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STABILITY OF BASEMENTS AND STRUCTURES IN PERMAFROST

UTILIZATION OF THE COOLING CAPACITY OF LIQUEFIED NATURAL GAS FOR THERMAL STABILIZATION OF GROUND

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The possibility of using the cooling capacity of liquefied gas to increase the all-season operational reliability of the ground bases of the gas field infrastructure with possible subsequent gas utilization is discussed. The results of computer simulation of the temperature and water-salt profiles of the ground bases in the presence of cryopegs are presented. The accompanying tensions are also assessed, allowing the optimum values of thermal stabilizer inlet temperature for the purpose of minimization of the frost cracking process.

Thermal stabilization of the ground, liquefied gas, all-season thermal stabilizer, salted ground, cryopegs, frost cracking, temperature shock

INTRODUCTION

Thermal interaction of grounds with engineering facilities in the permafrost soil (PS) areas results in reduction of the carrying capacity of the ground bases due to grounds transition to the plastic frozen state or their melting. Ground salinity, which may be characteristic of cryopegs, exerts significant negative impact on this process, a feature characteristic of the arctic seas shelf and of littoral plains (Yamal Peninsula, etc.). Cryopegs are located at different depths in the ground as isolated lenses, which have no connection with each other and with surface and ground waters. For their chemical composition, cryopegs are close to sea waters; their mineral content is usually 10–250 g/L, and their composition is primarily chloride-sodium with an insignificant amount of sulfates. Salinity of the upper seabed layers of the arctic sea shelf is comparable to the mineralization degree of seawater.

In design and operation of the infrastructure facilities of the gas condensate deposits located in the permafrost regions, the use of thermal ground stabilization methods serves as one of the ways to minimize such negative impact. When the ground base is preserved in the frozen state in construction, the following is used: the cooling potential of atmospheric air in the winter period on the basis of seasonal cooling natural-circulation vapour-liquid devices of the vertical and horizontal types, and machine-based cooling methods with forced ventilation of the cooling agent.

Partial use of the cooling potential of the target product, liquefied petroleum gas (LPG), as well as of the products of its rectification (ethane and propane), having a low negative boiling point, may be a perspective solution of the problem of raising reliability of all-season functioning of the infrastructure foundations based on plastic-frozen and saline grounds.

The technological standard of LPG storage is assessed as the daily evaporative capacity of the storage tank, which amounted to 0.1 % of the liquefied petroleum gas in one tank. This loss is generated by the heat flows from the environment to the tank – in which LPG is stored at the temperature of –163 °C. The daily use of LPG is estimated to be less than 0.15 % of the liquefied gas mass. It is proposed to use these technological gas leaks for the purpose of thermal ground stabilization. Unlike the conventional seasonal thermal stabilizers, the cooling agent of the LPG complex has the following benefits: reliable operation of the facility on a year-round basis, irrespective of climatic conditions; utilization of the gas for cooling the facility foundation by its compression and liquefaction; a much higher ground freezing rate with minimization of ground bulging due to decrease of the amount of the water flow migrating to the freezing front; freezing the cryopeg lenses of any concentrations. It is possible to use the cooling resource of LPG for the local purpose of thermal stabilization of the ground base in liquidation of emergencies. Compared to the methods of machine ground cooling, the use of the LPG vapor effluents, followed by their utilization, will be economically effective. The source of raising the LPG performance is the possibility of introducing an additional contour into the technological process of thermal stabilization of the ground base, in order to extract rare inert gases (xenon, etc.) from the gas flow. Such facilities are available in the Russian Federation.

However, the use of LPG as a cooling agent in the design of an all-season thermal stabilizer (TS) may result in negative processes: 1) cracking on the boundary "TS wall–ground", related to emergence of large temperature gradients (thermal shock); 2) frost cracking of ground between piles in various layouts in terms of the plan and geometry of TS clusters and piles. In this regard, special attention should be paid to selection of the optimal value of the TS inlet gas temperature and of the design solutions in order to rule out (minimize) the cracking processes.

There is no methodology of using LPG recuperative cooling facilities for ground freezing in Russia. There is experience of using liquid nitrogen for ground freezing by flushing it into the pipe system in emergency liquidation in the functioning metro of Leningrad, as well as there are methods of solving the problems related to low-temperature underground storage of liquid hydrocarbons [*Rachevsky, 2009*].

The methodology of predicting interaction of an all-season thermal stabilizer with ground should include assessment of the temperature and water-ion behavior of grounds and cryopegs, as the latter determine the freezing start temperature, the content of unfrozen water, and the thermophysical and mechanical characteristics of frozen ground.

DESIGN FIGURES, SIMULATION AND SOFTWARE PRODUCT

Consider the uncoupled problem of thermoelasticity of a mass of ground which may include a cryopeg lens.

Setting a problem of computer simulation of ground freezing to determine the temperature fields in the rocks consists in the following. At the initial moment, the temperature on the TS surface of radius R_S and with length L_S of the mass of ground with the surface temperature T_{GS} drops to the gas temperature T_G and is maintained constant in time τ. On condition T_G is lower than the freezing start temperature of the pore water T_{bf}, the freezing zone begins to get formed, the depth of which grows in time. The phase transition of moisture into ice begins on the conditionally determined moving boundary – the freezing front $R_\xi = f(\tau)$, which divides the ground mass into melted and frozen zones and continues till the latter one, where distributed heat sources (stocks) work uniformly. Thus, a case is considered when massive cryogenic texture gets formed in the rocks. Heat is transported to the phase transition area across the frozen and thawed zones by way of conductive flux. The thermal physical characteristics in the indicated zones are piecewise constant and jump on the boundary of the zone division: $\lambda_T \neq \lambda_F$, $C_T \neq C_F$ и $a_T \neq a_F$, where λ_T, λ_F – thermal conductivity coefficients; C_T, C_F – volumetric heat capacity of thawed and frozen grounds, respectively.

The conditions around the TS are assumed to be equal. Therefore the problem may be stated as two-dimensional (axial symmetry). A thermal conductivity equation under conditions of enthalpy, where the enthalpy value (heat content) H is a continuous function in the entire temperature range and may include the thermal effect of phase transitions, looks like

$$\frac{\partial H}{\partial \tau} = \frac{\partial}{r\partial r}\left[r\left(\lambda\frac{\partial T}{\partial r}\right)\right] + \left(\lambda\frac{\partial^2 T}{\partial z^2}\right),$$

$$\tau > 0,\ z \in (0, L_S),\ r \in (R_S, R_{CD}); \qquad (1)$$

$$C(T) = \begin{cases} C_{ef}(T), & T < T_{bf} \\ C_T, & T > T_{bf} \end{cases};$$

$$\lambda(T) = \begin{cases} \lambda_F(T), & T < T_{bf} \\ \lambda_T, & T > T_{bf} \end{cases};\quad T = \begin{cases} T_F, & T < T_{bf} \\ T_T, & T > T_{bf} \end{cases};$$

$$H(T) = \begin{cases} H_F(T), & T < T_{bf} \\ H_T, & T > T_{bf} \end{cases},$$

where $H = \int_0^T C dT;\ C_{ef} = C_F + \psi\left(\frac{\partial \rho_0 W_{UW}}{\partial t}\right)$ – effective heat capacity, considering the phase transition heat; ψ – specific heat of a phase transition; ρ_0 – density of the ground matrix; W_{UW} – content of unfrozen water in the ground; the Oz axis is directed downwards down the thermal stabilizer axis, the Or axis is directed along the radius on the ground surface; L_S, R_{CD} is the calculated area.

Starting condition: $T(r, z, 0) = T(z)$, $T(r, 0, 0) = T_{GS}$, $z \in [0, L_S]$.

Boundary conditions: $T(r, 0, \tau) = T_{GS}(\tau)$, $\tau > 0$; $r \in (R_S, R_{CD}]$; $T(R_S, z, \tau) = T_G$, $\tau > 0$, $z \in [0, L_S]$; $\left.\frac{\partial T}{\partial r}\right|_{r=R_{CD}} = 0;\ \left.\frac{\partial T}{\partial z}\right|_{z=L_S} = 0.$

Special conditions for the moving boundary of the zone division $R_\xi = f(\tau)$ will be written as a temperature continuity condition at the temperature front and a heat balance equation for the moving boundary:

$$T_F(R_\xi, \tau) = T_T(R_\xi, \tau) \equiv T_{bf},$$

$$\lambda_F \left.\frac{\partial T_F}{\partial r}\right|_{r=R_\xi(\tau)} - \lambda_T \left.\frac{\partial T_T}{\partial r}\right|_{r=R_\xi(\tau)} = q_{PT}\frac{dR_\xi}{d\tau},$$

where q_{PT} – heat spent on phase transitions, proportional to the volume water content of the rock.

The problem was solved with the software product [*Software program..., 2014*]. A clear mesh scheme with regularity was used, allowing manifold increase of time pacing and corresponding reduction of the computation time, as well as an enthalpy form of presentation and a balance method. This leads to vivid physical interpretation of the results and essentially enhances the accuracy of determining the melting-freezing boundaries.

The chemical aspect of modeling the behavior of the water-salt systems in the area of negative temperatures consists in the calculation of the phase composition of compounds of different bulk chemical composition, characterized by certain temperature and pressure values. To evaluate the water-salt state of the ground mass, data on the ground properties were used, borrowed from the standard construction regulations document SP 25.13330.2012, for the cryopegs experimental data on the chemical composition of the cryopeg samples of the Yamal Peninsula were used, borrowed from the study made by *Kritsuk* [*2010*] and processed with the *FREEZBRINE* code [*Komarov et al., 2012*]. The following characteristics were calculated: the freezing start temperature; the temperature dependence of the phase composition; solution densities, their heat capacity, and conductivity. The *FREEZBRINE* code includes the following chemical components of the system:

– solution (23 components), including cations, anions, and neutral compounds: Na, K, Ca, Mg, Cl, SO_4, HCO_3, H_2O(l), $CaCO_3$(aq), $MgCO_3$(aq), etc.;

– solid phases (56 components): H_2O(cr,I), $NaCl{\cdot}2H_2O$, $Na_2SO_4{\cdot}10H_2O$, $CaSO_4{\cdot}2H_2O$, sylvite, calcite, magnesite, dolomite, siderite (ferrous carbonate), etc.;

– gases (8 components): H_2O(g), CH_4(g), CO_2(g), etc.

The input data for the software code included: starting total mineral content and concentration of the main components of the chemical composition of a cryopeg sample obtained by chemical analysis. The output data included: content of water, ions, and salts in the liquid, solid and gaseous phases; density and phase volumes; pH of the solutions; mass in moles, chemical potential and other values calculated for a certain interval and the pace set for the temperature or pressure. The code function was tested on large experimental and testing material. In particular, the field data were processed on the composition of 48 cryopegs of the Yamal Peninsula located on different geomorphological levels (terrace, floodplain, laida) [*Komarov and Kiyashko, 2012*].

The high freezing rate of the ground around a thermal stabilizer, related to low temperatures of the cooling agent, results in large temperature gradients in the frozen zone near its surface. This causes cracking and affects the carrying capacity of the ground bases. Due to the low temperatures of the cooling agent, the general problem may be viewed in the framework of the theory of linear thermoelasticity and of a mass model as layers deformed in the non-uniform temperature field of the layers. For the given case, the problem in its first approximation may be stated as an uncoupled problem, i.e., its temperature profile at each moment of time is stable in relation to changes in the tension and strain fields. Analysis of the condition of coupling (cohesiveness) for the thermoelasticity equations is provided in [*Komarov, 2003*]. In accordance with the major statements of the theory of thin shells, the value of maximum temperature strains σ ("thermal shock") may be approximately evaluated by the formula [*Kovalenko, 1971*]

$$\sigma = -\frac{E\alpha_T \Delta T}{2}\left[1+\frac{\sqrt{1-\nu^2}}{\sqrt{3(1-\nu)}}\right], \qquad (2)$$

where E – the elasticity modulus of the ground; α_T – the linear expansion coefficient of the ground; ν – Poisson's constant; ΔT – the temperature drop in frozen or freezing ground layer (depending on the start of switching the TS – in the winter or summer period), located near the TS wall.

In solving the problem of the possibility of cracking, the value σ calculated from equation (2) should be compared to the value equal to the limit of instant tear strength σ_{TS}, while for grounds subject to seasonal temperature fluctuations it should be compared to the value equal to the limit of lengthy tear strength σ_{LS}.

COMPUTER SIMULATION RESULTS

As thermal stabilizer, a recuperative heat exchange device was used (a Field tube). It is schematically shown in Fig. 1.

The gas flow velocity in the annular gap of the Field tube is 25 m/s. The climatic data are taken as provided by the weather station for the district of Marre-Sale. A one-layer mass was considered for the purpose of the estimate calculations, composed of non-saline sand and saline loam, the hydrophysical and thermal physical qualities of which are shown in Table 1, considering the information contained in [*SP25.13330.2012*].

The initial temperature distribution was selected on the basis of preliminary calculations modeling establishment of a quasi-stationary temperature field. Options for the summer and winter periods of the operation start for the TS were considered for different input temperatures of the cooling agent T_{GS} = –40, –60, –80 °C. The strength and strain properties of grounds for a wide range of negative temperatures are shown in Table 2. They were selected according to the strength and strain properties of grounds from [*Komarov and Isayev, 2010*].

The behavior of the temperature fields around the TS for the summer and winter periods of the TS

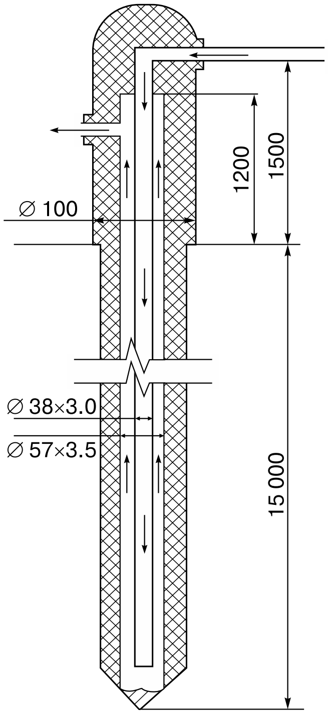

Fig. 1. A schematic view of a Field tube.

The arrows denote the direction of the cooling agent's movement in the TS; the crosshatched regions indicate the TS wall material; the diameter of the inlet-outlet chamber ∅ = 100 mm; the external tube diameter ∅ = 57 mm, with the wall thickness 3.5 mm; the internal tube diameter ∅ = 38 mm, with the wall thickness 3 mm.

operation start is shown in Fig. 2. Evaluation of the temperature strains has shown that in the winter period the allowed cooling agent temperature for nonsaline sands is within the range from –40 to –50 °C. For loamy severely saline soils, a TS may be established in the entire range of negative temperatures. In the summer period, the temperature gradients on the boundary between the TS and the ground may result in the emergence of strains above the value of instant tear strength for both types of ground in the given temperature range. In the summer period, it is reasonable to put a TS into operation at higher temperatures of the cooling agent, known from the experience of the operation of seasonal cooling devices [*Khrustalev, 2005; Anikin and Spasennikova, 2014; Dolgich et al., 2014*].

The potential for freezing cryopegs with the maximum mineral content is an evident advantage of the method of low-temperature thermal stabilization. For example, according to the preliminary calculations made, the cryopeg lenses with the mineral content varying from 81.1 to 91.9 g/L at the temperature of the cooling agent equal to –40, –60, –80 °C, get frozen up to 0.6, 0.75, and 0.9 m, respectively, while within a year the area frozen by a thermal stabilizer increases to 2.1, 2.6, and 3.0 m. The temperature dependence of the phase composition of the cryopegs and the behavior of their thermal physical properties were calculated by the method proposed by [*Komarov et al., 2012*].

Table 1. **The hydrophysical and thermophysical properties of grounds**

Ground	ρ, kg/m^3	W_{tot}, u.f.	D_{sol}, %	T_{bf}, °C	*C*, MJ /(m^3·K)		λ, W/(m·K)		Q_f, MJ/m^3
					thawed ground	frozen ground	thawed ground	frozen ground	
Nonsaline sand	1880	0.23	0.07	–0.02	2.58	1.95	1.7	2.5	144.9
Saline loam	1320	0.30	2.10	–4.30	0.657	0.492	1.2	1.4	70.3

Note. ρ – matrix density; W_{tot} – total moisture content; D_{sol} – degree of salinity; T_{bf} – freezing start temperature; *C* – heat capacity; λ – thermal conductivity; Q_f – phase transition heat.

Table 2. **Comparison of calculated by the formula (2) and experimental values of instant tear strength for different temperatures of the cooling agent**

Ground	T_{GS}, °C	*E*, MPa	α·10^5, K^{-1}	σ_r, MPa	Δ*T*, °C		σ_r^*, MPa	
					NTP	PTP	NTP	PTP
Nonsaline sand	–40	25 000	2.2	3.3	8.0	26	3.18	10.34
	–60	25 000	2.2	3.5	19.0	39	7.23	14.83
	–80	25 000	2.3	3.6	30.0	62	11.40	23.59
Saline loam	–40	5000	2.4	6.2	7.5	32	1.90	7.98
	–60	5000	2.6	7.0	20.0	45	5.40	12.10
	–80	5000	1.6	7.0	30.5	56	5.06	9.30

Note. T_G – cooling agent temperature; *E* – elasticity modulus; α – linear expansion coefficient; σ_r – instant tear strength; Δ*T* – temperature drop on the TS-ground boundary; σ_r^* – calculated instant tear strength; NTP – negative temperatures period; PTP – positive temperatures period; Poisson's constant ν = 0.15.

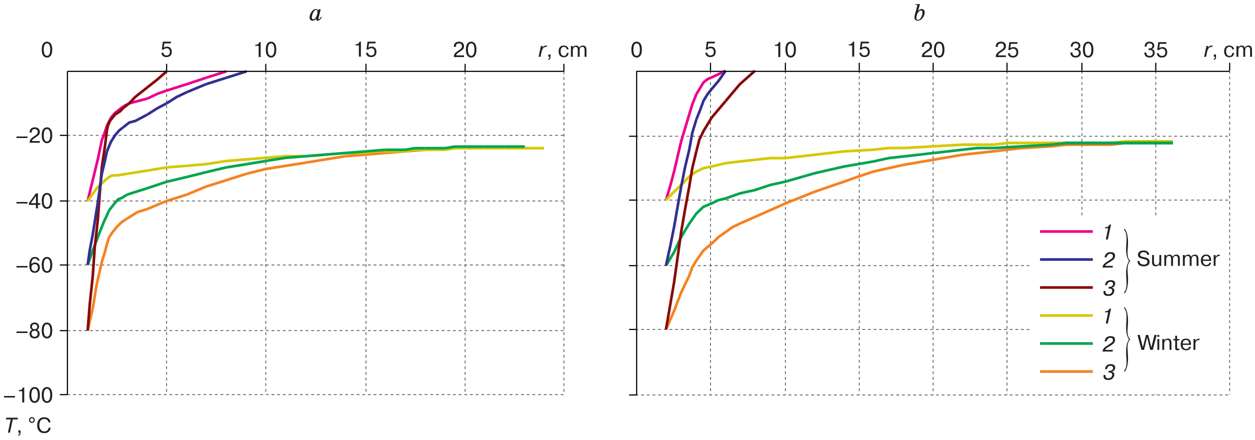

Fig. 2. The temperature profile (*T*) near the stabilizer-ground boundary in the periods with negative (winter) and positive (summer) for nonsaline sand (*a*) and saline loam (*b*) for different cooling agent temperatures:

1 – T_{GS} = –40 °C, *2* – T_{GS} = –60 °C, *3* – T_{GS} = –80 °C. *r* – the distance from the thermal stabilizer wall.

CONCLUSIONS

1. The use of a cooling resource of liquefied petroleum gases and the products of their rectification (ethane, propane) for the purpose of thermal stabilization of the ground bases of gas production infrastructure facilities in operation under severe permafrost conditions seems to be effective due to the following factors: all-season functioning, high intensity of freezing with minimization of the ground bulging process, the possibility for freezing cryopegs with a high mineral content. This technology allows utilization of the gaseous LPG product used for thermal stabilization of the ground by directing the reverse flow of gas into the technological circuit for the purpose of further compression and liquefaction.

2. The modeling estimations demonstrate that the most favorable conditions for putting a TS into operation, in terms of ground stability on the boundary with the TS wall, exist in the winter period. In the summer period of putting a TS into operation, the temperature of the cooling agent should be changed stepwise. As the beginning of the formation of an ice and ground cylinder around a TS, it should correspond to the values known from the empirical experience of operating seasonal cooling devices.

3. At the low negative temperature of the cooling agent, the surrounding freezing area of a cryopeg lens, even with the mineral content of 92 g/L, may reach 1 m per month, and 3 m per year.

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