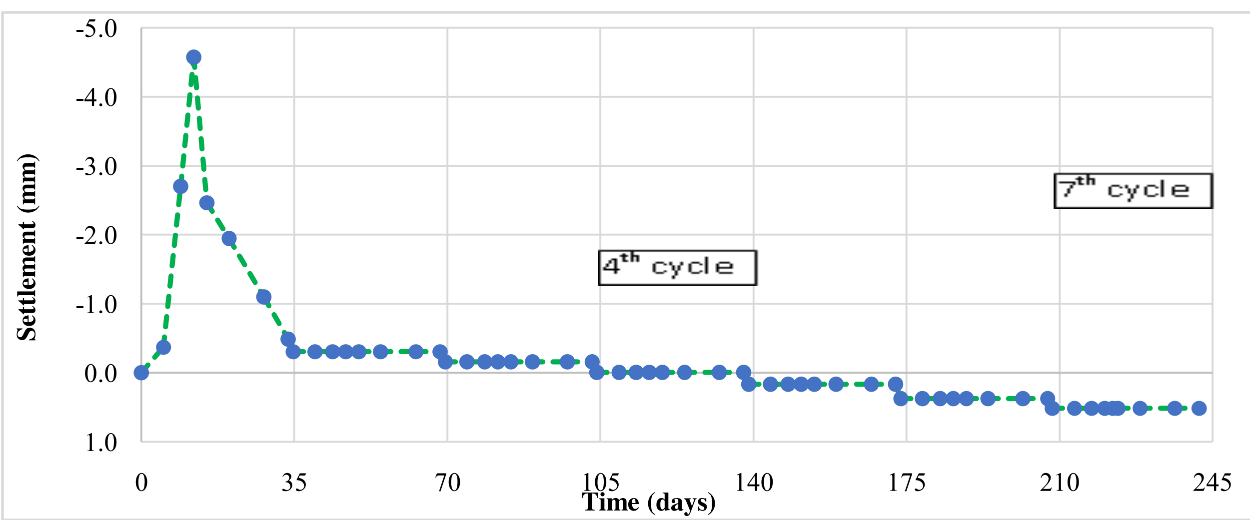


Fig.5 Effect of cyclic thermo mechanical loading on pile head settlement

In the first cycle, where temperature alone is varied without the mechanical load, elongation of the raft is found to be proportional to the applied thermal load, the maximum value being recorded at the maximum temperature of 21.8 ^oC. The elongated pile doesn't return to the original position while unloading the thermal load in this cycle, except in the fourth cycle, after about 40 % of the mechanical load is applied together with the thermal load cycles. The dominance of the mechanical load is evident in all the cycles following the first (thermal loading cycle), where the variation of the temperature has not been reflected on the settlement. This is an indicator of the advantage of having energy piles to reduce the settlement of high-rise buildings.

CONCLUSIONS

Due to the ever increasing demand of energy, this research has focused on introducing the idea of shallow energy foundations for the demands of heating and cooling purposes of high-rise buildings in Ethiopia. Based on energy demand analysis of some of the buildings in Addis Ababa, a preliminary estimation of the number of energy piles for covering the heating and cooling demands of the already constructed United Bank office building has been performed. It was found out that only 88 % of the total number of structural piles could sufficiently satisfy the HVAC demand of the same building.

For the purpose of understanding of the thermo-mechanical behaviour of energy piles for introducing of energy piles in our country, numerical analysis of a practical application of energy piles in layered soils has also been incorporated in the research. After preliminary analyses using different constitutive models, the hypo plasticity model of Masin has been found to simulate the cycling loading reasonably with the computed values showing very good agreement with the measured ones. The induced settlements of the foundation were also found to be reduced significantly due to the coupled thermo-mechanical loading.

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