Energy design of energy piles

Introduction

The goal of this exercise is to perform the preliminary energy design of a group of energy piles. With reference to the features of a building that founds on a piled foundation, the purpose of the calculations that follow is to define: (i) the number of piles that need to be equipped as geothermal heat exchangers and will operate as energy piles, (ii) the thermal powers applied to each energy pile and (iii) the associated temperature changes for given operational periods. Typical data that in practical applications are provided by the various practitioners involved are assumed to be available. The design follows official recommendations for energy piles (SIA-D0190 2005). A final analysis of the features of some of the analytical models that are used to solve this exercise will be requested.

Available data

The building is to be founded on 162 piles that are 0.8 m in diameter and whose average length is 19.2 m. The piles penetrate in three layers. The first layer is 2 m thick and made of backfill material. The second layer is made of moraine and extends from 2 m to 18 m below the pile head. The third layer upon which the piles rest is made of molasse. A groundwater survey identifies a water table almost at the soil surface, whose flow velocity is estimated to $\bar{v}_{rw} = 0.2$ m/day. A thermal response test carried out at the site indicates a natural temperature of the ground of 11 °C and an effective thermal conductivity of $\lambda = 1.5$ W/(m °C). The ground thermal diffusivity is approximately of $\alpha_d = 6.4 \cdot 10^{-7}$ m^2/s.

The needs for the heating and cooling of the building are as follows:

- The heating of the building requires a peak power of 340 kW and a quantity of heat of $E_{H,tot} = 738$ MWh/year. The heating period lasts from October to May (i.e., 8 months).
- The cooling of the building requires a quantity of heat of $E_{C,tot} = 105$ MWh/year homogeneously distributed over the warm period. The cooling period lasts from June to September (i.e., 4 months).
- The heat pump to be installed has a nominal heating power of $\dot{Q}_s = 60$ kW and a coefficient of performance of $COP = 3.5$.
- The cooling during warm periods is to be achieved using direct cooling (i.e., bypassing the heat pump).

The relation that links the amount of energy supplied by the heat pump, Q_s, to the energy required from the piles, Q_r, is:

$$Q_s = \frac{COP}{COP-1} Q_r \tag{1}$$

In the analyses, consider on average 29.5 days per month and assume negative thermal powers for extraction while positive thermal powers for injection.

Aspects to address

1. *Maximum thermal powers involved*

Considering the flow chart proposed by the SIA-D0190 (2005) (cf., annex) and using the soil data available, estimate the linear thermal powers applicable to the piles for heating (i.e., heat extraction) and cooling (i.e., heat injection). Consider that a thermal recharge of the ground is achieved by injecting 70 to 90% of thermal energy in this medium.

Answer: With the ground conditions of interest, the SIA D0 190 prescribes a linear thermal power of -25 to -30 W/m for heat extraction and a maximum linear thermal power of 30 W/m for heat injection.

2. *Heating supply*

From the heating needs and the heat pump features, estimate the minimum number of piles that are to be equipped with absorber pipes as energy piles. Estimate the total amount of heat that can be obtained through this design with the minimum number possible of equipped piles.

Answer: The most important demand is related to the heating of the building. The nominal power of the heat pump has to be distributed over the equipped piles. With the given COP, the extracted power from the piles can be calculated by inverting equation (1) as:

$$\dot{Q}_r = \frac{COP-1}{COP}\dot{Q}_s \tag{2}$$

where $\dot{Q}_r$ is the required (extracted) thermal power from the ground and $\dot{Q}_s$ is the supplied thermal power to the building comprising the power given by the work of the heat pump.

Thus

$$\dot{Q}_r = \frac{3.5-1}{3.5} \cdot (-60) = -42.9 \text{ kW}$$

The above thermal power corresponds to a heat energy extracted from the ground that is associated with the $\dot{Q}_s = 60$ kW of thermal power supplied by the heat pump for the heating of the building per unit time t. The associated energy to this power reads

$$Q_{r,H} = \dot{Q}_r t \tag{3}$$

With the available data, the aforementioned heat energy reads

$$Q_{r,H} = \dot{Q}_r t = -42.9(8 \cdot 29.5 \cdot 24) \cdot 10^{-3} = -243 \text{ MWh}$$

According to the SIA-D0190 (2005), the maximum linear thermal power that can be extracted from the piles is of -30 W/m. Considering that the total linear thermal power that can be extracted from a group of n_{EP} piles with a given thermally active length L is

$$\dot{q}_l = \frac{\dot{Q}_r}{n_{EP} L} \tag{4}$$

This leads to the following inequality

$$n_{EP} \geq \frac{\dot{Q}_r}{\dot{q}_l L} \Rightarrow n_{EP} \geq \frac{42.9 \cdot 10^3}{30 \cdot 19.2} = 74.4 \approx 75$$

Therefore, at least 75 piles must be equipped with absorber pipes.

The amount of heat that can be supplied after the heat pump operation for heating can be calculated according to the following relation

$$Q_{s,H,actual} = \dot{Q}_s t \tag{5}$$

Otherwise, once $Q_{r,H}$ is calculated through equation (3), $Q_{s,H}$ can be directly determined from equation (1). Based on equation (5), the supplied heat energy to the building reads

$$Q_{s,H} = \dot{Q}_s t = -60(8 \cdot 29.5 \cdot 24) \cdot 10^{-3} = -340 \text{ MWh}$$

Because $Q_{s,H} < E_{H,tot}$, another technology (conventional heating systems) needs to be used to provide the remaining amount of heat of -738-(-340) = -398 MWh.

Would it be possible to provide all the heating through the energy piles while respecting the prescriptions of the SIA-D0190 (2005)? Assume that pile is equipped with a 2-U pipe configuration.

If all the heating is targeted from the energy piles, the peak power of -340 kW must be respected. With heat pumps with a COP of 3.5, a peak power of

$$\dot{Q}_r = \frac{COP-1}{COP} \dot{Q}_s = \frac{3.5-1}{3.5} \cdot (-340) = -243 \text{ kW}$$

should be extracted from the piles. This corresponds to a maximum linear thermal power of

$$\dot{q}_l = \frac{\dot{Q}_r}{n_{EP} L} = \frac{-243 \cdot 10^3}{162 \cdot 19.2} = -78 \text{ W/m}$$

The aforementioned linear thermal power is higher than that proposed by the SIA-D0190 (2005) and therefore is considered unachievable.

3. *Estimation of the temperature variation in the piles due to heating*

Based on the highest linear thermal power involved with heat extraction (in absolute value), estimate the temperature change at the end of the heating period (i.e., $t = 8$ months) through the simplified infinite cylindrical-surface source model (Carslaw and Jaeger 1959) and the simplified infinite line source model (Carslaw and Jaeger 1959; Ingersoll et al. 1954)

$$T(t, R) - T_0 = \dot{q}_l G_f(t, R) = \dot{q}_l \frac{1}{4\pi\lambda}\left[\ln\frac{4\alpha_d t}{R^2} - \gamma_E + \frac{R^2}{2\alpha_d t}\left(\ln\frac{4\alpha_d t}{R^2} - \gamma_E + 1\right)\right] \quad (6)$$

$$T(t, R) - T_0 = \dot{q}_l G_f(t, R) = \dot{q}_l \frac{1}{4\pi\lambda}\left(\ln\frac{4\alpha_d t}{R^2} - \gamma_E\right) \quad (7)$$

where R is the energy pile radius, T_0 is the initial temperature, $G_f(t, R)$ is the G-function and $\gamma_E = 0.5772$ is the Euler constant. Note that these analyses do not account for any pile thermal resistance.

After having developed the previous analyses, based on the assumption of a 2-U pipe equipment per energy pile, estimate the appropriate value of thermal resistance R'_{ghe} for the considered case study through the figure proposed by the SIA-D0190 (2005) depicting typical values of thermal resistance for energy piles (cf., annex). Next, perform two different analyses with the infinite cylindrical-surface source model and the infinite line source model to estimate the temperature change in the energy piles according to the following more rigorous approach

$$\Delta T = \dot{q}_l\left[R'_{ghe} + G_f(t, R)\right] \quad (8)$$

Answer: The following temperature changes are estimated to occur in the energy piles due to heat extraction. The thermal resistance R'_{ghe} value used is 0.11 m °C/W.

Modelling approach		Modelled temperature change, ΔT [°C]
Infinite cylindrical-surface source model	**Simplified approach**	**- 8.4**
	Rigorous approach	**- 11.8**

Infinite line source model	**Simplified approach**	**- 8.3**
	Rigorous approach	**- 11.6**

The minimum temperature value in the soil of 1 °C may be prescribed to prevent freezing and the heat pump performance to drop. Is this margin respected considering the worst-case prediction of the models? If no, define the maximum linear power for which, in the worst-case scenario among those considered above, the considered requirement is respected. Modify the number of piles to are to be equipped accordingly.

Answer: The prescribed margin is not respected considering the worst-case prediction of the models. The maximum linear thermal power for which an absolute temperature of 1 °C is observed (i.e., associated to a temperature change of ΔT = -10 °C from the natural temperature of the ground of 11 °C) is -25.3 W/m. To guarantee the supplied thermal power for the heating of the building, the number of piles to be equipped as energy piles needs to increase up to

$$n_{EP} \geq \frac{-42.9 \cdot 10^3}{-25.3 \cdot 19.2} = 88.3 \approx 89$$

By lowering the applied thermal power to satisfy the aforementioned prescription, the temperature change characterising the energy piles varies according to the different methods. The updated following temperature changes are estimated to occur in the energy piles for a thermal power of -25.3 W/m.

Modelling approach		**Modelled temperature change, ΔT [°C]**
Infinite cylindrical-surface source model	**Simplified approach**	**- 7.0**
	Rigorous approach	**- 10.0**
Infinite line source model	**Simplified approach**	**- 7.0**
	Rigorous approach	**- 9.8**

4. Cooling supply

Assuming that the cooling power is constant during the period of interest, estimate the linear thermal power that is applied to the energy piles.

Answer: The continuous power associated with the amount of energy that need to be supplied for cooling over four months can be estimated as

$$\dot{Q}_s = \dot{Q}_r = \frac{E_{C,tot}}{t} = \frac{105 \cdot 10^6}{(4 \cdot 29.5 \cdot 24)} = 37 \text{ kW}$$

As a result, the linear thermal power applied to the piles is

$$\dot{q}_l = \frac{\dot{Q}_s}{n_{EP} L} = \frac{37 \cdot 10^3}{89 \cdot 19.2} = 21.65 \text{ W/m}$$

Based on the flow chart proposed by the SIA-D0190 (2005), is the long-term temperature evolution of the ground a concern for this design? If yes, please define the range in which the amount of heat injected should remain while using direct cooling. Does this range provide acceptable linear heat injection levels? If no, how many piles would you need to equip? How does the linear power evolve during heat extraction?

Answer: Yes, the long-term temperature is a concern. This fact can be appreciated by comparing the amount of injected and extracted heat through the piles. During warm periods, $Q_{s,C}$ = 105 MWh are injected in the soil. During cold periods, $Q_{s,H} = -243$ MWh are extracted. The above corresponds to a ratio $|Q_{s,C}/Q_{s,H}| = 43\%$. The SIA-D0190 (2005) prescribes to inject at least 70 % of the extracted energy and at maximum 90 % to maintain the long-term efficiency of the system. As a result, a long-term drop in ground temperature is to be expected, with a consequent reduction in heating efficiency.

The range between 70-90 % proposed by the SIA-D0190 (2005) corresponds to 170-219 MWh/year. To reach this level, one solution may be to increase the amount of injected heat to each pile that is foreseen to be equipped as geothermal heat exchanger. The corresponding range of linear thermal power would be

$$\dot{Q}_s = \frac{Q_{s,C}}{t} = \frac{170 \cdot 10^6}{(4 \cdot 29.5 \cdot 24)} = 60 \text{ kW} \quad \text{(with a percentage of 70 \% of the extracted heat)}$$

$$\dot{Q}_s = \frac{Q_{s,C}}{t} = \frac{219 \cdot 10^6}{(4 \cdot 29.5 \cdot 24)} = 77.3 \text{ kW} \quad \text{(with a percentage of 90 \% of the extracted heat)}$$

$$\dot{q}_l = \frac{\dot{Q}_s}{n_{EP} L} = \frac{60 \cdot 10^3}{89 \cdot 19.2} = 35.1 \text{ W/m} \quad \text{(with a percentage of 70 \% of the extracted heat)}$$

$$\dot{q}_l = \frac{\dot{Q}_s}{n_{EP} L} = \frac{77.3 \cdot 10^3}{89 \cdot 19.2} = 45.2 \text{ W/m} \quad \text{(with a percentage of 90 \% of the extracted heat)}$$

The aforementioned solution cannot be considered because it exceeds the limit of 30 W/m prescribed by the SIA-D0190 (2005). To overcome this issue, another solution may

be to consider only the minimum amount of heat to inject (i.e., 70% of the extracted) to minimise the number of piles to be equipped and to vary the number of piles. This approach yields to a total number of piles of

$$n_{EP} = \frac{\dot{Q}_s}{\dot{q}_l L} = \frac{60 \cdot 10^3}{30 \cdot 19.2} = 104.2 \approx 105$$

The extraction rate decreases therefore from -25.3 W/m to

$$\dot{q}_l = \frac{\dot{Q}_s}{n_{EP} L} = -\frac{42.9 \cdot 10^3}{105 \cdot 19.2} = -21.3 \text{ W/m}$$

The aforementioned solution can be considered because it does not exceed the lower limit of -25 W/m prescribed by the SIA-D0190 (2005). Furthermore, it is associated to the following temperature changes.

Modelling approach		Modelled temperature change, ΔT [°C]
Infinite cylindrical-surface source model	Simplified approach	- 5.9
	Rigorous approach	- 8.4
Infinite line source model	Simplified approach	- 5.9
	Rigorous approach	- 8.4

How much heat is needed to guarantee the feasibility of this solution in addition to the 105 MWh? From which source this heat could be obtained to ensure the sustainability of the system?

Answer: An additional amount of 170-105 MWh = 65 MWh of heat is needed. This amount of heat could be obtained from alternative heat sources such as solar thermal panels.

5. *Estimation of the temperature variation in the piles due to cooling*

Based on the linear thermal power involved with heat injection, estimate the temperature change at the end of the cooling period (i.e., $t = 4$ months) through the four methods considered thus far.

Answer: The following temperature changes are estimated to occur in the energy piles due to heat injection.

Modelling approach		Modelled temperature change, ΔT [°C]
Infinite cylindrical-surface source model	**Simplified approach**	**7.3**
	Rigorous approach	**10.8**
Infinite line source model	**Simplified approach**	**7.2**
	Rigorous approach	**10.5**

6. *Conclude on the present design*

Based on the obtained results presented in this study, specify the number of piles that are to be equipped with energy piles, the maximum linear thermal powers involved for heating and cooling as well as the resulting temperature changes in the piles.

The final energy design, which neglects any geotechnical or structural consideration about the performance of the piles, involves the equipment as geothermal heat exchanger of 105 energy piles over the 162 piles that are required for structural support. The features corresponding to this design are listed in Table 1.

Table 1: Summary of energy design.

	Injection	Extraction
Heat transfer rate [W/m]	**30**	**-21.3**
Temperature variation [°C]	**10.8**	**-8.4**

7. *Comments on the simplified infinite cylindrical-surface and line source models*

Assuming a linear thermal power of 1 W/m and considering the material properties employed this far, estimate with the simplified infinite cylindrical-surface and line source models (i.e., do not consider the pile thermal resistance) the evolution of the temperature change from the energy pile wall with radial distance from the pile axis up to the value of $r = 10D$. Plot the evolution of the temperature change from the pile wall with radial distance obtained with the two approaches for time steps of t = 1, 5, 10, 20, 40, 80, 160 and 182.5 days. With reference to the pile wall and for the considered time steps, estimate the error between the two solutions. Justify the obtained results.

Modelling approach		Modelled temperature change, ΔT [°C]
Infinite cylindrical-surface source model	**Simplified approach**	**- 0.2**

	Rigorous approach	**- 0.4**
Infinite line source model	**Simplified approach**	**- 0.2**
	Rigorous approach	**- 0.3**

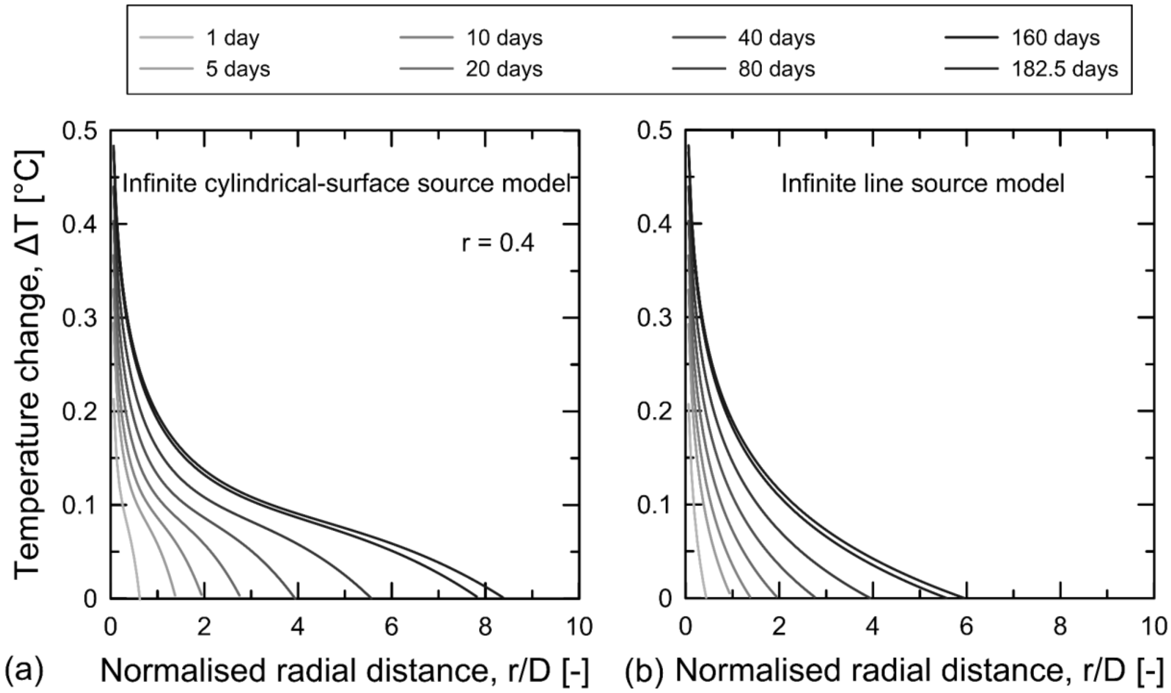

Figure 1: Comparison between the (a) infinite cylindrical-source and (b) line source analytical solutions.

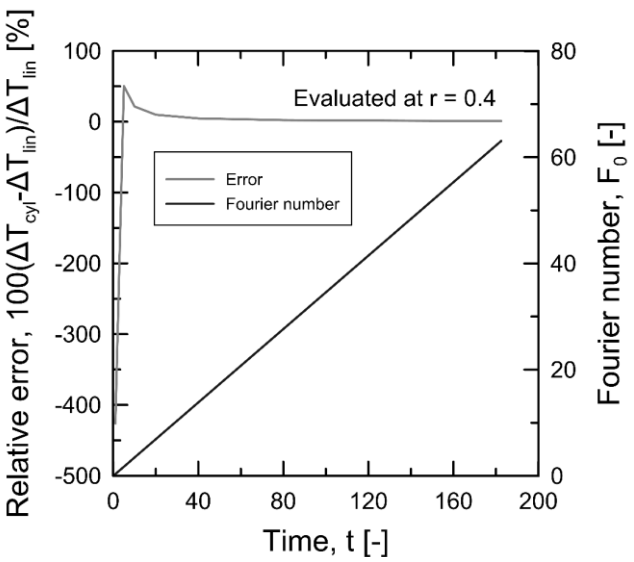

Figure 2: Error between the analytical solutions and the Fourier number with time.

References

Carslaw, H., and Jaeger, J. 1959. Conduction of heat in solids. Oxford University Press, Oxford, United Kingdom. pp. 510.

Ingersoll, L.R., Zabel, O.J., and Ingersoll, A.C. 1954. Heat conduction with engineering, geological, and other applications. Mc-Graw Hill, New York, United States. pp. 325.

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Annex

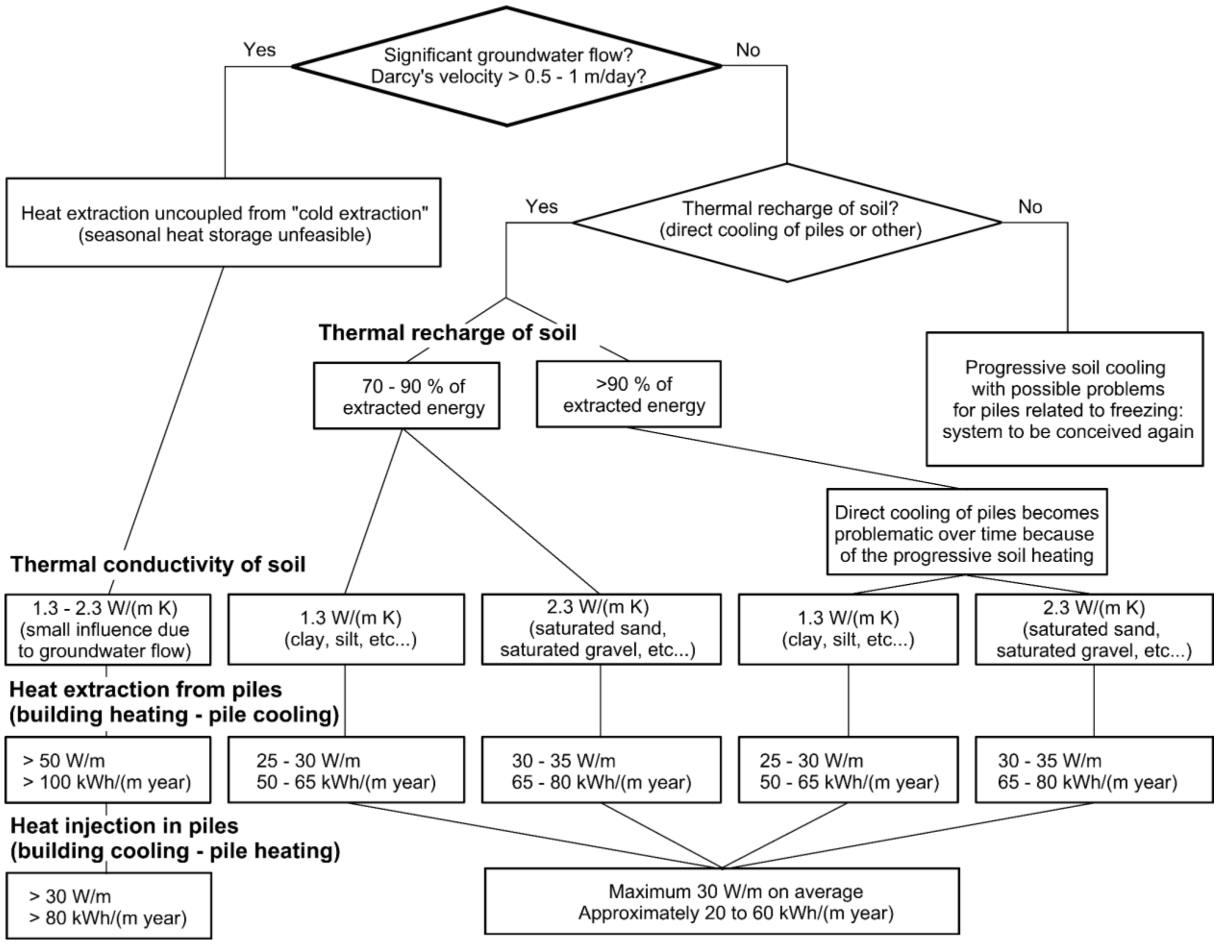

Figure 3: Design chart for energy design of energy piles (SIA-D0190 2005).

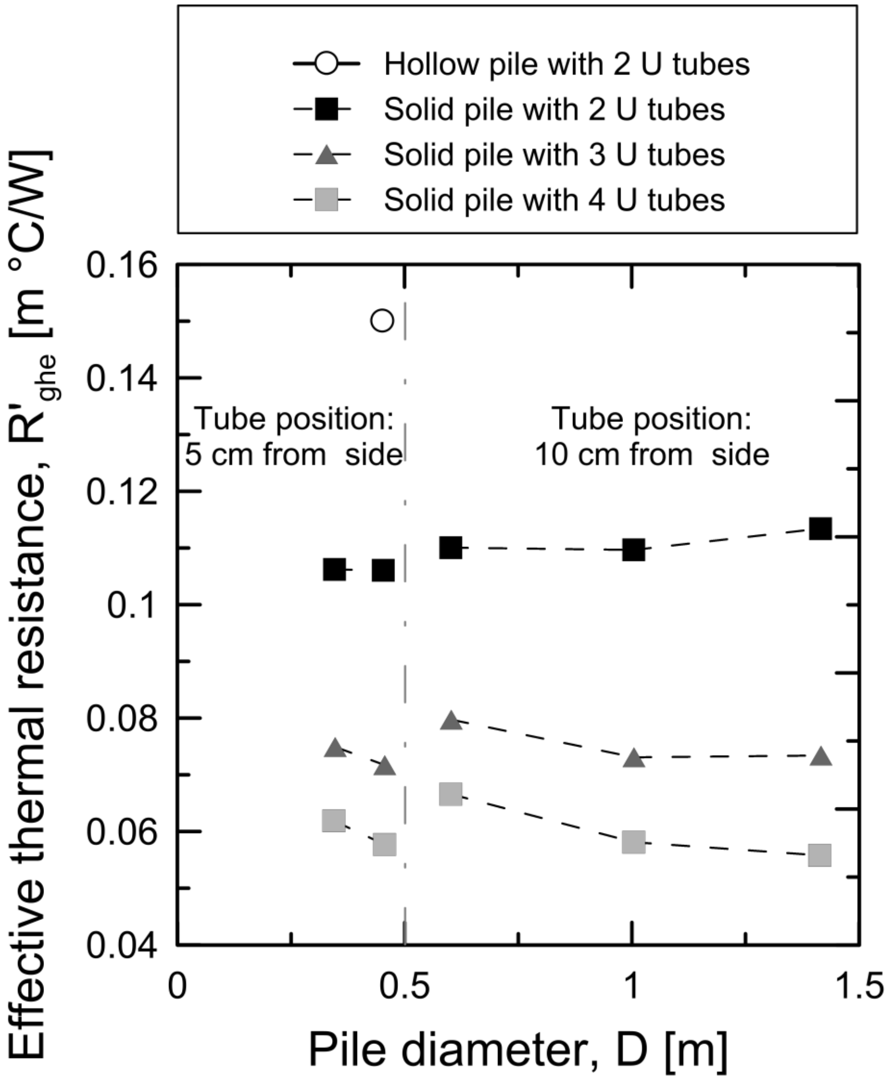

Figure 4: Design chart for energy design of energy piles (SIA-D0190 2005).