Special features of frost heave of a buried chilled gas pipeline

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ABSTRACT

A method of estimating the maximum additional linear load on pipelines from frost heave, based on mathematical simulation, is presented and documented. This method includes the simulation of the freezing around the pipeline and stresses in the surrounding soil.

Analysis of the the simulation results revealed the following special features of the process: the maximum linear load from frost heave increases with a decrease of the permeability coefficient of the soil, and with an increase in the freezing rate of the soil; application of thermal insulation to the pipeline results in a decrease in the linear load of frost heave. Appropriate thermal insulation can eliminate frost heave entirely.

KEY WORDS: frost heave; freezing rate; freezing soils; stress-strain state; linear load; buried chilled gas pipeline; permeability coefficient.

INTRODUCTION

It is well known that frost heave occurs on sites with thawed (under ponds, lakes, bogs) and nonanchored frozen soils from the action of chilled gas pipelines. This event is associated with a specific stress-strain state in freezing soils. Estimation of displacement of a buried pipeline from frost heave has been a problem because of the lack of an appropriate theoretical treatment.

The phenomenon of frost heave of chilled pipelines from unfrozen soils has been studied since 80 years over the last century. The first approximate theoretical consideration of this phenomenon was offered in the study (Grechishchev, 1994). An experimental investigation of frost heave of buried chilled pipe was carried out under natural conditions (in vivo) in France (Williams, 1986, 1989) and Alaska (Akagawa et al, 2004, Kanie et al, 2004).

The calculation of maximum possible force of frost heave has remained a principal problem.

A simplified method of calculation of the maximum possible additional linear load from frost heave which the pipeline can tolerate without heaving is given in what follows (Grechishchev, 2004).

The input parameters for this method (freezing upward from the pipe, freezing downward from the pipe, the maximum annual freezing rate of soil downward from the pipe) are obtained from thermodynamic calculations.

METHOD

Statement of the problem

A schematic crossection of the affected area in the vicinity of the buried pipeline is shown in Fig. 1.

The values *hu* and were calculated by solution of the thermodynamic equations. . In this case a special program of simulation PROGNOZ (RSN 67-87) and its modification PROGISTO created in the author's institute were used. Mathematical simulation in these programs is carried out by an enthalpy finite-difference method on an explicit two-layered grid; the chosen calculation method was a two-dimensional (x-y plane) simulation due to homogeneity in the longitudinal direction z. hb

Values and aH are set. Values and are calculated according to the following formulas: fh

$$f = \frac{2 \cdot a + hu + hb}{2} \qquad (1)$$

$$h = \begin{cases} (H\text{-}hu) & \text{if } hu < H \\ 0 \cdot m & \text{otherwise} \end{cases} \qquad (2)$$

Freezing of soil at the rate occurs on boundary $f \backslash r = J$. The value of is determined by thermodynamic solution. Also, there is increase in the volume of soil on boundary at the following rate $f \backslash r = J$:

$\delta = \alpha \cdot w \cdot f\backslash$, (3)

where - volumetric soil water content of thawed soil, $w\, \alpha = 0{,}09$ - the relative increase in volume at freezing water.

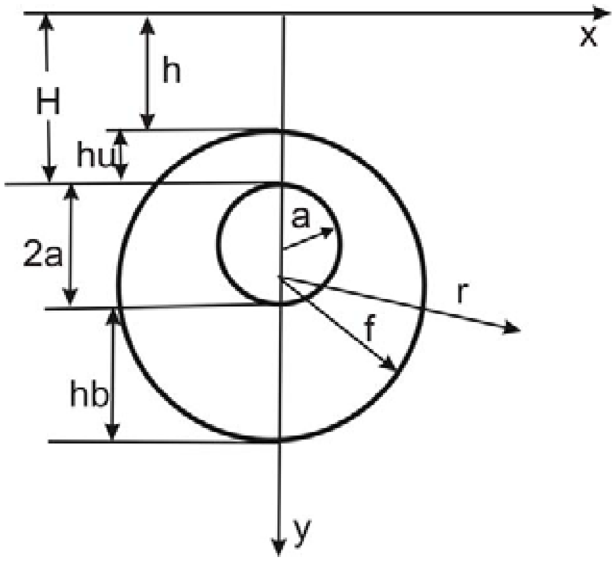

Fig. 1 Schematic crossection of area covered by calculation.

x , - the coordinates; y
a - the radius of pipe;
H - distance from the surface of soil down to the pipe top;
hu - freezing upwards from the pipe;
hb - freezing downwards from the pipe;
h - distance from the surface of soil down to the frozen cylinder top;
J - an average radius of the frozen cylinder.

The rate of increase of excess soil volume δ is counterbalanced by expulsion of water and particles of thawed soil out of the frozen cylinder. In this case, there are stresses in a soil skeleton σs and pore pressure on a boundary. The stresses and the pore pressure are inhomogeneously distributed on the freezing boundary. As a result, the values of the stresses and the pore pressure are higher under the frozen cylinder, than the values of the same parameters above the frozen cylinder. Therefore, the frozen cylinder moves upwards and this is frost heave. $p r = J$

It is necessary to calculate the linear load acting on the frozen cylinder, to design anchors to eliminate of frost heave of the frozen cylinder and the pipe. This linear load has been named as “shut - off pressure” in the study (Williams, 1986, 1989).

System of the equations

The problem can be solved following definition of the following values on a boundary of the frozen cylinder, as indded there is no internal boundary of the thawed soil domain: $f < r < \infty$
qw - rate of movement of pore moisture;
$qs1$ - rate of soil skeleton displacement;
$\sigma \max$ - stress σ_y in a skeleton of thawed ground on bottom of the frozen cylinder;
$p \max$ - pore pressure p of thawed soil on bottom of the frozen cylinder.

A calculation method containing inadequately identified parameters was proposed in the study (Grechishchev, 1994). In contrast to it, the above values are defined in through a simplified form system of the following equations as follows:

$\sigma\max + \alpha \cdot p\max = \Delta T$ (4)

$qw - \varepsilon \cdot qs = Kff1 \cdot p\max$ (5)

$qw + qs = \delta$ (6)

$qs = fvv1 \cdot \sigma\max$ (7)

where ε - coefficient of porosity of thawed soil, , , are the values determined as a result of the solution of corresponding thermodynamic phenomena. $\Delta T\, Kff1 fvv1$

This system of equations is valid for any point on the freezing boundary.

Explanations to the above equations 4 - 7 are given below.

Equation 4. In contrast to the study (Grechishchev, 1994) the process of freezing boundary moving is considered as a quasi-static process because of its slow rate. The equation of phase balance at the freezing boundary of a porous environment is valid for this process (Grechishchev et al, 1980).

$$\frac{L \cdot |\Delta t|}{T0} - vi \cdot \sigma s_n - (vi - vw) \cdot p = 0$$ (8)

where L - latent heat;
Δt - temperature at freezing boundary, °C;
$T0 = 273K$ - normal temperature of phase balance;
vi, *vw* - specific volumes of ice and water;
σs_n - effective stresses (normal to freezing boundary) in soil skeleton;
p - pore pressure.

The value Δt is difficult to calculate, but it can be expressed through the freezing rate. In this way experimental data can be used taking into account the study (Grechishchev et al, 1996). The experimental data are approximated by the expression:

$|\Delta t| = b2 \cdot \sqrt{fv}$ (9)

where - freezing rate; - empirical coefficient. $fv\, b2$

The approximate values of from the study (Grechishchev et al, 1996), are given in table 1. $b2$

Having substituted the last expression into the equation of phase balance and replacing σs_n with $\sigma\max$ and - with ,we obtain from equation 4 by substituting: $p\, p\max$

$\Delta T = b3 \cdot \sqrt{fv}$ (10)

$$b3 = \frac{L \cdot b2}{vi \cdot T0}$$ (11)

Values are given in Table 1. $b3$

Equation 5. Equation Darsi - Gersevanov (Grechishchev et al, 1980) [2] is used

$$qw - \varepsilon \cdot qs = -\frac{Kf}{\rho \cdot g} \cdot \frac{dp}{dr}$$, (12) $r < f$

where - permeability coefficient, m/s; $Kf\, \rho$ - density of water, g - gravity acceleration.

Table 1.Values of coefficients and $b2b3$

Material	$b2$, $\frac{K \cdot s^{\frac{1}{2}}}{m^{\frac{1}{2}}}$	$b3$, $\frac{N \cdot s^{\frac{1}{2}}}{m^2 \cdot m^{\frac{1}{2}}}$
Water	30	$33 \cdot 10^6$
Loam (Yamal)	60	$66 \cdot 10^6$
Loam(Salekhard)	85	$93 \cdot 10^6$
Clay (Kudinov)	170	$186 \cdot 10^6$

The last expression is considered as a boundary condition of the problem of permeability consolidation for a thawed soil domain, . The equation of permeability consolidation taking into account movement of boundary with a freezing rate under a one-dimensional case is given by: $f \le r < \infty y \ge 0 j fv$

$$\frac{d^2 p}{dr^2} + \left(\frac{1}{r} + \kappa\right) \cdot \frac{dp}{dr} = 0 \quad (13)$$

$r \ge j$, , $y > 0$

$$\kappa = \frac{fv}{Kf} \cdot \frac{n \cdot \rho \cdot g}{E} \quad (14)$$

$y = 0, \quad p = 0$

$r = j$, $\frac{dp}{dr} = -\frac{\rho \cdot g}{Kf} \cdot (qw - \varepsilon \cdot qs$ (15)

$r \to \infty$, $p = 0$

n - soil porosity; E - elasticity modulus of thawing soil.

The problem under the specified boundary conditions is solved by the superposition of polar - symmetric determinations for the upper and lower half plane, that allows the following form of equation 5 for the downward forming frozen cylinder:

, $p = p\max$

$qw - \varepsilon \cdot qs = Kff1 \cdot p\max$ (2)

$$Kff1 = \frac{-Kf \cdot \exp(-\kappa \cdot f)}{\rho \cdot g \cdot f \cdot [Ei(\kappa \cdot f) - Ei(\kappa(3 \cdot f + 2 \cdot h))]} \quad (16)$$

(16)

E_1 - integrated indicative function.

And for the upward forming the frozen cylinder ,

$p = p\min$,

$$p\min = \frac{qw - \varepsilon \cdot qs}{Kff2} \quad (17)$$

$$Kff2 = \frac{-Kf \cdot \exp(-\kappa \cdot f)}{\rho \cdot g \cdot f \cdot [Ei(\kappa \cdot f) - Ei(\kappa \cdot (f + 2 \cdot h))]} \quad (18)$$

Equation 6. The equation 6 expresses that the sum of rates of mineral particles volumes which pushed away from freezing boundary and porous moisture is equal to rate of an increment of excess volume of the frozen cylinder.
Equation 7. The task solution of the theory of elasticity for the stress-strained condition of half plane around aperture with radius (Lejbenzon, 1947) is used for definition of the stress-strained condition of a thawed soil skeleton. Thus, domain $f < r < \infty$, is used under the following boundary conditions: $y > 0$

$$\frac{du_r}{dr} = \frac{qs}{fv}, \quad r = f$$

$$\sigma_y = 0, \qquad y = 0.$$

Using an elastic solution, we equation 7 for bottom of the frozen cylinder can be expressed as :

$$qs = fvv1 \cdot \sigma \max \quad (7)$$

$$fvv1 = \frac{fv}{2 \cdot G \cdot \left[1 - \frac{f^2}{(3 \cdot f + 2 \cdot h)^2}\right]} \quad (19)$$

and for top of the frozen cylinder:

$$\sigma \min = \frac{qs}{fvv2} \quad (20)$$

$$fvv2 = \frac{fv}{2 \cdot G \cdot \left[1 - \frac{f^2}{(f + 2 \cdot h)^2}\right]} \quad (21)$$

The solution of the basic system of the equations 4 - 7. The approximate solution of system of the equations 4 - 7 gives:

$$qw = \delta - \Delta T \cdot fvv1 \quad (22)$$

$$qs = \Delta T \cdot fvv1 \quad (23)$$

$$\sigma \max = \Delta T \quad (24)$$

$$p \max = \frac{\delta - \Delta T \cdot fvv1 \cdot (1 + \varepsilon)}{Kff1} \quad (25)$$

Calculation of linear load. The forces which are pushing the frozen cylinder and the pipe upwards, are caused by a differential stresses of in the soil skeleton and of pore pressure moisture formed by freezing of thawed soil above and under the cylinder. We designate these differences as , $\Delta p \Delta \sigma$:

$$\Delta p = p \max - p \min \quad (26)$$

$$\Delta \sigma = \sigma \max - \sigma \min \quad (27)$$

Linear heave load caused by pore pressure *Qp* and by stresses in a skeleton $Q\sigma$ are calculated according the formulas:

$$Qp = \int_{-\pi}^{+\pi} \Delta p \cdot Cos \frac{\varphi}{2} \cdot f \cdot d\varphi = 4 \cdot f \cdot \Delta p \quad (28)$$

$$Q\sigma = \int_{-\pi}^{+\pi} \Delta\sigma \cdot Cos\frac{\varphi}{2} \cdot f \cdot d\varphi = 4 \cdot f \cdot \Delta\sigma \quad (29)$$

The total heave linear load is calculated according to following formula:

$$Qh = Qp + Q\sigma \quad (30)$$

The heave linear load *Qh* will be partially eliminated by the weight of the frozen cylinder, the pipe, and of the thawed soil overburden submerged weight, that creates the following linear load, $Q\rho$:

$$Q\rho = \left[\pi \cdot (f^2 - a^2) + \left[2 \cdot f \cdot (f+h) - \frac{\pi \cdot f^2}{2}\right]\right] \cdot \rho b \cdot g - \left[2 \cdot f \cdot (f+h) + \frac{\pi \cdot f^2}{2}\right] \cdot \rho \cdot g \quad (31)$$

The linear load *Qa* which has to be resisted by anchors (or a different way) is defined according to formula:

$$Qa = Qh - Q\rho \quad (32)$$

Thus, in the case of use of the anchors, *Qa* is the anchor pulling capacity (shut - off pressure).

INITIAL DATA

The above method was applied for analysis of frost heave of a buried chilled gas pipeline under conditions encountered on the the Yamal peninsula. Conditions cited below are those of the Yamal-Ukhta natural gas pipeline. The calculations are carried out for the perennial nonanchored frozen soil (the permafrost top lies beneath the base of the freezing layer) with a permafrost base depth of 10 m and with the soil temperature of minus 0,2 °C on a depth of zero annual amplitude. The soil is a loam that has the following characteristics: the density of a skeleton $\rho s = 1{,}63 \cdot 10^3 \frac{\kappa z}{m^3}$, the volumetric water content $w = 0{,}33$, the coefficient of permeability $Kf = 10^{-9}\, or 10^{-10}\, \frac{m}{s}$, the elastic modulus of .The diameter of the gas pipeline is 1400 mm. The center of the pipeline is at the depth of 1,5 m. $E = 340 \cdot 10^5 \cdot Pa$

The calculations were carried out for the following condition of operation of the gas pipeline:

- 1 - at gas transportation with temperature of minus 2 °C during the year;
- 2 - at gas transportation with temperature of minus 7 °C in summer and of minus 2 °C in winter.

The following variables were considered: a pipeline without thermal insulation; a pipeline with thermal insulation with thermal resistance to a heat transfer 2,8 and 4,2 (m^2.°C)/W.

RESULTS OF CALCULATIONS

Two sets of calculations were executed: thermal influence of a cold gas pipeline on surrounding soils; an estimation of additional linear load of heaving which has to be applied to the pipeline for the frost heaving prevention. The second calculation depends on results from the first one.

The depth of freezen soils varies from 0,2 to 2,8 m under influence of chilled gas pipelines with different temperature of gas (Fig. 2). The colder the temperature of gas in the pipeline, the greater the frozen soil depth.

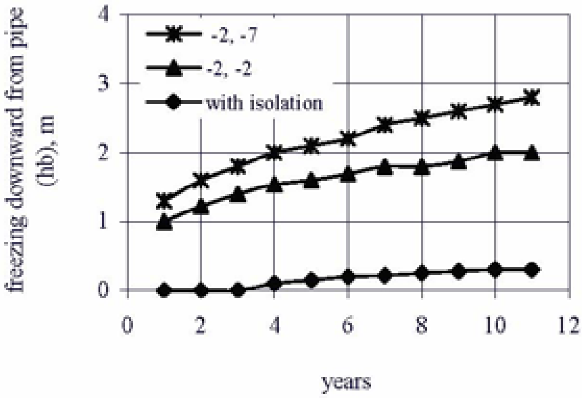

Fig. 2 Change of depth freezing downwards from a chilled gas pipeline under various operating conditions

The input parameters (freezing upward from the pipe (hu), freezing downward from the pipe (hb), maximum annual freezing rate of soil downward from the pipe (fv)), are obtained from thermodynamic calculations.

The permeability coefficient () has a significant influence on the value of the heave linear load (*Qh*) based on analysis of the results submitted on Fig. 3. The value of heave line load increases with the decrease of permeability coefficient. Kj

Also, the heave linear load () increases with an increase of the freezing rate of soil. Qh

The value of heave linear load (*Qh*) changes in time and depends on operatuing conditions of the gas pipeline (Fig. 3). It has maximum value in the first year of operation of a gas pipeline.

Freezing downward from the pipe in first three years does not occur when thermal insulation with thermal resistance of 2,8 (m^2.°C)/W is applied irrespective of the conditions of gas transportation of (Fig. 2). In this case the frost heave of the pipeline does not occur. A small amount of freezing downward from the pipe occurs in the next years and linear heave load () of 1,8 t/m at Kf =10Qh^{-10} m/s occurs for the seventh year.

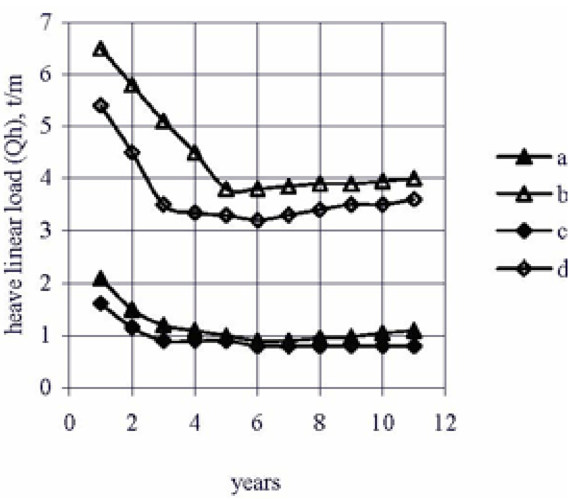

Fig. 3 Variation of heave linear load with time and permeability coefficient (a - $Kf = 10^{-9}\frac{m}{s}$, T gas=-2, -7 °C; b - $Kf = 10^{-10}\frac{m}{s}$, T gas=-2, -7 °C; c - $Kf = 10^{-9}\frac{m}{s}$, T gas=-2, -2 °C; d - $Kf = 10^{-10}\frac{m}{s}$, T gas=-2, -2 °C) and with various temperatures of gas in a pipe

Freezing downward from the pipe does not occur when thermal insulation with thermal resistance 4,2 (m^2.°C)/W is applied. It is possible to select a sufficient thickness of thermal insulation to attain the necessary thermal resistance so that frost heave of the gas pipeline will not occur.

Thus, application of the appropriate thetrmal insulation is an effective method for protection of chilled gas pipelines against frost heave

CONCLUSIONS

The analysis of the results of simulation revealed the following special features of the process of interactions of chilled gas pipelines with surrounding soils:.

1. The maximum frost heave linear load increases with the decrease of soil permeability coefficient and with an increase of the freezing rate of the soil.

2. The maximum heave line load changes with pipeline operation time (years) and depends on a operating conditions of the gas pipeline. Thus, l heave linear load and thermodynamic calculations should be carried out jointly to assess the required capacity of anti-heave anchors.

3. Application of the thermal insulation to the pipeline results in a decrease of the additional heave linear load (including its elimination) as necessary for frost heave prevention. Accordingly, application of the thermal insulation is an effective method for protection of buried chilled gas pipelines against frost heave.

In summary, a method for estimating the maximum possible frost heave linear load using mathematical simulation was demonstrated. Analysis of the simulation results revealed the special features of pipeline soil interactions during frost heave. Furthermore, this method can be used to define engineering solutions for protection of buried chilled gas pipelines against frost heave.

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