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SAFETY OF STRUCTURES AND FOUNDATIONS IN PERMAFROST

THERMAL INFLUENCE OF GAS AND OIL BOREHOLES ON THE STABILITY OF A GRAVITY PLATFORM LOCATED ON THE ARCTIC CONTINENTAL SHELF

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The paper addresses the problem of thermal effect of gas and oil producing wells on the permafrost base of a gravity platform located on the Arctic shelf. This effect is distributed over a large area and substantially reduces the platform shear resistance, given the influence of wave and ice loads, which jeopardizes the offshore platform stability.

Permafrost, shelf, gravity platform, thaw bulb, shear resistance, foundation reliability

INTRODUCTION

Continental shelf is commonly defined as littoral offshore zone of seas extending from the shoreline as far as the continental slope, usually less than 200 km in width. According to recent estimates, the continental shelf hosts about 70 % of the world's hydrocarbon reserves, which largely accounts for the great interest, currently being shown by all countries to their development.

Russia's interests consist primarily in the mineral resource development on the Arctic shelf, comprising the Barents, Kara, Laptev, East Siberian and Chukchi Seas.

Ice is known to be a dominant feature of the Arctic shelf, since its waters develop a thick layer of sea ice on the surface, and it is also present in subaqueous part. The latter is concentrated below the seafloor within the bottom sediment, and is commonly termed perennially frozen rocks (permafrost). They encompass the entire shoreline and extend further towards the sea to a distance of 60–80 km and more. The permafrost thickness on the shelf is not uniform: it tends to be greater near the shore and reaches 600–800 m, gradually decreasing to zero seaward. At this, its upper boundary (permafrost table) either immediately underlies the seafloor, or occurs below it to a depth of some 10–20 m.

The presence of ice does provide additional challenges to the Arctic resource development [*Khrustalev*, 2000]. Driven by wind and currents, drift ice floats on the surface of water and the pressure it exerts both onto floating and fixed offshore installations is an order of magnitude more powerful than the pressure of storm waves. It is not rare that drilling rigs are reported overturned by ice piling. Seafloor ice imparts special properties to the bottom rocks, depending on their temperature and salinity. Since these rocks serve as engineering structures bases, the stability of the latter is largely determined by their properties.

As is known, any increase in temperature will undermine the strength of frozen rock. The fluid coming from the depths has a high positive temperature, which ultimately leads to a temperature rise in the vicinities of oil and gas facilities. As a result, a thawing bulb forms around the wellbore, with the thermal effect expanding down into the structure foundation, thus reducing its safety. Especially hazardous is temperature warming in the foundation of gravity platforms located in the deep offshore parts, where ice load created by the floating ice floes is immense.

The worst conditions, though, are experienced by the drilling platforms resting on the frozen seafloor (i.e. subsea permafrost section), which makes them particularly susceptible to the influence of thermal effect from wells. Such platform withstands ice loads only at the expense of adfreezing force and frictional resistance at the "platform base – frozen bottom rock" interface. In turn, these forces are largely controlled by the composition of rocks, their temperature and salinity. Shear resistance force tends to decrease, however, with time due a rise in the permafrost temperature caused by the thermal effects from producing wells. Failing to take this into account when gravity platform is designed, one runs the risk of the platform losing stability in the operating mode, which is fraught with many other unpredictable consequences. This issue is discussed below in more detail by the example of gravity platform, resting on the frozen seafloor, with an oil well located in one of the platform supports.

Platform configuration

Fig. 1 shows a general overview of the platform, consisting of a topside structure with drilling rig derrick and attendant equipment that rest on the four tapered supports, which, in turn, transmit the load onto the caisson with a skirt embedded inground. The supports are hollow, their diameter at water level is 15 m, and 28.8 m at the level of the caisson. The bottom-founded caisson dimensions are 174.62 × 131.42 m (areal extent), its height is 13 m. The skirt height is 5 m. The weight of the above-water structure is $2{\cdot}10^6$–$3{\cdot}10^6$ kN, and that of the subaqueous part, given the floating force is $3{\cdot}10^5$–$6{\cdot}10^5$ kN.

Producing well design

As was previously stated, a producing well does have a thermal impact on the surrounding perennially frozen deposits (PFD) of the permafrost strata. To mitigate it, different methods are available and applied to enhance the thermal resistance at the "wellbore – permafrost strata" contact boundary. These include the following solutions: air gap between production and intermediate strings; O-ring insulated tubing; vacuum between the production and intermediate strings. Since the latter proved a disappointment in practice, therefore, only the first two methods are currently applicable to the production processes, with the thermal insulating of tubing throughout the permafrost interval widely accepted as the most effective. This design solution was used by the authors in the calculations, given below.

Production well consists of four strings (DST) (Fig. 2). The first intermediate string (direction) with 402 mm diameter is submerged to a depth equal to one third of the PFD thickness. The second intermediate string (conductor) with 324 mm diameter runs through the entire thickness of permafrost and descends below its base to a depth of 30 m. The conductor casing is succeeded by production string plunging into the pay zone. The production casing has a variable diameter, which is 244.5 m from its top at the permafrost base, which grades into 168 mm in the tapered part. This is necessary to ensure that within the permafrost strata thermal insulation of expandable poly styrene (EPS) is applied around the tubing, which is emplaced into the production casing and designed for lifting the fluid. The inner diameter (ID) of the tubing is 144 mm, the outer diameter of the annular insulation is 168 mm.

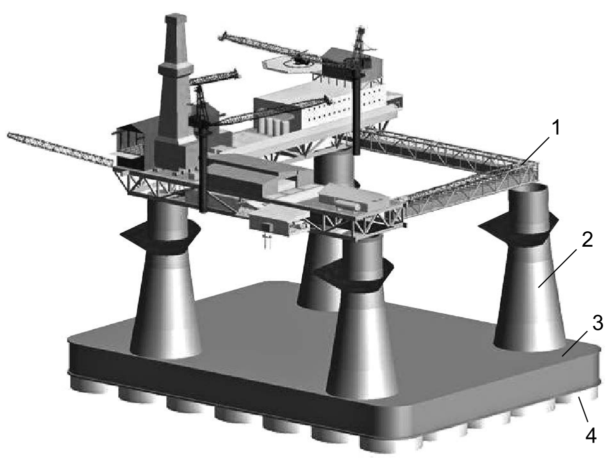

Fig. 1. Overall view of gravity platform.

1 – topside facility; 2 – support; 3 – caisson; 4 – skirt.

Calculation methods for thermal and mechanical "gravity platform – permafrost rocks" interaction

Thermal interference. According to [*Khakimov, 1957*], the frost (warmth) affected zone of vertical cylindrical source expands at a distance of $r_0 = 6.5r_f\ (r_{th})$, where r_0, r_f, r_{th} is a range radius of frost or thaw, respectively. Temperature distribution within the range $T(r)$ is governed by the quasistationary law.

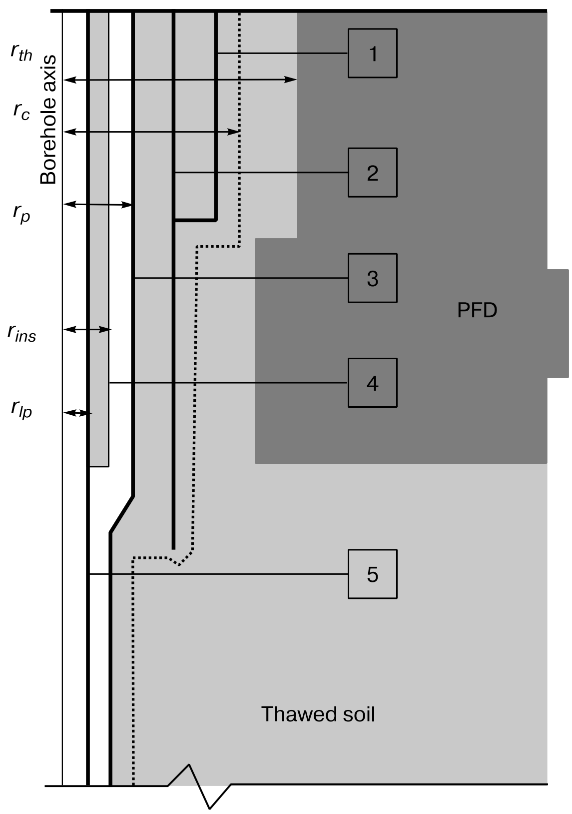

Fig. 2. Producing well design.

1 – first intermediate string; 2 – second intermediate string; 3 – production string (with radius r_p); 4 – O-ring insulation (with radius r_{ins}); 5 – tubing (with radius r_{lp}); r_{th} – permafrost thaw radius around producing well; r_c – outer radius of cement sheath.

When applied to permafrost thaw, it can be written down as

$$T(r) = T_{bf} - \left(T_{bf} - T_0\right)\frac{\ln\left(r / r_{th}\right)}{\ln\left(r_0 / r_{th}\right)}, \qquad (1)$$

where T_{bf} – thawing temperature of frozen ground; T_0 – frozen ground temperature under natural conditions.

Calculation of the radius of thawing around the borehole is done using the formula from [*STO Gazprom..., 2008*]

$$r_{th} = \eta_a r_c , \qquad (2)$$

where r_c is outer radius of cement sheath, m; η_a is nomograph-determined dimensionless parameter (Fig. 3).

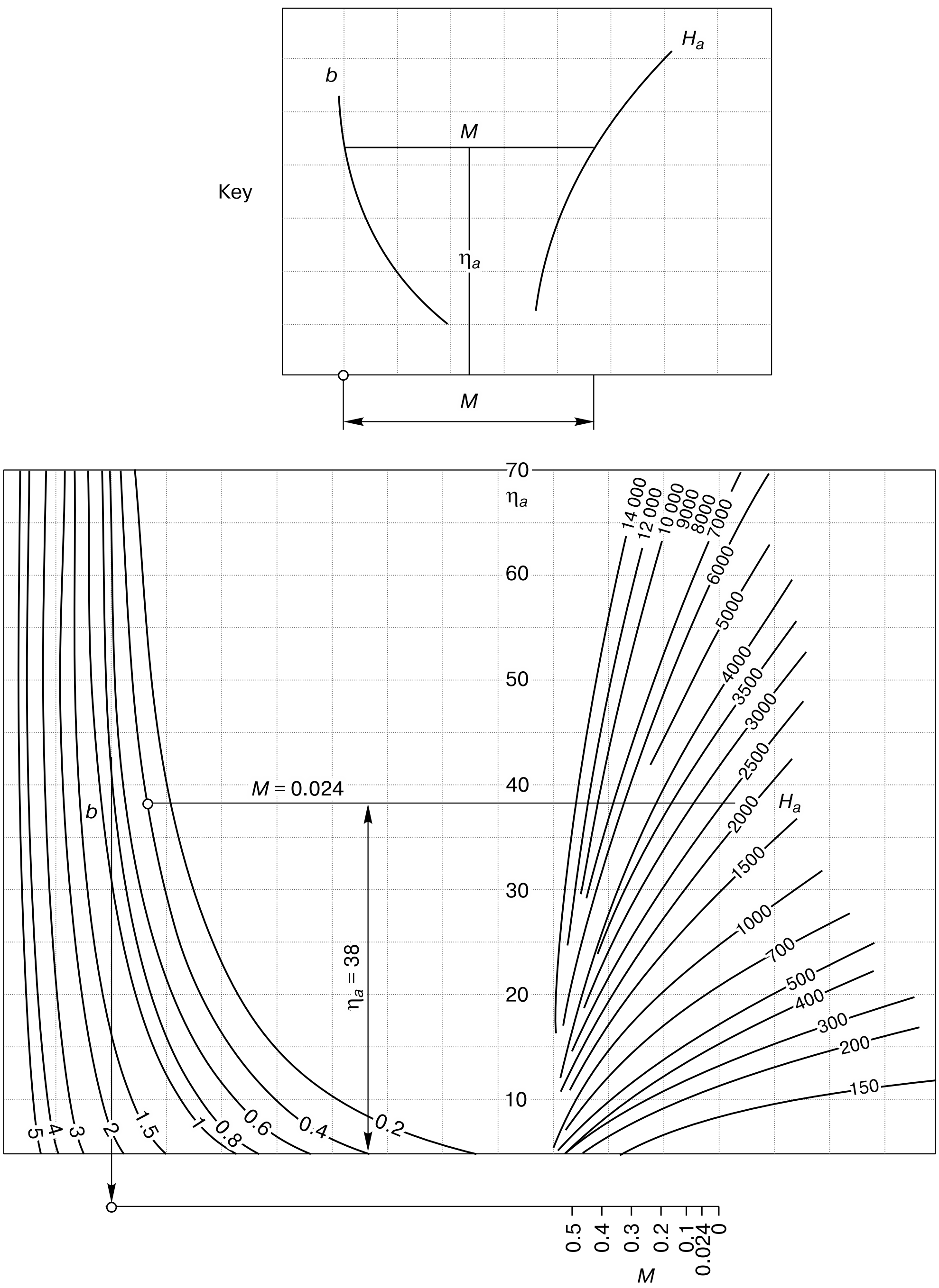

Fig. 3. Nomogram for calculation of thaw radius (explanations provided in the text).

The input parameters for nomogram plots are given below:

$$b = \lambda_{th} R_{in} / r_c; \tag{3}$$

$$M = \frac{\lambda_f \left(T_{bf} - T_0\right)}{\lambda_{th}\left(T_g - T_{bf}\right)}; \tag{4}$$

$$H_a = \frac{\lambda_{th}\left(T_g - T_{bf}\right) t_{th}}{r_c^2 L_v}; \tag{5}$$

where b – borehole thermal resistivity; M – temperature; H_a – time (nondimensional); R_{in} – thermal resistance at borehole–rock interface, m^2·°C/W; λ_{th}, λ_f – thermal conductivity factor of rocks around the wellbore, for their thawed and frozen state, W/(m·°C); T_g – fluid temperature, °C; t_{th} – well operation time, h; L_v – heat of thawing frozen rock, W·h/m^3;

$$R_{in} = \frac{1}{\alpha} + \frac{r_{ins}}{\lambda_{ins}} \ln\left(\frac{r_{ins}}{r_{lp}}\right) + R_{air} + \frac{r_c}{\lambda_c} \ln\left(\frac{r_c}{r_p}\right), \tag{6}$$

where α – heat-exchange coefficient between fluid and inner side of tubing, W/(m^2·°C) (for gas, it equals 25 W/(m^2·°C)); r_{lp}, r_{ins}, r_p – radii of tubing, annular heat conservation insulation and production string, m, respectively; λ_{ins}, λ_c – coefficients of thermal conductivity of thermal insulation and cement sheath, W/(m·°C); R_{air} – thermal resistance of air gap between outer surface of heat conservation insulation and inner side of production string, m^2·°C/W;

$$\alpha = \eta \frac{v^{0.8}}{\left(2 r_{lp}\right)^{0.2}}, \tag{7}$$

where v – fluid flow velocity in tubing, m/s; η – empirical coefficient, taken equal to $5.42 \cdot 10^{-3}$ for gas, and 122 for liquids;

$$L_v = L_0 \rho_f \frac{w_{tot} - w_w}{1 + w_{tot}} + C, \tag{8}$$

where L_0 – heat of ice fusion, equal 94.8 W·h/kg; ρ_f – frozen soil density, kg/m^3; w_{tot}, w_w – total moisture content of frozen soil and unfrozen water content, u.f. (unit fraction); C – correction for thermal capacity of rock, W·h/m^3;

$$C = \frac{C_{th}\left(T_g - T_{bf}\right)}{3.17 + 1.15b} + C_f\left(T_{bf} - T_0\right), \tag{9}$$

where C_{th}, C_f – heat content of rocks, in the thawed and frozen state, respectively, W·h/(m^3·°C).

Mechanical interaction. Calculation approaches for resistance to shear at the "structure base–ground" interface is commonly known [*STO Gazprom..., 2005*]. They primarily factor in the ground bond with the footing base and sliding friction along the base of the structure, controlled by the angle of internal friction and vertical load of the installation. In frozen ground, both the bond and angle of internal friction are dictated by temperature. Analytically, the dependence of resistance forces on bond strength and internal friction angle is written down as follows:

for thawed soils $$F_R = \left(c_{th} + \sigma_1 \operatorname{tg} \varphi_{th}\right) S; \tag{10}$$

for frozen soils $$F_R = \left[c_f(T) + \sigma_1 \operatorname{tg} \varphi_f(T)\right] S, \tag{11}$$

where c_{th}, c_f are cohesions of thawed and frozen soil, kPa, and φ_{th}, φ_f – internal friction angles for thawed and frozen soil, respectively, degrees; σ_1 –vertical pressure onto the platform base, kPa; S – platform footing base area, m^2;

$$\sigma_1 = \frac{P_{abw} + P_{unw}}{S}, \tag{12}$$

where P_{abw} – weight of the topside facilities, kN; P_{unw} – weight of the subaqueous parts of the structure, given the buoyant force of water, kN.

Shear resistance force with out thermal influence of producing oil well taken into account is calculated according to the formula:

$$F_R = \left[c_f\left(T_0\right) + \sigma_1 \operatorname{tg} \varphi_f\left(T_0\right)\right] S. \tag{13}$$

To calculate shear resistance forces, taking into account thermal influence of the wellbore where frozen soil temperature changes in the surrounding space, the thaw bulb area (the extent of thawed zone around borehole) should be divided into n circles with radius r_i and the following formulas are to be applied

$$F_R = F_1 + F_2; \tag{14}$$

$$F_1 = \left(c_{th} + \sigma_1 \operatorname{tg} \varphi_{th}\right) \pi r_{th}^2 + \sum_{i=1}^{n} \left\{\left[c_f\left(T_i\right) + \sigma_1 \operatorname{tg} \varphi_f\left(T_i\right)\right]\left(S_i - S_{i-1}\right)\right\}; \tag{15}$$

$$F_2 = \left[c_f\left(T_0\right) + \sigma_1 \operatorname{tg} \varphi_f\left(T_0\right)\right]\left(S - S_n\right), \tag{16}$$

where S_i is area of a circle with radius r_i within the contours of the platform base footing, m^2; S_n is area of a circle with radius r_0 (zone of thermal influence of the well) within the platform footing base contours, m^2; T_i – temperature of frozen deposits at a distance r_i from the borehole center, °C.

Calculations of thermal and mechanical interaction between the permafrost and gravity platform

Input data for calculations. Basic engineering design data. Lateral dimensions of the platform foundation in plan (base of the caisson): 174.62 × 131.42 m. Area of the footing base S = 22 948.56 m^2. Platform dead load: topside facilities $P_{abw} = 3 \cdot 10^5$ kN, that of the subaqueous part, given the floating force: $P_{unw} = 2 \cdot 10^6$ kN. Coordinate locations of oil producing well are: x = 44.11 m, y = 13.00 m (with the origin

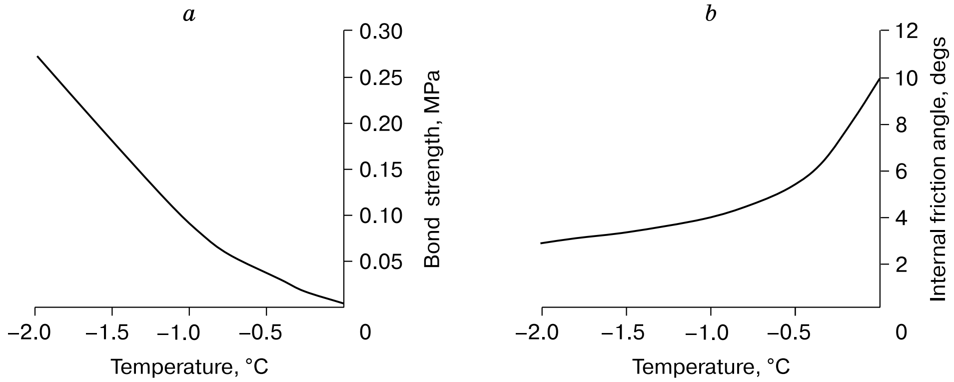

Fig. 4. Dependence of frozen clay strength on temperature.

a – cohesion; *b* – internal friction angle.

of coordinates in the right bottom corner of the platform footing base; x runs along the longer side, y – along the shorter side). The wellbore dimensions are defined by radii r_{lp} = 0.072 m, r_{ins} = 0.084 m, r_p = 0.122 m, r_c = 0.213 m; thermal conductivity coefficients λ_{ins} = 0.04 W/(m·°C), λ_c = 1.28 W/(m·°C), thermal resistance of the air gap between the outer surface of the insulation and the inner side of production casing R_{air} = 0.06 м^2·°C/W, according to [*STO Gazprom..., 2005*].

Operational parameters. Oil temperature at the level of platform base T_g = 30 °C, production life of well t_{th} = 30 yrs.

Physical and mechanical properties of rock. The literature data search for estimated characteristics of soils (i.e. geophysical and geotechnical properties) was challenged by the lack of data on temperature-dependent bond strength and the angle of internal friction of frozen saline soil. These dependences for non-saline clay with moisture (water) content w_{tot} = 0.44 and density ρ_f = 1728 kg/m^3 were found only in the monograph by *N.K. Pekarskaya* [*1963*]. To this end, they were factored in our calculations (Fig. 4).

The bonding strength and angle of internal friction of thawed clays with approximately identical moisture content and density is taken into our calculations c_{th} = 6 kPa, φ_h = 10° from the paper by [*Tsarapov, 2008*]. Other characteristics were selected from [*SNiP 2.02.04-88*] for clays with required moisture content and density, specifically: unfrozen water content w_w = 0.08 at T_0 = –1.9 °C (taken to be equal to temperature of seawater); λ_{th} = 1.57 W/(m·°C), λ_f = 1.8 W/(m·°C) thermal conductivity in the unfrozen state; heat capacity in the thawed C_{th} = = 858 W·h/(m^3·°C) and frozen C_f = 586 W·h/(m^3·°C) state; freeze-thaw temperature T_{bf} = –0.2 °C.

Calculation of permafrost thaw radius around producing well. Firstly, thermal conductivity coefficient α = 116 W/(m^2·°C) is defined, by the formula (7). Then, thermal resistance at the borehole – rock interface R_{in} = 0.486 m^2·°C/W is calculated using the formula (6). By formula (3), the dimensionless parameter b = 3.58 is defined. Then, formula (9) is applied to calculate a correction for specific heat of the rock C = 4552 W·h/m^3. By formula (8), we define heat capacity of the thawing of frozen rock as L_v = = 45 505.6 W·h/m^3. The formulas (4) and (5) are used to define dimensionless parameter M and H_a. Using nomogram shown in Fig. 3 the dimensionless parameter is defined as η_a = 35, which corresponds to the values of b, M, H_a. The thaw bulb radius around producing well is calculated by formula (2) at its production period end r_{th} = 35·0.213 = 7.46 m.

Next, the thaw bulb radius is defined as r_0 = = 6.5·7.46 = 48.5 m. The calculation results is shown in Fig. 5.

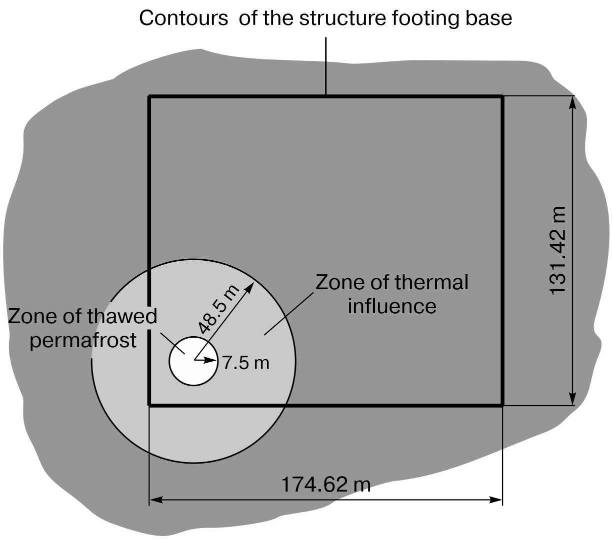

Рис. 5. Thermal effect of oil producing well on temperature of rocks of the permafrost base of gravity platform.

Table 1. **Results of calculation of shear resistance strength (F_1) of the platform footing base**

r_i, m	S_i, m^2	T_i, °C	$c(T_i)$, kPa	$\varphi(T_i)$, degrees	R_i, kPa	F_i, kN
7.5	176.7	$>T_{bf}$	6	10.0	23.632 74	4175.905
11.6	246.0	–0.600 89	41	5.0	49.748 89	12 238.23
15.7	327.9	–0.875 73	70	4.3	77.519 06	25 418.50
19.8	369.1	–1.086 44	104	3.8	110.642 00	40 837.97
23.9	399.1	–1.257 34	130	3.6	136.291 50	54 393.93
28.0	440.9	–1.401 12	158	3.4	163.941 10	72 281.63
32.1	572.4	–1.525 21	178	3.2	183.590 90	105 087.40
36.2	572.5	–1.634 37	198	3.4	203.941 10	116 756.30
40.3	608.9	–1.731 81	213	3.2	218.590 90	133 100.00
44.4	754.5	–1.819 79	230	3.0	235.240 80	177 489.20
48.5	375.9	–1.900 00	250	2.8	254.890 80	95 813.46
S_n	4843.9				F_1	837 592.50

N o t e. S_i – area of a circle with radius r_i within the contours of the platform footing base, m^2; S_n – area of a circle with radius r_0 (zone of thermal influence of the well) в within the platform footing base contours, m^2; T_i – temperature of frozen deposits at a distance r_i from the borehole center; $c(T_i)$ – bond strengh of rocks, corresponding to T_i; $\varphi(T_i)$ – the angle of internal friction of rock, corresponding to T_i; R_i – specific shear resistance within i-th zone of the base.

Calculation of shear resistance strength of gravity platform. First, using formula (12) the vertical stress developed due to the structure weight is defined for the base of gravity platform: σ_1 = 100 kPa. Using formula (13), shear resistance strength of the platform is then calculated without taking into account thermal effect from the well: F_R = = 5 849 490 kN. F_1 is determined by (15), with all the calculations written down in the form of tables (Table 1). F_2 = = 4 614 798.5 kN is calculated by formula (16). The formula (14) is used for calculating shear resistance force with thermal effect from the producing well factored in: F_R = 5 452 391 kN. The calculation error disregarding the thermal effect from the well constitutes ΔF_R = 5 849 490 – 5 452 391 = 397 099 kN, or ≈7.3 %.

CONCLUSION

Over 30 years of operation of only a single well, its thermal influence extended over a fairly long distance of 48.5 m. This have caused a decrease in the shear resistance strength of the perennially frozen deposits by 7.3 %. Typically, as many as 60 wells are emplaced on the gravity platform. In this case, it can be ascertained a priori that the gravity platform resting on the frozen seafloor will not be able to endure additional ice-induced loads.

In our opinion, there are two ways which may preclude such consequences, specifically: through area of the platform bearing on the seafloor increased proportionally to the permafrost thaw zones; by developing a borehole design, which removes its thermal effect on the enclosing PFD. In case this problem is neglected prior to the gravity platform installation in the offshore areas where the seafloor is permanently frozen, the outcome will become hazardous.

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