Modeling of accidental leaks from utility lines during calculation of the temperature regime of permafrost soil bases of buildings

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Abstract. Article presents technique for numerical calculation of temperature regime of the buildings on permafrost soils with consideration of thermal effects of leakage from utilities. Enthalpic model of heat exchange is used.

1. Article
Accidental leaks from utilities are significant and problematic to predict factor that forms the temperature regime of soil bases of buildings structures in the conditions of permafrost soils. Thermal effects caused by such accidents on thermal stress-strain state of soil bases negatively affects operational reliability of structures built on permafrost. According to the Federal state statistics service in the Republic of Sakha (Yakutia) there is a high proportion of damaged buildings, whose share in 2016, amounted for 16.5% of the total number of permanent buildings erected on the territory of the Republic [1,2,3,4,5,6]. The main reason behind this situation is systematic crash of utilities, including new residential construction, which, unfortunately, is impossible to predict and even prevent the for the entire life cycle of buildings and, especially, during operation and reconstruction of dilapidated buildings.

At the present time, strictly speaking, there are no common standards even for high-quality classified assessment for risks, reliability and durability of buildings and structures, especially for the ones designed and operated in the regions with permafrost (cryolithozone) for different types of leaks (hot and cold water, sewage, various oil products and liquid wastes from chemical and mining industries and the like).

The situation is aggravated by the trend of last 50-60 years for the climate warming of the planet. Together with anthropogenic factors and, first and foremost, with accidental releases from heating networks and sewage systems, modern climate situation contributes to the degradation of permafrost strata in general and in built up areas especially. [7,8,9,10,11,12,13,14] Given that the bearing capacity of permafrost soils, is mainly depends on the temperature regime of soils, it has become a relevant task to predict the temperature regime of the soil under the influence of various factors of natural and technogenic origin.
Specificity of temperature fields calculation at the base of the building in permafrost conditions is determined by the fact that in the mass of frozen soil with temperature distribution from "+" to "," a non-stationary section front of thawed and frozen zones is formed. The main difficulty in calculation of thermal phase change problems is to account for changes in thermal characteristics depending on temperature. To simplify calculation of this type of tasks Dusenberg (1958) and Baxter (1962) proposed a method, which is called "enthalpy – flow temperature". In this case, the solution uses Goodman substitution (enthalpy)

$$H(T) = \int_{T_0}^{T} c \, dT$$  \hspace{1cm} (1)

And Kirchhoff substitution (thermal flow)

$$\Phi(T) = \int_{T_0}^{T} \lambda \, dT$$ \hspace{1cm} (2)

Then nonlinear differential equation takes the following form

$$\frac{dH}{dT} = \frac{d^2 \Phi}{dT^2}$$ \hspace{1cm} (3)

Latent heat of phase transitions is not accounted by Stephen's condition, and introduction of the generalized heat capacity $C(T)$ which tend to infinity at the temperature of phase transitions.

Enthalpy approach allows to exclude the need to define the position of the phase boundary from calculation. This gives you the opportunity to obtain a continuous solution and to consider frozen and thawed zones as one area, which greatly simplifies the calculation of the problem by numerical methods.

Several models for enthalpy of soils are developed and tested at the present time, they suggest different dependencies of heat capacity, thermal conductivity coefficient, enthalpy and thermal heat flow of soil from its temperature. Closest to modern ideas about the freezing-thawing processes of permafrost soils is the enthalpy model by Kronik [15,16] which suggests that there are four main areas:

1 area of melt and supercooled soil
2 freezing area (thawing) of the free pore water or the area of the maximum of phase transitions,
3 freezing area (thawing) of the bound pore water,
4 area practically frozen soil.
Unlike enthalpy models of other authors in the model by Kronik characteristic temperatures of soil, and, namely, the temperature of beginning of freezing of free and bound water and the temperature of practically frozen soil are not constant, but in the general case are variables that depend on the type of soil, its state of humidity, density, applied pressure, concentration of the pore solution and the speed of freezing.

Numerical value of enthalpy is proposed to be calculated by four allocated areas according to the following formulas:

\[ H_1 = \int_{T_{bf}+273}^{T_{th}+273} C_{ef}(T) dT + H_2 \]  
\[ H_2 = \int_{T_{bf}+273}^{T_{th}+273} C_{ef}(T) dT + H_3 \]  
\[ H_3 = H_4 + C_f(T_{bfw} + T_f) + \frac{(C_{th}+C_f(T_f-T_{th}))^2}{2(T_{bf}-T_f)} + \rho * \gamma_{df} \int_{T_{bfw}+273}^{T_{th}+273} \frac{dw}{dT} \partial T \]  
\[ H_4 = \int_{0}^{T_f+273} C_f * dT + C_f(T_{th} + 273) \]

To calculate the problem of non-stationary thermal regime of permafrost soil base, with consideration of heterogeneity of soil and phase transition we adopt enthalpic thermomechanical model by Kronik, as being the most appropriate formulation, that takes into account physical nature of the freezing - thawing processes of the soil.

Basic design diagram is shown in figure 2. This diagram allows to account for the thermal effect of a buried collector and surface-laid heating network from the collector to the building.

**Figure 2.** Design diagram for the calculation of the temperature regime of permafrost soils in the base of the building (marked number 3) that was built according to the 1-st principle with consideration of buried collector (marked number 1 on the diagram) and heating line of the surface laid heating network (marked number 2).
To assign the calculation start time we will use Feldman G. M. recommendations. [17], according to which it is advisable to start the calculations from the period in which the initial thermal state of the ground layer of annual temperature fluctuations, on the one hand, to a lesser extent depends on the previous period, and on the other hand, to a lesser extent, affects on the next period. This corresponds to late winter or late summer.

The choice of the finite-difference mesh is determined primarily by the physical requirements of the task. In this regard, at the edges of the computational domain finer mesh is used, to reduce the influence of systematic errors on the temperature distribution in the inner part of the domain. In the locations of the local heat sources and in areas where more detailed examination of the temperature field is needed, finer finite-difference mesh is also used. The nodes of the finite-difference mesh should not lie directly on the borders of areas with different thermal characteristics, as otherwise difficulties occur to specify the design characteristics in these nodes.

To determine the optimal dimensions of calculated soil body, a number of methodical problems were set and solved. The height of the computational domain is determined not only by the design of the underground part of the foundations of the building and by the depth of underground utilities, but also by the influence of boundary conditions specified at the lower boundary of the domain.

Thus, combinations of one-dimensional heat conduction problem with estimated heights of 15 and 30 meters were calculated. In the first option (15 m) temperature field is obtained, in which the upper boundary of the area of zero annual amplitude is at a depth of 14 m. In the second option (30 m) same indicator is at 11.5 ... 12.0 m, which is closer to the data of field observations. In addition, as shown by field observations, thermal influence of leaks has an effect on the changes in temperature of the soil to a depth of over 15 meters. In the calculation of the temperature field at a depth of 30 meters by the end of year 4, forecast of temperature changes in the lower 2...3 layers of finite-difference mesh (spacing of 1-2 m) is not observed with all considered changes of boundary conditions at the upper boundary of the body.

The width of the computational domain was selected in such a way that the thermal influence of the buried collector did not influence the formation of the temperature regime of the outermost areas with a width of 7 ... 10 meters. This condition is true for collector buried 2.5 m into the ground at a distance from the edge of the canal of the collector to the boundary of the considered area at least 30 m, which corresponds to approximately one half-length of the building. This way, the total length of the computational domain it is recommended to be set equal to (2.5 ... 3.0) B, in cases when formulation of the problem requires consideration of heat influence from the buried collector.

To predict temperature regime of a soil base of the building in interaction with the environment in climatic conditions of the Far North it is required, first and foremost, to obtain exact characteristics of all climatic and thermal effects. External environment, surrounding the calculated area consists of atmosphere, with its climatic characteristics and part of the soil body immediately adjacent to the soil base, characterized in northern conditions by permafrost state and complicated geological, cryogenic and thermo-mechanical processes.

The main climatic and geocryological characteristics of the external environment on the calculated soil body are the following:

- The average temperature of external air;
- The temperature of the permafrost soil base at the depth of zero amplitude and temperature distribution along the depth of the base in a natural state before the construction of the structures;
- Characteristics and boundaries of permafrost grounds in area and depth;
- The amount of precipitations (rain or snow) and their distribution during the year, to account for in calculations, for example as thermal insulation during winter;
- The temperature and duration of water leakage from utilities, heating systems and buildings.

Calculated thermophysical characteristics of the soil base are taken based on engineering-geological surveys. When calculating thermal regime at the base of the building with a ventilated
basement temperature value on the surface of the soil under the building is set with a decreasing coefficient of 0.93 in accordance with the recommendations of Building Codes. The temperatures at the surface of contact of soil with the surface-laid heating network and with deep laying collector are set according to the results of field observations and available experience of operation of buildings in permafrost area.

In addition to the above-mentioned natural effects, calculations should take into account man-made effects caused by technological factors during the construction and operation of the facility. One of the most important man-made factor that impacts soil base is the thermal pulse from water leakage from utilities and heating systems.

Two-dimensional problem of Stefan type was set and solved with phase transition to the enthalpic formulation with thermal conductivity to develop methods of calculation of non-stationary thermal regime of permafrost soil base with consideration of thermal effect of leakage. Influence of the leakage is modeled by the combinations of the local point-like and linear discontinuous heat sources causing at the time of application of the heat load almost instantaneous temperature change on the surface of the soil at the point or plot of effect on the temperature of the water coming out of a building or water supply. Design characteristics of these heat sources, i.e. the geometric dimensions, temperatures, start time, and duration of exposure are taken respectively to the simulated leaks.

In the proposed engineering methodology the impact of the leak is modeled by the combinations of local (point-like) and linear discontinuous heat sources causing, at the time of application of the thermal load, instantaneous temperature change on the surface of the soil at the point or at the site of impact on the temperature of the water coming out of the building or utilities with respect to the model of buildings series 664BM with a corridor system and communications under the floor of the corridor on the first floor along the longitudinal axis of the building.

In contrast to the similar problems with no consideration of thermal effects from leaks, in formulation of mathematical problem with accounting for this effects, we add following boundary condition on the surface where the leak appears

\[ T(x,y,t) = T_{\text{const}} \]  

(8)

For the initial temperature field, based on which thermal calculations with consideration of leakage are done, we apply quasi-stationary temperature distribution obtained from calculation of the task for the year 10 of simulated operation.

To develop criteria for a standardized approach to the use of the proposed method, author jointly with Kronik [18,19,20] proposed following unified classification of emergency leaks, mostly from systems of utilities (water and wastewater), compiled on the basis of analysis and synthesis of many years of field observations and studies (monitoring).

Unified classification accidental water leaks:
1 – on the time of effect
   1.1 short term leaks up to 3...4 days;
   1.2 temporary – 5...20 days;
   1.3 long term – more than 20 days.
2 – on the season of effect:
   2.1 winter;
   2.2 summer.
3 – on location of the leak:
   3.1 directly under the building, including:
      3.1.a in proximity of the contour of the building;
      3.1.b under the central (axial) part (under the corridor-laid communications);
      3.1.c between sectional and panel seams;
   3.2 close to the building, outside the contour;
   3.3 combined.
4 – on the shape of the area:
   4.1 point-like;
4.2 linear (extended);
4.3 zonal, including
   4.3.a local - less than 25% of the area of the building;
   4.3.b extensive - more than 25% of the area of the building
5 – on the temperature of water:
   5.1 low-temperature – with water temperature below 5 °C
   5.2 high temperature - with water temperature of 5...50 °C;
   5.3 hot – water temperature above 50 °C
6 – on intensity (water consumption in l/h at 1 linear meter for linear and point-like leaks or 1 m2 for the aerial leaks):
   6.1 weak – up to 20 l/h;
   6.2 medium intensity – 20...200 l/h;
   6.3 strong – over 200 l/h.
7 – on the chemical composition:
   7.1 non-saline with concentration Ku less than 3%
   7.2 slightly saline with concentration of Ku over 3%:
       7.2.1 slightly saline – Ku=3...10%;
       7.2.2 saline – Ku=10...20%;
       7.2.3 strongly saline – Ku more than 20%.
   7.3 saturated and oversaturated brines from Ku more than saturation concentration of at least one of the chemical components of the brine.
8 – on biological safety:
   8.1 safe;
   8.2 biologically active and dangerous;
   8.3 hazardous, toxic and radioactive.

Criteria for classification and grading of accidental leaks are selected factors that have a significant effect on the change in the temperature regime of frozen soil base of buildings and structures. The main task of the development of the classification is the possibility for rapid implementation of a qualitative assessment of the potential impact of the accidental leakage of water from the communications and urgent action within the scheduled or emergency activities of monitoring the condition of the structure's soil base and adoption of measures to eliminate accidents and to ensure safety of interconnected system "soil base-structure-environment".[21,22]

For easy comparison of the results obtained at the initial stage, it determined that for the conducted series of calculations, temperature of the water leaks within a thermal effect (heat stamp) \( E_{\text{leak}} = +20.0 \, ^\circ\text{C} \), and the duration of its impact the test body is 20 days.

![Figure 3. Calculations of the impact of accidental leakage on the formation of temperature regime of the frozen base of the building built by the I-st principle.](image)
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Figure 3 shows isolines of equal temperatures obtained at the time of removing of heat load from leakage on 17, 50 and 150 days after the elimination of accidental leakage. Gray shaded is the area in the circuit of which temperatures has changed. Numerical calculation results has received sufficient confirmation when comparing them with in situ observations. As you can see the heat impact of test leakage affects the temperature distribution of frozen soil to a depth of up to 9 meters, while after 150 days residual effect is manifested to a depth of 5 meters directly below the edge of the building at the place of application of the heat load from leaking. Intensive restoration of the initial temperature regime due to the natural cold is prevented by "warm curtain" produced by the surface-laid heating systems, which not only forms a local zone with higher temperatures, but also forms local melting cup in piping location.

Given that in this place thermal influence is also caused by surface-laid heating system and buried collector, the projected loss of bearing capacity of piled foundations according to calculations will range from 20 to 36% depending on duration and intensity of the accidental leak and the time of year. In addition, ensuring stability of the piled foundations to the effects of frost heaving gets significantly complicated in the area of effect of the leak.

2. Conclusions

Method to account for the local temporal thermal effects of accidental leaks when calculating temperature regime of permafrost soil bases of the buildings is given. This method of temperature calculations is recommended for wide introduction in practice of design and, especially, for the express analysis of damaged buildings in permafrost area for assessment of accident causes.

Using proposed method it is advised to assess the situation on the actual condition of the buildings located on permafrost with regard to the effects of leakage on the background of climate warming, to develop technical recommendations and practical measures to timely stabilize the temperature and stress-strain state of the buildings and ensure their operational reliability.

In accordance with the requirements of safe operation of buildings and structures unified classification of accidental leaks of water from engineering communications according to the degree of influence on the formation of temperature regime and thermal stress-strain state of permafrost soil bases of buildings, which allows numerical prediction of the temperature regime of the buildings on permafrost soils was developed.

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