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EVALUATION OF THE EFFECTIVENESS OF RING THERMAL INSULATION FOR PROTECTING A PIPELINE FROM THE HEAVING SOIL

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Abstract

Areas with heaving soil are one of the most complex hindrance for the design and construction of underground pipelines. Inhomogeneity of the geological structure of the base leads to irregular uplifts of soil and pipelines. At least these processes reduce the actual service life. In the worst case, frost heave can cause emergency depressurization, oil or oil products spill and natural gas emission 'into the atmosphere. At the present time, a quantitative evaluation of the of frost heaving dynamic and designing of the protection systems has low accuracy that is confirmed by a numerous accidents occurring on the pipelines every year. To investigate the interaction of pipelines with the heaving soil and the engineering protection system the authors have developed and for the first time ever applied in practice a numerical investigation procedure that allows calculating the stress-strain state of a pipeline taking into account the dynamics of heat and mass transfer and stress-strain state of the soil. The results of the article show the boundaries of applicability of ring thermal insulation for the pipeline in concrete geological conditions. Additionally it was found that in the short sections of frost heaving (length about 3 m) additional stresses from bending are 2.2 times more than in long sections (length 20 m and more). Since the exact location of heaving soil boundary is usually unknown, engineering protection must overlay a dangerous area with a significant margin on both sides to exclude unprotected sections up to 3 m in length.

Keywords: Frost heaving, Heat and mass transfer in soil, Ring thermal insulation, Soil-water potential, Stress-strain state of pipeline.

1. Introduction

Pipelines in the northern regions of Russian Federation is built and operated in extreme climatic and geotechnical conditions, which is characterized by the low air temperatures, high groundwater level (often above the surface of the soil), bogginess and deep seasonal freezing in areas of local uplifts and saturation of areas during the spring and autumn floods [1, 2]. Combination of low air temperatures and high groundwater levels leads to the formation of local frost heaving zones. [3]. Frost heave is one of the most dangerous process for underground pipelines, which is due to the huge development effort acting tangentially and along the normal to the surface of the pipeline [4]. These efforts cause a change in the stress-strain state of the pipeline.

This process becomes more dangerous with a negative product temperature, because in this case, pipeline becomes a source of cold for the formation of frost heaving [5]. In addition to changing the stress-strain state, the high danger of frost heaving is associated with the smallness of the absolute values of deformations and the practical impossibility of their diagnosis in conditions of high snow cover and without a system of planned-high-altitude position monitoring, which is a rarity for existing pipeline systems [6]. At the present time, a quantitative evaluation of the of frost heaving dynamic and designing of the protection systems has low accuracy, that is confirmed by a numerous accidents occurring on the pipelines every year [4]. Therefore, it is necessary to improve the methods of calculation.

Frost heave is a process that is being studied for many decades. The first significant results of the research are contained in the works of the Russian scientist Stukenberger [7]. Since, the approaches to studying have changed significantly. Kiselev [8] developed a method for calculating foundations on the heaving soil, which is now mandatory for the design of foundations in the Russian Federation. However, the freezing conditions around the pipeline and the shallow foundation are significantly different for known reasons. Yuryevich [9] developed the methodology for calculating stress-strain state of a pipeline on heaving soils. However, this methodology did not take into account the stress-strain state of the soil around the pipeline, which is continuously changing in time and space. The authors is eliminated this absence.

The cheapest way to protect pipelines from frost heaving is a ring thermal insulation that levels the surface temperature of a pipeline and soil. However, the insulation has a limited thickness [10]. Therefore, if the product temperature is significantly lowered, it is necessary to evaluate the possible irregular deformations of the pipeline and stress-strain state.

In this article, the authors solved the following problems:

- Evaluation of frost heaving forces taking into account heat and mass transfer and stress-strain state of the soil and vertical displacements of the pipeline depending on the temperature of the product and the thickness of the ring thermal insulation ;
- Evaluation of the stress-strain state of the pipeline, depending on the length of the frost heaving area, product temperatures and the thickness of the thermal insulation.

2. Material and Methods

To calculate the stress-strain state of pipelines, the authors used numerical. This problem was solved by authors consistently in three stages:

Stage I «Heat and mass transfer problem». Bulk frost heaving of soil was calculated at this stage. The calculation scheme is shown on Fig. 1.

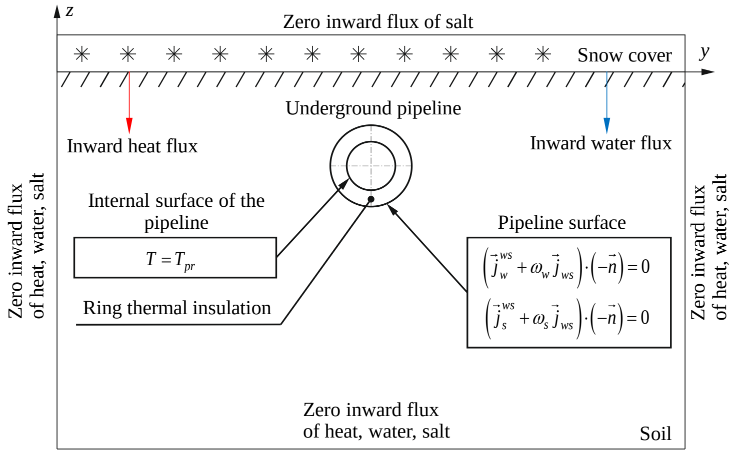

Fig. 1. The design scheme for determining the spatial distribution of the increase in the volume of soil in the case of frost heaving.

The calculations were performed on the basis of a heat and mass transfer mathematical model, which is described in details in [11-13]. Basic assumptions of the mathematical model:

i. The transport of substances in the gaseous phase is insignificant, which is typical for the water-saturated heaving in Western Siberia;

ii. The intraporous water-salt solution remains electrically neutral at any time, i. e., the effects of Peltier and thermoelectric effect are small;

iii. The value of the dissipative terms is not large, which is due to low velocities of motion;

iv. The motion of a fluid is described by quasi-stationary equations (for example, Darcy's law);

v. Crystallization of ice and salt occurs through the phase of metastable states and is described by the equations of chemical reaction of the first order [14].

vi. The solution is binary, i.e., the combined transfer of salts is considered.

vii. The solution moves under the action of the gradients of the soil-water potential and gravity. The components of the solution diffuse according to Fick's law.

viii. When the intraporous space is fully filled and there is no drain, the solution remains immobile. The gradient of hydrostatic pressure balances the force of gravity. It was taken into account in the equations by means of a factor (1-*hav(εV))*, which nullifies the force of gravity when the volume of intraporous substances exceeds the pore volume.

Below authors showed the basic equations of the mathematical model of heat and mass transfer. Equation (1) describes conductive and convictive heat transfer taking into account phase transitions of water and dissolved salt. The unknown value is the temperature *T*:

$$\left(\wp_{sk}c_p^{sk}+\wp_w c_p^w+\wp_{ice}c_p^{ice}+\wp_s c_p^s+\wp_{ns}c_p^{ns}\right)\frac{\partial T}{\partial t}=$$

$$=\nabla\cdot\left(\lambda_T\vec{\nabla}T\right)+L_s\frac{\partial\wp_{ns}}{\partial t}-\left\{\vec{j}_w^{\,ws}\left(c_p^w-c_p^s\right)+\vec{j}_{ws}\left(\omega_w c_p^w+\omega_s c_p^s\right)\right\}\vec{\nabla}T+$$

$$+\left(L_w+\left(c_p^w-c_p^{ice}\right)\left(T-T_{wi}\right)\right)\frac{\partial\wp_{ice}}{\partial t}. \quad (1)$$

Equation (2) describes the convective and diffusive transport of water in thawed and frozen ground in a saturated and unsaturated zone, taking into account diffusion and phase transitions. This equation is written in the form when the unknown value is the soil-water potential ψ_w:

$$\frac{\partial\wp_w}{\partial\psi_w}\frac{\partial\psi_w}{\partial t}=\nabla\cdot\left(-D_{ws}\wp_{ws}\vec{\nabla}\omega_s\right)-\frac{\partial\wp_{ice}}{\partial t}+$$

$$+\nabla\cdot\left(\frac{\omega_w\lambda_P}{g}\left(\rho_w\vec{\nabla}\psi_w-\rho_{ws}\left(1-hav\left(\varepsilon_V\right)\right)\vec{g}\right)\right)\cdot \quad (2)$$

Equation (3) describes the convective and diffusion salt transfer analogously to Eq. (2), but is written in a form where the unknown value is salt concentration ω_w:

$$\left(\frac{\wp_s+\wp_w}{\omega_w}\right)\frac{\partial\omega_s}{\partial t}=-\frac{\omega_s}{\omega_w}\left(\frac{\partial\wp_w}{\partial\psi_w}\right)\frac{\partial\psi_w}{\partial t}+\nabla\cdot\left(D_{ws}\wp_{ws}\vec{\nabla}\omega_s\right)-\frac{\partial\wp_{ns}}{\partial t}+$$

$$+\nabla\cdot\left(\frac{\omega_s\lambda_P}{g}\left(\rho_w\vec{\nabla}\psi_w-\rho_{ws}\left(1-hav\left(\varepsilon_V\right)\right)\vec{g}\right)\right)\cdot \quad (3)$$

Equation (4) describes the rate of the water-ice phase transition:

$$\frac{\partial\wp_{ice}}{\partial t}=\frac{\Omega_w-\Omega_{ice}}{\tau_{\Omega1}}hav\left(\Omega_w-\Omega_{ice}\right)\cdot hav\left(\wp_w\right)+\frac{\Omega_w-\Omega_{ice}}{\tau_{\Omega2}}\cdot$$

$$\cdot\left(1-hav\left(\Omega_w-\Omega_{ice}\right)\right)hav\left(\wp_{ice}\right). \quad (4)$$

Eq. (5) describes the rate of the phase transition: dissolved salt - undissolved salt:

$$\frac{\partial\wp_{ns}}{\partial t}=\frac{\wp_{ws}\left(\omega_s-\omega_s^{max}\right)}{\tau_{s1}}hav\left(\omega_s-\omega_s^{max}\right)\cdot hav\left(\wp_s\right)+\frac{\wp_{ws}\left(\omega_s-\omega_s^{max}\right)}{\tau_{s2}}\cdot$$

$$\cdot\left(1-hav\left(\omega_s-\omega_s^{max}\right)\right)hav\left(\wp_{ns}\right) \quad (5)$$

To solve the system of Eqs. (1) - (5), it is necessary to establish a connection between the integral conservation laws and the empirical laws of matter and energy transfer. Below authors showed the empirical laws.

The curve of the soil-water potential is described by the expressions [15]:

$$\psi_w=\psi_{ww}\left(\frac{\wp_{ww}}{\wp_w}\right)^{\gamma}; \quad (6)$$

$$\gamma = log_{\left(\frac{\wp_{ww}}{\wp_{wl}}\right)}\left(\frac{\psi_{wl}}{\psi_{ww}}\right). \tag{7}$$

The moisture conductivity in the thawed and frozen zone is described by the Maulem's formula [16] with taking into account the ice content [15]:

$$\lambda_P = \frac{\lambda_{P0}\left(\frac{\wp_w}{\wp_w^{max}}\right)^{2\gamma+2,5}}{\left(1+\frac{(e+1)\wp_{ice}}{e\rho_{ice}}+\frac{(e+1)\wp_{ns}}{e\rho_{ns}}\right)^2}. \tag{8}$$

The difference between the thermodynamic potentials of water and ice is described by the classical thermodynamic formula:

$$\Omega_w - \Omega_{ice} = \psi_w + \mu_w^c - \frac{L_w(T - T_{wi})}{T_{wi}} \tag{9}$$

The decrease in the chemical potential of water in a NaCl solution is described by the logarithmic dependence on the concentration:

$$\mu_w^c = \frac{RT}{M_w} ln(1 - f\omega_s). \tag{10}$$

Porosity ratio depends on the density of dry soil and the density of solid particles:

$$e = \frac{\rho_{s.p.} - \wp_{sk}}{\wp_{sk}}. \tag{11}$$

The thermal conductivity of the soil depends on the ice content in the soil:

$$\lambda_T = \frac{\lambda_T^{th}\wp_w}{\wp_w + \wp_{ice}} + \frac{\lambda_T^{fr}\wp_{ice}}{\wp_w + \wp_{ice}}. \tag{12}$$

The maximal concentration of *NaCl* in solution depends on the temperature:

$$\omega_s^{max} = \frac{(T-273)+5523}{21000}hav(T-273) + \frac{(T-252)+163.1}{700}hav(T-252)\cdot$$
$$\cdot(1 - hav(T-273)). \tag{13}$$

The convective flow of the water-salt solution is described by the following expression:

$$\vec{j}_{ws} = -\frac{\omega_w\lambda_P}{g}\left(\rho_w\vec{\nabla}\psi_w - \rho_{ws}(1 - hav(\varepsilon_V))\vec{g}\right). \tag{14}$$

The diffusion flow of water and the counter diffusion flow of salt are described by the classical Fick law:

$$\vec{j}_w^{ws} = -\vec{j}_s^{ws} = D_{ws}\wp_{ws}\vec{\nabla}\omega_s. \tag{15}$$

The heat flux through the soil is described by the classical Fourier law:

$$\vec{j}_q = \lambda_T\vec{\nabla}T. \tag{16}$$

The result of the solution of the system of Eq. (1) - (16) is the bulk frost heaving value:

$$\varepsilon_V = \frac{\wp_{ws}}{\rho_{ws}} + \frac{\wp_{ice}}{\rho_{ice}} + \frac{\wp_{ns}}{\rho_{ns}} - \frac{e}{e+1} . \quad (17)$$

To solve equations (1) - (17), an implicit finite differences method in the Cartesian coordinate system was used. The proof of the stability of the finite differences scheme is given in [17]. The boundary conditions on the surface of the soil correspond to the climate in the city of Urengoy (Russia). The pipeline has a diameter of 530 mm. The initial conditions correspond to the flood thawed soil with the temperature of +273.65 K at a depth of 20 m and the coincidence of the soil surface and the groundwater level. The calculations used soil characteristics corresponding to the average statistical clay loam in the region (Table 1).

Table 1. Characteristics of clay loam.

λ_{P0}	γ	$\wp_{ww}/\wp_w^{max}$	$\wp_{sk}$	ω_{sk}
1×10^{-7}	5	0.260	1450	0.00001
f	ρ_w	$\rho_s = \rho_{ns}$	c_p^w	c_p^{ice}
0.86	1000	2165	4190	2100
$c_p^s = c_p^{ns}$	T_{wi}	L_w	M_w	$\wp_{wl}$
870	273.15	3.3×10^5	0.018	258
$\wp_w^{max}$	$\wp_{ww}$	λ_{ins}	$\rho_{s.p.}$	ρ_{ice}
463	120	0.03	2700	917
τ_{s1}	τ_{s2}	$\tau_{\Omega 1}$	$\tau_{\Omega 2}$	D_{ws}
100	1×10^5	1×10^4	1	5×10^{-11}

The coefficients of thermal conductivity and heat capacity of the soil was calculated in accordance with the requirements in Russian requirements document SP 25.13330.2012 for foundations on permafrost soils.

Stage II "Stress-strain state of the soils". At this stage, the maximum forces and the maximum vertical displacement of the pipeline was calculated. The calculation scheme is shown in Fig. 2.

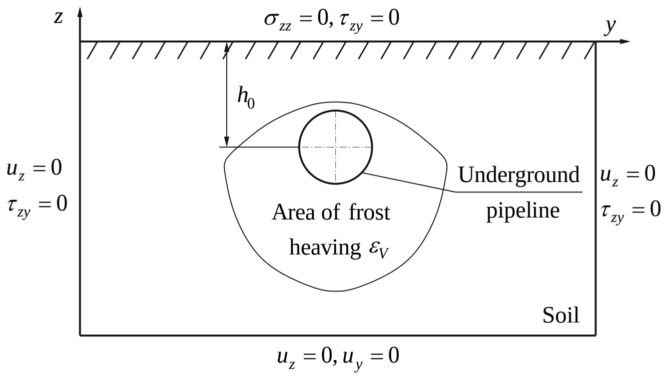

Fig. 1. Calculation scheme, for validation of linear-elastic material model.

Linear elastic material model was used for the calculations. A brief description of the model and evidence of the possibility of using it for frost heaving soils is given in [18]. The following equations were used as a generalized Hooke's law:

$$\varepsilon_{xx} = \frac{1}{E_{\text{soil}}}\left(\sigma_{xx} - \nu_{soil}\left(\sigma_{yy} + \sigma_{zz}\right)\right) + \frac{\varepsilon_V}{3}; \tag{18}$$

$$\varepsilon_{yy} = \frac{1}{E_{\text{soil}}}\left(\sigma_{yy} - \nu_{soil}\left(\sigma_{xx} + \sigma_{zz}\right)\right) + \frac{\varepsilon_V}{3}; \tag{19}$$

$$\varepsilon_{zz} = \frac{1}{E_{\text{soil}}}\left(\sigma_{zz} - \nu_{soil}\left(\sigma_{xx} + \sigma_{yy}\right)\right) + \frac{\varepsilon_V}{3}. \tag{20}$$

Two calculations of the stress-state were carried out at this stage:

i. The surface of the pipeline is free from fastening. It allows to find the maximum vertical displacement H_{max}.

ii. The surface of the pipeline is fixed in a stationary state. It allow to find the coefficient of soil reaction k_{fh}, acting on the pipeline from the side of the soils:

$$k_{fh} = \frac{D_{out}}{2H_{max}}\int_0^{2\pi}\left(\tau_{zx}cos\left(\vec{n},x\right) + \tau_{zy}cos\left(\vec{n},y\right) + \sigma_{zz}cos\left(\vec{n},z\right)\right)d\varphi. \tag{21}$$

Subgrade stiffness modulus was E_{soil}=10^7 Pa, Poisson ratio of soil was ν_{soil} = 0.35 u.f. in the calculation to corresponds to any type of soil (sand, sand clay, clay loam, clay) in the melted state [4] and frozen state [19]. Depth of pipeline axis was h_0=1.545 m. Stage III "Stress-strain state of the pipeline". At this stage, the stress-strain state of the pipeline is calculated. The calculation scheme is shown in Fig. 3.

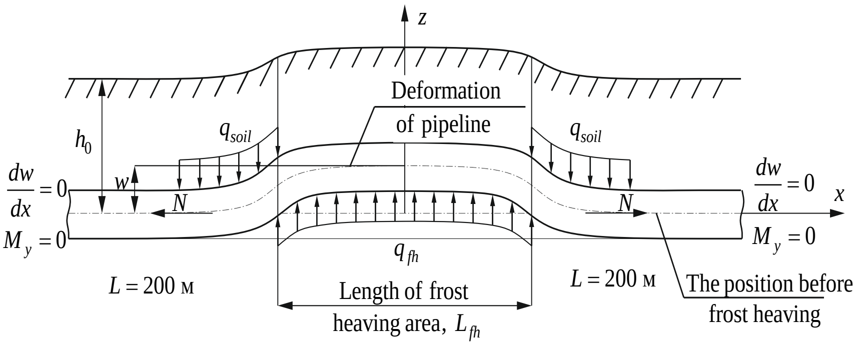

Fig. 2. Calculation scheme, for validation of pipeline stress-strain state.

The design scheme corresponds to a section of a straight underground pipeline, which is modeled as a beam on an elastic-plastic base:

$$\frac{E_{st}\pi\left(D_{out}^4 - D_{in}^4\right)}{64}\frac{\partial^4 w}{\partial x^4} - N\frac{\partial^2 w}{\partial x^2} = q; \tag{22}$$

$$N = \frac{\pi\left(D_{out}^4 - D_{in}^4\right)}{4}\left(\frac{2\nu_{st}P_{in}D_{out}^2}{D_{out}^2 - D_{in}^2} - \alpha_{st}E_{st}\Delta T + E_{st}\left(\sqrt{1+\left(\frac{dw}{dx}\right)^2} - 1\right)\right). \tag{23}$$

The pipeline is influenced by the longitudinal force N (that communicated with the temperature drop and the internal pressure) and the load from the frost heaving of the soils, which is calculated by the following expression:

$$q_{fh} = k_{fh}\left(H_{max} - w\right). \quad (24)$$

The length of the frost heave zone is selected in accordance with the geotechnical survey and the structure of the base.

The initial data for the calculations are given in Table 2.

Table 2. Initial data for stress-strain state calculating of the pipeline correspond to the main condensate pipeline in the Urengoy condensate field.

D_{out}	D_{in}	E_{st}	ν_{st}	α_{st}
0.53	0.5158	2.06×10^{11}	0.3	1.2×10^{-5}
ρ_{st}	R_{st}	ΔT	P_{in}	ρ_{pr}
7850	371·106	30	6.3×10^{-6}	750
h_0	E_{soil}	ν_{soil}	ρ_{soil}	η_{bf}
1.545	107	0.35	2000	0.3
c_{soil}	φ_{soil}	ρ_{ins}		
2000	16	40		

The adjacent nonfrost-susceptible soil resists upwards vertical moving of the pipeline and creates force q_{soil}, which calculates by the technics given in [20, 21]. The length of nonfrost-susceptible soil is 200 m provides the reduction of edge effects in the design scheme to negligible values.

3. Results and Discussion

The product temperature was assumed [-3.5, -5.0, -6.5] ºC for pipelines with expanded polystyrene thermal insulation 80 mm and [0.00 -0.25, -0.50] ºC for pipelines without thermal insulation.

The results of calculations in Stage I for the pipeline 15 years after the beginning of the operation are shown in Figs. 4-7.

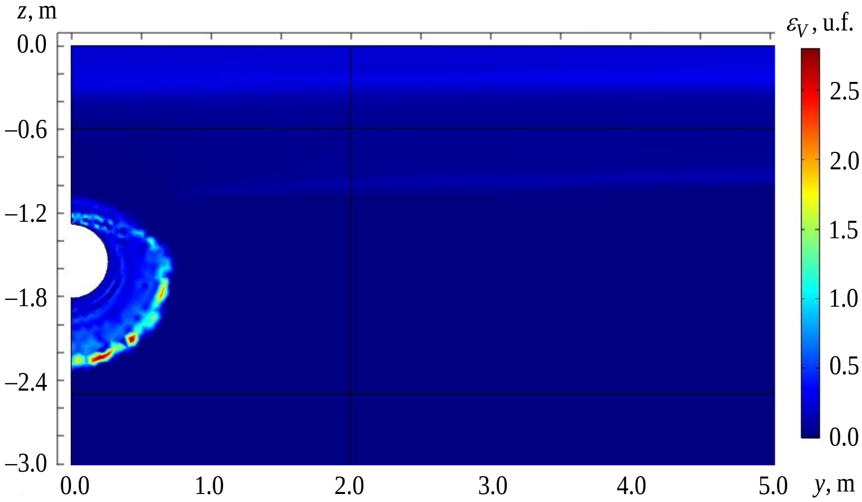

Fig. 3. Distribution of bulk frost heaving (ε_V) 15 years after the beginning of operation of the pipeline with the temperature of product T_{pr}=-0.25 ºC.

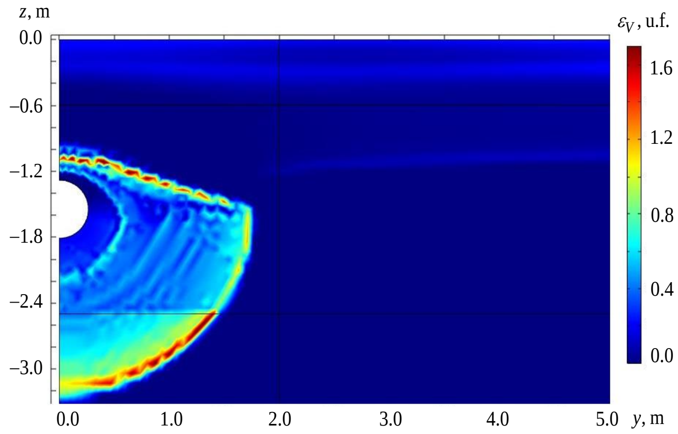

Fig. 4. Distribution of bulk frost heaving (ε_V) 15 years after the beginning of operation of the pipeline with the temperature of product T_{pr}=-1.00 °C.

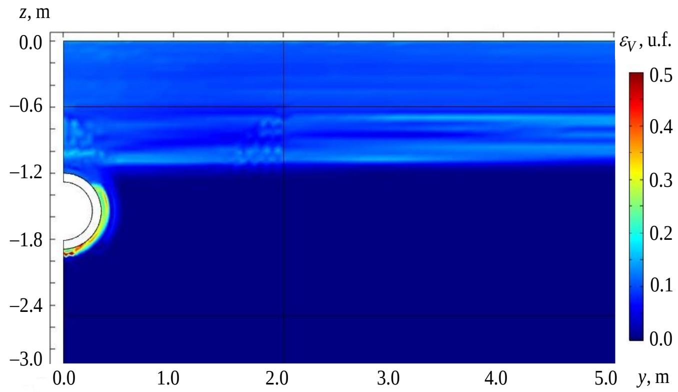

Fig. 5. Distribution of bulk frost heaving (ε_V) 15 years after the beginning of operation of the pipeline with the temperature of product T_{pr}=-3.50 °C and ring thermal insulation with thickness 80 mm.

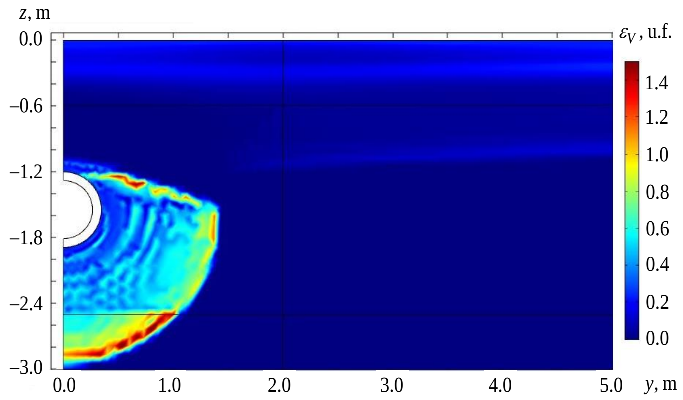

Fig. 6. Distribution of bulk frost heaving (ε_V) 15 years after the beginning of operation of the pipeline with the temperature of product T_{pr}=-8.00 °C and ring thermal insulation with thickness 80 mm.

Numerical research has shown that a volume of frost heaving zone rapidly increases with a decrease in the temperature of the pipeline. Therefore, thermal insulation can significantly reduce the frost heaving zone.

The results of calculation in Stage I was used in Stage II to calculate maximal vertical deformation H_{max} and coefficient of soil reaction k_{fh}. The results of the calculation are shown in Table 3.

Table 3. The results of calculating of the force impact of the soils on the pipeline.

T_{pr}	H_{max}	k_{fh}
Without ring thermal insulation		
0.00	0.000	3.7654×10^6
-0.25	0.085	3.7654×10^6
-0.50	0.168	3.7654×10^6
With ring thermal insulation, thickness 80 mm		
-3.0	0.000	4.1523×10^6
-5.0	0.124	4.152×10^6
-6.5	0.187	4.1523×10^6

The results of the calculation in Stage II show that a decrease in a product temperature causes a significant increase in the vertical deformations of the pipeline. Coefficient of soil reaction does not depend on product temperature, but depends geometry of the design scheme. The rigidity increases when the diameter of the pipeline increases due to by 160 mm thermal insulation.

The results of calculation in Stage II was used in Stage III to calculate stress-strain state of the pipeline. The results of the calculations are shown in Figs. 8-10.

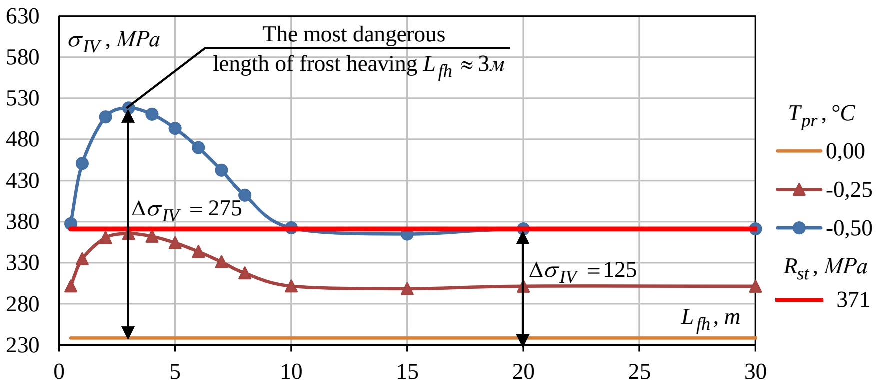

Fig. 7. Maximal von Mises stress (σ_{IV}, MPa) in the pipeline without thermal insulation depending on length of frost heaving area (L_{fh}) for the different temperature of the product T_{pr} in pipeline.

The dependence of the maximum stresses in the pipeline on the length of the heaving zone along the pipeline axis has a pronounced extremum (Fig. 8). The stress has a maximum value under the length of the heaving zone is L_{fh}=3 m. The difference of $\Delta\sigma_{IV}$ between T_{pr}=-0.50 °C and T_{pr}=0.00 °C is the additional stress. For the length of frost heaving zone L_{fh}=20 m additional stress is $\Delta\sigma_{IV}$=125 MPa; for L_{fh}=3 m additional stress is $\Delta\sigma_{IV}$=275 MPa. So, additional stress for the shot section (2 m) of frost heaving zone can be more 2.2 times if compare with long section (20 m and more).

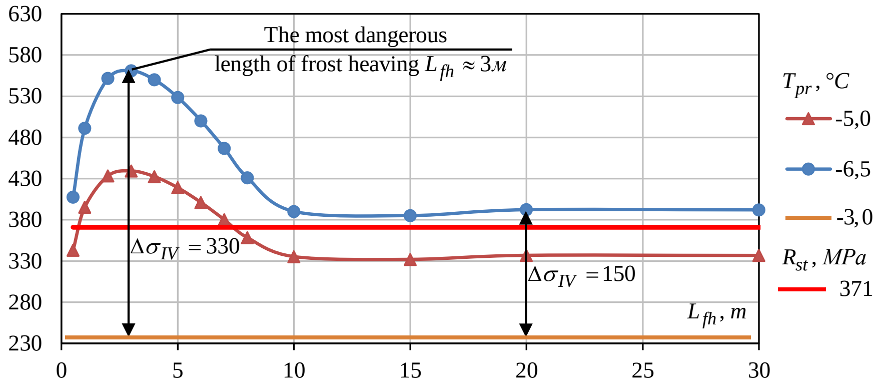

Fig. 8. Maximal von Mises stress (σ_{IV}, MPa) in the pipeline with ring thermal insulation (thickness 80 mm) and thermal conductivity 0.03 W/(m·K) depending on length of frost heaving area L_{fh}, for the different temperature of the product T_{pr} in pipeline.

For the pipeline with ring thermal insulation, the dependence σ_{IV} of L_{fh} has the same character. Here, additional stress for the shot section (3 m) of frost heaving zone also more 2.2 times if compare with long section (20 m and more).

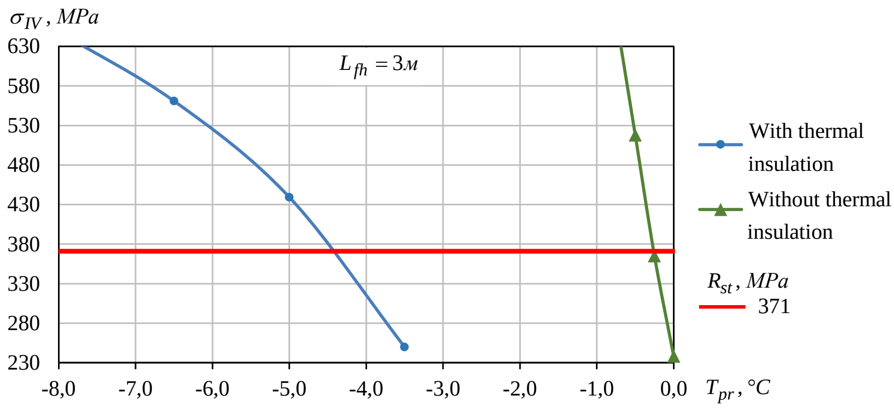

Fig. 9. Maximal von Mises stress (σ_{IV}, MPa) in the pipeline with ring thermal insulation (thickness 80 mm) and thermal conductivity 0.03 W/(m·K) and without thermal insulation depending on temperature of the product T_{pr} among any L_{fh}.

It is expected that the minimum safe temperature for pipelines with thermal insulation 80 mm is -4.8 ºC, without thermal insulation -0.3 ºC for any length of the heaving zone.

4. Conclusion

The mathematical model used by authors allow to describe the volume of segregated ice in the freezing zone, the stress-strain state of the soil, the forces acting on the pipeline in heaving soils and the stress-strain state of the pipeline.

A nonlinear dependence of the maximum stresses in the pipelines on the length of the heaving zone was detected, and the extremum was at L_{fh}=3 m. At this length of the heaving zone additional stress in the wall of pipeline can be 2.2 times more than at L_{fh}=20 m. This character determines an increased risk of local frost heaving processes.

In geotechnical surveys, the wells for soil sampling are created every 50-100 m. This sampling frequency does not allow to determine the exact location of frost heaving boundary. Interpolations allow to find only approximate location of boundary. An error in interpolation and, as a consequence, a short section of pipelines that has been left without engineering protection (2-4 m), can become emergency-dangerous (Figs. 8 and 9). Hence, an important practical recommendation follows: in engineering practice, the protection of the pipeline against frost heaving should cover a dangerous area with a significant margin on both sides.

It is shown that usage of the thermal insulation (with the maximum available thickness of 80 mm for pipeline with diameter 530 mm), permits to lower the permissible temperature in the pipeline from -0.3 ºC to -4.5 ºC. With a further lower in product temperature, special solutions are required to eliminate water transport and reduce the frost heaving force. These methods will be considered in the following works of the authors.

Nomenclatures

c_p^{sk}	Isobaric heat capacity of soil skeleton, J kg^{-1}K^{-1}
c_p^{w}	Isobaric heat capacity of water, J kg^{-1}K^{-1}
c_p^{s}	Isobaric heat capacity of dissolved salt, J kg^{-1}K^{-1}
c_p^{ns}	Isobaric heat capacity of undissolved salt, J kg^{-1}K^{-1}
c_p^{ice}	Isobaric heat capacity of ice, J kg^{-1}K^{-1}
c_{soil}	Adhesion of the soil in the not heaving soil, Pa
D_{ws}	Diffusion coefficient, m^2 s^{-1}
D_{out}	Outside diameter of the pipeline, m
D_{in}	Inside diameter of the pipeline, m
e	Porosity ratio
E_{st}	Young modulus of the steel, Pa
E_{soil}	Deformation modulus of soil, Pa
$hav(x)$	Heaviside function of argument x,
h_o	Depth of pipeline axis, m
j_w^{ws}	Diffusion flow of water, kg s^{-1}m^{-2}
j_s^{ws}	Diffusion flow of salt, kg s^{-1}m^{-2}
j_{ws}	Convective flow of water-soil solution, kg s^{-1}m^{-2}
k_{fh}	Coefficient of soil reaction, N m^{-2}
L_w	Latent heat ice-water transition, J kg^{-1}
L_{fh}	Length of frost heaving area, m
L	Length of not heaving soil, m

L_{fh}	Length of frost heaving area, m
M_y	Moment around axis y, N m^1
M_w	Molar mass of water, kg mole^{-1}
q_{fh}	Frost heaving force per unit length, N m^{-1}
q_{soil}	Force per unit length from not heaving soil, N m^{-1}
q_{soil}	Force per unit length from not heaving soil, N m^{-1}
P_{in}	Inside pressure, Pa
R_{st}	Maximal stress with safety factor, Pa
T	Temperature of soil, K
T_{wi}	Ice-water transition temperature at atmospheric pressure, K
T_{pr}	Temperature of product in pipeline, ºC
u_z	Displacement of soil along the axis *z*, m
u_y	Displacement of soil along the axis *y*, m
w	Deformation of pipeline along the axis *z*, m

Greek Symbols

α_{st}	Coefficient of linear thermal expansion of steel, K^{-1}
γ	Exponent of soil-water potential
ΔT	Temperature difference from start to current condition, K
ε_V	Bulk frost heaving
η_{bf}	Reduction of deformation modulus of soil in the backfill
λ_{P0}	Hydraulic conductivity in saturated soil, ms^{-1}
λ_{ins}	Thermal conductivity of ring insulation, W m^{-1}K^{-1}
ν_{soil}	Poisson ratio of soil
ν_{st}	Puasson ratio of the steel
$\wp_{ice}$	Content of ice in soil, kg m^{-3}
$\wp_{ns}$	Content of undissolved salt in soil, kg m^{-3}
$\wp_w$	Content of water in soil, kg m^{-3}
$\wp_s$	Content of dissolved salt in soil, kg m^{-3}
$\wp_{sk}$	Density of dry insoluble soil, kg m^{-3}
$\wp_w^{max}$	Maximal water content, kg m^{-3}
$\wp_{ww}$	Water content at ψ_w=-1500 J/kg, kg m^{-3}
$\wp_{wl}$	Water content at ψ_w=-33 J/kg, kg m^{-3}
ρ_{ice}	Density of ice, kg m^{-3}
ρ_w	Density of water, kg m^{-3}
ρ_s	Density of dissolved salt, kg m^{-3}
ρ_{ns}	Density of undissolved salt, kg m^{-3}
$\rho_{s.p.}$	Density of solid particles of soil, kg m^{-3}
ρ_{st}	Density of the steel, kg m^{-3}
ρ_{pr}	Density of the product in pipeline, kg m^{-3}
ρ_{soil}	Density of the soil in the not heaving soil, kg m^{-3}
ρ_{ins}	Density of the thermal insulation, kg m^{-3}
σ_{zz}	Displacement of soil along the axis z, Pa
σ_{xx}	Displacement of soil along the axis x, Pa
σ_{yy}	Displacement of soil along the axis y, Pa
$\tau_{\Omega 1}$	Parameter of water crystallization, J s m^{3}kg^{-2}
$\tau_{\Omega 2}$	Parameter of ice melting, J s m^{3}kg^{-2}
τ_{s1}	Relaxation time for salt crystallization, s
τ_{s2}	Relaxation time for salt dissolution, s^{-1}
τ_{yz}	Tangential stresse along the z axis to the y axis, Pa

τ_{zy}	Tangential stresse along the y axis to the z axis, Pa
φ_{soil}	Friction angle of the soil in the not heaving soil, grad
ψ_w	Soil-water potential, J kg^{-1}
ω_s	Concentration of salt,
ω_{s0}	Average concentration of salt,

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