Influence of soil thermophysical properties on the flow of thermal energy taken by the energy pile

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Abstract. The depletion of traditional fossil energy sources leads to an increasing development of non-traditional energy sources. One of the promising directions of alternative energy is the use of low-potential energy of the soil for heating buildings and structures for various purposes. Heat extraction is possible through the use of energy foundation. However, their rational design is impossible without a careful assessment of a large number of factors that affect the potential value of thermal energy extracted from the soil. The purpose of this work was to build a whole methodology to assess the degree of influence of soil thermophysical properties, in particular, such as heat capacity and thermal conductivity, on the amount of heat energy selected energy pile. The formulation and analysis of the numerical experiment to identify the desired dependencies. The matrix of experiment planning is made. The numerical simulation of the energy pile of different geometric parameters in different soil conditions is performed. Statistical processing of the obtained experimental data was carried out. A quadratic regression equation was developed to determine the amount of heat through the side surface of the pile depending on the length of the pile, its diameter, heat capacity and thermal conductivity of the soil. The analysis of this equation for the purpose of estimation of degree of influence of initial thermophysical parameters of soil on value of thermal energy of the selected pile is carried out.

1. Introduction
The increasingly vivid tendency of mankind's turn towards non-traditional energy sources leads to a very rapid and inevitable introduction of the results of research in this area into the daily life of a person. At the same time, attention is increasing to saving energy resources, in particular, additional requirements are introduced to increase the economic efficiency of the use of energy resources in the operation of buildings and structures, which in many countries are established at the legislative level. [1-4].

One of the most effective ways to increase energy efficiency, as well as the degree of autonomy of buildings, is the use of low-potential soil energy for heating buildings in the cold season. [5-7].

Numerous studies have established that, starting from a certain depth, the temperature of the soil remains constant and lies in the range of 5-10 ° C. These temperatures are sufficient to provide buildings with heat energy. The increase in the temperature of the coolant to operating values is carried out by including a heat pump in the heat supply flow diagram. [8-9]

In the absence of a regulatory framework on the territory of the Russian Federation in the field of designing energy-efficient foundations, there are no approved calculation methods. A special role in
the development of technology is played by field research and analysis of the work of already implemented projects [10-11].

The number of factors influencing the efficiency of energy foundations is enormous. The influence of the climatic parameters of the outside air, the frequency of operation of the energy pile is noticeable. The thermophysical properties of the soil also play a significant role [12-15].

This article presents the results of a numerical experiment to assess the influence of the heat capacity and thermal conductivity of the soil on the amount of thermal energy obtained using an energy pile.

2. Materials and Methods

The research methodology of the influence of the thermal conductivity and heat capacity of the soil on the amount of thermal energy taken by the energy pile consists in the repeated calculation of the value of the heat flux for various soil conditions.

An experiment planning matrix was compiled. The pile radius, pile length, thermal conductivity and heat capacity of the soil were taken as the parameters of variation [16].

For a three-level design with four significant factors, a matrix of 24 design points was built. The levels of variation of the main factors are presented in table 2. The experiment planning matrix is shown in table 1 [17-19].

| № experiment | X1 | X2 | X3 | X4 | Y  |
|--------------|----|----|----|----|----|
| 1            | 1  | 1  | 0  | 0  | $Y_1$ |
| 2            | 1  | -1 | 0  | 0  | $Y_2$ |
| 3            | -1 | 1  | 0  | 0  | $Y_3$ |
| 4            | -1 | -1 | 0  | 0  | $Y_4$ |
| 5            | 1  | 0  | 1  | 0  | $Y_5$ |
| 6            | 1  | 0  | -1 | 0  | $Y_6$ |
| 7            | -1 | 0  | 1  | 0  | $Y_7$ |
| 8            | -1 | 0  | -1 | 0  | $Y_8$ |
| 9            | 0  | 1  | 1  | 0  | $Y_9$ |
| 10           | 0  | 1  | -1 | 0  | $Y_{10}$ |
| 11           | 0  | -1 | 1  | 0  | $Y_{11}$ |
| 12           | 0  | -1 | -1 | 0  | $Y_{12}$ |
| 13           | 0  | 0  | 1  | 0  | $Y_{13}$ |
| 14           | 0  | 0  | 1  | -1 | $Y_{14}$ |
| 15           | 0  | 0  | -1 | 1  | $Y_{15}$ |
| 16           | 0  | 0  | -1 | -1 | $Y_{16}$ |
| 17           | -1 | 0  | 0  | 1  | $Y_{17}$ |
| 18           | -1 | 0  | 0  | -1 | $Y_{18}$ |
| 19           | -1 | 0  | -1 | 1  | $Y_{19}$ |
| 20           | -1 | 0  | -1 | -1 | $Y_{20}$ |
| 21           | 0  | 1  | 0  | 1  | $Y_{21}$ |
| 22           | 0  | 1  | 0  | -1 | $Y_{22}$ |
| 23           | 0  | -1 | 0  | 1  | $Y_{23}$ |
| 24           | 0  | -1 | 0  | -1 | $Y_{24}$ |
Numerical modeling was carried out in the GeoStudio/TEMP software package. The output parameter was the value of the heat flux density through the unit of the lateral surface of the energy efficient pile. This parameter was reduced to the amount of heat energy taken by the pile per unit of time. An axisymmetric model was adopted. The selection of thermal energy by the pile was provided by setting the boundary condition \( t = 1 \, ^\circ\text{C} \) along its lateral surface.

The studies were carried out for the climatic conditions of the city of Perm (Russia). Climatic conditions were set by the boundary condition on the upper boundary of this model. Air temperature, snow cover thickness, solar radiation value, wind speed were taken as climatic parameters. The value of the parameters was determined as the average according to the results of meteorological observations from 2008 to 2018 for the city of Perm. A fragment of the initial data table is presented in table 3 [20].

### Table 2. The levels of variation of the main factors

| Factors, units rev | Coded value | Levels of variation |
|--------------------|-------------|---------------------|
| Pile radius \( r \), m | \( X1 \) | -0.15 | 0.35 | 0.55 |
| Pile length \( l \), m | \( X2 \) | 6 | 13 | 20 |
| Thermal conductivity \( \lambda \), W/m\( ^\circ\text{C} \) | \( X3 \) | 0.5 | 1.5 | 2.5 |
| Heat capacity \( c \), MJ/m\( ^3\)\( ^\circ\text{C} \) | \( X4 \) | 1.2 | 1.8 | 2.2 |

3. Results & Discussion

The coefficients of the quadratic regression equation were obtained by processing experimental data in the STATISTIKA 13.5 software package. Analysis type - response surface regression. The dependent parameter is heat flow. Independent parameters are the main factors presented in table 1.

The numerical model is shown in figure 1.
After each experiment, the depth-averaged value of the flux density was determined, which was reduced to the value of the heat flux through the pile. The result of processing the experiment in the STATISTICA program is presented in Table 4.

**Table 4. Calculation result in the STATISTICA program**

| The coefficients of the regression equation | Value       |
|--------------------------------------------|-------------|
| b0                                         | 84.6852     |
| b1                                         | -23.0320    |
| b2                                         | -4.9385     |
| b3                                         | -19.6787    |
| b4                                         | -62.5935    |
| b11                                        | 140.1583    |
| b22                                        | 0.2451      |
| b33                                        | -6.4060     |
| b44                                        | 10.7175     |
| b12                                        | -5.8841     |
| b13                                        | -26.3860    |
| b14                                        | -6.2579     |
| b23                                        | 5.0107      |
| b24                                        | 2.5596      |
| b34                                        | 16.5980     |

**Figure 1.** The numerical model (numbers indicate soil temperature).
For various combinations of the length and radius of the energy piles, nomograms of the dependence of the heat flow on the heat capacity and thermal conductivity of the soil were built. An example of a nomogram is shown in figure 2.

![Figure 2. Nomogram of heat flow (pile 13 m long, 0.15 m radius).](image)

**4. Conclusions**

Analysis of the research results led to the following conclusions:

1. The thermal conductivity of the soil has the greatest influence on the efficiency of heat exchange between the soil and the energy pile.
2. With a change in the heat capacity of the soil, the value of the extracted thermal energy changes insignificantly.

**5. References**

[1] Amis T and Loveridge F 2014 Energy piles and other thermal foundations for GSHP Rehva journal 32–5
[2] Zakharov A V 2010 Application of geothermal energy of soil for heating buildings in climatic and geological conditions of the Perm region Bulletin of Civil Engineers 2(23) 85–9
[3] Brandl H 2006 Energy foundation and other thermo-active ground structures Geotechnique 56 81–122
[4] Gao J, Zhang X, Kui J, Li S and Yang J 2018 Thermal performance and ground temperature of vertical pile-foundation heat exchangers A case study. Applied Thermal Engineering 28 2295–304
[5] Zakharov A, Ponomarev A and Mashchenko A 2012 Energy structures in underground construction (Perm: PNRPU Publishing House)
[6] Zhang T, Wang C, Liu S, Zhang N and Zhang T 2020 Assessment of soil thermal conduction using artificial neural network models Cold Regions Science and Technology 169
[7] Bourne-Webba P, Bodas Freitas T and Freitas Assunção R 2019 A review of pile-soil interactions in isolated, thermally-activated piles Computers and Geotechnics 108 61–74
[8] Brandl H, Adam D and Markiewicz R 2006 Ground-Sourced Energy Wells for Heating and Cooling of Buildings Acta Geotechnica Slovenica 3 5–27
[9] Huang J, Mc Cartney J, Perko H, Johnson D, Zheng C and Yang Q 2019 A novel energy pile: The thermo-syphon helical pile Applied Thermal Engineering 159
[10] Johansen O 1977 Thermal Conductivity of Soils (Trondheim, Norway)
[11] Belookaia N and Pivovarova E 2015 Review of alternative energy sources. Geothermal energy Proc. of universities. Investments. Construction. The property 1(12) 67–72
[12] Kong G, Cao T, Hao Y, Zhou Y and Ren L 2019 Thermomechanical properties of an energy micro pile – raft foundation in silty clay Underground Space
[13] Arkhangelskaia T and Lukashchenko K 2009 Modern approaches to the computational assessment of the thermal properties of soils Proceedings of the Samara Scientific Center of the Russian Academy of Sciences 1(7) 1408–12
[14] Chudnovsky A 1976 Soil Thermal Physics (Moscow: Nauka)
[15] Vasiliev G 2006 Thermal storage of buildings and structures using low-potential thermal energy of the surface words of the Earth (Moscow: Moscow Publishing House)
[16] Korolev V 1997 Soil thermodynamics (Benefit: Publishing house of Moscow State University)
[17] Korolev V 1982 Principles of thermodynamics in engineering geology Materials of the School-Seminar: Basic Problems of Geology (Moscow) pp 15–24
[18] Filipov T 1982 Recommendations on the use of methods for mathematical planning of experiments in concrete technology (Department of scientific and technical Information NIIZhB)
[19] Knatko V et al 1988 Mathematical methods and experimental planning in priming and engineering geology. Study guide (Leningrad: Leningrad University)
[20] Ovchinnikov N and Zakharov A 2019 Investigation of the influence of climatic parameters of the environment on the operation of an energy pile Proc. of the Int. Scientific and Practical Conf. "Modernization and scientific research in the transport complex" pp 312–7