Pipelines on Russian North: review of problems of interaction with permafrost

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Abstract

Construction and operation of pipelines in cryolithozone leads to forming or activation of geocryological processes developing in a zone of direct interaction of soil with the pipeline and surrounding land. As a result of an increase of up to 2 times the depth of the active layer, development of thermokarst depression of up 2.0 м and thawing of frozen soil there is formation of taliks along gas pipelines operating a temperatures above 0C. There are significant horizontal and vertical deformations of the gas pipelines resulting in occurrence of intense stress - corrosion of pipes, and swamping of the surrounding land occurs. For pipelines operating below 0C there are new problems associated with the freezing of taliks crossed by the gas pipeline, and the subsequent freezing. Recent statistics show a large number of failures on the northern pipelines; some of them are induced by the permafrost processes.

Keywords

Permafrost, pipeline, freezing, thawing, failure

Introduction

The world consumption of oil and natural gas is still increasing; however, recourses are limited. North is one of most promising reserves, and Russian northern resources are located both on land and on the continental shelves. Exploration sites and pipelines disturb the earth surface: change water flows, relief, and animal migration. The major feature of the Northern environment is permafrost. Permafrost is widely distributed, especially in Asia, and permafrost landscapes are extremely sensitive to disturbance. Gas and oil pipelines were maintained in cryolithozone of Russia from middle of sixties of the last century (Table 1). It is the only country operating long-distance pipelines in permafrost conditions. There are one hundred and fifty thousands kilometers of pipelines in Russia. Generally two types of pipelines are in use: feeder pipes delivering gas from the wells to plants (mostly above ground) and gathering pipelines (typically buried at depths of 1.5±2 m); both types are affected by cryogenic processes. An artificial warming is considered to be one of the most important factors affecting pipeline interaction with permafrost. Average age of the major Russian pipelines is about 22 years. More than 30% of the compressor stations need to be refurnished, 15% of them work more than 25 years. Total number of failures of oil and gas pipelines is about fifty thousands a year, according official data of Gosgortechnadzor of Russian Federation, third part of them leads to massive leaks.

Underground pipelines are considered economically reasonable, protected and safe. However failures of the underground pipelines are forty times more than above ground ones in Norilsk area. It was considered that the thawing of soil under the influence of a thermal flow from the gas pipeline would result in loss of bearing capacity. Surrounding areas are also disturbed, thus interaction between pipeline and permafrost may be a reason for damage of pipes. However it is still poorly known, which part of the failures is connected to cryogenic processes. Unfortunately, in spite of widely distributed opinion of danger of pipeline-permafrost interaction, failures caused by frost heave or thawing of soil, as well as other processes need to be proven: Detailed analyses of the occurrences of failures including stress-strain calculations are not published yet. A number of publications both Russian (Chigir et al., 1997; Remizov, 2000;) and Western (Rowley et al., 1975; Nixon et al., 1983; Carlson & Butterwick. 1983; Burgess et al.,1993; Razaqpur and Wang, 1996; Seligman, 2000) consider many aspects of the problem; however, the present conditions of the pipelines and failures connected to permafrost in the Russian North still needs to be examined.

Experience of pipelines construction on the Russian North

The first in the world gas pipeline in the area of permafrost (Promushlenny - Yakutsk) was constructed in 1965 - 1967 in Yakutia - Saha Republic (Luglaev etc., 2001). The first gas pipeline located above the polar circle in the area of permafrost distribution (Messoyaha - of Norilsk) was above ground (partly underground) and entered into operation in 1969 (Table 1). In 1972 in Medvezh'ye (Western Siberia) gas field the pipeline Medvezh'ye-Nadum-Punga was constructed with diameter 1220 and 1420 mm. The pipeline from Urengoy field was entered into operation in April, 1978; the pipeline from Yamsovei gas field was put into operation in 1997. Zapoliarny pipeline was constructed in 2001. The first gas pipeline Hariaga-Usinsk in the European North of Russia was constructed in 1980.

Failures on the northern pipelines

Pipeline failure rates continue to increase in many countries. A regular statistical estimation of failures of main pipelines in Russia (Soviet Union) was begun at the end of 1970 (Seduh, 1993). As failure data for the last 10 years show the frequency of failures was 0.18 – 0.21 for 1000 km in average. However, in 1996 – 1997 the frequency increases up to 0.25 – 0.26, and failures become more serious and expensive to repair. Half of failures occur on pipelines with diameter 1420 mm. On the north of the Western Siberia about 65 failures were registered during the last 20 years. The statistics on failures on main gas pipelines are contained in the paper of Remizov (2000). It is considered that the basic reason causing damage is the underground corrosion and internal erosion, which accounts for about 40 % of all failures. Corrosion cracking of pipes under stress is accepted as the reason of the failures of main gas pipelines of diameter 1020-1420 mm (Tuhbatullin etc., 2000). However, in many cases the actual reason of a failure is difficult to find. For example, for twenty years about sixty failures occurred on pipelines Taas-Tumus-Yakutsk and Mastakh-Yakutsk (Konstantinov & Gurianov, 2001).

The gas pipelines with diameter of 1020 mm have the worst incident of failures. In 1990 the frequency of failures due to defects of pipes was on 1000 km of extent for pipelines with diameter: 1420 mm - 0,018; 1220 mm - 0,028; 1020 mm - 0,066; 720 mm - 0,045; for a network of gas pipelines as a whole - 0,036. It is shown that time of operation of present gas pipelines and equipment is high enough: 30 % of gas pipelines – up to 10 years; 56 % of gas pipelines from 10 to 30 years; and 14 % of gas pipelines - more than 30 years. Improved diagnostic service of Gasprom recently lowered the accident rate of main gas pipelines 1.4 times (to 0,18 cases on 1000 km per one year in average), which looks comparable to the world level (Remizov, 2000). About 50 large-scale failures at oil and gas pipelines in Russia occur every year.

According Gosgasnadgor, distribution of failures in 1992 – 96 due to the following reasons (%):

- outer corrosion of pipe – about 25;
- stress corrosion – about 17;
- mechanical failures – 23;
- construction defects and spoilage – 21;
- metal and equipment defects - 14

In European North of Russia 21 emergency ruptures of main gas pipelines are registered since 1993, and the main cause was stress corrosion (Salukov etc., 2000).

Dependence of failures on season is obvious (Figure 1). Pipes break during the freezing; statistically about 40% of all failures occur during freezing in autumn and beginning of winter. In the Western Siberia 65% of all failures occur from July to September, and 75% from June-September. An investigation made by Kamensky (1988) on gas pipeline Mastakh-Yakutsk has shown, that the majority of failures occur in winter. There were many emergencies on sites of underground lining of gas pipeline Messoyaha - Norilsk for two years only (Table 2). Most dangerous places are borders of landscapes.

Basics of the interaction of pipelines with permafrost

1. Thermal interaction

The gas temperature has an influence on frozen soil; the problem was considered in a number of publications (Gretchischev etc., 1983; Jahns, 1983; Nixon, 1987; Riseborough et al., 1993). All variety of possible modes can be simplified to four variants (Figure 2). Depending on a combination of temperature mode of soil and pipe the picture of thermal interaction of the pipeline with frozen and thawed soil will essentially vary. At transport of gas with temperature above 0C during all periods of operation at locations of permafrost taliks around the pipe will to be formed, and the depth of active layer above the pipeline can be reduced.

In taliks during wintertime the seasonal areas (halos) of freezing of soil will be formed. There are intermediate cases. The transported gas with low temperature ("cold (chilled) pipeline") does not prevent thawing of soil, because minimal temperature is about 2ºC (Sharigin etc., 2000. Under certain permafrost conditions in all cases damaging processes influencing stability of the pipeline are possible. In the first case at crossings of the pipeline with taliks long-term frost heaving of soil occurs. In the second case on sites of permafrost at freezing of seasonal halos in wintertime seasonal frost heave of soil damaged pipelines is also probable. On thawed sites opposite directed vertical moving of the pipeline can occur. In the summer, when the seasonal halo of thawing under the pipeline is formed, movement of the pipeline down is possible; on sites of weak soil, for example peat, surfacing occurs.

At transportation of gas at temperatures above 0C ("warm" pipeline) in areas of frozen soil, destabilization of natural thermal processes and halo of thawing soil is formed. The halo reaches 3-10 м and more after 7-10 years of operation for pipelines with diameter 1220 and 1420 mm depending on the soil conditions. It is considered that (Seligman,

2000) the presence or absence of an artificial warming influence (compressor stations or gas processing plants) is the most important factor influencing interaction variability. However in both cases (“cold” or “warm” pipeline) displacement of pipe leading to damages is possible. Though many of these problems could be avoided by regulating gas temperatures, the technique of temperature mode management still needs to be developed. Existing gas temperatures 5-20°C after compressor stations (Khasyreyskaya, Pangody etc., for example) in Western Siberian icy soil create conditions for thawing and deformations.

As it has been shown by Kydriavtchev et al. (1971), the following simple formula could be used to determine thawing around pipeline with air temperature):

$$h=\xi(d/(d+h))^{-2} \quad (1)$$

where ξ – active layer depth, d – diameter of the pipe.

Modern technology of gas temperature regulation is not applied on the major pipelines yet (Galiullin et al., 1996). Presently only Yamburg and Nadym compressor stations have operational cooling units. Average temperature of gas is about 20ºC in summer and 10ºC in winter in most cases; compressor stations with cooling units decrease summer gas temperature to +2 ÷ +4ºC. Pipelines transporting chilled gas are distinguished by less deformation.

2. Mechanical interaction: an example from Medvezh’ye gas field, Western Siberia

Dynamics of process of freezing and thawing around the pipe and vertical movement is seasonal. In autumn with the beginning of freezing of soil the pipe moves together with the soil upwards. It is important to note that the rate of freezing of soil around of pipe in is usually more, than from the surface. Then a vertical moving of pipe occurs due to frost heave. The maximum strains and deformations of pipe are reached at the end of freezing soil.

Laboratory tests show (Figure 3) that strains in the soil can reach considerable values. Relationship between strains, stresses and properties of soil and pipe could be presented as:

$$dP_h = \frac{d\varepsilon_h - d\varepsilon_{shrink}}{\frac{1}{k_{gr}} + \frac{1}{k_g} + \frac{l_{mlt}}{E_{mlt}} + \frac{l_{fr}}{E_{fr}}} \quad (2)$$

where ε_h - potential deformation of frost heave of soil; $d\varepsilon_{shrink}$ – shrink of unfrozen part due to dehumidification of soil; K_r - rigidity of sensor (or object to affect, for example, pipe); K_{gr} – factor of decreasing of freezing pressure in soil, if the soil is allowed to expand; P_h - pressure (strain) acting in the system; l_{fr} and l_{mlt} - size of frozen and unfrozen part respectively; E_{fr} and E_{mlt} - compression modulus of frozen and unfrozen part of soil respectively

It has been found from experience of operation of gas pipeline Messoyaha - Norilsk in 1970-1979 that in summer, time of deformation of gas pipeline on sites of underground lining practically were not observed. However stresses in the pipe at freezing of soil around at negative temperature of gas can reach critical values.

In 1999 the authors have executed an inspection of gas pipelines (collectors) on the Medveje gas field. The gas pipeline of high pressure by extent of 120 kms and by a diameter of 1420 mm (thickness of walls of 15, 7 mm; on sites of transitions - from 18.7 up to 20 mm) was constructed in 1972. The area is characterized by distribution of permafrost, discontinuous in the southern part and continuous in the northern area. Temperature of frozen soil varies from 0ºC in the south up to -3.0º ÷ -5.0ºC in the north. Ice content of frozen soil changes from 0.0 up to 0.3-0.5 and more. Practically all lithological types at freezing are characterized by frost heaving. A rejection of the design principles of use of soil have resulted in numerous deformations of collectors. The project supposed preservation of permafrost status of soil. For this purpose thermal insulation of pipelines was provided. A polysterol shell of 100 mm thick should be used as the basis of design of the pipeline. However, at the construction the thermal insulation of pipelines was not made, and areas of thawing of various sizes (from 5-6 to 13 m) were formed under the pipelines on sites of permafrost distribution. The most deformed sites of the collectors are typical for the places of soil lining. In the period, when the pipelines yet have not lost the rectilinear configuration, the area s of thawing and thermokarst depressions are formed which in turn promote destruction of embankment on sites of soil lining. On the lowered sites and depressions under influence of thermokarst processes and superficial waters the embankment was completely destroyed, however pipe was not displaced downward, since its floating capability interfered in wet conditions. It was no pipe jam in soil on these sites; and pipelines have had a possibility to be deformed, and displacements reached 5-10 m. There are three areas in total of the extreme horizontal and vertical deformations by extent of 75 km (of 120 km pipeline), the amount of the deformed sites exceeds 40 (Figure 4 -6).

Before construction continuous permafrost was distributed there; temperature was -1.8ºC ÷ -2.0ºC, active layer depth was 1.2 ÷ 1.6. After construction an area of thawing was created around the pipeline. Now its geometrical size is 4.5 m wide and 8.5 m deep.

Stress of the pipe σ could be found from (Reference book …, 1960)

$$\sigma=-ql^2v/12W(1+v), \quad (3)$$

where $v=45I/4Ff^2$; $\boldsymbol{f}$ – deflection of a pipe, m; $\boldsymbol{q}$ - weight of 1 m pipe, kg; $\boldsymbol{I}$ - moment of inertia of pipeline section, m^4; $\boldsymbol{F}$ – square section of the pipe, m^2; $\boldsymbol{W}$ –axial moment of resistance of pipe section, m^3; $\boldsymbol{l}$ –length, m.

If we consider diameter of pipe 1420 mm, thickness of wall of 15.7 mm, distance between support, 100 m, intensity of the distributed load 6000 Н/м. weight of a pipe 54026 kg; the axial moment of inertia of section of a pipe 0.017 $м^4$; the axial moment of resistance of section of a pipe 0.024 $м^3$. In this case the stress (the central section) 312 МПa, and greatest deflection of a pipe 2178 mm. In spite of the fact that the given calculations are rather approximate, stresses caused by the deflection of pipe (Figures 7 and 11) are big and can result in destruction of metal.

It is important to consider another, rather frequently occurred in practice case of transition of the underground pipeline through a thawed zone – valley or creak, or lake (Figure 8). The experimental measurements of stresses of pipeline are extremely limited. For example, on an experimental site of the pipeline by a diameter 27.3 см and length 18 м in Caen, France, the vertical displacements of pipe have reached 11 cm, and stresses exceeded 100 MPa (Pipelines and frost heave, 1984).

The more the model is refined, the more complicated it becomes to evaluate the parameters. First of all the calculation requires an adequate knowledge of the mechanical properties of the surrounding soil. Even taking into account the reaction modulus of the soil leads to result, which mostly depends on value of the modulus (Pipelines and frost heave, 1984). The uplift resistance of the pipe, which is generated by the frozen soil, could be measured experimentally (Nixon & Hazen, 1993). Thus we decided not to apply special models adapted to pipelines (Marche, 1973, Nixon & Hazen, 1993), but to use the simplest approach. Pipeline is considered to be immobile on the ends of talik in frozen soil (Figure 8)

In case of freezing of a thawed soil in the winter as a result of cooling influence of the cold pipeline stacked in soil on the depth of 1 м, frost heaving occurs, which causes moving the pipeline upwards together with a soil. The degree of frost heaving depends on water content of soil and temperature mode. If it is assumed it has reached 20 cm, that can be, if soil is water-saturated. The pressure of frost heave can be very big. Approximately the pressure is defined in the case of the closed system under condition of equality of pressure in ice and in water $P_{ice} = P_w$ from the Clapeiron equation:

$$Q\frac{dT}{T} + (v_{ice} - v_w)dp = 0 \qquad (4)$$

v - specific volume, Q - mole heat of phase transition, T - temperature. Thus, the pressure can reach about 13.4 MPa/ºC. If, as it occurs, apparently, in most cases, the free water outflow happens from freezing (Pw = 0), we have the following expression:

$$Q\frac{dT}{T}+v_{ice}dp_{ice}=0 \quad (5)$$

Therefore, the increase of frost heave pressure P_{ice} occurs almost 10 times less, because

$$\frac{v_{ice}-v_w}{v_{ice}}\approx 0.1 \quad . (6)$$

In this case the pressure can reach about 10^7 H per metre of the pipeline of the large diameter.

At a width of a thawed site of 10 m and if the pipeline moves together with the freezing soil and remains immobile in permafrost, using the formula (3) we have a diameter of pipe 1420 mm, thickness of wall of 15.7 mm, distance between support, 10 m, intensity of the distributed load 5000000 H/м. weight of a pipe 5402 kg; the axial moment of inertia of section of a pipe 0.017 $м^4$; the axial moment of resistance of section of a pipe 0.024 $м^3$. In this case the stress (the central section) 2598 МПа, and greatest deflection of a pipe 181 mm. Thus, the increase stress in the considered case can be big enough to cause destruction of the pipe. The value of displacement of pipe is quite reasonable; such that the vertical deformations were observed on many pipelines. In case of pipe of a smaller diameter, for example, 529 mm with wall thickness of 9 mm, similar stress conditions could be found if distance between support, 10 m, intensity of the distributed load 7000 H/м. the axial moment of inertia of section of a pipe 0.00049 $м^4$; the axial moment of resistance of section of a pipe 0.0018 $м^3$. In this case the stress (the central section) 46 МПа, and greatest deflection of a pipe 183 mm.

Apparently, the fact that at smaller diameter of pipeline the value of stress even at appreciable deformations remains within the limits allowed has resulted in the widespread underestimation of influence of cryogenic processes on pipelines.

Half of the failures occur on pipelines with diameter 1420 mm. It should be taken into account that the stresses have been accumulating over many years of displacement of pipes. A comprehensive analysis of this problem requires a finite element modeling in relation with a simulation of a heat and mass transfer in soil. Uncertainty of conditions of mechanical interaction of pipe and soil, including rigidity and compression modulus, values of loads and temperature mode makes difficult creation of an adequate model of the stress-strain condition of the pipeline. In this case stresses could be found using measured values of deformations.

Therefore, estimation of stresses on base of measured values of deformations occurred on present pipelines shows that in some cases of permafrost processes development of the stresses are close to the strength of the material and could cause a failure.

Review of cryogenic processes affecting pipelines

Construction and operation of pipelines lead to activation of geocryological processes. As a result of thawing of frozen soil, the formation of extended taliks along pipelines occurs. It causes softening of soil and displacement of pipe downwards. For example, on a site of 0-250 km of gas pipeline Urengoy-Nadum-Punga the general extent with completely or partially naked pipe as a result of floating-up of pipeline reaches 60-70 % on frozen soil, and 22-48 % on thawed. There are significant horizontal and vertical deformations of the pipelines: deviations of a design up to a few meters, vertical and horizontal arches, and other defects. Increase of about 1.5 times of depths of seasonal thawing of soil happens; development of thermokarst depressions up to 2.0 m depth, and swamping of surrounding area are observed. At the same time on some sites there is a significant reduction of thickness of active layer. Long-term frost heave develops from 25 up to 100 cm high. “Warm” pipelines are especially dangerous on the icy frozen soil. The processes occur so intensively, that sometimes the operation of the pipeline becomes practically impossible in some years. The infringement of vegetative cover, change of temperature mode and depths of seasonal thawing - freezing of soil makes active solufluction and thermoerosion. Cutting of trench also results in partial or complete release of lakes and creating of permafrost in depressions of the drained lakes. It was found the biggest vertical and horizontal displacements of pipelines were observed for non-flat areas: slopes, small valleys)

Exposures of pipes. Underground pipelines are affected by floatage (Figure 9): the numerous surveys executed on pipelines show that the majority of embankments completely collapse on sites of on soil lining in 2-3 years, and the pipe is exposed. In conditions in the central areas of Russia, water-saturated soil from burial of pipelines achieve a density up to 70 % of the density of the natural soil for three - five years, in conditions of Urengoy and Yamburg sites - for eight - eleven years, and on Yamal even longer (Muhametdinov, 1999). The extent of emerged sites of gas pipelines belonging to Gasprom, has reached many hundreds kilometers, and the annual gain of floating gas pipelines makes 40-60 km (Bogushevskay etc., 2000). There are floating pipelines with length of 1.5 – 2 km on Medvezh'ye gas field. Floated up pipelines are exposed to seasonal temperature fluctuations and to surface geological processes such as erosion.

Frost heave: The basic danger to gas pipeline is not the frost heave itself, but its non-uniformity (Smith et al., 1985). The overwhelming part of the most complex deformations of underground gas pipeline is dated to zones of contact of sites of permafrost formation, where long-term freezing and frost heave takes place. The transitions of gas pipeline through lake depression and coastal parts of large rivers are such places. The long-term frost heave of soil occurs most intensively in the initial period, so deformations are observed for the first years of operation of gas pipeline. The annual frost heaving of soil varies on sites of line Urengoy-Nadum-Punga from 3 up to 147 mm (Nevecherya, Goralchuk, 1978). This area represents taiga forest with annual soil temperatures of about -4ºC to +1ºC and massive-island permafrost; active layer consists of water-saturated sandy silts and silts. It results in frost heaving of pipe with diameter of 1220 mm up to 16-86 mm and to occurrence of additional bends. Annual frost heaving on gas pipeline Mastakh-Yakutsk (Gaidaenko, Konstantinov, 1989) depending on geocryological conditions reaches from 46 to 262 mm, vertical moving of pipe is up to 229 mm, horizontal - no more than 20 mm. In the summer period the thawing of frozen soil is accompanied by settlement, reaching 40-50 mm. The very large non-uniformity of frost heaving (up to 30-50 cm on 1 m) was observed on site of a lowered lake, gas pipeline of Messoyaha-Norilsk, diameter 425 mm, 10 mm wall thickness. In the Enisei river valley, where the pipeline is buried, it has ruptured a few times due to 50-60 mm displacements by frost heave (Kharionovsky, 1994). It is important that frost heave of pipe continues some time after complete freezing of active layer. Raised sections of Urengoy's gas gathering system crossing small rivers and streams have been observed displaced by frost jacking of piles (Remizov et al., 1997).

The process of frost heave on tap sites and temperature equalisers is most dangerous, since result in deformations of pipelines and occurrence of emergencies. Similar deformations were developed on a site of gas pipeline from Yamsovei to the main system Urengoy - Petrovsk in two years after commissioning (Figure 10). The deviation of the crane on a vertical reached 10º, which has caused a temporary stop of gas transport for repairs.

The greatest difficulties in construction and operation of gas pipeline of Messoyaha-Norilsk have arisen in areas of transition through p. Yenisei. In this connection a long-term geocryological research by the faculty of a geocryology MSU here was executed, in which the author was participating. Complex geocryological conditions in there, presence of frozen and unfrozen soil, wide range of annual mean temperatures (from 0 up to -5ºC), presence of icy deposits and massive ice in a combination with an extreme temperature mode of operation of a gas pipeline (from +30C in the summer up to -56C in the winter) have resulted in development of geocryological man-made processes and occurrences of stresses in pipe, and failures. Due to transportation of chilled gas an area of seasonal thawing of soil around of the pipeline in November - January was completely frozen, therefore a pipe is squeezing. The longitudinal strains in the pipeline in this period reach 320 MPa that exceeds resistance for welded connections up to 40 % and metal up to 20%.

Frost cracks. The destruction of vegetation, reduction of snow cover, transportation of chilled gas cools superficial layers of frozen soil considerably. It can result in temperature strains and formation of cryogenic cracks in fragile frozen soil. It could be the reason for stretching strains in chilled pipelines leading to infringement of isolation of pipe and corrosion (Gretchischev etc., 1983). However, the problem still needs to be studied.

Thermoerosion. Thermoerosion is especially dangerous on icy soil. Practically all thermoerosion forms are created on slopes of valleys of rivers and creeks along the trench of gas pipeline or roads (Figure 11). The operation of lining underground pipe is usually done in the winter. Thus the soil cover has a broken structure and is hashed with snow and ice-saturated peat; therefore the soil strength is very small. Additional watering due to seasonal thawing of permafrost leads to intensive erosion. The length of actively growing ravine has increased from 100 up to 280 м on the inner collector of Yamburg gas-condensate field, for 7 years of operation (1993-2000), and its average growth rate has reached 25 м per one year. The depth near to a mouth of ravine reaches 10 m At intensive wash-out of soil there can be a displacement of pipe, its vertical and horizontal bend and deformation. Before construction of gas collector of Medvezh'ye field the process of thermoerosion practically was developed poorly, and on a site of 66-85 km of Urengoy-Nadum-Punga pipeline was not distributed. After the construction factor of staggering of the territory by erosive processes has reached 0,16-0,33 on gas collector Medvezh'ye and 0,11-0,20 on gas pipeline Urengoy-Nadum-Punga (Kozlov, Parmuzin, 2002). Inspection of system of pipelines from Yamsovei on a site 0 - 50 km has shown that thermoerosion processes occupy 75 % of slopes. As a result sagging of the pipe at lengths of 40-50 m will appear.

Slope processes. Slopes unstable on fine soil; thawed soil are especially unstable. The development of thermoerosion processes is usually connected to such slope processes as solufluction, mud-streams, landslides. Their joint or separate appearance is rather dangerous to stability of gas pipeline. For example, on the territory of Bovanenkovo gas field solifluction develops on slopes of an insignificant steepness (3-5º) even in the undisturbed conditions. At the length from 50 to 700 м and width from 30 to 100 м volume of the displaced soil can reach twenty thousand cubic meters and more.

Thermokarst. The depth of seasonal thawing of soil near pipes often exceeds depth of thawing in natural conditions by 2 times, and temperature of frozen soil is higher up to 2°C on many northern pipelines. Thermokarst, which is the growth of depressions after permafrost melting, is especially developed in areas of massive ice distrubution. Thermokarst processes are also widely distributed at turf areas crossing by pipelines (Figure 12). Inspection of gas collector in Medvezh'ye gas field (length of 120 km, diameter 1200 mm) have shown, that 20 % of total length of pipeline is in the area of thermokarst development.

The increase of the active layer depth due to surface disturbance during pipeline construction Promishlenny – Yakutsk and Mastah – Yakutsk – Pokrovskoe reaches 2 - 2.2 times on dry sites and 1.3 – 1.5 times on wet sites. Vertical displacements are close in values to frost heave movements of soil, and ten and more times more than horizontal displacements. On the pipeline of Мессояха-Norilsk on the left bank of Yenisei River the depth of thawing near pipe is 0.9-1.0 м, and the pipe settlement reaches 25 cm.

Swamping. On sites of peat tundras and in downturn of relief along lines of gas pipelines process of swamping develops widely, that promoted by superfluous humidity of thawing soil, small evaporation, affinity of confining bed - frozen soil (Figure 13). If in natural conditions factor of staggering by swamping makes from 0,04-0,20 (gas pipeline Medvezh'ye-Nadum-Punga) up to 0,11-0,60 (gas pipeline Urengoy-Nadum-Punga), after lining of gas pipelines it is increased up to 0,26-0,44 (gas pipeline Medvezh'ye-Nadum-Punga) and to 0,85-0,91 (gas pipeline Urengoy-Nadum-Punga).

Icing is also one of the processes affecting pipelines. The pipeline of Мессояха-Norilsk have been affected by icing on the left bank of the Enisei River.

Bearing capacity of soil might be getting low; especially thawed soil are not stable as well as **frozen saline soil**, which are widely distributed in the Artic coast; they have high corrosion activity and low bearing capacity, which decrease twice and more with salinity.

Forest fires and permafrost disturbance represent a problem, which becomes significant due to global climate change. Forest fires are very common in the Eastern Siberia; their number significantly increased in the last few years. Coming **global warming** can cause permafrost to melt; drastic changes and activation of all dangerous processes may happen. Large territories of Russia could be involved in considerable landscape development, thermokarst depressions formation, watering and swamping.

Geotechnical problems at compressor stations

On the average at compressor stations in Western Siberia annually there are 10-15 various emergencies, and they are caused by interaction with permafrost. The construction of compressor stations is accompanied by change of geocryological conditions, increase of temperature of soil and reduction of their bearing capacity. The most powerful heat source is the devices for air cooling of gas (AAC). The fans used in their operation in the recirculation mode forces warm air directly to the base. Thus after a few years of operation taliks are formed; their depth reaches 10-12 м (Figure 14). One of failures has taken place in 1996 at the Urengoyskay compressor station. The thawing of ice-saturated frozen soil in the basis has resulted in a settlement, deformation of the base and failure 3-rd bloc for a long time. For the period 1995 ÷ 2002 more than 20 shutdowns of compressor stations on Yamburg and Urengoy gas field occurred. The reason of the shutdowns - necessity of repairs on liquidation of deformation, connected with non-uniform settlements of the frozen soil at thawing.

Deformations of pipelines are also caused by non-uniform seasonal and long-term frost heave. The tap devices and places of an output of gas pipelines on a surface at their connection to compressor units are most vulnerable area. The process of deformations development in areas of the automatic crane on Pravohettinskay is given on Figure 15. Frost heave of more than 300 mm have resulted in a bend of pipe, deformations of crane sites, and in November, 1994 - to automatic block of the crane and failure of the gas pipeline. The similar case happened on Longuganskay compressor station of gas pipelines Urengoy - Novopskov in August, 1997; there was an explosion of crane site, and the pipeline was out of operation for more than 2 weeks.

Conclusion

Construction and operation of pipelines in cryolithozone leads to forming or activation of geocryological processes developing in a zone of direct interaction of soil with the pipeline and on adjacent territory. As a result of increase of up to 2 times of depths of active layer, development of thermokarst depression of up 2.0 м and thawing of frozen soil there is a formation of taliks along gas pipelines with positive temperatures. There are significant horizontal and vertical deformations of the gas pipelines resulting in occurrence of intense stress - corrosion of pipes, and swamping of the territory occurs. At transportation of gas chilled up to negative temperatures there are new problems connected to freezing of taliks crossed by a gas pipeline, and to return freezing. As a result of non-uniform frost heaving and the raisings of pipelines occur. The formation of cup of thawing under the pipeline causes a non-uniform displacement and promotes deformation of embankment (failures and funnels, slipping of slopes). Statistics shows a large number of failures on pipelines.

Geotechnical problems connected to change of geocryological conditions appear on compressor stations. Most vulnerable parts of pipelines are crane sites and places of connection to compressor stations.

In a direction from north to the south the role of dangerous cryogenic processes on the surface decreases and the share of failures connected to change of temperature mode of the frozen bases is increased.

Uncertainty of conditions of mechanical interaction of pipe and soil, including rigidity and compression modulus, values of loads and temperature mode does not allow to create an adequate model of the stress-strain condition of the pipeline. Estimation of stresses on base of measured values of deformations occurred on present pipelines shows that in some cases of permafrost processes development the stresses are close to the strength of the material and could cause a failure.

Permafrost processes seem to be underestimated in pipeline design and construction. For the long time it was not taken into account that stresses induced by interaction of pipeline and permafrost (frost heave, cracking, slope processes) could reach strength of the pipe.

In spite of obvious evidences of possible danger of the permafrost-related processes to pipelines, and list of references, there are still no investigated and proved cases of failures caused by them, because engineering and geocryological research combined with stress-strain calculations needs to be done. The realization of the study (mathematical modeling, laboratory and field experiments) of thermal and mechanical interaction of pipelines with seasonally frozen soil and permafrost is particularly necessary for future exploration. A part of the study should be the wide experience of construction and long-term operation of main pipelines in North of Russia.

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Tables

Table 1. History of pipelines construction from major northern Russian gas fields

Commissioning years	Fields	Number of pipes	Total length within permafrost, km
1969	Messoyaha	2	720
1972	Solenenskoe	1	380
1972 - 1976	Medvezh'ye*)	3	1860
1978 - 1986	Urengoy	10	6 700
1986 - 1991	Yamburg	9	7 200
1993	Yubileynoye*)	2	30
1997	Yamsovei*)	2	90
2001	Zapolyarnoe*)	3	420

*) Total length of these pipelines is estimated from gas field to existing pipelines network

Table 2. Emergencies on sites of underground lining of gas pipeline Messoyaha - Norilsk in 1972 - 1974 (infringements connected to deformation of the pipeline)

Date of deformation	Element of relief	Type of infringement
12.01.72	Right side of creek	Break of welded seam
21.01.72		
15.12.72	Channel of creek	Crack on joint

19.12.72		
24.01.73	Right side of creek	Break of joint
24.01.73	Side part of lake depression	
24.01.73		
	Surface of high flood-lands Yenisei	
26.01.73		
19.11.74	Right coast creek	

Figure captions

Figure 1. Distribution of annual failures on pipelines in Sakha Republic (Kamensky, 1988)

Figure 2. Schematic position of pipeline and frozen soil: a position of the border of frozen (dark color) and thawed (light color) soil during summer (left side) and winter (right side) in the permafrost (a, b) and talik (c, d) areas at temperatures of pipeline: below (a, c) and above zero (b, d)

Figure 3. Strains in the soil during freezing of water-saturated silt sample of size 5 cm : 1 – one-dimensional; 2 – all-dimensional freezing. Rigidity of sensor is 1500 MPa/m

Figure 4. Horizontal position of pipeline, site 411 (I line), from the point of 654 to the point of the 659; total length is 500м

Figure 5. Horizontal position of pipeline, site 525 (I line), from the point of 602+30 to the point of the 595+40; total length is 690 м

Figure 6. Vertical position of pipeline, site 525 (I line), from the point of 602+30 to the point of the 595+40; total length is 690 м

Figure 7. Deflection of pipeline, Yamburg-Eletz, between Yamburg and Nyda compressor stations

Figure 8. Model of interaction of pipeline with freezing soil in talik

Figure 9. Upheavals of buried pipes, pipeline Urengoi-Center

Figure 10. Deformation of tap site due to frost heave, Yamsovei pipeline

Figure 11 Thermoerosion destruction of banking-up and soil at the base of gas pipeline. Yamburg-Eletz

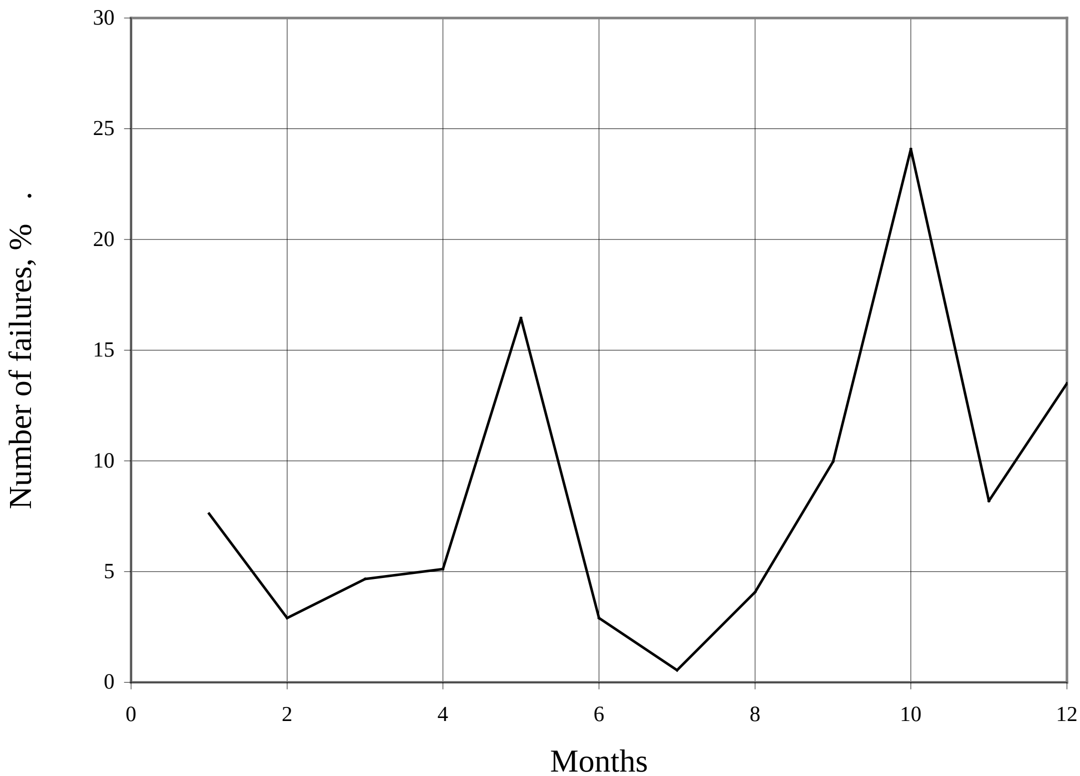
Figure 12. Thermokarst processes on pipeline Yamburg – Tula, 15 km from Naduinskay compressor station

Figure 13. Swamping on sites of peat tundra pipelines Urengoi-Center

Figure 14. Temperature in base of compressor station Medvezh'ye: before (a) and after 5 years (b) construction in August 1993

Figure15 . Deformation as a combination of the settlement and frost heave up to 37 cm of the automatic crane on compressor station Pravohettinskay due to change of geocryological conditions and thawing of permafrost

Figures



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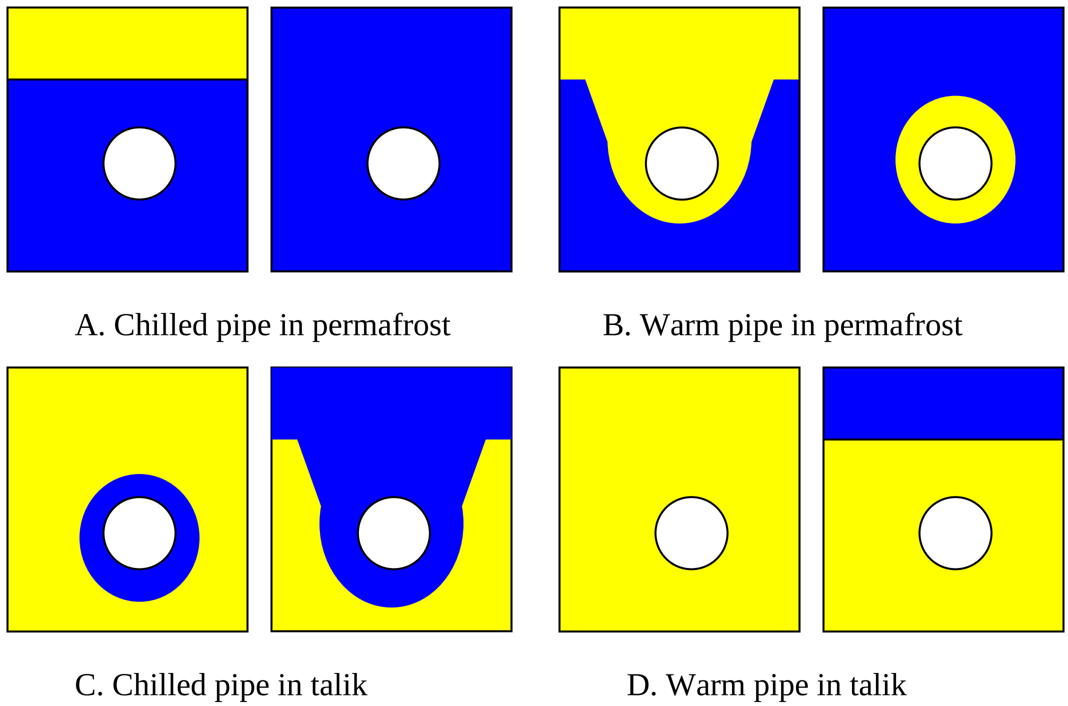

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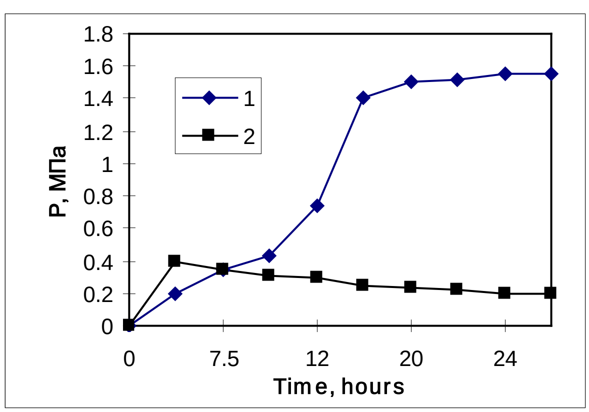

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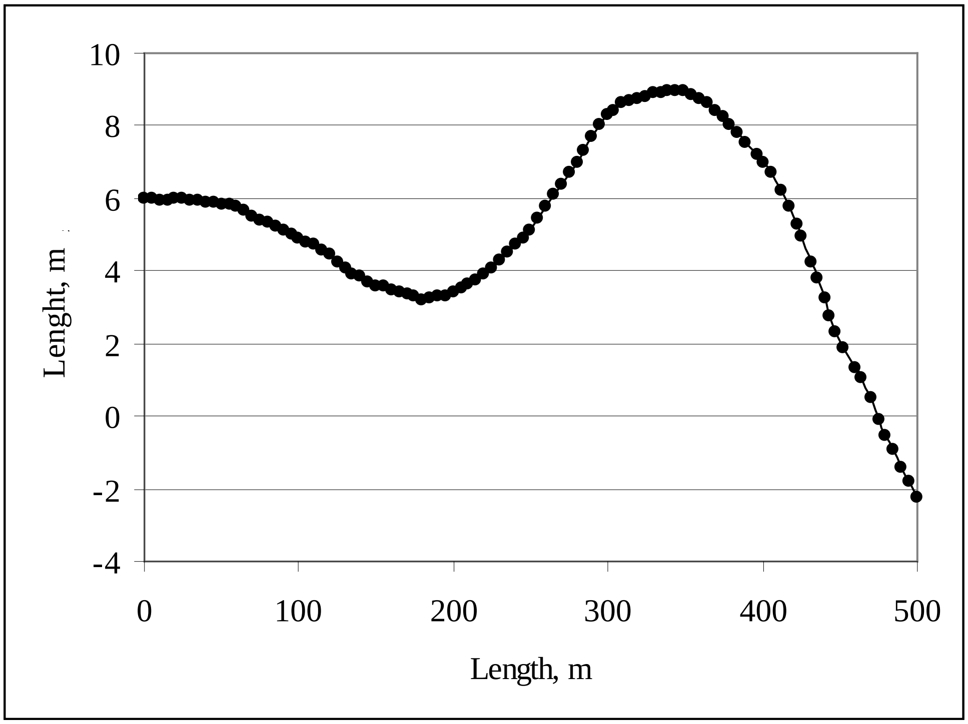

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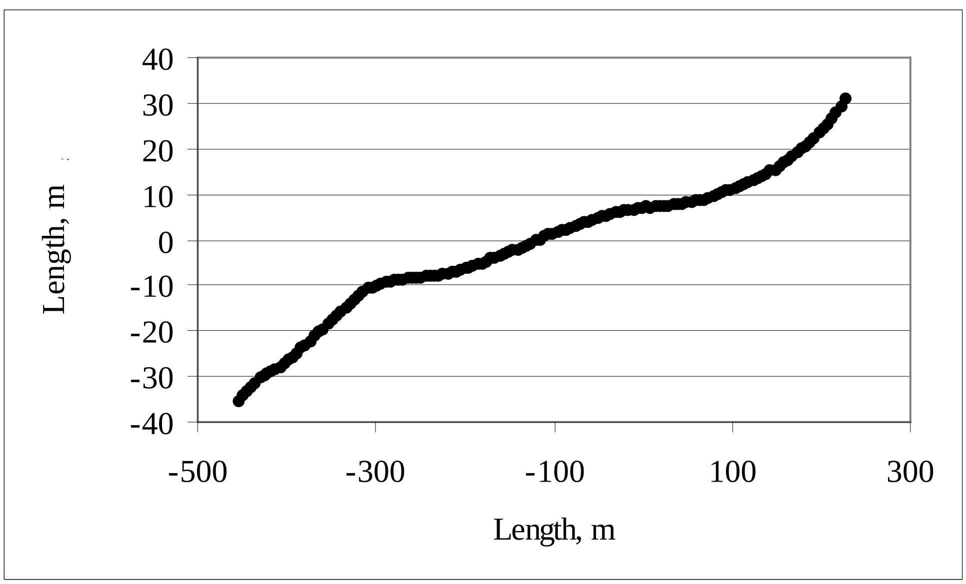

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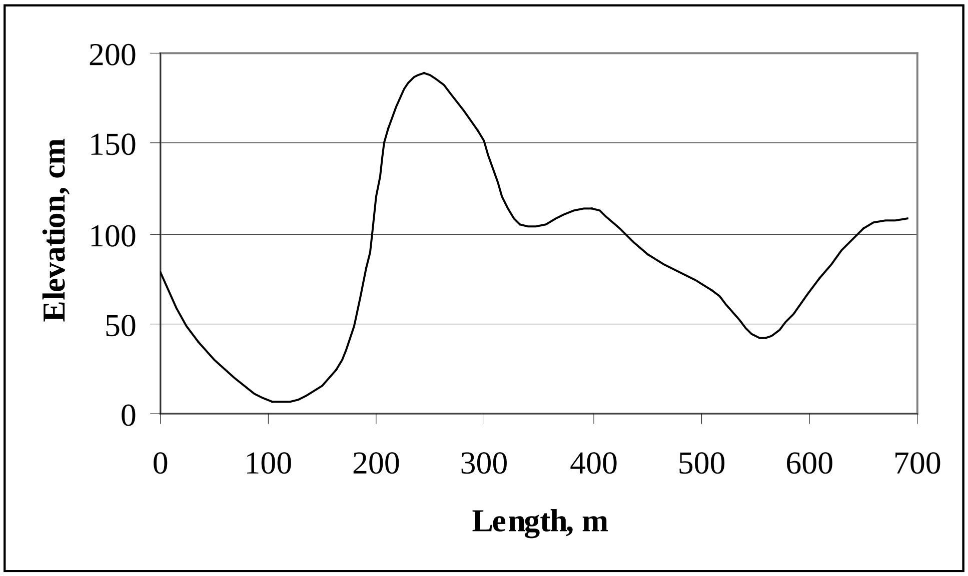
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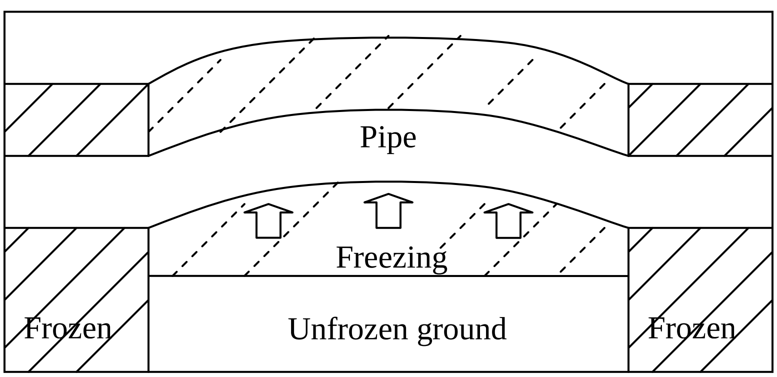
Figure 6.

Figure 7.



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a)

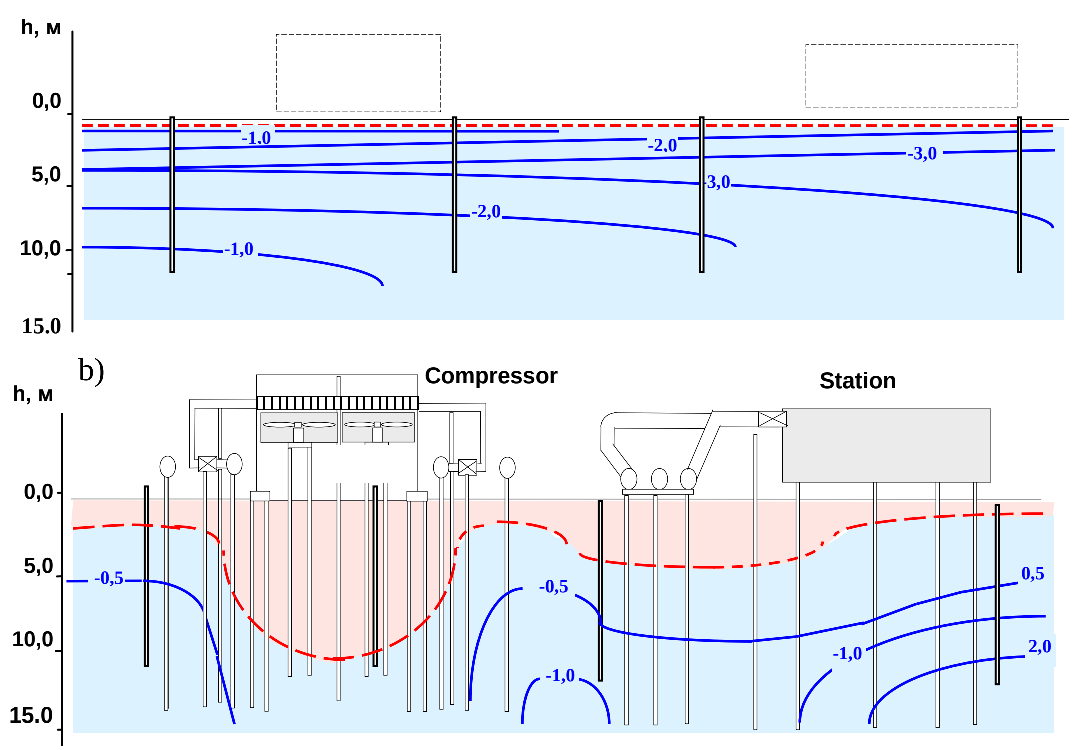
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Figure 14

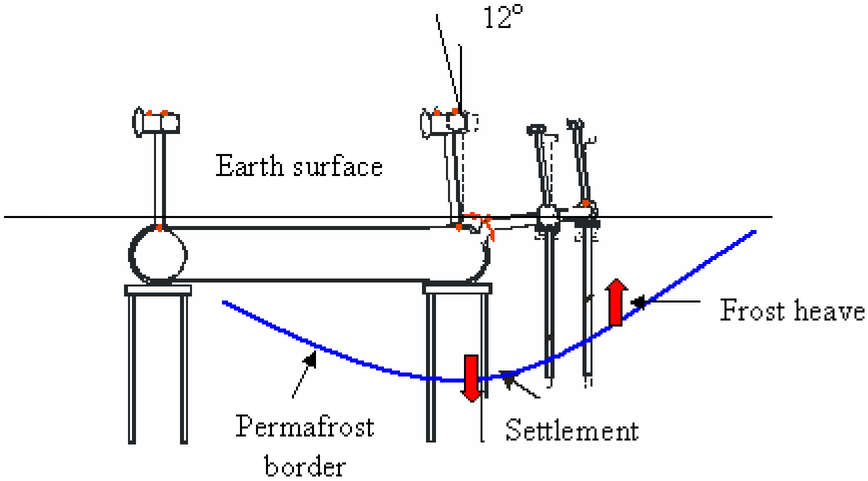

Figure15