Numerical simulation of the process of geothermal low-potential ground energy extraction in Perm region (Russia)

Modélisation numérique du procès de la sélection géothermale d'énergie potentielle basse du sol dans les conditions de la région de Perm (Russie)

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ABSTRACT: The aim of our research is to study the interaction of energy foundations with the ground mass and to develop methods for their construction on the example of the city of Perm. Field studies of ground were carried out in a specially chosen pilot site to determine temperature distribution in the ground mass, change of ground-water level and physical-mechanical and thermal-physical characteristics of the ground mass. The diagrams of depth temperature distribution in the ground and its seasonal variations were obtained on the results of monitoring, and also the average groundwater level. To carry out numerical simulation, software-complex "GeoStudio" was selected. Its basic differential equation is the fundamental heat conduction equation with an internal heat source. The purpose of the numerical simulation was quantitative evaluation of the thermal energy extracted from different energy foundations under soil conditions in the city of Perm. By results of the spent numerical experiments the equations of regress and nomographs dependences of size of received thermal energy on geometrical parameters of the projected power bases to hydro-geological and climatic conditions of the Perm region are constructed.

RÉSUMÉ : Le but de notre recherche est l'étude de l'interaction des fondations énergétiques avec le sol et l'élaboration de leur méthode de construction sur l'exemple de la ville de Perm (Russie). Des études de la répartition des températures dans le sol, des changements du niveau de nappe aquifère, des propriétés physico-mécaniques et thermo physiques sont faites au cours de recherches in-situ sur un terrain expérimental choisi. Les résultats obtenus ont permis de déterminer des diagrammes de répartition des températures dans le sol et leurs changements saisonniers, ainsi que les changements du niveau des nappes aquifères. Pour la modélisation numérique nous avons choisi le logiciel Geostudio, dont l'équation différentielle de base est l'équation de conductivité de la chaleur avec une source de chaleur intérieure. Le but de la modélisation numérique était l'évaluation quantitative de l'énergie thermique en provenance des fondations énergétiques de différents types de sols de la ville de Perm. Selon les résultats des expériences numériques, nous avons construit des équations de régression et des nomogrammes de dépendance de la valeur de l'énergie thermique en fonction des paramètres géométriques des fondations énergétiques en conditions hydrogéologiques et climatiques de la région de Perm.

KEYWORDS: geothermal ground energy, ground thermal energy, energy foundation.

1 INTRODUCTION

One of the ways of increasing energy consumption efficiency when heating buildings is the use of renewable (alternative) energy sources. In developed countries ground thermal energy makes up a considerable proportion of energy used for heating.

Although studies of this problem have taken much time, technologies based on them are rather young. Nowadays, these technologies are widely used in many countries, such as Canada, Australia, the United States, and most European countries. Energy geothermal systems together with important environmental aspect have a great number of advantages:

- They allow reduced energy consumption for heating buildings by 50-70 %.
- The use of foundations as ground heat exchangers necessary from the structural point of view becomes possible.
- They have fewer current costs in operation.

Technologies that use geothermal energy have been used very rarely in Russia so far. Taking into account the advantages of the technology given and the state policy in the area of energy consumption we think that the problem of ground thermal energy investigation when laying foundations and building underground structures is pertinent.

The aim of our research is to study the interaction of energy foundations with the ground mass and to develop methods for their construction based on the example of the city of Perm.

2 PROBLEM STATEMENT

Heating system using ground thermal energy consists of three main parts: the system of pipelines embedded in the ground mass or in contact with the ground (primary circuit); the system of pipelines intended for heating or conditioning (secondary circuit) and a heat pump combining these pipeline systems (Grigorjev V.A. et al. 1982, Katzenbach R. et al. 2007).

The primary circuit is used to generate ground thermal energy and is located in the body of energy foundations. Piles, foundation plates, "slurry walls", diaphragms, anchors, walls of the underground floors and other constructions being in contact with ground can be used as energy foundations.

The advantage of energy foundations is that these structures (piles, foundation plates, etc.) are required for the conditions of constructional safety (that is, to ensure bearing capacity and deformability). Correspondingly, there is no need in their additional construction. Therefore, they are double-purpose structures acting as load-bearing elements and ground heat exchangers.

The secondary circuit is a closed heating system in the walls and slabs of a building.

The functions of the heat pump are to increase the temperature of the primary circuit heat carrier to the necessary one.

Ground is a multiphase system with a complex mechanism of heat transmission, which includes (Grigorjev V.A. et al.

1982): conductivity, convective transfer (convection), the processes of evaporation and condensation (latent heat transfer), heat radiation, ion exchange, freezing – thawing processes.

If the size of soil particles and pores is significantly small in relation to the total soil, the complex process of heat transfer in the ground can be reduced only to conductivity, which dominates in the case of energy foundations.

If there is an internal heat source (internal heat generation) in the concerned ground quantity, the basic equation of heat conductivity is as follows:

$$\frac{\partial t}{\partial \tau} = \alpha \Delta t + \frac{q_{\upsilon}}{\rho c} \qquad (1)$$

where, α is thermal diffusivity, Δt is Laplace operator, q_{υ} is power of internal heat sources, t is temperature, τ is time, c is specific thermal capacity and ρ is density of solid medium.

Differential equations of heat conductivity show a character of the process and have many solutions. To obtain the solution of a specific task it is necessary to have initial and boundary conditions. Because of mathematical difficulties, the analytical solutions of these equations are possible only for simple cases. At present, a number of software packages that solve the problem of heat transfer in soils, including calculations of energy foundations have been developed.

3 EXPERIMENTAL INVESTIGATIONS

Field studies of ground were carried out at a specially chosen pilot site to determine temperature distribution in the ground mass, change of ground-water level and physical-mechanical and thermal-physical characteristics of the ground mass.

Engineering and geological structure of the site was defined by the results of the research done. Geologically, the experimental platform is composed of Quaternary alluvial-diluvial clay soils, at the base with pebbles up to 60-70 % of the total thickness of 11.6 m, overlapped by the thickness of filled-up ground of 6.0m thick. Bedrock is argillites, uncovered at a depth of 17.6 m.

The following physical-mechanical and thermal-physical characteristics of the experimental site ground were obtained on the results of laboratory work:

Table 1. Characteristics of the experimental site ground

№	Soil classification	Deep (m)	ρ (t/m^3)	w	e	c (kJ/ kg°C)	λ (W/ m°C)
1	Filled-up ground	0-6	1.91	0.25	0.73	1.27	1.33
2	Low plasticity loam	6-13	1.92	0.22	0.8	1.25	1.21
3	Gravel ground	13-17.6	1.69	0.007		0.85	0.41
4	Heavily weathered, cracked and waterlogged argillite	17.6	2.27	0.1	0.31	1.07	0.59

The diagrams of depth temperature distribution in the ground and its seasonal variations were obtained on the results of monitoring (Fig.1). Temperature fluctuations in the ground mass starting from the depth of 6.0 m are negligible. The maximum deviation from the mean temperature is less than 0.24°C. The temperature of the ground mass deeper than the depth of 6.0 m varies from 13° to 10° C, gradually decreasing with depth, being equal to 12°C before the depth of 12.0 m, 11°C from the depth of 10m to 16m and 10°C at the depth of more than 16m.

Positive surface temperature of the soil caused by the construction of overall housing for the recording equipment.

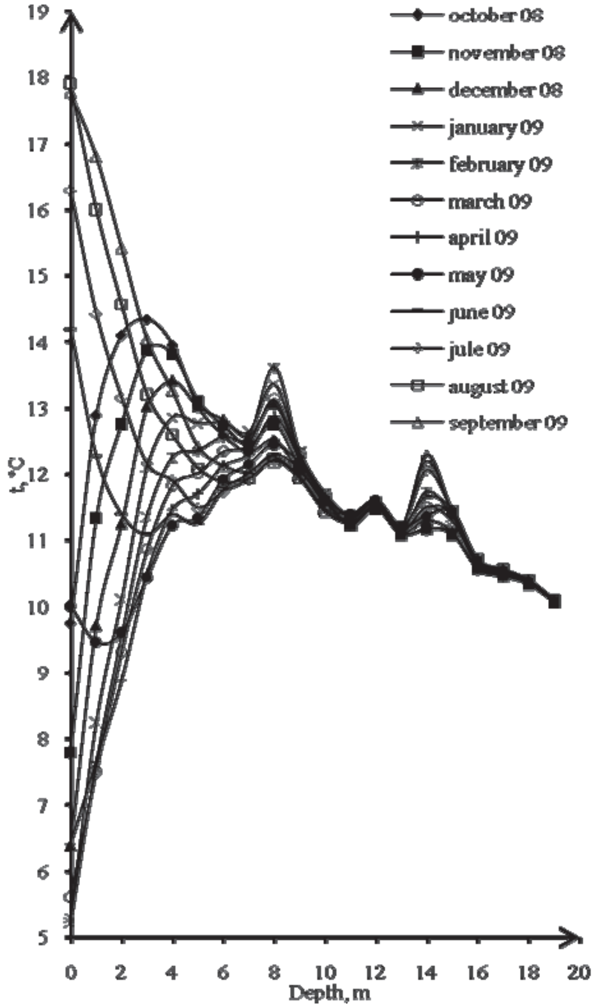

Figure 1. Diagram of depth distribution of temperature in the ground mass.

On the results of groundwater level monitoring it was established that the average groundwater level was 2.55 m. Groundwater level variations with time are negligible.

To carry out numerical simulation, software-complex GeoStudio was selected. Its basic differential equation is the fundamental heat conduction equation with an internal heat source (Grigorjev V.A. et al. 1982).

Test problems for three main types of underground structures being in contact with ground were preliminary solved:

- a pile with a diameter of 1.2m and 20m long;
- a 24m wide slab foundation, the depth of foundation is 20m;
- a slurry wall of 20m deep.

The temperature at each node in the initial period of time was taken as initial conditions. Boundary conditions were specified for the ground surface and for the lower boundary of the model. The boundary conditions of the lower boundary were taken as time-constant value of the heat flow density. The boundary conditions for the surface were set by applying climatic characteristics in the city of Perm in 2009.

Time parameters of the simulation (number of annual cycles) were taken on the condition of setting a “new” temperature regime of the ground mass taking into account the thermal energy that was extracted.

The boundary conditions for the surface of the construction situated below the soil freezing level as a time-constant temperature +1°C were additionally set. Thus, a maximal extraction of thermal energy through the surface of ground-structure contact was simulated.

To determine the minimal time parameters for the numerical simulations of various types of foundations, calculations were carried out and values of the heat flow density through the contact surface of the ground with the foundations were obtained for several calendar years. Figure 2 shows the values of the average heat flow density for the heating period.

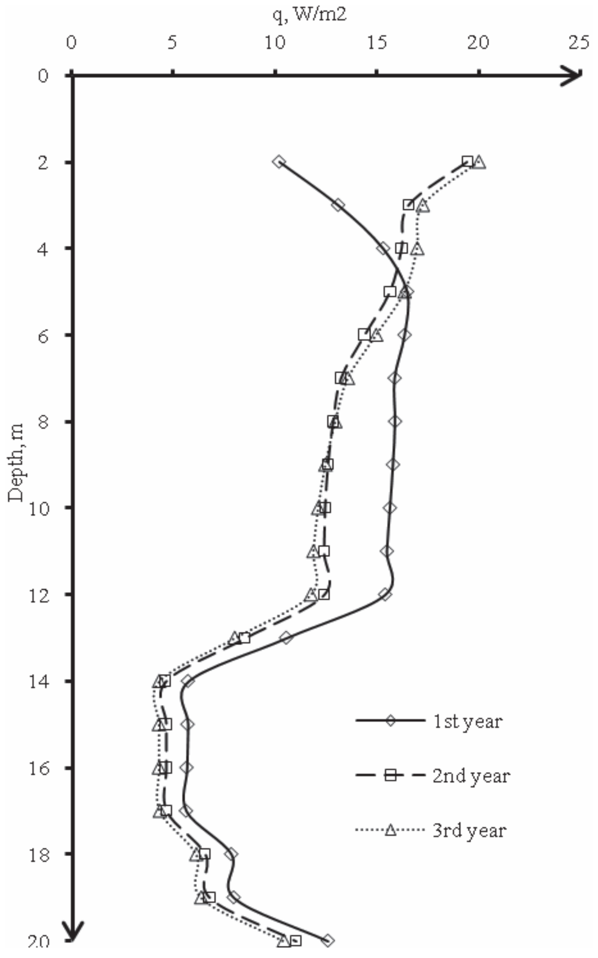

Figure 2. Diagram of average heat flow density through the contact surface of the soil with a 20 m long pile during the heating period

The minimal time parameters for the numerical simulation of different energy foundations maintenance were determined on the solution of the test problems. They are the following: 3 years for a single energy pile, 7 years for a slab foundation and 5 years for a slurry wall.

The purpose of the numerical simulation was quantitative evaluation of the thermal energy extracted from different energy foundations under soil conditions in the city of Perm. Thereto, main types of ground bases typical for the city of Perm were ascertained and numerical experiments were carried out. Based on them regression equations were obtained.

According to the studies done (Kaloshina S.V. et al. 2006), engineering-geological conditions in Perm can generally be reduced to two types. The first one is represented by low plasticity loam and gravel ground with sandy filling aggregate. The second type is medium sand, under which gravel ground with sandy filling aggregate lies. Low-compressible Upper Permian semi- rock occurs below gravel ground.

The experimental site refers to the ground base of the first type. When carrying out the numerical experiment, dependences on various factors of average heat flow density through the contact surface of the deep building parts with the ground were determined.

As two main types of ground conditions with concrete values of physical and thermal-physical characteristics of the ground were identified, their impact on energy foundations was taken into account through numerical calculations and obtaining the dependences for each type.

Therefore, geometrics parameters and underground structure depth were chosen as the main factors, namely:

- for a single pile: a pile radius (*r*) and pile tip depth (*d*);
- for a sunk slab foundation: foundation width (*b*) and foundation depth (*d*);
- for a slurry wall: foundation depth (*d*).

The following regression dependences based on numerical simulation results were obtained and nomograms were plotted. An example of a nomogram is shown in Fig. 3.

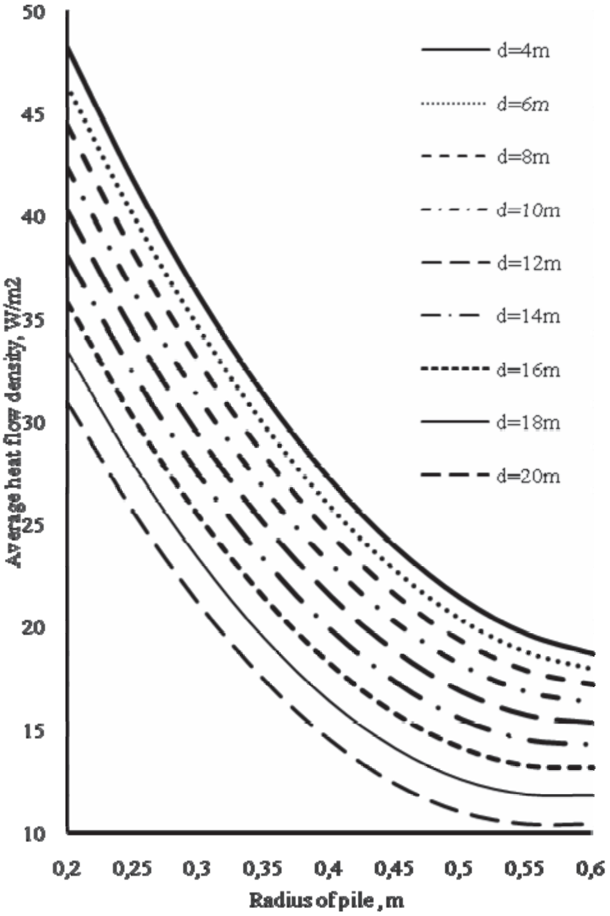

Figure 3. Nomogram of dependence of the heat flow density ($\bar{q}$) through the pile-ground contact surface on the radius (*r*) and the pile point depth (*d*). Engineering-geological conditions of the first type.

Example of distribution of temperature fields in the soil mass at work energy pile is shown in fig. 4.

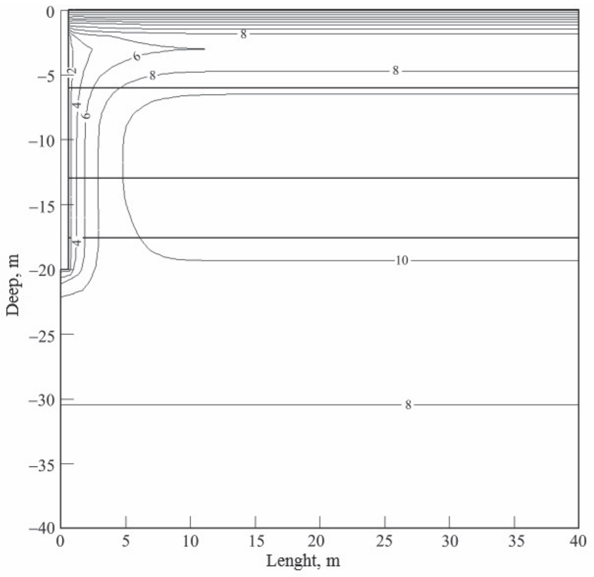

Figure 4. Distribution of temperature fields in the soil mass at work energy pile.

4 CONCLUSIONS

On the bases of the analysis of regression equations derived and nomograms plotted we can draw the following conclusions:

1. Heat flow density ($\bar{q}$) through the contact surface of an energy foundation will depend on:

- for a single pile – on its radius (r) and foundation depth (d). In this case, the heat flow density decreases with the increase of the radius and the length of the pile;

- for a sunken slab foundation – on its width (b) and foundation depth (d). In this case, the heat flow density decreases with the increase of the width and the foundation depth;

- for a slurry wall – on the foundation depth (d). In this case, the heat flow density decreases with the increase of the foundation depth.

2. The amount of heat flow density is higher for the engineering-geological conditions of the second type than for those of the first type, namely ≈ 10 % higher for a single pile and ≈ 6 % higher both for a slab foundation and a slurry wall.

5 REFERENCES

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