Computational technologies for modeling thermal processes in permafrost zone

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Introduction

In this work, we present results of numerical simulations of thermal processes with phase change. This problem is considered in a three-dimensional formulation with a complex variable geometry. The computational domain is a multi-layer soil, taking into account the installation of a large number of piles with a small diameter.
Numerical simulation of the problem was carried out with the following variants of the geometry:

Stage 1 - geometry with soil and vegetation layer;

Stage 2 - geometry after removal of soil-vegetation layer;

Stage 3 - geometry with the addition of a mound;

Stage 4 - geometry taking into account the installation of piles.

To solve the problem used FEniCS - computing platform and the programm developed by us, Heat Transfer.

Mathematical model

The law of heat conduction

$$\left(\alpha(\phi)+\rho^{+}L\phi'\right)\frac{\partial T}{\partial t}-\operatorname{div}\left(\lambda(\phi)\operatorname{grad}T\right)=0,$$

with phase change in T^* in domain $\Omega=\Omega^-\cup\Omega^+$:

$$\phi_\Delta=\left|\begin{array}{ll}0, & T\le T^*-\Delta\\ \dfrac{T-T^*+\Delta}{2\Delta}, & T^*-\Delta<T<T^*+\Delta\\ 1, & \ge T^*+\Delta\end{array}\right.$$

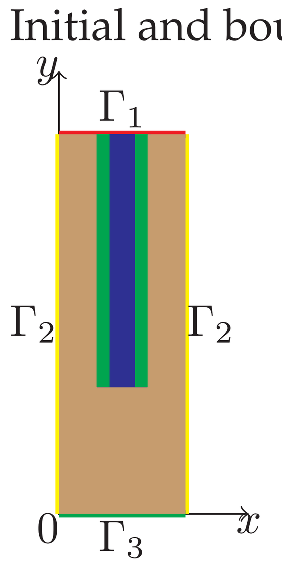
$$\alpha(\phi)=\rho^-c^-+\phi(\rho^+c^+-\rho^-c^-),$$

$$c^-\rho^-=(1-m)c_{sc}\rho_{sc}+mc_i\rho_i,$$
$$c^+\rho^+=(1-m)c_{sc}\rho_{sc}+mc_w\rho_w.$$

$$\lambda(\phi)=\lambda^-+\phi(\lambda^+-\lambda^-),$$

$$\lambda^-=(1-m)\lambda_{sc}+m\lambda_i,$$
$$\lambda^+=(1-m)\lambda_{sc}+m\lambda_w.$$

Initial and boundary conditions



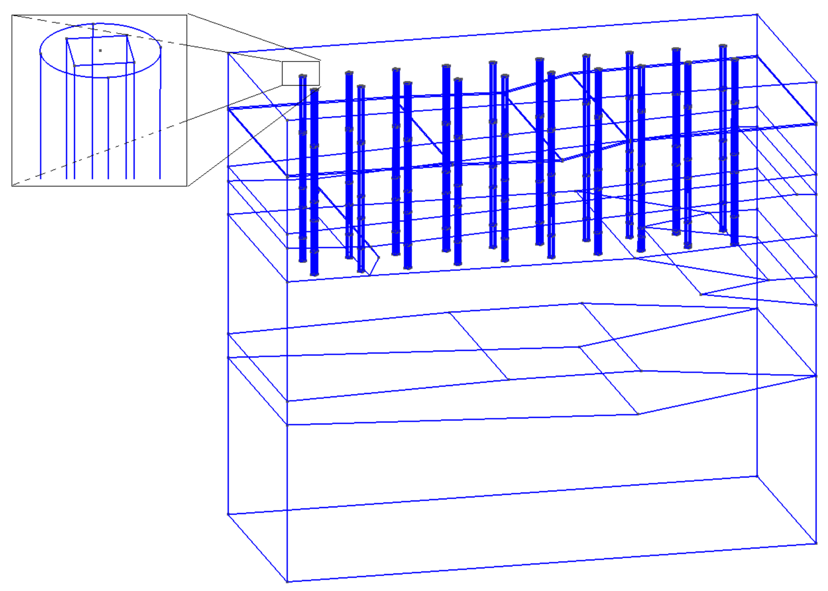
$$T(x,0)=T_0,\quad \mathbf{x}\in\Omega,$$

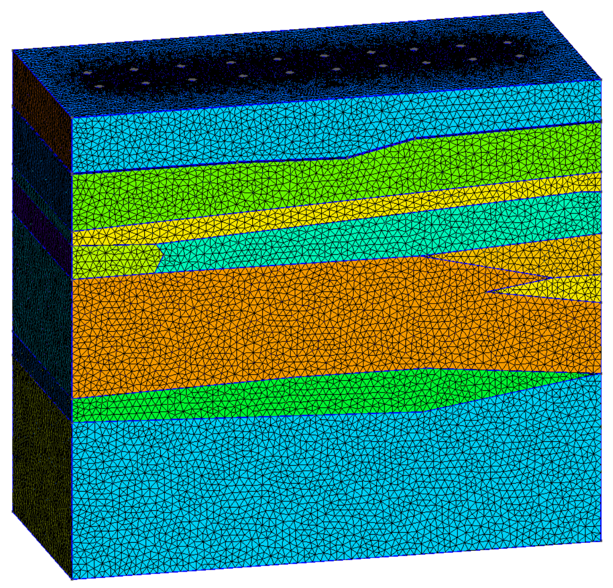
$$-k\frac{\partial T}{\partial n}=\frac{Q(1-A)+I-\alpha(T-T_{air})}{\alpha R+1},\quad \mathbf{x}\in\Gamma_1,$$

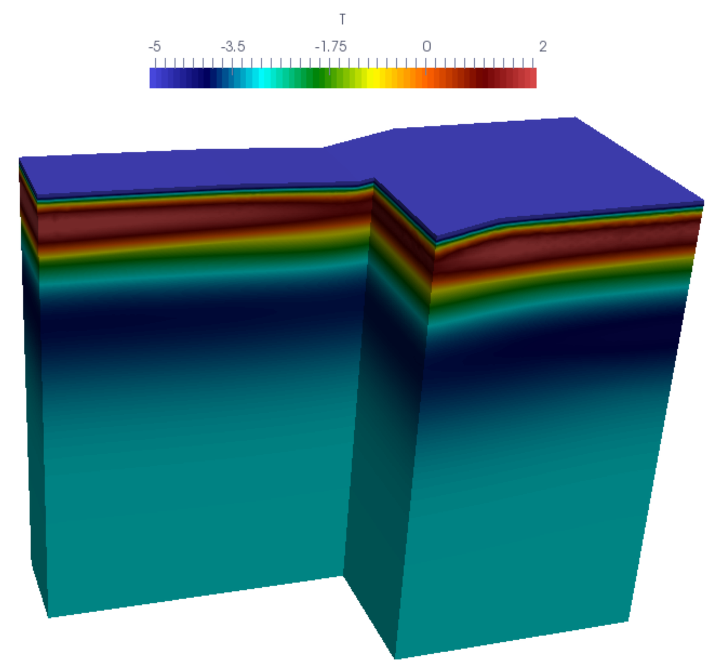
$$-k\frac{\partial T}{\partial n}=0,\quad \mathbf{x}\in\Gamma_2\text{and }\Gamma_3.$$

The results of calculations of the thermal regime at the construction stages

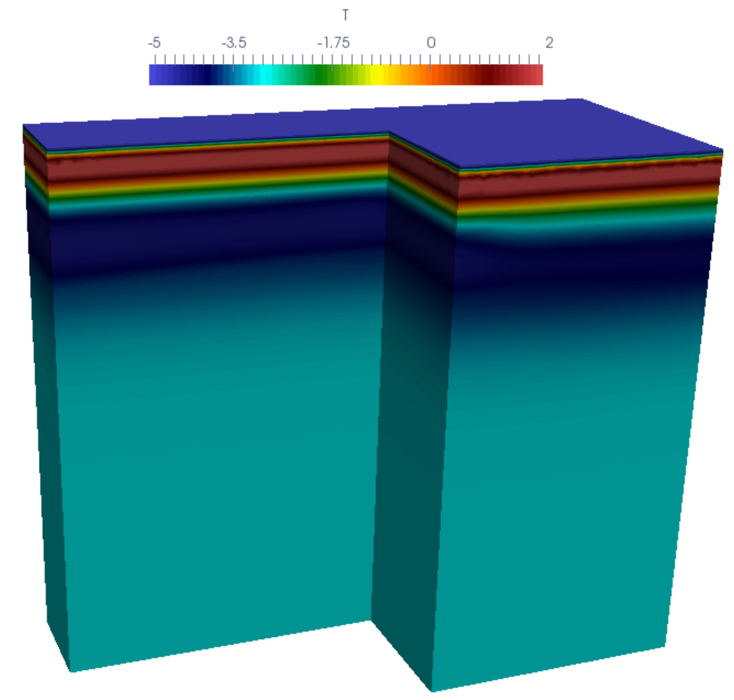
The geometric domain consists of several engineering geological layers and contains 20 piles with a radius of $r=0.2$ meters and a length of 14 meters. The design area has the size $L_x=15$, $L_y=54$ and $L_z=50$ meters. The computational mesh is presented in below and contains about 260 thousand nodes and about 1.5 million tetrahedral cells. The calculations were carried out at $t_{max}=2$ years in 1-day step.



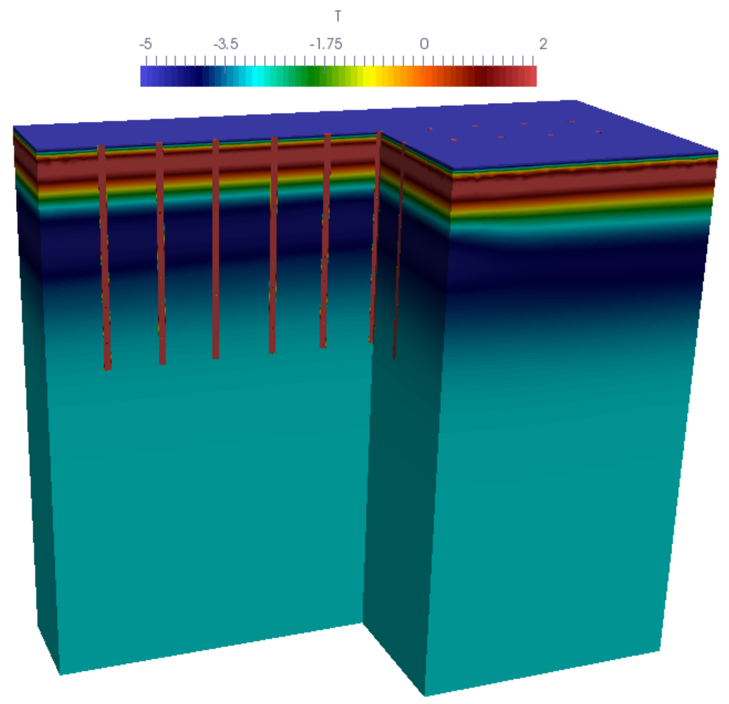




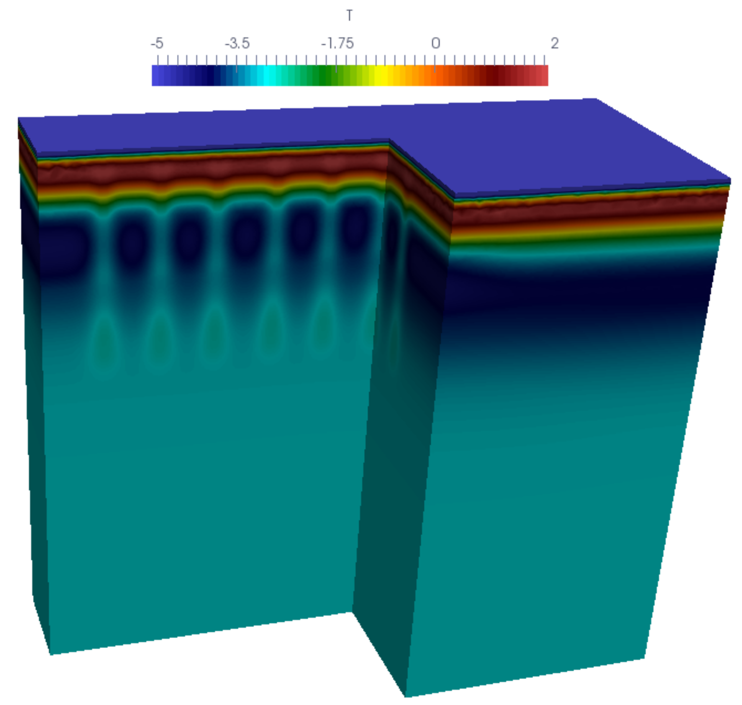
Heat distribution in geometry with soil-vegetation layer $t=365$



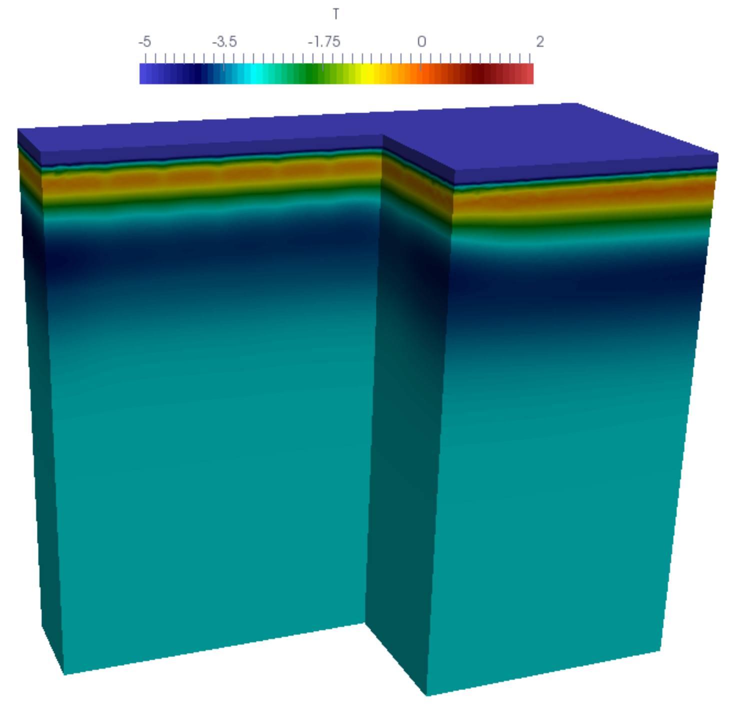
Heat distribution with the addition of a mound $t=365$



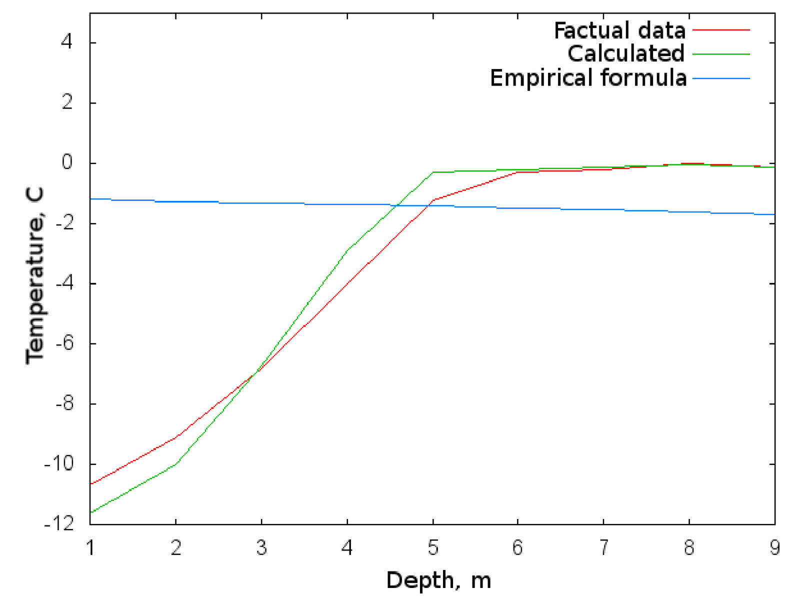
Heat distribution on day to installation of piles



5 days after installation of piles



30 days after installation of piles



Compare results with factual data and calculated by empirical formula used by builders

Conclusion:
The soil-vegetation layer can be replaced by a coefficient of heat exchange, taking into account the thickness of the soil-vegetation layer and its thermal conductivity;
The addition of a mound under the building from suitable materials of sufficient height can keep the soil itself under the building in a frozen state.

Application software Heat Transfer

We developed a heat transfer simulation software consisting of the following modules:

- project module;
- geometry builder module;
- solver module;
- visualisation module;

Our application software provide some features that connected with intuitive GUI, advanced problem configurator. Physical properties, numerical parameters easily can be changed without programming experience. This software take into account intersections so user can easily develop complex geometries. Using the visualization module, you can use filters and get a quick visual result.
Software been developing based on Open-Source libraries, e.g. VTK, FEniCS, Gmsh, Qt.
The problem presented above was used to verify the correctness of the software.
For software, we received a certificate of registered software.