Dependence sandy soil thermal conductivity on grain-size composition

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Abstract. The development of renewable energy sources technologies is relevant. Sun radiant energy, wind energy, water energy, earth low-potential energy are main renewable energy sources. Energy foundations are used for earth low-potential energy extraction. The research results this paper presented can be used for energy foundations calculations. It is necessary to know soil thermal characteristics to the energy foundations calculations. At the moment, there are many calculation methods for determining soil thermal characteristics, but none of them take into account their grain-size composition. The research purpose is to assess the dependence sandy soil thermal conductivity on grain-size composition. According to the research results, firstly, the influence of the density and moisture content of the soil on its thermal conductivity was confirmed, and secondly, it was established that, at the same moisture content and density, the size of the soil grains matters. Particle size distribution affects the sandy soil thermal conductivity. With an increase in the particle size, sandy soil thermal conductivity increases.

1. Introduction
The work is aimed at investigating the dependence of sandy soils thermal conductivity of various grain-size composition when changing parameters such as moisture, density.

Assessment of the dependence of thermal conductivity on grain-size composition using the example of sandy soils is the goal of the work.

To achieve the goal, the following tasks were solved: analysis of existing methods for assessing the thermal conductivity of soils was carried out, experiment planning done, a series of experiments was carried out, the results were processed by methods of mathematical statistics, the analysis of the results has been carried out [1].

The process of heat transfer in soils, as well as the assessment of their thermal conductivity, is a difficult task due, first of all, to its heterogeneity. The presence of intergranular space in soils filled with air and water sharply complicates the process of heat transfer [2-4].

In existing studies, many calculation methods have been proposed for assessing the thermal conductivity of soils, which allow taking into account the type of soil, its density, and moisture [5-7].

Analysis of the studies carried out in the field of using low-potential thermal energy of the soil, it can be concluded that today the methods for determining the thermal conductivity of inert materials with subsequent practical application in the field of construction have been widely studied, but none of them takes into account grain-size composition.
Thus, carrying out a study in order to determine the dependence of thermal conductivity on the grain-size composition of the soil, taking into account changes in their moisture and density, is relevant.

The work finds its practical application in calculating energy efficient foundations [8-16]. The desired dependence will allow at the early design stages to assess the possibility of using energy foundations without conducting complex geological and laboratory studies of soils, only on the basis of the available physical characteristics of soils in standard geological surveys.

2. Materials and Methods

Experiment planning and experiment planning matrix compiled.

The experimental technique is as follows. Artificially prepared sandy soil samples were used as the object of research.

Input parameters are:

- $X_1$ - soil density $\rho$, varied within $1.73$-$1.89$, t/m$^3$;
- $X_2$ - soil moisture $\omega$, varied within $0.04$ – $0.12$, e.e.

Output parameter soil thermal conductivity – $\lambda$, W/(m*K).

Three series of experiments were carried out to obtain separate dependencies for three fractions of sandy soil 0.5; 0.25; 0.1 mm.

For a linear or incomplete quadratic model, two values of each factor (two factor levels) are sufficient when calculating the coefficients of the regression equation. If we divide the distance between these values of the factor on the coordinate axis in half, then we get the value of the main - zero level. The difference between the upper or lower and zero level - the interval of variation of the factor.

The following form of the regression equation is adopted:

$$\lambda = b_0 + b_1 X_1 + b_2 X_2 + b_{12} X_1 X_2$$

(1)

where: $X_0$ - free term, $X_0 = 1$; $X_1$ - soil density; $X_2$ - soil moisture; $b_0$, $b_1$, $b_2$, $b_{12}$ are the coefficients of the regression equation.

The interval was defined as half the difference between the upper and lower values of the factor. Moreover, the upper level of the factor is (+1), the lower one is (-1).

The coded value of the factor is:

$$x_i = \frac{2(X_i - X_0)}{\Delta i}$$

(2)

where: $x_i$ is the coded value of the factor; $X_i$ is the true value of the factor; $X_0$ is the true value of the zero level; $\Delta i$ - factor variation interval.

Table 1 shows the levels of variation of the main factors.

| Level | Factors       | Soil density, t/m$^3$ | Soil moisture, e.e. |
|-------|---------------|-----------------------|---------------------|
|       | $X_1$         | $X_2$                 |                     |
| 1     | 1.89          | 0.12                  |                     |
| -1    | 1.73          | 0.04                  |                     |

The plan of each experiment (for each fraction) is presented in table 2.
Table 2. Experiment planning matrix.

| № experiment | Soil density | Soil moisture | Response values |
|--------------|--------------|---------------|----------------|
|              | Coded value  | True meaning, t/m³ | Coded value | True meaning, e. | Soil thermal conductivity, W/(m*K) |
|   x₁ |   Y₁ |   x₂ |   Y₂ |   λ₁ |
| 1  | -1  | 1.73 | -1  | 0.04  | λ₁ |
| 2  | 1   | 1.89 | -1  | 0.04  | λ₂ |
| 3  | -1  | 1.73 | 1   | 0.12  | λ₃ |
| 4  | 1   | 1.89 | 1   | 0.12  | λ₄ |

3. Results & Discussion

According to the method described above, the input parameters and the limits of their variation were determined. The object of research was selected - sand sampled in the Perm region [16]. According to the GOST 25100-2011 classification, the sand is fine.

A natural experiment was carried out on the material and technical basis of the laboratory of the Department of Construction Production and Geotechnics (figure 1).

![Figure 1. Trial experiments.](image)

A series of experiments was carried out according to the following technique. Fractions of fine sand were used as material: 0.5; 0.25 and 0.1 mm. The sand was sifted through sieves to the required fraction, then the sandy soil samples were moistened with water to a moisture value of 0.04-0.12 for each fraction and compacted on a hydraulic press to a given density in the cylinder (figure 2 to 4).
The thermal conductivity of the samples under study was determined by the probe method using the "MIT-1" device (figure 5).

Thermal conductivity was measured in accordance with GOST 30256-94. The study of thermal conductivity was carried out on twelve sand samples. Table 3 shows the experimental data obtained for sand fraction 0.5; 0.25; 0.1 mm with specified moisture and density values.

The results obtained were processed by the methods of mathematical statistics in the MS EXCEL software package.

Regression equation coefficients are determined for each fraction. The model has been tested for adequacy. After processing the results of the numerical experiment, the desired dependence was determined in the form of a regression equation.
Table 3. Experiment results.

| № experiment | Fraction, mm | Soil density, t/m³ | Soil moisture, e.e. | Soil thermal conductivity, W/(m*K) |
|--------------|--------------|--------------------|---------------------|----------------------------------|
| 1            | 0.5          | 1.73               | 0.04                | 2.246                            |
| 2            | 0.5          | 1.89               | 0.04                | 2.437                            |
| 3            | 0.5          | 1.73               | 0.12                | 2.213                            |
| 4            | 0.5          | 1.89               | 0.12                | 2.359                            |
| 5            | 0.25         | 1.73               | 0.04                | 1.175                            |
| 6            | 0.25         | 1.89               | 0.04                | 1.412                            |
| 7            | 0.25         | 1.73               | 0.12                | 1.470                            |
| 8            | 0.25         | 1.89               | 0.12                | 1.486                            |
| 9            | 0.1          | 1.73               | 0.04                | 1.059                            |
| 10           | 0.1          | 1.89               | 0.04                | 1.022                            |
| 11           | 0.1          | 1.73               | 0.12                | 1.173                            |
| 12           | 0.1          | 1.89               | 0.12                | 1.277                            |

The regression equation for the 0.5 mm fraction is:

\[ \lambda = -0.055 + 1.34 \rho + 5.74 \omega - 3.55 \rho \omega \]  \hspace{1cm} (3)

The regression equation for the 0.25 mm fraction is:

\[ \lambda = -2.72 + 2.17 \rho + 33.42 \omega - 17.19 \rho \omega \]  \hspace{1cm} (4)

The regression equation for the 0.1 mm fraction is:

\[ \lambda = 2.15 - 0.67 \rho - 17.56 \omega + 10.57 \rho \omega \]  \hspace{1cm} (5)

The graph of the dependence of thermal conductivity on moisture and density for a fraction of 0.5 mm is shown in figure 6.
Figure 6. The graph of the thermal conductivity of sand with a fraction of 0.5 mm at various soil moisture.

4. Conclusions
Analysis of the research results led to the following conclusions:

1) Two factors have a significant effect on the thermal conductivity of soils: density and moisture, which confirms the results of previous studies.

2) At the same moisture content and density, the size of the soil grains is of significant importance, the grain-size composition affects the thermal conductivity of the sandy soil. With an increase in the grain size, the thermal conductivity of the sandy soil increases.

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