PAPER • OPEN ACCESS

Simulation of influence of various technical systems on permafrost boundaries movement

To cite this article: M Yu Filimonov and N A Vaganova 2018 *IOP Conf. Ser.: Earth Environ. Sci.* **193** 012068

View the article online for updates and enhancements.

Simulation of influence of various technical systems on permafrost boundaries movement

M Yu Filimonov[1,2] and N A Vaganova[1,2]

[1] Ural Federal University, Yekaterinburg, Russia
[2] IMM UB RAS, Yekaterinburg, Russia

E-mail: `fmy@imm.uran.ru`

Abstract. Prediction of dynamics of cryogenic processes in soil and foundations is of great importance in the development and operation of oil and gas fields in the Arctic and Subarctic regions. These processes are influenced by the thermal effects of various technical systems available on the well pads. The thawing of permafrost due to such impacts will be accompanied by subsidence of the earth's surface around engineering facilities and development of dangerous geological process called thermokarst. This may lead to major technological accidents at well pads with great harm to the environment. To simulate cryogenic processes in a specific geographical area, algorithms and programs are developed, taking into account the climatic factors and lithology of the soil. An algorithm for determining the features of the area under consideration in the computer simulation of the propagation of thermal fields in frozen ground is described and the results of numerical calculations are presented.

1. Introduction

In Russia, more than 60% of its territory is occupied by permafrost. It is most widely distributed in Eastern Siberia and in Baikal regions. In these areas the main Russian oil and gas fields are located. The production in these fields leads to thawing of permafrost and to possible dangerous earth surface subsidence around engineering facilities at the well pads. Most of the industrial structures in the permafrost zones are constructed and operated on the base of principle of conserving the frozen state of the soils foundation. Studying the dynamics of permafrost boundaries and the movement is of great importance for design and construction of various structures in these territories and is also associated with climate change problems [1–3]. Therefore, the problem of reducing the intensity of the thermal interaction in the "heat source – permafrost" system is an urgent task and has a special significance for safety, saving costs and improving the operational reliability of engineering structures problems.

For long-term simulation of cryogenic processes, a mathematical models and approaches to solving such problems are described in Chapter 5 of [4], on the base of which are developed numerical algorithms [5–8], used in the arrangement of 12 Russian oil and gas fields, when various technical systems operate [9–11] taking into account specific climatic and geographical conditions [12]. Since detailed calculations of the long-term prediction of permafrost boundary changes require considerable computing power, a parallel approach to solving such problems is also developed [13].

This paper presents a mathematical model and numerical calculations for some technical systems used in northern oil and gas fields. A detailed description of the technique which allows

to take into account the specific conditions in the model related with the well pad area, and take into account the most significant climatic and physical parameters that affect the propagation of thermal fields in the ground.

2. Object of simulation and mathematical model

Following [4, 12] we will state the problem. Let $T = T(t, x, y, z)$ be soil temperature at the point (x, y, z) at the time moment t. Simulation of unsteady three-dimensional thermal fields, such as oil and gas fields (the well pads) located in the area of permafrost, is required to take into account the different technological (figure 1a) and climatic (figure 1b) factors.
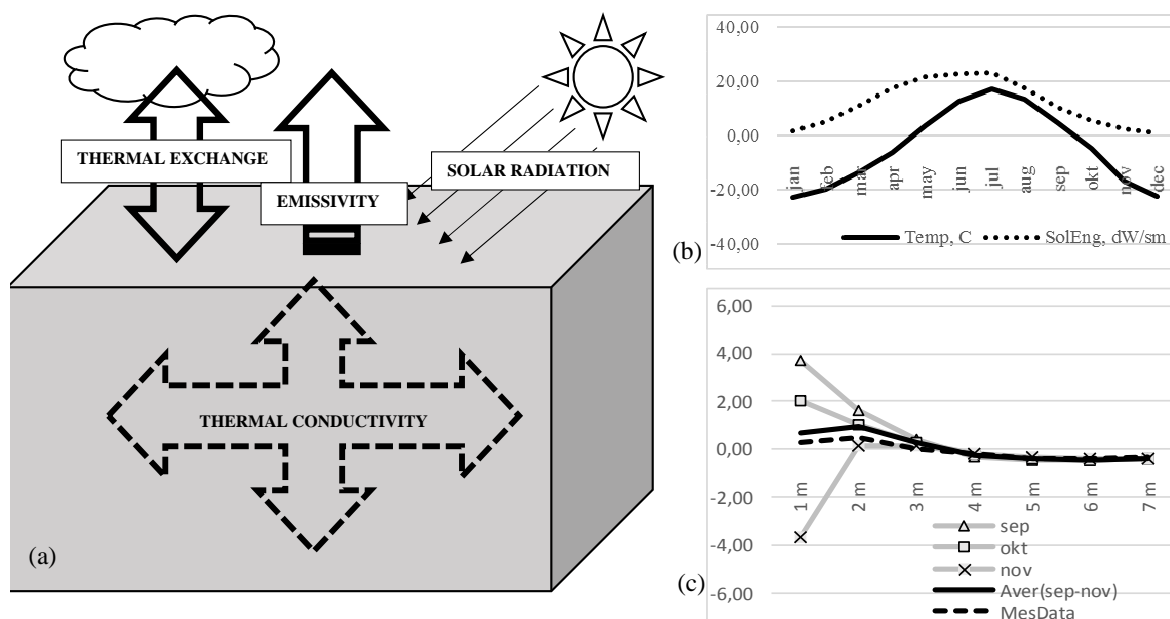

Figure 1. Thermal flows, which form temperature fields in a soil (a); an example of average annual temperatures (solid line) and solar radiation (dotted line) (b); temperatures in soil: measured (dashed line) and computed (solid lines) (c).

Let the modeling area in figure 1a is the box $\Omega = \{(x, y, z) : -L_x \leq x \leq L_x, -L_y \leq y \leq L_y, -L_z \leq z \leq 0\}$, which is defined by positive numbers L_x, L_y, L_z. Simulation of processes of heat distribution is reduced to solution of three-dimensional diffusivity equation with non-uniform coefficients including localized heat of phase transition — an approach to solve the problem of Stefan type, without the explicit separation of the phase transition in Ω [14]. The equation has the form

$$\rho(c_\nu(T) + k\delta(T - T^*))\frac{\partial T}{\partial t} = \nabla(\lambda(T)\Delta T), \tag{1}$$

with initial condition

$$T(0, x, y, z) = T_0(x, y, z). \tag{2}$$

Here ρ is density $[kg/m^3]$, T^* is temperature of phase transition $[K]$,

$$c_\nu(T) = \begin{cases} c_1(x, y, z), & T < T^*, \\ c_2(x, y, z), & T > T^*, \end{cases} \text{ is specific heat } [J/kg\ K],$$

2

$$\lambda(T) = \left\{ \begin{array}{ll} \lambda_1(x,y,z), & T < T^*, \\ \lambda_2(x,y,z), & T > T^*, \end{array} \right. \text{is thermal conductivity coefficient [W/m K]},$$

$k = k(x,y,z)$ is specific heat of phase transition, δ is Dirac delta function.

The nonlinear condition on the surface of the ground has the form

$$\alpha q + b(T_{air} - T(x,y,0,t)) = \varepsilon\sigma(T^4(x,y,0,t) - T_{air}^4) + \lambda\frac{\partial T(x,y,0,t)}{\partial z}. \tag{3}$$

The possibility of adaptation of the numerical algorithm to a specific geographic area, taking into account various climatic and physical factors, and the importance of the correct setting of the boundary condition (3) are discussed in [12].

At the boundaries of the computational domain the boundary conditions are given

$$\left.\frac{\partial T}{\partial x}\right|_{x=\pm L_x} = \left.\frac{\partial T}{\partial y}\right|_{y=\pm L_y} = 0, \quad \left.\frac{\partial T}{\partial z}\right|_{z=-L_z} = \gamma. \tag{4}$$

In (4) γ is a positive number, corresponding to a geothermal flux value. As a rule γ is a small number and it is possible to be set zero in calculations.

3. Numerical results

With using ideas [14], to solve problem (1)–(4) in three-dimensional box a finite difference method is used with splitting by the spatial variables and taking into account the inner boundaries from different technical systems. Solvability of the same difference problems approximating (1)–(4) is proved in [15]. An experimental data and numerical estimations obtained during 3 years of monitoring the changes in the thawing zone boundary around an operating well and predicted on the basis of the developed software package for the problem (1)–(4), respectively, are in a good agreement (5% in position of thawing boundary).

To conserve the soil in the frozen state seasonal cooling devices (SCDs) are used [9], operating on the basis of physical laws, and creating zones of additional freezing on winter. Let consider a system of several SCDs located in frozen soil. The thermal fields around SCD's have been stabilized after 3–4 years of simulation. In figure 2 there are presented thermal fields on December (left figures) and September (right figures) from 9 SCDs after 3–4 years of simulation. In figure 3 there are presented thermal fields on December (left figures) and September (right figures) from 4 SCDs after 3–4 years of simulation.

December illustrates the soil freezing under SCDs operation and September shows the thermal trace of SCDs effect after the season the soil warmed up.

Let consider the operating mode of a horizontal flare system (HFS) when it works continuously, or when HFS runs periodically with the specified mode of switching. To simulate the thermal trace from the HFS on the surface $z = 0$, there was used the temperature or the heat flux. It is necessary to calculate the predicted change in the temperature regime of the foundation soils under HFS, taking into account the adopted design of the heat-insulating screen, which ensures the preservation of permafrost in the base for the period of operation of the HFS. The temperature fields are shown in figure 4 in the first and fifth years of operation of the HFS, respectively, in the xz plane.

4. Conclusion

Thus, the developed mathematical model and software product allow to carry out detailed numerical calculations on long-term forecasting of temperature field changes from different technical systems in the near-surface layer of soil. Numerical simulation of thermal fields around SCDs have shown that it is possible to choose an optimal number of SCDs for thermal
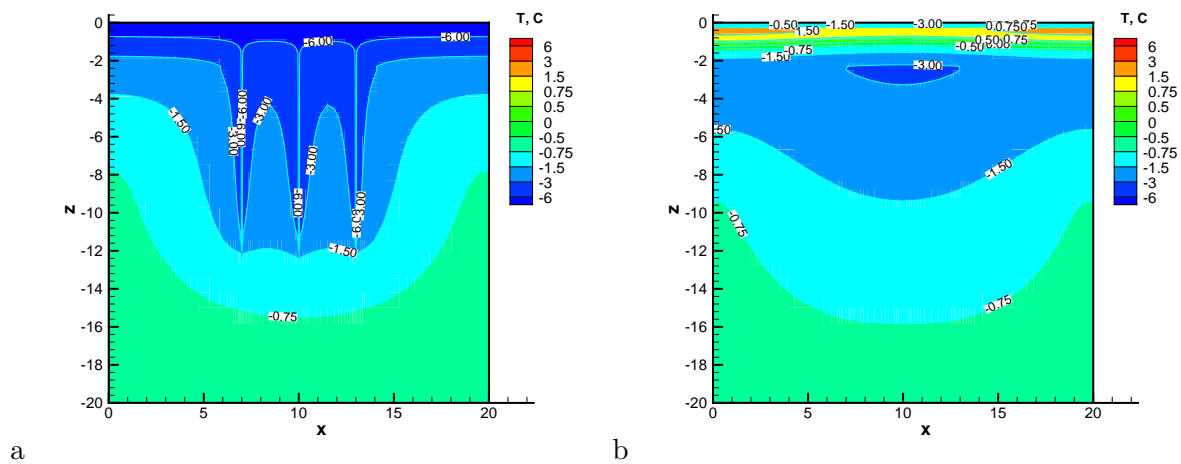
Polar Mechanics 2018

IOP Publishing

IOP Conf. Series: Earth and Environmental Science **193** (2018) 012068

doi:10.1088/1755-1315/193/1/012068

Figure 2. Thermal flows, which form temperature fields in a soil from 9 SCDs with distance 3m between SCDs: a — in December, b — in September.
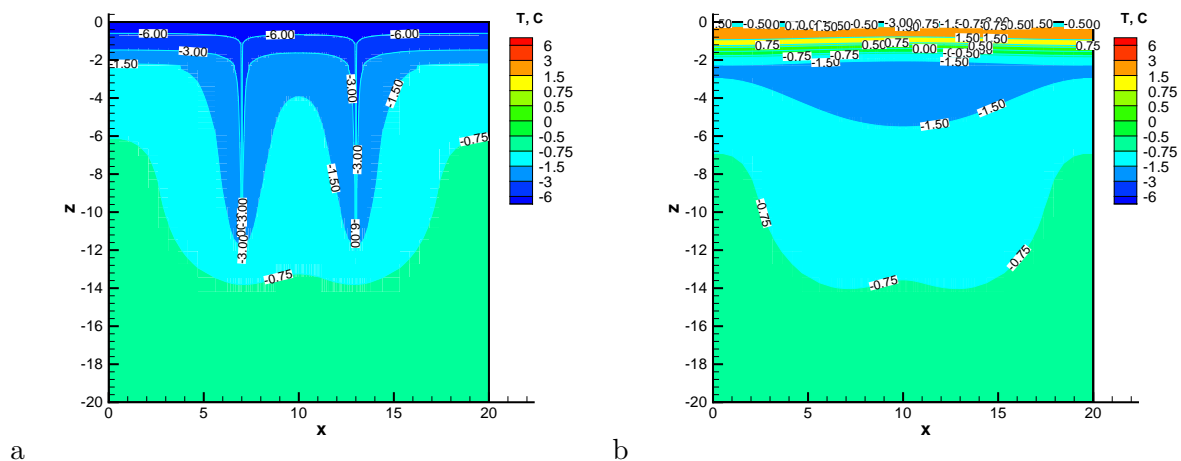

Figure 3. Thermal flows, which form temperature fields in a soil from 4 SCDs with distance 6m between SCDs: a — in December, b — in September.

stabilization of soil depending on the technical conditions of operation of the technical systems or engineering structures. Since the stabilization of thermal fields around SCDs is achieved after 3 to 4 years of SCDs operating, it is advisable to provide thermal stabilization of the soil for three years, if necessary, or to use an additional thermal insulation before starting construction. The operating mode of HFS can be described by using a variable time step. Carried out computer simulation allows one to solve specific applications related to the design of the foundation construction under HFS, as well as the task of compiling an optimal schedule for switching on and off the HFS in order to reduce the thermal impact on the basis for HFS and permafrost.
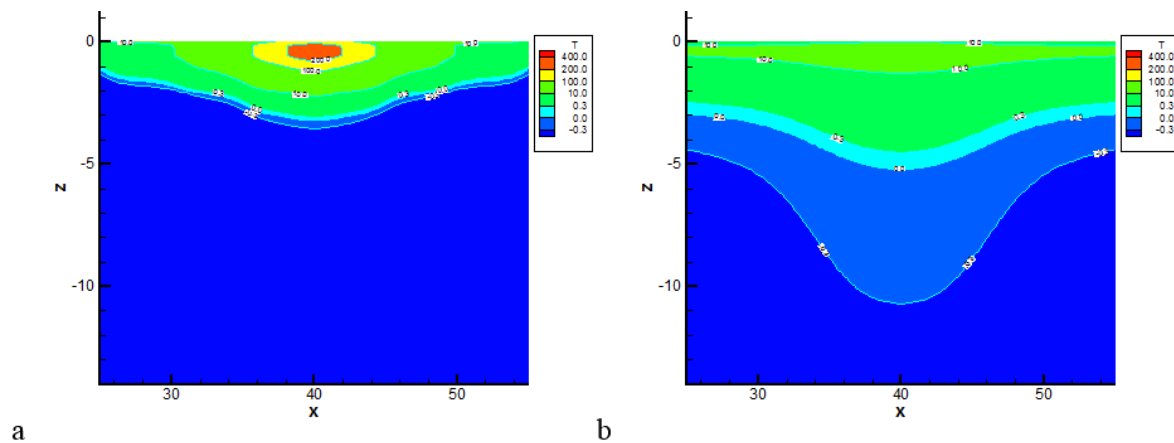
Figure 4. Temperature fields from the HFS in the fifth year: a — in May, b — in October.

Acknowledgments

References

[1] Zhang T, Barry R G, Knowles K, Heginbottom J A and Brown J 2008 *Polar Geography* **31**(3) 47
[2] Vaganova N and Filimonov M 2017 *IOP Conference Series: Earth and Environmental Science* **72** 012005
[3] Filimonov M and Vaganova N 2017 *IOP Conference Series: Earth and Environmental Science* **72** 012006
[4] Filimonov M and Vaganova N 2017 *Advances in Environmental Research. Vol. 54. Chapter 5. Numerical Simulation of Technogenic and Climatic Influence on Permafrost* (New York: Nova Science Publishers)
[5] Vaganova N A 2017 *Applications of Mathematics in Engineering and Economics, (AMEE'2017)* (*AIP Conference Proceedings* vol 1910) ed Pasheva, Popivanov N and Venkov G (Melville, NY: American Institute of Physics) p 020006
[6] Filimonov M Y and Vaganova N A 2017 *Journal of Physics: Conference Series* **899** 092004
[7] Filimonov M Y and Vaganova N A 2016 *Journal of Physics: Conference Series* **754** 112004
[8] Vaganova N A and Filimonov M Y 2015 *6th International Conference on Finite Difference Methods - Theory and Applications* (*Lecture Notes in Computer Science* vol 9045) ed Dimov, Farago and Vulkov L (Germany: Springer Verlag) p 185
[9] Filimonov M Y and Vaganova N A 2013 *Applied Mathematical Sciences* **7** 7151
[10] Filimonov M and Vaganova N 2016 *Modern Problems in Mathematics and its Applications, (MPMA 2016)* (*CEUR Workshop Proceedings* vol 1662) ed Makhnev A and Pravdin S (CEUR-WS.org) p 253
[11] Vaganova N A and Filimonov M Y 2015 *Applications of Mathematics in Engineering and Economics, (AMEE'2015)* (*AIP Conference Proceedings* vol 1690) ed Pasheva, Popivanov N and Venkov G (Melville, NY: AIP Publishing) p 020016
[12] Filimonov M Y and Vaganova N A 2018 *Information Technologies and Mathematical Modeling for Efficient Development of Arctic Zone, (IT&MathAZ 2018)* (*CEUR Workshop Proceedings* vol 2109) ed Filimonov M, Blisorukova M and Kruglikov S (CEUR-WS.org) p 18
[13] Vaganova N and Filimonov M 2015 *Ural Workshop on Parallel, Distributed, and Cloud Computing for Young Scientists, (Ural-PDC 2015)* (*CEUR Workshop Proceedings* vol 1513) ed Sozykin A, Akimova E and Ustalov D (CEUR-WS.org) p 42
[14] Samarsky A A and Vabishchevich P N 1995 *Computational Heat Transfer, Volume 2, The Finite Difference Methodology* (Wiley)
[15] Vaganova N A 2008 *Proceedings of the Steklov Institute of Mathematics* **S1** S260