Soil cryogenensis as a natural risk factor for gas pipelines in the permafrost zone during modern warming

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Abstract. The paper summarizes the experience of studying the effect of modern warming on the thawing depth of sandy and loamy soils in the permafrost zone. The definition of soil cryogenesis as a natural process and facies as the end result of soil cryogenesis as a process is given. The effect of soil cryogenesis facies on stress corrosion cracking of gas pipes of the Gazprom system in cold and warm seasons has been studied. It was found that the facies of soil cryogenesis are interconnected by the process of energy and mass exchange. It is shown that in the annual cycle, each facies formed by soil cryogenesis is the basis for the development of stress corrosion cracking of gas pipelines.

1. Introduction

Corrosion of gas pipe metal in the soil is the main reason for the rapid deterioration of gas transmission systems. The service life of gas pipelines is now coming to an end. Therefore, assessing the condition and prolonging the service life of gas pipelines is the most urgent task of the present time. Studies of soil and ground corrosiveness assessment have shown that corrosiveness is based on biological and chemical interaction processes in the system gas pipe metal – chemical and biological properties of the soil containing the pipe.

Identification of mechanisms of corrosion aggressiveness of different soils of zonal series is necessary for development of technologies of gas pipelines service life extension, for development of forecasting rates in different types of zonal soils, for substantiation of methods of pipe corrosion protection. For the development of reliable protective technologies against corrosion aggressiveness of the soil containing the pipe, it is necessary to have a qualitative and quantitative characteristic of corrosion aggressiveness of soils and grounds of each natural zone. On the other hand, the obtained chemical, physicochemical and biological characteristics of the corrosion aggressiveness of soils and grounds did not provide reliable information for the development of technology to increase the service life within a certain soil-climatic zone. Application of the results obtained for a different soil-climatic zone does not lead to the desired result, as evidenced by numerous data [1]. However, it has been shown that the intensity of corrosion process development is largely determined by the temperature conditions of the soil and the temperature of the pumped gas. Modern warming will lead to the intensification of soil cryogenesis as a process, which will undoubtedly be accompanied by the risks of gas pipes.
The goal of this work was to study the influence of soil cryogenesis as a process and facies as the end result of soil cryogenesis on the intensity of gas pipe risk development in the permafrost zone under conditions of modern warming.

2. Objects and methods
The object of the study is soil cryogenesis:
- as a result of climate dynamics and
- facies as the end result of soil cryogenesis as a process of impact on the metal pipe of the gas pipeline in the permafrost zone.

3. Results and discussion

3.1. Modern warming in the permafrost zone
Modern warming in the cold and warm seasons is observed at the global, continental, and regional levels [2]. Modern warming is not in doubt, but there is no consensus about the causes of warming. Most scientists associate warming with human activity, primarily with emissions of carbon dioxide into the atmosphere, which forms the greenhouse effect [3]. Another part of scientists associates warming with a shift in the inclination of the earth's axis. The theory of warming associated with the resonant effect of anthropogenic environmental pollution by the products of economic activity that form the greenhouse effect and the natural increase in the energy parameters of the modern climate, has no less right to exist [4].

3.2. Changes in the thaw depth of soils in the permafrost zone during warming as a risk factor
An increase in the depth of seasonal thawing-freezing of soils in the permafrost zone is a special problem due to modern warming [5, 6]. Significant spatial heterogeneity of soil temperature changes during warming has been shown in the permafrost zone [7, 8]. For soils of light textures and free water drainage, modern warming is accompanied by an increase in the depth of seasonal thawing. In loamy soils underlain by permafrost in poor drainage conditions, warming is accompanied by formation of suprapermafrost water. An ice-saturated soil profile requires increased heat consumption for ice-water phase transitions during thawing, which leads to a decrease in the depth of seasonal thawing and a decrease in the heat supply of soils during the warm season [9].

Previously, it was predicted by model simulations that, given the rate of permafrost temperature increase up to 0.05°C per year in the 21st century, the depth of seasonal thawing should be expected to increase [10–12]. In the least aggressive anthropogenic scenario, the seasonal permafrost thawing layer will increase from 0.4–0.5 m on average in Western and Eastern Siberia to more than 2–2.5 m in the Baikal region by the end of the 21st century. In the most aggressive scenario, the depth of seasonal permafrost thawing will increase from 0.7–1.2 m in the high latitudes of Eurasia and North America to 3–6 m at the southern border of the permafrost zone [13].

The risk of catastrophic consequences for soils and soil cover, industrial facilities and social infrastructure associated with permafrost degradation increases sharply with increasing depth of seasonal thawing-freezing. The increase in the depth of seasonal soil thawing is associated with climate warming [11, 14], with increasing thickness of snow cover as a heat insulating natural factor [6], with changes in the vegetation cover [15] and anthropogenic activities [16].

O.V. Makeev [17] divided the soil cover of the Earth into frozen, cold, and warm formations according to the degree of influence of subzero and negative temperatures on the soil. The permafrost soil formation includes soils in which the seasonal permafrost merges with the perennial permafrost. The cold soil formation includes soils of seasonal freezing-thawing. Formation of warm soils includes soils with no seasonal permafrost. In permafrost and cold soils, a fundamental role in the development of gas pipe risks is played by soil cryogenesis as a natural factor and facies as the end result of cryogenesis as a process.
3.3. Soil cryogenesis as a process of changing soil properties and regimes during freezing–thawing and facies as the end result of the process are risk factors

Soil cryogenesis as a natural process is a change in soil properties and regimes under the influence of zero, negative and positive temperatures and water–ice–water phase transitions during freezing, preservation in the frozen state, thawing and staying in the thawed post-cryogenic state. Soil cryogenesis as a natural process is a constant risk factor for gas pipelines in the Eurasian permafrost zone. The diversity of forms, their combination and intensity of cryogenesis in soils are associated with temperature and hydrological processes, which determine risks of gas pipelines catastrophes in cold (when soil is frozen and in frozen state) and warm (when soil is thawed and in thawed state) periods of the year.

Analysis of the definition of soil cryogenesis as a natural phenomenon shows that soil cryogenesis in the annual cycle has cold and warm climatic periods of development, the end result of which are temperature and hydrological facies during freezing and the soil staying in frozen state and temperature and hydrological facies of the warm season.

The facies is the end result of soil cryogenesis as a process. Soil cryogenesis as a process is considered as the end result of climate dynamics of each soil-climatic zone of the permafrost formation soils. In climatic terms, the facies, as the end result of the soil process, is considered in the work during cold and warm periods of the year.

From the description of soil cryogenesis as a natural process, it follows that the main factors of soil cryogenesis determining corrosion risks of gas pipelines in cold and warm periods of the year are:

- temperature facies,
- hydrological facies,
- microrelief facies.

Ultimately, the work considers the facies as a triad – a factor, a process, a result of a process.

3.4. Temperature facies of soil cryogenesis

Types of soil-climatic facies in the annual cycle:

3.4.1. Temperature facies of the cold period as a factor. The cold season is frozen soil with zero and negative temperatures. These soils include tundra and taiga soils of the permafrost zone, which are frozen for up to 9–10 months a year.

3.4.2. Temperature facies as a cold period process. Penetration into the soil of zero, negative temperatures and water-ice phase transition in the cold season is accompanied by compression of the gas pipe.

3.4.3. Temperature facies as a result of the process. This is a permafrost microrelief: hillocks, aufeis (naled in Russian), etc.

3.4.4. Temperature facies as a warm season factor is the presence of positive temperatures in the soil during the warm season. Heating a gas pipeline with atmospheric heat and the temperature of the pumped gas is accompanied by an increase in the length of the gas pipeline, causing stress corrosion cracking.

3.4.5. Temperature facies as a warm season process. It is the penetration of zero and positive temperatures and ice-water phase transitions into the soil. Heating of the soil and the gas pipeline in the range of positive temperatures during the warm period of the year under conditions of modern warming and heating of the gas pipeline with the temperature of the pumped gas is accompanied by an increase in the depth of thawing of icy soils.
3.4.6. **Temperature facies as a result** of the ice-water phase transition process and soil heating from 0°C to its maximum summer values. These are thermokarst voids, wedges, pockets, cracks on one side, etc.

3.5. **Hydrological facies of soil cryogenesis**

3.5.1. **Hydrological facies, as a factor of soil cryogenesis of the cold season**, is characterized by the presence of moisture in the soil in the form of ice. Ice content is one of the factors of soil cryogenesis. Ice content, as a hydrological facies of soil cryogenesis, is the end result of the water-ice phase transition when the soil is at zero and negative temperatures. In soils and grounds, depending on their water saturation, ice content is presented in the form of ice-cement, mesh, lenses and ice veins of various thicknesses, etc., forming a physical and chemical spatial heterogeneity of soils and grounds.

3.5.2. **Hydrological facies as a process of ice accumulation in the cold season** is characterized by water-ice phase transitions and ice freezing in the soil. In the seasonal cycle, water-ice phase transitions are one of the factors that determine the risks of disasters during long-term operation of gas pipelines. A distinctive feature of the properties of water is that in the autumn period of penetration into the soil of zero and negative temperatures in the profile of permafrost soils, moisture accumulates in the form of ice, the supply of which can exceed the total porosity by 1.5–2.0 times or more. During the freezing period under conditions of moisture inflow from the upper parts of the slope, ice accumulates in the near-pipe part, as a result of which additional pressure on the pipe arises under the weight of the pipe, ice and soil. In one case, this pressure is accompanied by stress corrosion cracking, in the other case, it is accompanied by the onset of solifluction – the thawed part of the soil sliding down the slope together with the gas pipe, creating additional stress, leading to cracking of gas pipes.

3.5.3. **Hydrological phase as the end result of soil cryogenesis as a process in the warm season** is characterized by ice-water phase transitions, water saturation of the soil and the presence of the soil in the range of positive temperatures.

In the warm period of the year, when the icy permafrost thaws, thermokarst, baydzharkhs, hydrolaccoliths, thermokarst-erosion gullies and other negative landforms are formed. Freezing of ice on the slopes in front of the gas pipe in the autumn-winter period should be considered as an input item of the water balance, which is in the soil in the form of ice, which enters into moisture circulation in the spring when the soil thaws. This part of the input item of the water balance plays an important role in the oversaturation of moisture in the soil containing the gas pipe. In a soil oversaturated with moisture, favorable environmental conditions are created for the development of gley processes and sulfate-reducing microorganisms, which ultimately leads to stress corrosion cracking of the gas pipe. Sagging of the gas pipe over cryogenic negative landforms leads to the development of a network of microcracks on the bends of the gas pipe, which ultimately leads to stress corrosion cracking of the gas pipe.

3.6. **Possible effects of the consequences of warming on soil cryogenesis as a risk factor Suprapermafrost water during warming. Warm period of the year**

One of the factors of corrosive aggressiveness with increasing depth of soil thawing during warming is the formed suprapermafrost water, which essentially acts as an electrolyte. When the pipe interacts with the electrolyte, the process of accumulation of damages on the metal surface in places with a damaged protective film is initiated. In addition, an important condition for the occurrence of stress corrosion cracking of a metal is the presence of active chemical compounds in the suprapermafrost electrolyte, which cause the accumulation of microdamages in cracks. These compounds are formed as a result of the vital activity of bacteria and chemical reactions of decomposition of organic substances of plant and animal origin. These compounds are carried away from the soil surface and enter the gas pipeline with surface and subsoil waters, which causes an increase in the concentration of active...
substances that cause stress corrosion cracking. It is known from experience that the most stress-corrosive effects are at the intersection of a gas pipeline with drying up streams. This is due to the higher concentration of active substances in the water, as well as to the change in anaerobic and aerobic conditions. At the same time, under anaerobic conditions, the growth of stress-corrosion defects occurs, and under aerobic conditions, the destruction of the primer and the adhesive layer of the insulating coating occurs, which leads to a loss of adhesion of the insulation to the pipe. A visual sign of anaerobic conditions is the presence of white corrosion products under the insulation, and aerobic conditions are the presence of brown corrosion products.

**Thawing of ice of soil and ground during predicted warming**

The current and projected warming by 2050 is and will be accompanied by an increase in the depth of soil thawing, which will lead to melting of vein ice and formation of intra-soil thermokarst filled with water or loosened soil, resulting in additional bending stress under the weight of pipe and soil, stretching the lower forming pipe and compressing the upper one, which will eventually result in cracking of the gas pipe bends.

The microrelief facies during the cold season is characterized by the formation of positive landforms, among which frost bumps play an important role, forming during the autumn freezing period when zero, negative temperatures penetrate the soil and the water-ice phase transition in the soil develops permafrost processes of ice saturation and swelling, testing the gas pipe for rupture.

**4. Conclusion**

The presented material allows us to conclude that the initial risk mechanism for gas pipes in the permafrost zone, among numerous factors, is the temperature facies, hydrological facies and microrelief facies.

**Temperature facies of soil cryogenesis as a risk factor**

In the work, the dynamics of temperature in the cold and warm periods of the year forms a dual facies. In the cold period, in the process of freezing in the soil, a facies of negative temperatures is formed. Compression cracks are formed in a metal gas pipe under conditions of negative temperatures. In the warm period of the year, in the process of heating the soil, a facies of positive temperatures is formed, in the conditions of which cracks of rupture of gas pipes are formed when heated. In the annual cycle, the dynamics of soil temperature from negative values in the cold season to positive in the warm season leads to additional stress and the appearance of stress corrosion cracks in gas pipes.

**Hydrological and microrelief facies of soil cryogenesis as risk factors**

During the autumn freezing period, when zero, negative temperatures and water-ice phase transitions penetrate the soil, permafrost processes of ice saturation and frost heaving develop in the soil, forming a bumpy microrelief. In the warm period of the year, thermokarst cavities are formed when zero and positive temperatures penetrate the soil during melting of ice lenses and other ice formations. Sagging of the gas pipe over these voids leads to stress corrosion cracking of the pipe.

Ultimately, in a long-term cycle, the annual freezing-thawing leads to the formation of a two-pronged hummocky-depression facies in the microrelief. The double hummock-depression facies is a natural formation in which the hummock and depression are united by a single energy and mass exchange. During the spring thaw and summer rains, erosional flows, together with the mineral mass of the soils of the mound, are redistributed into depressions. During the period of freezing in the autumn and when the soil is in a frozen state, the moisture of the depression saturates the soil of the hillock with water, increasing the ice content of the hillock soil. The increase in soil ice content during freezing is accompanied by an increase in the height of the mound. The constant rise of the bump when it is saturated with ice tests the gas pipe for rupture upon fracture, leads to the appearance of cracks and the development of stress corrosion cracking.

Modern warming in the permafrost zone will lead to an increase in the depth of soil thawing. This will lead to the melting of ice wedges and buried ice lenses, and the formation of thermokarst formations under the main gas pipelines. Sagging gas pipelines over thermokarst voids will dramatically increase corrosion risks.
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