Modeling of subsidence of anthropogenic soil containing ice lenses

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Abstract. The paper considers the possibilities of modelling of cyclic thermal effects on clastic water-saturated soil anthropogenic origin containing permafrost soil and ice lenses. In the formulation of the problem, there is uncertainty in the description of the structure of the layers, permeability coefficients, heat capacity and thermal conductivity. It is shown that the soil model allows the simultaneous implementation of filtration and convection modes depending on the degree of water cut in the layer. A formulation of the inverse problem is proposed, allowing an adequate interpretation of the log data.

1. Introduction
The practical significance of the task of assessing the condition and characteristics of anthropogenic clastic soils is determined by the tendency of building compaction within certain urban areas. The areas may become attractive from the infrastructure point of view, and therefore from the economic point of view. Such sites are often affected by intense gully-erosion, previously they could have been used for domestic waste landfills, snow dumps, etc. Certain sections may place within the river valleys crossing the territory of a settlement.

In Novosibirsk, the example of such territory is the right-bank part of the city, which is historically the oldest and characterized by a high degree of infrastructure development. This territory from east to west - towards the Ob, the main river of the city, is intersected by its numerous tributaries, - the rivers Kamenka, 1st and 2nd Yeltsovka, Plyushchikha and others.

For many years the valleys of these rivers and the ravines adjacent to them have been filled with chaotically household rubbish, construction garbage and bulk soil, some areas were used as long-term snow dumps. As a result, ice lenses (compacted snow) and permafrost soil were formed in the thickness of the anthropogenic soils.

Another one example is a section of the soil massif on the right side of the river Kamenka which channel in the 60s of the last century for about 5 km, up to its mouth, was placed in a reinforced concrete reservoir and washed by a sand-gravel mixture taken from the river Ob channel. After that, the sides of the valley, right up to the moment of modern development, were used as places for snow dumps and dumps for construction waste.

Modern building development of such sites because of incomplete analysis of the heat transfer process, as well as an incorrect diagnosis of the causes of subsidence of the soil, led to deformations of the building and the adjacent economic territory, as a result of which the engineering structures and site improvement lost their operational qualities.
The effectiveness of the use of land within the river valleys is essentially determined by the possibilities of analyzing the state of soils, both according to engineering and geological surveys and based on reconstruction of the history of the formation of the soil mass. It should also be taken into account that information on the soil and hydrogeological conditions of the sites of the proposed development are incomplete, and the available information is not adequate. In modeling these circumstances lead to inverse problems of mathematical physics.

The main approach of the investigations of phase transfer liquids inclusions in ground structures concerned of the problems of ground energy conversion stations. The thermal conductivity properties of various species of soil were investigated in [1]-[4]. The phase couples considered in papers is water-steam and carbon oxide in saturated and gaseous phases.

In this paper, we consider the coupled problem of heat transfer and filtration of ground water in an array consisting of four layers, different in degree and phase state of water content. Sequentially arrangement of the layers is as follows:

- bulk soil - sandy loam with admixtures of loam and sand with a small degree of water cut,
- bulk soil saturated with water,
- frozen sand with streaks of ice,
- ice.

These layers are underlain by natural soils (sandy loams and loams of the Middle Quaternary age or modern loams with interlayers of sandy loams), or alluvial sands.

At the boundaries of the layers, the conditions of hydraulic and thermal connectivity are fulfilled, while the boundaries of the layers are mobile. The modeling parameters are the heat flux through the free surface, the permeability coefficient in the layer saturated with water, the ice content in frozen sand, the temperature of the ice. The subsidence of the soil is due to the melting of the ice layer and the subsequent watering of the soil lying above this layer. When determining the heat flux on a free surface, data on seasonal changes in air temperature in Novosibirsk are used.

2. Mathematical model

The heat flux \( q \) in layers not containing inclusions of the liquid phase is determined by the Biot – Fourier law:

\[
q = -\lambda_i \frac{\partial \theta}{\partial z},
\]

here \( \lambda_i \) – effective coefficient of thermal conductivity of the layer, \( \theta(z) \) – temperature at depth \( z \).

Heat transfer in the layer over time formulated by the temperature determined by the heat equation:

\[
\rho_i c_i \frac{\partial \theta}{\partial t} + \lambda_i \frac{\partial^2 \theta}{\partial z^2} = 0,
\]

here \( \rho_i, c_i \) – the average density and specific heat of the layer material, respectively. Determination of the temperature distribution in layers containing water is in compliance with convective heat transfer in the equation (2):

\[
\rho_i c_i \left( \frac{\partial \theta}{\partial t} + w \frac{\partial \theta}{\partial z} \right) + \lambda_i \frac{\partial^2 \theta}{\partial z^2} = 0,
\]

here is the vertical component of the fluid flow \( w \) defined by Darcy’s equation:

\[
w = -\frac{k_i \partial p}{\mu_i \frac{\partial z}{\partial z}},
\]

here \( k_i \) – permeability of the layer material, \( \mu_i \) – fluid viscosity. The heat flux at the boundary between layers containing and not containing a liquid phase is determined by the heat transfer coefficient \( \alpha_y \), on the border between the layers not containing liquid, heat transfer coefficient \( k_y \).
3. Numerical simulation
To verify the proposed model, the problem of the joint propagation of heat and the liquid phase in a rectangular prismatic core was considered. A model material with a melting point close to the melting point of ice was considered. The initial state was determined by the region occupied by the liquid phase and the temperature of the horizontal faces of the sample. The temperature of the upper horizontal face was kept constant; on the lower face, the condition that the temperature gradient was equal to zero was accepted. On the lateral vertical faces, the condition that the temperature gradient is equal to zero and the liquid phase flow is equal to zero was fulfilled. On the frontal and lateral faces, the conditions for smooth continuation of the solution were set, simulating the equilibrium state of the heat fluxes and the liquid phase between the sample and the volume containing it. An excess hydrostatic pressure was set on the frontal face. On the back of the conditions for temperature, pressure and flow was not set. Such a face models a free surface (ravine wall) on which the liquid phase and heat can escape into the atmosphere. Under these conditions, one should expect heating of the sample in the vertical direction, realization of a phase transition at the interface, convective and diffusion flow. The solution was obtained numerically using the finite volume method. For calculations, we used a finite-volume numerical modeling software package, distributed under the terms of the GPL license.

4. Calculation results
The dependence of the distribution of volume concentration of the liquid phase $\varphi$ along the vertical axis of symmetry of the core, ordered in time, is shown in Fig. 1. The core temperature distribution corresponding to the same time points is shown in Fig. 2. It can be seen that the front of the liquid phase moves monotonously down the sample, this movement of the front in the temperature graphs corresponds to a change in the position of the corner point. A change in the position of horizontal asymptotic sections in the temperature dependences corresponds to heating of the solid phase. The dependence of temperature on the vertical coordinate is monotonous only in the initial stage of heating (curves 1-5 in Fig. 2).

![Figure 1. Liquid phase front moving](image1)

![Figure 2. Temperature distribution dynamics](image2)

When sufficient thickness of the liquid phase layer is reached, the conditions for the occurrence of thermocapillary convection are formed, which is illustrated by the formation of a local minimum of the dependence of temperature on depth in the region occupied by the liquid phase (curves 6-8 on Fig. 2).

Figure 3 shows the flow stream lines in the middle section of the sample parallel to the lateral faces, obtained for time points 2, 5, 8. When convective flow is realized, the streamlines are closed in the flow region; in the filtration mode, the flow lines are closed at infinity. One can also see the formation of separate regions of the convective flow, corresponding to the decay of the flow into circulation cells. The areas in Fig. 3, by unfilled streamlines, correspond to the area of flow stop. With
necessity, such regions appear in the zone of possible filtration in the vicinity of the free surface (on the right in the figure). It should be noted that the realization of the vortex flow is impossible as a result of heat transfer only, determined by the solution of the heat conduction equation monotonic in coordinates.

**Figure 3.** The evolution of streamlines over time

5. Discussion

The above results can illustrate the process of melting in a layer when heat is supplied through the upper face. In practice, you have to deal with a fundamentally more complex situation. Layers can be not two, but four-five (up to ten), while obviously more than two different rocks are involved in the formation of layers. Even in the case when the main factor of soil subsidence is the movement of liquid in the flooded layers and the liquid released during ice melting, many cycles of partial freezing and thawing should be considered. These circumstances necessarily lead to the formulation of the inverse problem. It should be noted that the extent of the field changes under consideration does not allow us to attribute the task to typical problems of mathematical geophysics.

Assuming further application of the methods of mathematical geophysics developed for solving inverse problems it is essentially needing to sketch the base difference in problems formulation and methodologically approach specific for this problem in comparing with other. The first problem in this way is significantly difference in scales and corresponding lack of verified experimental or observed data on structural, mechanics and thermodynamics data on problem in focus. It is known lot of experimental and theoretical investigations [5]-[8] concerned to geophysical properties of thermal reservoirs.

The scale of investigated Geo surface area in this case varied from ten’s to thousand kilometers and accompanied this depth scale in kilometers. The scale of inclusions, local specifies, reservoirs in this problems varies from kilometers to hundred kilometers. Despite of the main governing equations is same as used in this papers – it’s include heat transfer equation, Bio’t law for liquid phase flow and equilibrium equation or moment equation for structural displacements the difference significant and concerned the time scale for essentially variation of the media property. Average scale for thermal conductivity of soils and rocks determined by sample length and temperature gradient also is differ than in this work case. Measuring methods also include few different techniques includes traditional thermal needle probe up to optical scanning technique.
6. Conclusion

Summarizing above it maybe conclude that problems concerned local properties of basement is quit differ than problems in geophysics. Another one research area lay close to actual aspects of waste placement. In this case also significant heat and liquid transfer throw the boundary of waste packet and natural ground. The problems arising in this description seems similar to discussed here: permeability coefficients, heat capacity and thermal conductivity is not defined well but is in strong influence on process.

Formulation of the reverse problem in this case seems to be founded on experience of sufficient class of partial problems. The first one must be separated problems for homogeneous (or quasi-homogeneous) media and media containing inclusions of solids with gap of transient coefficients on boundary. In this case the focus is the arising and growing of porosity connected to inclusion. It is various mechanisms for porosity evolution. The first one is the inclusion displacement inspired by structural deformation or cyclic ice-water transition in connected soil. Another one is the porosity generation by temperature and stress gradients inspired by inclusion. Sufficient set of such and similar solutions may perform adequate base for reconstruction actual process by image recognition in problem with lack of verified information.

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