Technical feasibility of using energy piles in tropical soils in the State of Rio de Janeiro: A numerical study

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Abstract. Over time, human development requires monitoring of the renewal of resources that is difficult to achieve, so the search for sustainable alternatives that cause less impact on nature is necessary across the planet. Although Brazil claims to have its energy matrix based on hydroelectric generation, the State of Rio de Janeiro differs from the Brazilian and, being one of the pillars of the Brazilian economy, any proposal to revise the production methods of energy is necessary. It is known that 96% of the energy consumed in Rio de Janeiro comes from non-renewable sources. Energy foundations, more precisely geothermal piles, are solutions widely studied in northern European countries. It is known to date that its use can reduce electricity consumption by up to 30% in cold countries like Sweden and Canada. It consists of a cooling and / or space heating system through the heat transfer from the soil depth to the construction structure made by a pump system, besides being promising, it is an ecological and sustainable alternative. The main motivation of this study is to verify whether, in tropical soils and tropical climates, such a reduction can also be achieved. To achieve the proposed objective, this work will consist of numerical analysis via Finite Element Method (FEM) implemented by the authors in the MatLab 2020 program so that there is greater mathematical rigor. Thus, according to the thermal performance of each soil with the interaction of the pile element, it is possible to predict an application checking its viability in each location.

Keywords: Energy foundations, geothermal piles, soft soil in Rio de Janeiro, FEM, Matlab.

1 Introduction

The search for sustainability has mobilized research in several areas of the natural, exact, and human sciences. In civil engineering, more precisely in geotechnics, works focused on the environmental area are common in landfill treatments, subsoil contamination, reuse of plastic materials for soil reinforcement, among other solutions. However, in the past two decades, geotechnical foundation engineering has turned to a new concept: energetic foundations.

The energetic foundations would be functional foundation elements, just like footings and piles, but that could simultaneously generate energy or allow the use of energy generated by natural sources. In this scenario, the concept of geothermal piles arose in northern Europe, USA and Canada [1] ,[2], [3]. The idea arose from a need in these countries for better air conditioning of environments, which energy expenditure reaches almost 70% compared to other needs, in addition to being obtained through non-renewable sources. The soil can provide heat or serve as a heat sink for a structure through a pump system.

Despite advances in research in this area in Nordic countries, little has been developed regarding the efficiency of such energetic foundations in tropical soils, often composed of organic soft soils that require deep foundations, and warm countries. Therefore, it has not yet consolidated itself in the market due to unanswered questions, tests and studies on different types of soils and even the design of some of the piles. The objective of this work is to check the feasibility of applying energy piles to tropical soils in the State of Rio de Janeiro, through modifications in theory and design, foreseeing their use in hot countries. The study focuses on the analysis of the thermal potential of the soil-pile interaction, without delving into the construction methods, type of driving or type of pile to be used. The transport of heat by the fluid present in the water table is also not considered. The two-dimensional analysis was performed with the implementation of the heat equation formulated for the finite element method (FEM) and a numerical study in the locations of the State of Rio de Janeiro was done to map possible areas of good thermal performance of the piles.

2 Theoretical review and methodology

2.1 Identification of the physical and mathematical problem

It is proposed to adopt a geological-geotechnical profile presented by a single layer of homogeneous and isotropic soil in its physical characteristics, as well as a pile driven into this soil, made of a material substantially different from the material that makes up the soil.

An infinitesimal control element taken inside the soil element, with dimensions dx and dy, allows the following energy conservation equation to be written:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q - \rho C_p \nabla T \cdot \boldsymbol{u} \tag{1}$$

Where ρ, C_p, T, k, Q and $\boldsymbol{u}$ are respectively the density of the medium, the specific heat, the temperature, the thermal conductivity, the heat source and the temperature convection speed. The last term to the right of equality can be discarded since the convection of the temperature by some external agent will not be studied. Now taking a control element that goes through the soil and the pile, equation (1) is rewritten such that:

$$\rho_1 C_{p_1} \frac{\partial T}{\partial t} + \nabla \cdot (-k_1 \nabla T_1) - Q_1 = \rho_2 C_{p_2} \frac{\partial T}{\partial t} + \nabla \cdot (-k_2 \nabla T_2) - Q_2 \tag{2}$$

Where sub-indices 1 and 2 symbolize soil and pile materials. The analysis of temperature exchange at the interface becomes natural through the hypothesis that there is no temporal change in the heat exchange between the elements, but only spatial interactions. Therefore, taking equation (2) as true, canceling the temporal term on both sides of the equation, we obtain:

$$\nabla \cdot (-k_1 \nabla T_1) - Q_1 = \nabla \cdot (-k_2 \nabla T_2) - Q_2 \tag{3.a}$$

Rearranging

$$\nabla \cdot (-k_1 \nabla T_1) - \nabla \cdot (-k_2 \nabla T_2) = Q_1 - Q_2 \tag{3.b}$$

If $Q = | Q_1 - Q_2 | > 0$ we have:

$$\nabla \cdot (-k_1 \nabla T_1) - \nabla \cdot (-k_2 \nabla T_2) = Q \tag{3.c}$$

From where the discontinuity boundary condition emerges, explained later in this work as:

$$\boldsymbol{n} \cdot |k_1 \nabla T_1 - k_2 \nabla T_2| > 0 \tag{3.d}$$

Similarly, within the same material, the condition of continuity will be expressed by the extreme case of the equation (3.d):

$$\boldsymbol{n} \cdot |k_1 \nabla T_1 - k_2 \nabla T_2| = 0 \tag{3.e}$$

Where **n** is the normal vector pointing outwards.

2.2 Finite element formulation

Take eq.(1) as valid. It is known that, due to the complexity of the boundary conditions, the initial conditions and the problem's own irregular geometry, the analytical resolution of the partial differential equation becomes not only difficult, but also impossible [4]. An approximate solution should then be found to satisfy the boundary conditions and be consistently good within the domain.

Let then be an approximate solution of *T* (*x, y; t*) given by:

$$\widetilde{\boldsymbol{T}}(x,y) = \sum_{j=1}^{N} T_j \boldsymbol{\phi_j} \tag{4}$$

And let it also be any arbitrary function, defined in the same vector space as T (x, y; t) as:

$$\boldsymbol{v}(x,y) = \ \textstyle\sum_{i=1}^{N} v_i \boldsymbol{\phi_i} \tag{5}$$

Replacing eq.(4) in eq.(1) and considering $\boldsymbol{u}$ = 0:

$$\rho C_p \frac{\partial \widetilde{\boldsymbol{T}}}{\partial t} + \nabla \cdot \left(-k\nabla\widetilde{\boldsymbol{T}}\right) - Q = R \tag{6}$$

Where *R* is a non-zero residue since we are no longer using the exact solution *T*, but an approximate one taken in a finite dimensional space, so the equality can never be zero. However, by the principle of orthogonality [3][4], aiming at minimizing errors -on average- between the exact and the approximate solution, we have:

$$\int_\Omega R \cdot \boldsymbol{v}\, d\Omega = 0 \tag{7}$$

Extensively:

$$\int_\Omega \rho C_p \frac{\partial \widetilde{\boldsymbol{T}}}{\partial t} \cdot \boldsymbol{v}\, d\Omega + \int_\Omega \nabla \cdot \left(-k\nabla\widetilde{\boldsymbol{T}}\right) \cdot \boldsymbol{v}\, d\Omega - \int_\Omega Q \cdot \boldsymbol{v}\, d\Omega = 0 \tag{8}$$

Replacing eq.(4) and eq.(5) in eq.(8):

$$\sum_{j=1}^{N} T_j \int_\Omega \rho C_p \frac{\partial \boldsymbol{\phi_j}}{\partial t} \cdot \boldsymbol{\phi_i}\, d\Omega + \sum_{j=1}^{N} T_j \int_\Omega \nabla \cdot \left(-k\nabla\boldsymbol{\phi}_{\mathbf{j}}\right) \cdot \boldsymbol{\phi_i}\, d\Omega - \int_\Omega Q\boldsymbol{\phi_i}\, d\Omega = 0 \tag{9}$$

Regrouping some terms:

$$\sum_{j=1}^{N} T_j \int_\Omega \left(\rho C_p \frac{\partial \boldsymbol{\phi_j}}{\partial t} \cdot \boldsymbol{\phi_i} + \nabla \cdot \left(-k\nabla\boldsymbol{\phi_j}\right) \cdot \boldsymbol{\phi_i}\right) d\Omega \ = \int_\Omega Q\boldsymbol{\phi_i}\, d\Omega \tag{10}$$

One can also use the integration by parts to reduce the order of the largest derivative of the system, thus relaxing the regularity conditions of the approximate solution and increasing the regularity conditions of the test function. In this precise case, after integration by parts, it is noted in eq.(11) that both functions will have the same regularity constraint, which is beneficial for the size of the error generated in the numerical analysis.

$$\begin{aligned} &\sum_{j=1}^{N} T_j \int_\Omega \rho C_p \frac{\partial \boldsymbol{\phi_j}}{\partial t} \cdot \boldsymbol{\phi_i}\, d\Omega \ + \int_\Omega k\nabla\boldsymbol{\phi_j} \cdot \nabla\boldsymbol{\phi_i}\, d\Omega \\ &= \int_\Omega Q\boldsymbol{\phi_i}\, d\Omega + \int_{\partial\Omega_N} k\, \nabla\boldsymbol{\phi_j} \cdot \boldsymbol{\phi_i} \cdot \boldsymbol{n}\, dS + \int_{\partial\Omega_D} k\nabla\boldsymbol{\phi_j} \cdot \boldsymbol{\phi_i} \cdot \boldsymbol{n}\, dS \end{aligned} \tag{11}$$

Where $\partial\Omega_N$ and $\partial\Omega_D$ are respectively the boundaries where Neumann's natural boundary conditions operate and the boundaries where Dirichlet's essential boundary conditions operate. All terms within the integral on the left side of the equality will form a matrix of *i* = N columns by *j* = N rows. The sum on the left will generate a vector of *j* lines. The integral to the right of the equality will generate a vector of i = N columns. The algebraic system then becomes:

$$\{T\}[M] = \{L\} \tag{12}$$

The choice of a triangular mesh with an average dimension of 0.5m generated a discretization of approximately 800 elements in the soil and 30 in the pile. This is the system that will be solved in MatLab R10 2020 to obtain the solution of the heat exchange problem between pile and soil. The time-dependent part was treated separately by the method of finite differences in an implicit scheme (Crank-Nicholson), whose detailed explanation is beyond the scope of this work.

2.3 Obtaining the parameters

The soil of the State of Rio de Janeiro is widely studied by geotechnical literature due to the presence of large pockets of soft soils. In a meta-analysis of the geotechnical profiles of the State of Rio de Janeiro, Futai [5] extracted the standard profiles of each neighborhood. In a large study on the thermal characterization of soil types, Andúja Márquez [6] proposed ranges of values for the C_p and k properties of different types of soils and rocks. To carry out this work, the data by Andúja [6] were analyzed so that one could extrapolate to the soils of Rio de Janeiro.

With the thermal and geotechnical parameters obtained, it is mandatory to find meteorological data on the temperature distribution in each proposed neighborhood during the period of one year. The data were obtained from the database of the National Institute for Space Research [7] and the meteorological service ClimaTempo [8].

According to Vasilescu [9], the temperature at 8m depth is constant throughout the year and this is the average of the highest and lowest temperature in the same period. Based on the information, it is proposed to adopt two constant temperatures, one in summer and one in winter, constant at 10m in each season, and the values obtained through the same calculation.

2.4 Methodology: the example of Barra da Tijuca in summer

Looking for a more cohesive and succinct explanation of the development of simulation and problem analysis, the case of Barra da Tijuca in the summer was adopted as an example to highlight the work of the abstract. Then be the following mathematical problem to be solved:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) - Q = 0, \qquad at\ \Omega_k\ ; k = soil, pile. \tag{13.a}$$

$$T = \theta°C, \qquad at\ \partial\Omega_k\ ; k = 1,2,4. \tag{13.b}$$

$$-\boldsymbol{n} \cdot \nabla T = 0, \qquad at\ \partial\Omega_k\ ; k = 3,5. \tag{13.c}$$

$$-\boldsymbol{n} \cdot (|k_1 \nabla T_1 - k_2 \nabla T_2|) > 0, \qquad at\ \partial\Omega_k;\ k = 6,7,8 \tag{13.d}$$

$$T(x, y; 0)_{Pile} = f(y) \tag{13.e}$$

$$T(x, y; 0)_{Soil} = g(y) \tag{13.f}$$

The boundaries $\partial\Omega_k$ can be best seen in Figure 1. Equation (13.a) defines the partial differential equation that governs the behavior within the volume of each element, be it the pile or the soil. A standard study window was also adopted, where the soil is 20m long by 10m deep. The pile was also standardized with a diameter of 80cm and a length of 6m. The physical properties of the pile were considered the same as for concrete, resulting in $C_p = 880\, J/m^3°C,\ k = 0.5\, W/m°C$ e $\rho = 2300 kg/m^3$. For the soil, composed of a single layer of soft clay, the geotechnical and thermal parameters adopted $C_p = 3400\, J/m^3°C$, $k = 1.7\, W/m°C$ e $\rho = 1200 kg/m^3$.

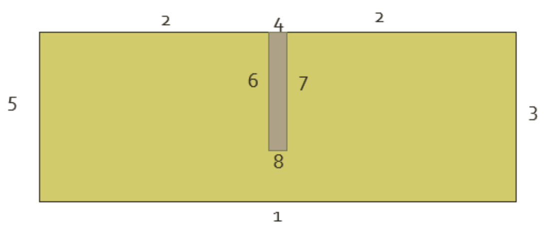

Figure 1. Determination of the problem boundaries (author, 2020).

Equation (13.b) defines the essential boundary conditions, or Dirichlet conditions, at the borders where the temperature is known. The bottom temperature, that is, the temperature at the border corresponding to the deepest soil, is known and has a value equal to the average temperature of the whole year. This approach was investigated and confirmed by Vasilescu [5]. At the surface of the terrain, the temperature is also known for summer and then an essential boundary condition is determined. Equation (13.c) is a zero-flow condition at vertically furthest boundaries. Equation (13.d) is the already demonstrated condition of non-continuity and determines the flow at the soil-pile interface, based on the difference in thermal conductivity of each element as well as in the direction of the gradient that exists on the border. Equations (13.e) and (13.f) are the initial temperature distribution conditions. It is adopted, for simplicity, that the distribution is linear along the pile and the soil and that, since it is assumed that the initial condition is already a situation of thermal equilibrium [13]. The mesh generated for the analysis of the problem was type T2Q2, that is, second order triangular and conform (isoparametric).

The generated temperature field was printed as a color map, using a scale from blue to red, indicating a variation from the coldest to the hottest, with values of extreme 15 ° C and 38 ° C. The color map for Barra da Tijuca's summer can be seen in Figure 2.

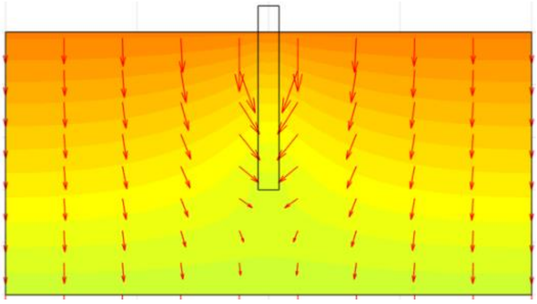

Figure 2. Temperature distribution in Barra da Tijuca profile during the summer (author, 2020).

With the color map printed, transversal sections were made at heights y = -9m, y = -6m, y = -3m and y = -1m. The section that passes through -9m does not reach the pile, and it serves as a witness sample so that it is possible to compare with the sections that pass through the pile element and that its influence can be quantified.

For a criterion for the classification of viable regions or not for the use of energy foundation technology to be used, the criterion presented by Zagorscak and Thomas [14] was adopted. For these authors, a difference in temperature at the soil-pile interface equal to or greater than 2 ° C would justify the use of the geothermal pile element.

3 Results and discussions

The script of numerical tests and analyzes was applied to the neighborhoods Barra da Tijuca, Botafogo, Caju, Duque de Caxias (REDUC), Centro, Vila do Pan, Itaguaí, Itaipú, Nova Iguaçu, Rio das Ostras, Santa Cruz and Silva Jardim. For each of these neighborhoods, the viability analysis of the thermal potential of the energy piles was carried out in the peak of summer and in the peak of winter, these being the extreme cases during the year. However, in the following analysis, some neighborhoods were omitted because they did not generate results whose discussion would be important.

Barra da Tijuca is not one of the neighborhoods where the analysis found the implementation of geothermal piles viable. However, it is not the worst case either. For this reason, the result found for the neighborhood will be described below, as a way of exemplifying an average case.

The temperature distribution in the soil is gradual and varies from 32 ° C to 28 ° C over the entire depth, in the soil strips furthest from the pile element. There is no significant concentration of heat in a specific part of the clay layer.

The pile element has a smooth distribution of temperature along its length. In the upper sections (y = -1m and y = -3m) the average temperature is 31 ° C. In the deepest section of the pile, the temperature is 28.5 ° C. The temperature difference along the pile reaches up to 8%.

In the region of the neighborhood of the pile-soil interface, there is a reduction in temperature in relation to the rest of the soil. In the last 5m of the horizontal distance between soil and pile, for a depth of elevation y = -6m, the temperature drops from 29.5 ° C to 28 ° C. For a depth of 3m, the temperature drops from 30.6 ° C to 28.8 ° C. In the region corresponding to a cut at y = -1m, it is noted that this temperature variation is lower than the rest.

In the cross section performed at a depth y = -1m along the entire length 20m, including the pile, it is noted that the temperature variation from pure soil (x = 0) to the center of the pile element (x = 10) is 1 ° C, or 3%. For depth y = -3, the temperature variation is 1.8 ° C (6%) and at the bottom of the pile (y = -6), the temperature varies 1.6 ° C equivalent to 5%. The section made at y = -9m serves as a witness sample to highlight the effect of the cutting on the heat distribution, as this cutting does not pass through the cutting element and therefore, consequently, causes a more uniform distribution of temperature along the sections.

In winter, the soil adopts a gradual temperature distribution, where the variation is 18 ° C on the surface to 22° in the depth, in the soil strips furthest from the pile. There is no significant concentration of heat. At the pile, the heat distribution is smooth in its length. In sections above 3m (y = -1m and y = -3m), the average temperature is 20° C, while in the deepest section (y = -6m), the temperature reaches 22 ° C.

There is a considerable increase in temperature around the pile-ground contact in relation to the rest of the soil. In the 5 m horizontal between the pile and the soil, at a depth of 6 m, there is an increase in temperature from 22 ° C to 23.5 ° C. In the y = -3m cut, there is a greater variation from 21 ° C to 23 ° C and closer to the surface, y = -1m, increases again approximately 1 ° C, from 19.5 ° C to 20.8 ° C.

It is noticed that in the contact of the clay soil with the pile, the heat leaves the pile for the soil, showing that the temperature is higher in the region around the pile. There is a symmetry in the summer and winter cases that can be justified by the homogeneity of the soil.

In the cross-section carried out at a depth y = -1m along the entire length 20m, including the pile, it can be seen that the temperature variation of pure soil (x = 0) until the center of the pile element (x = 10) is e 1 ° C, or 3%. For depth y = -3, the temperature variation is 1.8 ° C (6%) and at the bottom of the pile (y = -6), the temperature varies 1.6 ° C equivalent to 5%. The section made at y = -9m serves as a witness sample to highlight the effect of the cutting on the heat distribution, as this cutting does not pass through the cutting element and therefore, consequently, causes a more uniform distribution of temperature along the section. A similar analysis has been carried for every neighborhood but could not be presented is this paper because of size limitation. Therefore, the results have been presented in a single chart (Figure 3) explained in the conclusion section.

4 Conclusion

The present study allowed some fundamental thermodynamic characteristics of soils and their consequences to be analyzed and understood in a practical application. It is proposed that four locations would have the potential for applicability of energy cutting technology in the summer, which is of great use in Rio de Janeiro, and only two of these locations were viable for the winter. The fact that the viable locations for winter, although not all, are the same as those noted for summer raises a question about what would make some soil profiles viable for summer rather than winter.

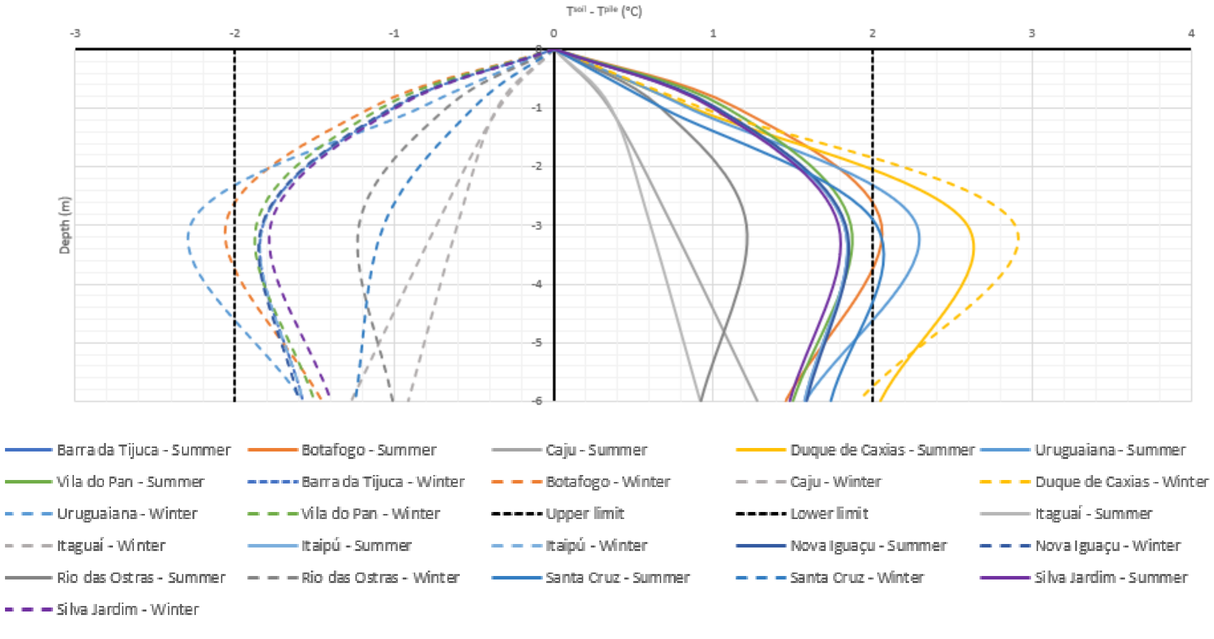

Figure 3. Temperature difference between soil and pile along depth (author, 2020).

In this sense, it was observed that geotechnical profiles with greater homogeneity, that is, with few stratifications or stratifications of soils of a similar nature, exhibit a symmetry in the heat exchange with the pile in the summer and winter scenarios. In other words, if such soil is viable in the summer because it has a temperature difference of x degrees between soil-pile, it would show a difference of -x degrees in the winter. This type of profile was observed in Barra da Tijuca, Vila do Pan, Itaipú, among other places where only one type of soil exists in the first 10 meters of depth or where the stratifications are related soil (clays and silts, embankments and silty sands) etc). Then the hypothesis is advanced that, depending on the variation of atmospheric temperature of the place, profiles with predominantly clay soils or composed of clay and sandy embankment can be viable for the use of energy piles.

In Santa Cruz, viability in the summer is mainly due to the combination of exceedingly high temperatures in the summer combined with a soil profile with approximately 3 meters of surface layer of landfill followed by an extensive layer of soft clay. The landfill accumulates a little heat but transfers it to the clay layer that dissipates it easily. The pile that is half its length in the landfill, due to its material properties, does not absorb all the heat stored by the landfill, but transfers in greater quantity the little heat received to the soft clay layer in which the second half of the pile is stuck. Thus, the result of thermal equilibrium is a pile cooler than the ground during the summer. By the same arguments, it is easy to understand that in the winter scenario the pile remains slightly warmer than the soil, but not enough for the installation of geothermal technology to be viable.

In Duque de Caxias (REDUC), it is noted that the pile remains colder than the soil during the summer, which makes it the best scenario of all the others in the study, with approximately 2.8 ° C difference between pile and soil. However, it is noted that during the winter, the pile also remains colder than the soil at more than 2 ° C, thus being the only curve in the graph shown that has summer and winter in the same quadrant. The specific case of Duque de Caxias is explained by the thin layer of sand underlying the upper layer of landfill. This layer of pure sand is a bad thermal conductor and therefore an excellent heat accumulator. Even during the winter, the layer of sand can remain hotter than the top layer of landfill. The heated sand layer then, because it is hotter than the rest of the profile, is also noticeably warmer than the pile, making it even colder than the average profile in winter, making it totally unfeasible. the application of energy piles in the region in the case of winter.

References

[1] Brandl, H. Energy foundations and other thermo-active ground structures, *Géotechnique*, 56, 81–122, 2006.
[2] Ennigkeit, A. and Katzenbach, R. The double use of piles as foundation and heat exchanging elements. *Proceedings of the 15th International Conference on Soil Mechanics and Geotechnical Engineering*, Istanbul. CRC Press/A A Balkema, pp. 893–896, 2001.
[3] Brenner, S.; Ridgway, L. The Mathematical Theory of Finite Element Method, *Text in Applied Mathematics*, Springer, 2008.
[4] Finlayson, B. *The Method of Weighted Residuals and Variational Principles*, Mathematics in Science and Engineering, 1987.
[5] Futai, M.M, Almeida, M.S.S & Lacerda, W.A. Propriedades Geotécnicas das Argilas do Rio de Janeiro, *Encontro Propriedades das Argilas Moles Brasileiras*, Rio de Janeiro, p.138-165, 2001.
[6] Andújar Márquez, J. et. al. Ground Thermal Diffusivity Calculation by Direct Soil Temperature Measurement. Application to very Low Enthalpy Geothermal Energy Systems, *MDPI*, 2016.
[7] Instituto Nacional de Pesquisas Espaciais, INPE, www.inpe.br, 2020.
[8] Climatempo, www.climatempo.com.br, 2020.
[9] Finlayson, B. *The Method of Weighted Residuals and Variational Principles*, Mathematics in Science and Engineering, 1987.
[10] Futai, M.M, Almeida, M.S.S & Lacerda, W.A. Propriedades Geotécnicas das Argilas do Rio de Janeiro, *Encontro Propriedades das Argilas Moles Brasileiras*, Rio de Janeiro, p.138-165, 2001.
[11] Instituto Nacional de Pesquisas Espaciais, INPE, www.inpe.br, 2020.
[12] Vasilescu, A. Impact of Temperature Cycles at Soil-Concrete Interface for Energy Piles, *Springer Nature Switzerland AG*, p 35-42, 2019.
[13] Laloui, L., Loria, A. Analysis and Design of Energy Geostructures. *Theoretical Essentials and Practical Application*, Academic Press, Elsevier, 2019.
[14] Zagorscak, R. and Thomas, H. R. A review on performance of energy piles and effects on surrounding ground. *INŽENJERSTVO OKOLIŠA Vol.3,* No.1, 33-45, 2016.