Numerical simulation of seepage processes in permafrost near a hydro unit

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Abstract In the territory of Western Yakutia, during the last 20 years, complex geophysical monitoring of hydraulic engineering units has been applied. Alongside field studies, numerical evaluation of permeable talik zone (thawing) origination and development in a broad zone around a dam was made. The non-steady problem of heat-mass transfer in fractured-porous saturated frozen media, interbedded in frozen impermeable strata is discussed. The model takes into consideration the main conditions causing initiation and development of talik near a reservoir: annual temperature and snow cover variation, seasonal water temperature distribution with depth in the storage basin adjacent to the dam, and evolution of permeability in rock due to thaw-freeze processes. The proposed model can be used to analyse more complex situations.

Key words permafrost; talik; hydro unit; geophysical monitoring; numerical modelling; Western Yakutia

INTRODUCTION

An artificial water reservoir in permafrost creates conditions for talik zone (thawing) formation and development along the shores flanking the reservoir. The stability of the dam and reservoir shores is the key to the safety of reservoirs (such as power station pools, water supply, tailing pits, etc.). Similar problems due to thaw may also occur in natural basins in permafrost regions – climate change may activate lake drainage causing hazardous situations. To avoid water loss and maintain the hydro unit's stability in a permafrost zone we need to use geophysical tools, including long-term monitoring for detecting a talik formation. Along with the required temperature control, different geophysical methods give information about variation of rock physical properties caused by thaw–freeze processes. Integrated geophysical monitoring allows the observation of time–space variations of physical fields, reflecting the evolution of thaw–freeze processes in the dam and the reservoir's flank shores. To better understand the situation of talik formation we have developed a numerical model describing a system that includes a water storage basin (with annual temperature variation), a frozen mass (with vein ice in fractures), snow cover (insulating the ground), and annual temperature variation.

GOALS AND OBJECTIVES OF THE STUDY

The study was conducted in the Aichal-Mirni region of Western Yakutia, a region of a potential development of different types of anthropogenic loads. There are many hydraulic engineering facilities of different function: hydropower installations, reservoirs for water supply, surface and underground storages for technogenic brines, etc. The permafrost rocks condition is very sensitive to natural and human-caused impacts. Consequently numerous thaw–filtration processes have been observed during the last two decades at a number of hydro-technical objects in Western Yakutia at Marha, Irelyah, Vilyui, Anabar, Sitikan, Kieng, Iyraaas-Yuryah (Velikin & Snegirev, 2004). The studies were focused on the detection and location of talik zones and seepage in a dam body and adjacent to reservoirs and dam areas as well as estimating the dynamics of seepage processes. At present, special attention should be focused on climate impacts on permafrost stability and particularly on engineering objects in permafrost zones as the objects are very sensitive "trigger points" for hazardous processes. Similar problems may also occur with natural basins in cold regions – climate change may activate lake drainage and irreversible changes in permafrost (Frauenfeld *et al.*, 2003). Our geophysical surveys (Milanovskiy *et al.*, 2008) were focused on:

I detection and location of inflow seepage near dams and areas adjacent to dams, detection and location of places of the most intensive permafrost thaw and seepage from the reservoir;
II investigation of talik geometry in the frozen mass;
III monitoring the dynamics of the progressive seepage in space and time.

TALIK THERMAL MODELLING

Talik can be formed in permeable soils, and spread over impermeable soils. Its intensity is mostly controlled by the freezing conditions; e.g. if the talik localized under riverbeds, the talik may change to part-permeable type. A specific feature of artesian (head) aquifers is the predominantly upward movement of pressure head in permeable zones (disjunctives, karsts zones in carbonates, fractured permeable zones in rocks). In the case of surface water basins, the pressure headwaters are constrained by the frozen dam with a set of engineering buildings, and including a by-pass channel (spillway) with waterway. This channel often has the role of a permanently-acting heat source in relation to the permafrost adjoining it. It is also possible to guess the presence of fractured water-saturated frozen rock strata (e.g. limestone) the rocks flanking the basin. Under frozen conditions the rocks are impermeable. Under thawing conditions, these strata may potentially become permeable, allowing filtration.

Problem definition

The non-steady problem of heat-mass transfer in a fractured-porous saturated frozen Stratum (II), interbedded in frozen impermeable adjacent strata (I, III) is discussed assuming a pressure head in an aquifer, explaining thawing in the saturated Stratum (II) and considering seasonal variations of temperatures of air and aquifer (Fig. 1)

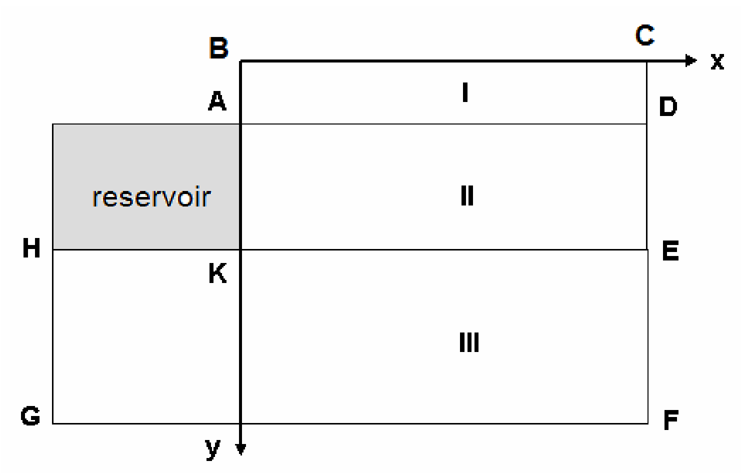

Fig. 1 Schematic geometry of the model.

The following assumptions for simplification of the pattern were made: strata I and III are dry, impermeable, rigid, homogeneous and isotropic, with conductive heat transfer only. It is supposed, that in Stratum II the matrix and fluid (ice) are in a temperature balance (local temperatures of the matrix and fluid are equal at any time), the fluid and matrix are incompressible, the only cause of filtration is water-head pressure, and vertical mass-transfer is neglected whereas the horizontal fluid flow is considered as stationary and incompressible.

Taking into consideration the above-mentioned limitations, the problem can be formulated by a general two-dimensional equation of energy:

$$\left(\rho_m c_{pm} + L_w \Theta \frac{\partial \Theta_u}{\partial T}\right)\frac{\partial T}{\partial t} + \rho_w c_{pw} V_x \frac{\partial T}{\partial x} = \lambda_m \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{1}$$

where ρ, c_p and λ are density, heat capacity and thermal conductivity, respectively (the subscripts m and w refer solid matrix and fluid, respectively), V_x is the Darcy velocity component:

$$V_x = -K \frac{\mathrm{d}H}{\mathrm{d}x} \tag{2}$$

where K is the coefficient of water permeability and H is water head in a saturated layer. Following the limitations described above, the equation of continuity will be written in the form:

$$\frac{\partial V_x}{\partial x} = 0 \tag{3}$$

The term $L_w \Theta(\partial \Theta_u / \partial T)$ on the left of equation (1) describes a heat quantity generated or absorbed by the media at variation of its temperature on ∂T as a result of phase change. Here L_w is the latent heat of melting of ice, Θ is the volumetric content of fluid in soil, and $(\partial \Theta_u / \partial T)$ is variation of the non-frozen water content with temperature variation of the medium (Fig. 2) Newman, (1996).

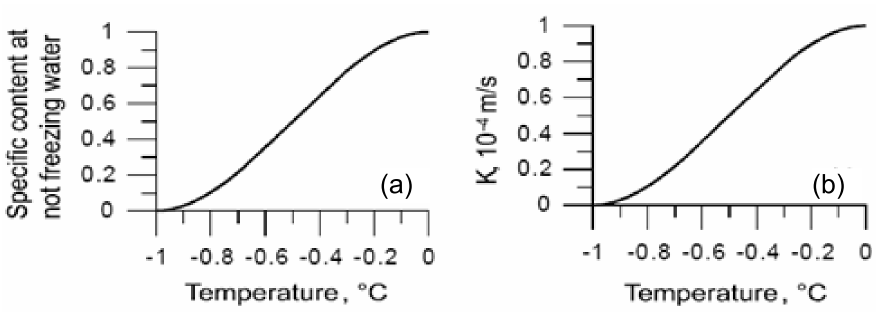

Fig. 2 Variation of the specific contents of non-frozen water (a) and coefficient of permeability K, 10^{-4} m/s (b) as a function of temperature in a zone of phase transfer (–1°C up to 0°C).

Thus, it is possible to prevent numerical instabilities and take into account the fact, that the phase change takes place not instantaneously, but in certain temperature range (in our case from –1°C to 0°C). In strata I and III, the equation (1) can be reduced to a simpler form:

$$\rho_m c_{pm} \frac{\partial T}{\partial t} = \lambda_m \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where values of density, heat capacity and thermal conductivity correspond to the physical properties of strata I and III.

As seen in Table 1, for Stratum II the heightened thermal conductivity relative to the adjacent strata is accepted. Such a stratum can be for example, a layer of fractured limestone or dolomite. Its substrate is the impermeable layer III (clay materials), with thermal properties identical to layer I (loams and other impermeable rocks are typical in the upper part of cross-sections). The

Table 1 Values of some physical parameters used in calculations.

	Thickness (m)	$\rho_m c_{pm}$ (MJ/m^3/K)	λ_m (W/m/K)	K (m/s)
Stratum I	5	1.49	1	0
Stratum II, frozen	10	1.96	3.5	0
Stratum II, thawed	10	2.52	3	10^{-4}
Stratum III	60	1.49	1	0

impermeable layer III underlies permeable Stratum II, bounding the lower level of filtration. Note that the permeability coefficient K of a Stratum II is equal to zero at temperatures below –1°C and gradually increases to magnitude 10^{-4} within the temperature range –1°C to 0°C. Therefore, if at the boundary D–E of Stratum II in a cold season the temperature drops below –1°C, which results, in theory, in impermeability there.

Initial and boundary conditions

At the surfaces (A–B, B–C, C–D, D–E and E–F in Fig. 1) we used the following expression for temperature, T_a (°C); equation (5) describes observed data well and is consistent with theoretical estimations by Shipitcina (1983):

$$T_a = -2^\circ + 17\sin\left(\frac{2\pi}{8760}t_h\right) \tag{5}$$

where t_h is time in hours.

The temperature of an aquifer T_w (°C) at the boundary A–K (Fig. 1) characterizes seasonal fluctuations, related to summer warming, winter cooling, the influencing of cold flood water and periods of rainfall, during which there is active mixing of water in the aquifer resulting in levelling of temperature with depth. A similar seasonal distribution of temperature with depth in an aquifer of a permafrost zone in Canada is given by Lai Yuanming *et al.* (2002). Here the seasonal temperature distribution (T_w) in water storage was described by the expression:

$$T_w = 5^\circ + \left(2.5 + 7.5\sin\left(\frac{2\pi}{8760}t_h\right)\right)\cdot\exp\left(-\frac{h}{2}\right) \tag{6}$$

where h is depth from the surface of a basin in metres and t_h is time in hours. As apparent from expression (6), temperature at a surface of an aquifer has seasonal fluctuations from 0°C to +15°C, which decreases with depth. The boundaries F–G, G–H, H–K are at constant temperature –3°C. It is necessary to note that both the initial value of temperature of the system, and the value of temperature on boundary F–G–H–K do not essentially influence the results. In a numerical experiment for initial and boundary conditions, at the lower boundaries various values down to –10°C were used. Despite that the talik evolution was similar, although this process evolved over the time. It demonstrates that for talik origination, the thermal properties and the geometry of the upper layer are key. At boundaries A–D and K–E the condition of continuity of heat flow (amount of heat input equals heat output) is assumed. A constant water layer in the water storage basin was assumed. Actually it has considerable oscillations, related to natural (flood, high water, rains) and technological (discharge water, off take, water exchange) reasons. An example of seasonal level variations for water storage in northern Quebec is presented by Lai Yuanming *et al.* (2002) that basically can be taken into account in the given formulation by input of a function of head H (t). In our case it was accepted that the drop of levels over Stratum II was fixed and equal to 10 m (base of Stratum II coincides with the bottom of water storage). Initially the system (including layer II) was at –3°C; later on there is an instantaneous infill of the aquifer with temperature T_w, and then the system moves to thermodynamic equilibrium.

To solve the problem, the finite difference approach was applied. The explicit scheme with accuracy $O(h^2 + \tau)$, where h and τ are steps in space and time. The stability was defined by the Courant condition.

RESULTS

We delivered a problem of determination of the conditions of talik origination, and also estimation of the dynamics of progress of a thawed zone in a permeable pressure head layer adjoining an aquifer. The results visually illustrating the process of origination and progress of the talik front were obtained and also the basic factors causing its initiation, were determined. The results show that the process of thermal evolution of frozen strata can conditionally be divided into two basic and two transient stages (Fig. 3). The first stage starts from the moment of infill of the water storage and represents installation of thermodynamic equilibrium in the absence of convection.

Rather quickly, in 2–3 years, a settled quasi-state conductive heat regime develops (Fig. 3), in which seasonal variations of surface temperature quickly decay with depth according to Fourier law, and the summer fire-setting boundary (thawing) migrates a little deeper each summer season.

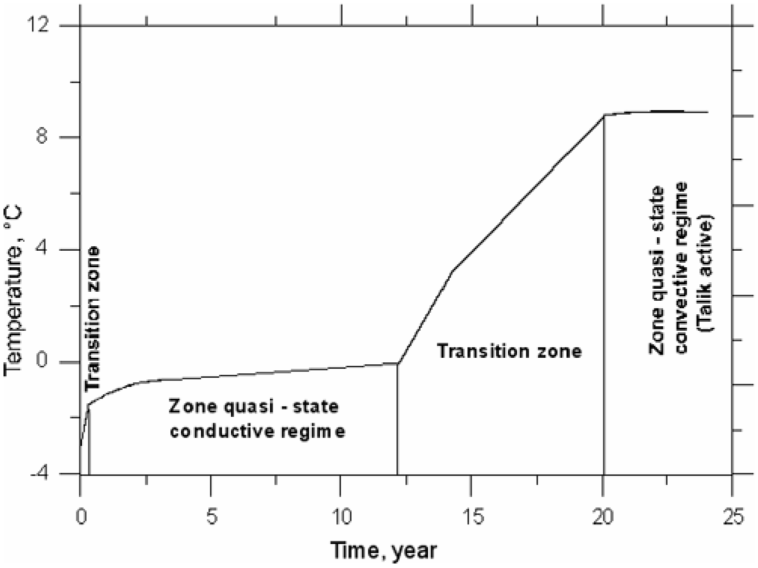

Fig. 3 Variation of seasonal T-maximum at the reference-point situated in the middle of the top of the permeable zone (talik zone) with time. (A–D length on Fig. 1 was 50 m).

Figure 3 shows that for 2–12 years the maximum seasonal temperature of a reference point at the top of the layer (middle of A–D) of Stratum II stays in the limits –1°C to 0°C, i.e. within the temperature limits when the ice filling in pores starts to thaw and the permeability of the environment becomes higher than zero. In this case, water pressure head can produce an advective (convective) heat-mass transfer, which is much more effective than conductive transfer. This is a key factor in our model of talik origination. In this case, the main parameters of a Stratum I – its thickness and thermal diffusivity – and also the average annual temperature of a near-surface stratum are extremely important. According to our numerical experiment, a lowering of average annual temperature of only 2°C results in no talik development at the given thickness of Stratum I. This leads us to the conclusion that for applied problems the basic critical (extreme) thermal and geometric parameters of the environment can be determined by solving a 1-D non-steady problem of heat-mass transfer in half-space with periodic perturbations of temperature on a surface (Turcotte & Schubert, 2002). A lot of complicated models exist for Stratum I, including phase transition for different degrees of water saturation of the ground. We used the simplest model which permitted us to obtain the principal estimations.

The duration of the transient period between the conductive and convective regimes of a system (Fig. 3) depends mainly on the temperature of water in the water storage, permeability coefficient of the thawed rocks and hydro-head. As expected, the frontal movement of talik takes place primarily during summer (warm) months and at first, primarily in the upper zone of Stratum II. Heated water very effectively transfers heat and results in fast talik progress. Over 3–4 summer seasons, the talik starts to occupy all of saturated Stratum II. Then, in quite a short time the system reaches a quasi-state regime with convective heat-transfer dominating. As mentioned above, in a cold period filtration is "locked" in the model; this follows from the *K* (permeability) value of Stratum II, which equals zero if temperature is lower than –1°C. Actually, filtration may occur in local zones of fractures, which remain permeable even in a cold winter period. This circumstance was taken into account hereinafter to construct a more advanced model that involves the special conditions of permeability at the boundary D–E. This model includes: (a) open crack(s) at the D–E boundary of limited length (5 m) penetrating into the frozen/thawed mass (Stratum II), or (b) the presence of a through-mass narrow permeable channel (crack) in frozen Stratum II. We can observe both special cases. For case (a), after forming a thawed zone we shall have year-round filtration without the winter freezing "lock" in the layer. For case (b), talik development for winter periods with a pre-existing transparent crack in the basement of Stratum II; the filtration process runs much faster. An interesting case is the "domino" or "puff cake" model, including more than one layer with Stratum II properties. If we have an existing water head in the "domino" model the thawing process runs deep into the frozen mass due to a combination of conductive and convective heating. We have also made long-term field observations of the thermal regime and radiowave monitoring of effective electric resistance and relative dielectric transmissivity inside forming talik zone on the shores of Sitikan Reservoir. (Milanovskiy *et al.*, 2008) These data are consistent with these modelling results and illustrate the evolution of the thaw–freeze process in time.

DISCUSSIONS AND CONCLUSIONS

We have carried out numerical modelling of the origination and development of talik in stratified media. According the modelling results, the maximum depth of a zero isotherm in relation to the top of the Stratum II is a key point for talik origination. It is noticeable that the dynamics of heating of the thawed zone is essentially controlled by the permeability coefficient (which depends on properties of the rock matrix) and its temperature (phase state of water). The most effective means to control the progress of filtration (seepage) could be artificial decrease of the permeability coefficient of the saturated layer. This can be obtained by a forced temperature drop in the environment (freezing), or by mechanical reduction of the permeability of the matrix at the boundary A–K using fine-grained clay material, piling with impermeable shields on the infiltration zone of Stratum II, or using special cryogenic liquids – cryogels based on polymer solutions with electrolytes addition. It seems that the second approach is most effective for several reasons: first, cooling a high-permeability pressure head layer needs much of energy, and secondly, the maintenance of strata in the frozen state will require incessant energy consumption. The second approach solves the problem at the diverse quality level and requires much less energy expense compared with freezing. Geophysical data show the non-uniform types (morphology) of talik zones (Milanovskiy *et al.*, 2008); however, it has a common characteristic feature – the presence of a triggering mechanism for talik initialization. For realization of this mechanism we need to know the pre-talik temperature history (for example – put global or regional temperature warming trends into the model), leading to preheating of the strata, existing fracture or pore channels (partly-open or ice cemented) and water head from reservoir. An important factor for the stability of long-existing constructions like hydro units or waste burial in permafrost zones is global climate change. The proposed simple model can be used for more complex situations. We can imagine a situation of similar geometry with alternation of thinner layers with physical properties of Stratum I and Stratum II instead of layer II with water head existing at the layer's boundary. In this case, development of seepage in Stratum II.1 will heat Stratum I.2 and then the domino effect will provide seepage in lower Stratum II.2 until the water head and thermal conditions permit. The real problem is essentially three-dimensional.

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