Analysis of the reliability of structures during operation of gas pipelines on piles in areas of heaving soils

B N Novik1, S Yu Podorozhnikov1,2 and M Yu Zemenkova1

1 Industrial University of Tyumen, 38 Volodarskogo str., Tyumen, 625000, Russia
2 sergey_urevih@mail.ru

Abstract. The routes of the main, field, and process gas pipelines in the Arctic regions of Siberia run through territories with difficult climatic conditions. Along the route, there are areas with heaving soils, which can be used as natural bases only with the use of special anti-heaving measures, since that they are characterized by high mobility, low bearing capacity, uneven settlement and increased compressibility. This raises concerns about a decrease in the bearing capacity of permafrost soils in the territories of Taimyr, Yamal and other regions. The paper discusses various methods of the above-ground laying of pipelines on heaving soils. A pipeline construction option ensuring safer operation is proposed.

1. Introduction
Fields in Western Siberia are located in an area with extremely difficult climatic conditions. Almost the entire territory of the region is characterized by the presence of permafrost soils, which thaw and freeze seasonally, leading to a loss of stability of the supporting structures of gas pipelines.

During the construction of new gas pipelines on such soils, there are many problems and tasks associated with the subsequent safe operation of the gas pipeline.

Frost heaving of the soil is its ability, within the seasonal freezing, under a certain combination of hydrothermal conditions, to increase in volume under the influence of crystallization forces of ice, accompanied by phase transformations of water contained in the soil and pulled additionally to ice crystals. The external manifestation of this property is the uneven elevation of the day surface of the soil through the formation of ice inclusions. [1-5]

There is one more definition of this term: cryogenic frost heaving of soils is the internal volumetric deformation of freezing moist soils, soft ground rocks and soils, which leads to an increase in their volume due to crystallization of water in them, as well as the formation of ice inclusions in the form of lenses, interlayers, polycrystals, etc. The external manifestation of this phenomenon is local uneven uplift of the surface layer of freezing soil, which is subsequently replaced by soil settlement during thawing. [6] Heaving soils, as a rule, are called soils, which, when frozen in conditions of natural occurrence, can increase in volume. [7]

According to the degree of frost heaving, soils are classified by the following criteria:

- particle-size composition;
- natural water content;
- depth of groundwater;
- estimated depth of soil freezing.
Soils according to this classification are divided into five varieties:

- heavily heaving;
- medium heaving;
- weakly heaving;
- conditionally not heaving;
- not heaving.

Loams, pulverescent sandy loams and pulverescent clays of plastic consistency at a groundwater level in the zone of seasonal freezing or below the standard freezing depth of no more than 0.5 m in sandy loams, and in clay and loams no more than 1 m are among the most heaving frosty soils.

Medium heaving soils include sandy loams, pulverescent sands, clays and loams with natural moisture that exceeds the consistency index of 0.5, with a groundwater level that exceeds the standard freezing depth by no more than 0.6 m in pulverescent sands, in sandy loams - not more than 1 m, in loams - not more than 1.5 m, and in clays - not more than 2 m, in terms of frost heaving.

The group of weakly heaving soils includes pulverescent and fine-grained sands, loams, sandy loams and clays with a stiff texture, and in addition, coarse-grained soils with a pulverescent-clay aggregate at a groundwater level exceeding the freezing depth: in fine-grained and pulverescent sands - no more than 1 m, in sandy loams - no more than 1.5 m, in loams no more than 2 m, in loams (plasticity more than 0.12) - no more than 2.5 m and in clays - no more than 3 m.

2. Materials and methods

The forces of heaving are due to:

- crystallization pressure of water contained in the soil, as well as migration moisture;
- disjoining by films of unfrozen water;
- shrinkage of adjacent soil layers.

Values of normal frost heaving forces, in addition to external pressure and soil properties, depend on:

- soil moisture conductivity;
- compressibility of underlying soil layers. [8, 9]

Values of normal heaving stresses of the soil surface are different from the stresses that develop in the soil mass near the foundations, where these stresses, among other factors, depend on the rigidity of the structures that absorb the frost heaving forces. [10, 11]
- heaving caused by migratory ice accumulation due to the crystallization of migrating moisture;
- disjoining pressure of non-freezing water films manifested as a result of moisture migration;
- soil shrinkage stresses.

The components of the heaving stresses are schematically shown in Figure 1.

On the one hand, the forces of frost heaving act as a function of the porosity of the soil, and on the other hand, they depend on excess water content, which leads to the appearance of ice, in volume exceeding the pore volume of the soil. [12]

Depending on the geological conditions, the structure of foundations, the features of the "base-pile" structure for supports with thermal stabilization of the soil, various versions of vertical soil thermal stabilizers are used.

Vertical thermal stabilizers can be most widely used to lower the temperature of heaving soils to negative temperatures to increase the bearing capacity of pile supports and prevent buckling of piles.

The installation of vertical thermal stabilizers ensures the formation of a frozen mass of soil near the piles, which ensures the attenuation of vertical movements (Figure 5).

![Figure 2](image.png)

**Figure 2.** Pile temperature stabilization by means of vertical thermal stabilizers: 1 - pile; 2 - vertical thermal stabilizer; 3 - frozen massif - ice-soil cylinder.

An example of the operation of a gas pipeline in the Arctic regions of Siberia was taken to assess the situation. Permafrost soils are represented by sands with sandy loam interlayers and lenses with pebbles and gravel. The cryogenic texture is massive with small inclusions of ice. The thickness of frozen rocks is from 300 to 500 m, the total water content of sands is at least 30%. Seasonally thawing soils are mainly represented by fine-grained sands, sandy loams and lenses of torn sand. In places, there are thick deposits of peat bogs (in low places) and clay (Table 1).

Frost heaving of tundra soils, together with excess water content, very often leads to a skew of the support crossbar on an operating gas pipeline (Figure 3). The stress-strain states of the pipeline are uneven along the length and with varying deformation values.
Table 1. Characteristics of seasonally thawing soils [14]

| Seasonally thawing soil composition | Soil characteristics | Water content, % | Average annual temperatures at the bottom of the layer, °C | Porosity coefficient, $\varepsilon$ | Liquidity index, $I_L$ |
|------------------------------------|----------------------|------------------|----------------------------------------------------------|---------------------------------|----------------------|
| Fine-grained, pulverescent, water-saturated sands | Fine-grained, yellow-gray sands; hard frozen, massive cryogenic texture, rarely interbeds of ice up to 0.1 m thick. When thawing, sand becomes flowing | At a depth of 10 m – minus 3.0-4.0 °C. | Maximum thawing depth 1.5-2.0 m | 0.5 | > 1.00 |

Figure 3. Loaded pile in the freezing soil:

1 - thawed soil, 2 - frozen soil, 3 - permafrost soil, $\xi_n$ - boundary depth of soil freezing around the pile, $X_{perm}$ - thickness of the permafrost layer, $L_{pile}$ - deepening of the pile, $P$ - support crossbar

Calculation of frost heaving forces for standard gas pipeline supports on heaving soils.

Data for calculation: soil temperature $t = -10^\circ C$, with a freezing soil layer of 1.5 m, the thickness of thawed soil is 0.5 m (based on their maximum thawing depth), the length of the underground part of the pile $L_{pile} = 4$ m, $x_{perm} = 2.0$ m.

Suppose that the heaving force is maximum and equal to the freezing force (in the freezing layer of thawed soil). Then, the motionlessness condition of piles has the form:

$$F_{frHeav} \leq F_{adhThaw} + F_{frPerm} + N$$

where $F_{frHeav}$ - freezing force (assumed heaving force) of piles with frozen soil, kN; $F_{adhThaw}$ - adhesion force of piles with thawed soil, which keeps the pile from buckling, kN; $F_{frPerm}$ - freezing force of piles with permafrost soil, kN; $N$ - sum of the own weight of the pile and the load on it, kN.

$$F_{frHeav} = (0.7 \times R_{af}) \times \xi_n \times U$$  

$$F_{adhThaw} = f \times (L_{pile} - x_{perm} - \xi_n) \times U$$  

$$F_{frPerm} = (0.7 \times R_{af}) \times x_{perm} \times U$$

where $R_{af}$ - specific strength on the surface of freezing, kPa (Table 2); $f$ - specific adhesion force of pile material with thawed soil, kPa; $U$ - circumference of the pile, m;
\( (L_{\text{pile}} - x_{\text{perm}} - \xi) \) - thickness of the layer of thawed soil located below the bottom of the freezing-thawing layer, m;
\( f \) - calculated resistance to shear of thawed soil along the pile surface, kPa (Table 3).

Table 2. Calculated resistance to shear on the freezing surface [15]

| Soil          | Calculated resistance \( R_{af} \), kPa, at soil temperature, °C |
|--------------|---------------------------------------------------------------|
|              | -0.3 | -0.5 | -1   | -1.5 | -2   | -2.5 | -3   | -3.5 | -4   | -6   | -8   | -10  |
| Clay         | 40   | 60   | 100  | 130  | 150  | 180  | 200  | 230  | 250  | 300  | 340  | 380  |
| Sand         | 50   | 80   | 130  | 160  | 200  | 230  | 260  | 290  | 330  | 380  | 440  | 500  |

The value of \( R_{af} \) should be multiplied by a factor \( \gamma_{af} \), depending on the kind of freezing surface.

For hot rolled metal surfaces \( \gamma_{af} = 0.7 \)

Table 3. Specific adhesive force of pile material with thawed soil [15]

| Average depth of the soil layer, m | Clay soils at a yield index \( I_c \), equal to |
|-----------------------------------|---------------------------------------------|
|                                   | large and medium-large size | small | pulverescent | - | - | - | - | - | - |
| 1                                 | ≤0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| 2                                 | 35   | 32  | 29  | 26  | 23  | 20  | 18  | 16  | 14  |
| 3                                 | 42   | 39  | 36  | 33  | 30  | 27  | 24  | 22  | 20  |
| 4                                 | 48   | 45  | 42  | 39  | 36  | 33  | 30  | 27  | 24  |
| 5                                 | 53   | 50  | 47  | 44  | 41  | 38  | 35  | 32  | 29  |
| 6                                 | 58   | 55  | 52  | 49  | 46  | 43  | 40  | 37  | 34  |
| 8                                 | 62   | 59  | 56  | 53  | 50  | 47  | 44  | 41  | 38  |
| 10                                | 65   | 62  | 59  | 56  | 53  | 50  | 47  | 44  | 41  |
| 15                                | 72   | 69  | 66  | 63  | 60  | 57  | 54  | 51  | 48  |

When calculating, the following conditions should be considered:
1. When determining the calculated resistance of soils on the lateral surface of piles, soil layers should be divided into homogeneous layers with a thickness of not more than 2 m.
2. The values of the calculated resistance of dense sand on the lateral surface of piles should be increased by 30% compared with the values given in the table.
3. The calculated resistance of sandy loam and loam with a coefficient of porosity of 0.5 should be increased by 15% compared with the values given in the table for any values of the yield index.

From (1), (2), (3), (4) it follows:

\[
\xi_{\text{cri}} = \frac{f \times L_{\text{pile}} - f \times x_{\text{perm}} + 0.7 \times R_{af} \times x_{\text{perm}} + \frac{N}{\gamma}}{0.7 \times R_{af} + f}
\]  

- critical freezing depth of each pile individually
Humidity, structure, composition, density and temperature of the soil affect the specific forces $R_{af}$ and $f$ included in the formula (4). In turn, the critical freezing depth for each of the piles will also change (Figure 4) since even at small distances the soil parameters may differ (shrub, snowdrift, uneven solar radiation, uneven load distribution from the gas pipeline due to its transverse displacement along the crossbar).

Let us denote (Figure 5) the distance between the centers of the two piles on which the crossbar rests as $b$, the displacement of the lower generatrix of the pipeline relative to the center of the crossbar as $\Delta b$, the load on the entire support from the weight of the pipeline as $N_{PL}$, the weight of the pile as $N_{PILE}$, the load on the pile from which the pipeline has shifted as $N_1$, the load on the pile towards which the pipeline has shifted as $N_2$.

The load on each of the piles is equal to the sum of the weight of the pile $N_{PILE}$ and the load from the part of the weight of the pipeline $N_{PL}$, falling on this pile ($N_{PL1}$ and $N_{PL2}$), $N_{PL} = N_{PL1} + N_{PL2}$:

$$N_1 = N_{PL1} + N_{PILE} = N_{PL} \times \left(\frac{1}{2} - \frac{\Delta b}{b}\right) + N_{PILE}$$

$$N_2 = N_{PL2} + N_{PILE} = N_{PL} \times \left(\frac{1}{2} + \frac{\Delta b}{b}\right) + N_{PILE}.$$

The gas pipeline with a diameter of 720 mm, thickness $s = 10$ mm, shifted 0.2 m with a distance between the centers of the piles of 2.2 m.

$$N_{PL} = q_m \times l_{between ~ supports}, \text{ (in our case } l_{between ~ supports} = 15 \text{ m) }$$

from (7) $N_{PL} = 175 \text{ kg/m} \times 15 \text{ m} \times 9.8 \text{ m/s}^2 = 25.73 \text{ kN}$.

Piles are made of steel pipes with a diameter of 325 mm and a wall thickness of 10 mm. The length of the above-ground part of the pile $L_{ag} = 3.5$ m.

Hence, the weight of the pile from (7) $N_{PILE} = 77.7 \text{ kN/m} \times 3.5 \text{ m} \times 9.8 \text{ m/s}^2 = 27 \text{ kN}$.

From (6) $N_{PL1} = 10.5 \text{ kN}$, $N_{PL2} = 15.2 \text{ kN}$.

**Figure 4.** Stress-strain state of a gas pipeline during pile heaving

**Figure 5.** Scheme of stress-strain state
\[ N_1 = 10.5 + 2.7 = 13.2 \text{ kH} \quad N_2 = 15.2 + 2.7 = 17.9 \text{ kH}. \]
\[ f = 3 \times 1.15 = 3.45 \text{ kPa} \text{ (Table 3)}, \quad R_{af} = 500 \text{ kPa} \text{ (Table 2)}. \]

By (5)
\[ \xi_{n1} = \frac{f \times L_{pile} - f \times x_{perm} + 0.7 \times R_{af} \times x_{perm} + N_1}{0.7 \times R_{af} + f} = \frac{3.45 \times 4.0 - 3.45 \times 2.0 + 0.7 \times 500 \times 2.0 + \frac{13.2}{3.14 \times 0.325}}{0.7 \times 500 + 3.45} = 2.04 \text{ m} \]
\[ \xi_{n2} = \frac{f \times L_{pile} - f \times x_{perm} + 0.7 \times R_{af} \times x_{perm} + N_2}{0.7 \times R_{af} + f} = \frac{3.45 \times 4.0 - 3.45 \times 2.0 + 0.7 \times 500 \times 2.0 + \frac{17.9}{3.14 \times 0.325}}{0.7 \times 500 + 3.45} = 2.05 \text{ m} \]

Using the module of frost heaving of the soil \( m_f = 3.5 \) [5] with a particle size of 0.15 mm, we find the annual increment of the difference in the amount of buckling of piles:
\[ \Delta = m_f \left( |\xi_{n1} - \xi_{n2}| \right) = 3.5 \times 0.01 = 0.035 \text{ m} \] [6] \( (8) \)

It follows from this that for:
\[ \xi_{n1} = \xi_{crit} = 2.04 \text{ m} \quad \text{and} \quad \xi_{n2} = \xi_{crit} = 2.05 \text{ m} \] over 1 year, the difference in the height of the supports can reach 3.5 cm; it was assumed that the heaving force is maximum and equal to the freezing force (in the freezing layer of thawed soil).

According to observations during seasonal thawing and freezing in different areas, the data on the actual buckling of piles of gas pipeline supports differ from these calculations, which confirms the heterogeneity of the lithological composition, dispersion, water content and strength of the soil. In many areas, there was an increased depth of drilling wells for piles - up to 6 meters. It does not always provide a positive result.

![Figure 6. Structural defect](image)

It is also necessary to take into account the moments of forces during the freely movable displacement of the pipeline in compensatory, longitudinally movable, especially high-altitude sections. These
moments (Figure 6), together with the thawing and freezing of seasonally thawing soil, lead to structural defects in the supports.

Recently, there has been a steady increase in climate and permafrost soils temperature, which means there are well-founded fears about a decrease in the bearing capacity of permafrost soils in the territories of Taimyr, Yamal and other regions. [19]

At the moment, supports with soil thermal stabilization (STS) are very efficient in operating on permafrost soils (Figure 5). [20,21]

In comparison with STS, soil modules (Figures 7, 8) [21, 22] do not have sufficient load-bearing capacity to ensure safer operation of the above-ground gas pipeline. The essence of the method of laying from soil modules is that a canvas made of Dornit synthetic non-woven material is laid on the soil surface, and soil modules of the GP-1500 type are installed on it and filled with soil. The soil is compacted, after which the height-adjustable support of the conductor is removed. A protective sand layer with a thickness of 50-100 mm is poured onto the module, on which, in turn, a thermally insulated pipeline is laid. The soil module is a cellular structure filled with local, including icy and silty clay soils. Soil modules are made of the estimated width from tapes of technical fabric with various cell sizes. The necessary bearing capacity of the soil base when taking into account static and dynamic loads (pipeline weight, snow cover and thermal insulation) is achieved by changing the size of the cells.

Figure 7. Supports with soil thermal stabilization

Figure 8. Scheme of laying a gas pipeline on soil modules: 1 - surface of weakly bearing soil; 2 - synthetic non-woven canvas material; 3 - conductor support, adjustable in height; 4 - near-surface compacted soil layer; 5 - soil compacted between non-woven synthetic material and the bottom end of the soil module; 6 - soil module; 7 - protective layer of sand; 8 - pipeline
3. Conclusion
There is a need for a qualitative review of permafrost construction methods. When choosing the optimal support structure, it is necessary to be guided by its versatility for different permafrost sections, with different soil characteristics. The relatively small amount of construction work, which, as a rule, on its own destroying the tundra cover of the Arctic, is one of the many and important reasons for premature thawing of soils, will also contribute to lower costs.

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