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Effect of Enclosed Space Configuration and Freezing Medium Volume on Refreezing Pressure

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Abstract. In building underground structures (bases and foundations of residential and industrial buildings, boreholes for hydrocarbon extraction, etc.) in cryolithic zones, cavities of various shapes and sizes saturated with liquid media often develop. When they refreeze, the refreezing pressure occurs; this may result in failure of the structural member continuity, and further failure of the structure as it is. The paper describes the calculation techniques for the refreezing pressure depending on cavity shapes and sizes.

1 Introduction

After field-geophysical research it has been stated that various enclosed spaces can develop in perennial frozen rock in-situ in structures built and being built in the Far North. As a rule, the cavities develop due to icy sands and sandy loams. The following types of cavities occur [1 - 5]:

- cylindrical cavities are the most common form of cavities. The diameter of these cavities usually reaches 1m, the height – over 15 m;
- spherical cavities are enclosed cavities developing during freezing of the supports and bases of the idle structures in the cold season. Spherical pits and cavities not exceeding 1-1.5m in diameter develop. However, in long-term operation their sizes may increase;
- slatted cavities are formed in subsidence of thawed rocks after long-term operation of structures. Freezing occurs more rapidly in the axial direction [5].

All types of cavities usually are water-saturated, therefore the phase transformation are causes the occurrence of overpressure through the ice formation, which causes the destruction of built construction.

As a result, ability of their current forecast is very relevant for substantiation of a technology that promotes the prevention of occurrence of the incident.

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2 Analysis of calculation techniques

After the authors [6 - 10], the water-ice volume balance in freezing of the enclosed volume V0 by the value dV is described as follows:

$$\alpha \cdot mdV = \left[\beta_T \cdot (V_0 - V) + \beta_M \cdot V + \beta_0 \cdot V_0\right]dp, \tag{1}$$

where: α = (ρв – ρl) / ρв - coefficient of volume expansion during the phase transition of water into ice; ρв and ρl - density of water and ice; m - water content; βm, βM, β0 - coefficients of volumetric compression of the thawed zone, refrozen rocks and frozen rocks; V - the current value of the solid phase volume; dp – pressure increase in freezing of the refrozen media by the value *dV*.

Integrating the equation (1), and taking into account that at V0 the pressure in the system is equal to P0, we obtain finite pressure value as of freezing:

$$P = P_0 + \frac{\alpha \cdot m}{\beta_M - \beta_m} \cdot \ln\left[1 + \frac{(\beta_M - \beta_m)}{\beta_m + \beta_0} \cdot \frac{V}{V_0}\right] \tag{2}$$

According to [11 ÷ 15] the current radius of the freezing cavities can be given for:
- cylindrical cavities

$$\lambda \frac{T_{fn} - T_n}{r \cdot \ln \frac{R}{r}} = \sigma \frac{dr}{d\tau}, \tag{3}$$

- spherical cavities

$$\lambda \frac{T_{fn} - T_n}{(R - r)^{-1}} = \sigma \cdot r^2 \frac{dr}{d\tau}, \tag{4}$$

- slatted cavities

$$\lambda \frac{T_{fn} - T_n}{r} = \sigma \frac{dr}{d\tau}, \tag{5}$$

where: λ – thermal conductivity of the frozen rocks; σ – heat of phase transition; r – current radius of the cavity; RK – initial radius of the cavity; τ – time; Tfn and Tn – temperatures of phase transition and frozen rocks correspondingly. Transforming the equation (2) and integrating the equations (3) ÷ (5), we obtain the formulas for determination of the pressure during freezing for the following cavities:
- cylindrical

$$P_i = P_0 + \frac{\alpha \cdot m}{\beta_M - \beta_T} \cdot \ln\left[1 + \left(\frac{\beta_M - \beta_T}{\beta_0 + \beta_T}\right) \cdot \left(\frac{R_K^2}{R_K^2 - R^2}\right) \cdot \left(1 - \frac{r_i}{R_K}\right)^2\right], \tag{6}$$

$$\tau = \tau_{i-1} + \frac{m \cdot \sigma \cdot R_K^2}{4\lambda} \cdot \frac{\left\{ \left(\frac{r_i}{R_K}\right)^2 \cdot \left[\ln\left(\frac{r_i}{R_K}\right)^2 - 1 \right] - \left(\frac{r_{i-1}}{R_K}\right)^2 \cdot \left[\ln\left(\frac{r_{i-1}}{R_K}\right)^2 - 1 \right] \right\}}{T_{fn} - T - \left(\frac{P_i + P_{i-1}}{P_{\max}}\right)}; \qquad (7)$$

- spherical

$$P_i = P_0 + \frac{\alpha \cdot m}{\beta_M - \beta_T} \cdot \ln\left\{ 1 + \left(\frac{\beta_M - \beta_T}{\beta_0 + \beta_T}\right) \cdot \left(\frac{R_K^2}{R_K^2 - R^2}\right)^{\frac{3}{2}} \cdot \left[\left(1 - \frac{r_i}{R_K}\right)^2 \right]^{\frac{3}{2}} \right\}, \qquad (8)$$

$$\tau = \tau_{i-1} + \frac{m \cdot \sigma \cdot R_K^2}{\lambda} \cdot \frac{\frac{1}{3} \cdot \left[\left(\frac{r_i}{R_K}\right)^3 - \left(\frac{r_{i-1}}{R_K}\right)^3 \right] - \frac{1}{2} \cdot \left[\left(\frac{r_i}{R_K}\right)^2 - \left(\frac{r_{i-1}}{R_K}\right)^2 \right]}{T_{fn} - T - \left(\frac{P_i + P_{i-1}}{P_{\max}}\right)}; \qquad (9)$$

- slatted (with one-sided freezing)

$$P_i = P_0 + \frac{\alpha \cdot m}{\beta_M - \beta_T} \cdot \ln\left[1 + \left(\frac{\beta_M - \beta_T}{\beta_0 + \beta_T}\right) \cdot \frac{h_i}{H} \right], \qquad (10)$$

$$\tau = \tau_{i-1} + \frac{m \cdot \sigma \cdot H^2}{2\lambda} \cdot \frac{\left(\frac{h_i}{H}\right)^2 - \left(\frac{h_{i-1}}{H}\right)^2}{T_{fn} - T - \left(\frac{P_i + P_{i-1}}{P_{\max}}\right)}, \qquad (11)$$

where: R — outer diameter of the outer surface; Pmax - maximum possible freezing pressure at the given temperature.

3 Results

The calculation was done step by step [16 ÷ 20] in the following way:

- the value ri/RK was given, P1,τ1(τ0 = 0, τi-1/R = 1) was calculated in (P1 + P0)/ Pmax. Then the ratio r2/RK was given, P2 and τ2 were calculated using the values of τ1 and (P1 – P0)/Pmax, etc. At each step of volume V freezing to the value Vi, the pressure Pi, was taken as constant. It was calculated as the mean pressure of the pressure obtained in the previous step Pi-1, freezing V to the value Vi-1, and the pressure at the given step Pi.

Fig. 1 shows the graphs of pressure changes in freezing of cavities of various geometric shapes.

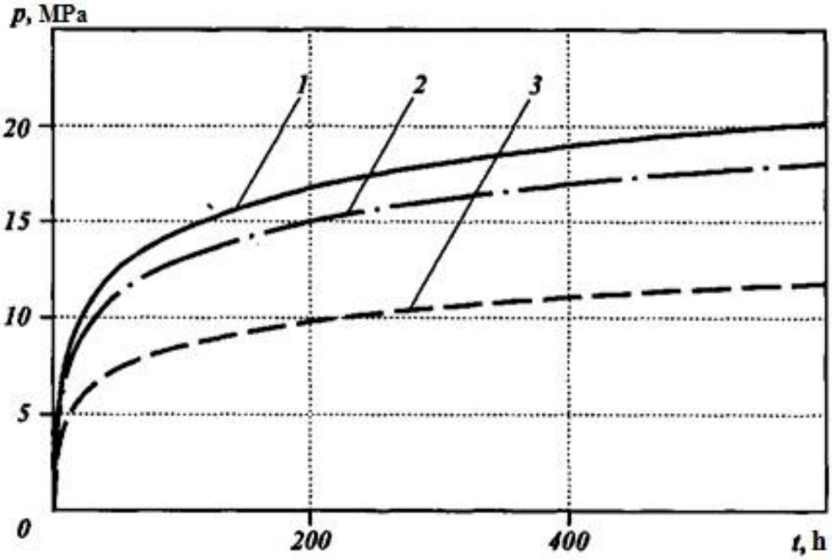

Fig. 1. Dynamics of pressure changes in freezing of enclosed cavities of various shapes: 1, 2, 3 — slatted, cylindrical and spherical correspondingly (***t*** = minus 2 °C, $R_к$ = 0.5 м, $\beta_0 = 0.001\ \text{MPa}^{-1}$, $\beta_M = 0.005\ \text{MPa}^{-1}$).

The graphs show that the shape of the cavities affects only the rate of pressure increase. Thus, freezing of the cylindrical cavities develops faster than that of the slatted ones and slower than the spherical ones.

Depending on the volumetric compression of freezing media and the size of the cavities, the pressures may be lower than the maximum possible values of freezing pressure (Tab. 1).

Table 1. Pressures in cavities depending on temperature and compressibility of freezing media.

№ of experiment	T, °C	Compressibility of medium, 10^{-2} MPa^{-1}		Cavity radius , R_K, m	$P_{calc.}$ (P_{max}), MPa	Percent of freezing, (%)
		β_0	β_M			
1	-2	0.144	0.144	0.3	17.0(26.8)	63.4
2	-2	0.06	0.36	0.3	26.8(26.8)	100
3	-2	0.58	5.86	0.5	15.0(26.8)	56
4	-2	0.144	0.144	0.5	26.8(26.8)	100
5	-5	1.80	3.60	0.3	26.0(67.0)	38.8
6	-5	1.80	3.60	0.5	30.0(67.0)	44.8
7	-5	0.06	3.60	0.5	67.0(67.0)	100

This is due to the deformation of the medium inclosing wall occurring under the influence of the refreezing pressure (Pc) [20 - 22]. As a result, the volume of cavities increases and the pressure releases to the value (Pp). In this case the thermodynamic equilibrium of the system is violated: the unfrozen water is in the state of compressive suffusion. As a result, additional icing leads to pressure increase in the cavities which becomes equal to (Pc) again, and thermodynamic equilibrium returns. Significant movement of the inclosing walls can result in a situation when the whole of free water becomes icy, and the pressure never reaches its maximum possible value.

In experiments 1, 2, 4, and 7 (Table 1) the cavities freeze completely and the maximum pressure values are 63 - 100% from the maximum possible calculated ones. The cavities do not freeze completely in the lower values of freezing media compressibility and the maximum pressures at the given temperatures are obtained (tests 3, 5 and 6). Thus, the refreezing pressure value depends on the ratio of the ice volume and unfrozen liquid in the cavities at the given temperature.

The results obtained make it possible to assume that if the cavity is a cylinder filled with water, with an infinitely large wall thickness and a height substantially greater than its diameter, the cavity wall (support) undergoes only the elastic deformations; according to the field data it is valid, since the heights of the cavities generated in the cryolithic zone are ten times greater than their diameter, and compression of low-temperature ice-sandy rocks is negligible.

The modulus of elasticity E (Young's modulus) and the transverse elasticity coefficient μ (Poisson ratio) are the main indicators of the elastic properties of frozen rocks. After N.A. Tsytovich [15], the Poisson ratio of frozen rocks has weak temperature-moisture dependence and can be taken as constant in calculation for rocks of various degrees of dispersion. Thus, it can be taken in the range of 0.2-0.22 for frozen sand, and for clays its mean value is approximately 0.37.

Young's modulus depends on several factors: the composition of the frozen rocks, their iciness, values of negative temperatures and the external pressure [5]. Frozen sand obtains the highest modulus of elasticity - from 8..2 MPa (at minus 0.2 °C) up to 2.25 • 104 MPa (at minus 10.2 ° C); frozen clays obtain the lowest modulus of elasticity - from 6.8 • 102 MPa (at minus 1.2°C) up to 2.78 • 103 MPa(at minus 8.4 °C). The modulus of elasticity of silty loams and sandy loams is of the intermediate value.

Let us point out the cavity volume VK with two planes perpendicular to the longitudinal axis and spaced apart by a length unit:

$$V_K = \pi \cdot R_K^2 \cdot K, \tag{12}$$

where: $K = 1 - \left(\frac{R}{R_K} \right)^2$ — coefficient of proportionality.

Increase of the freezing cavity volume is compensated by the change of its original volume by the value ΔVK caused by the deformation of the frozen rocks, compression of ice ΔVL and the unfrozen water ΔVB. Let us take a final value of movement Uc at the inner radius of the cavity RK from the constant internal pressure Pc which can be evaluated by the formula:

$$U_C = \frac{1+\mu}{E} P_C R_K, \tag{13}$$

where: E, μ — elastic constants of frozen rocks.

Transforming the equation (1), considering $\beta_0 = 2\frac{1+\mu}{E}$ we obtain the formula:

$$P_P - P_0 = \frac{\varepsilon \cdot \chi}{\beta_L \cdot m + \beta_B \cdot (1-m) + A}, \tag{14}$$

where: $\chi = \frac{V_A}{V_K + \Delta V_K}$; $A = 2 \cdot \frac{1+\mu}{E + 2(P_C - P_0)\cdot(1+\mu)}$.

Then the dependence of the pressure that occurs when water freezes in the cavity (Pp) from the amount of generated ice is as follows:

$$P_P - P_0 = \frac{\varepsilon \cdot (\chi + \chi')}{\beta_A \cdot (\chi + m') + \beta_B \cdot (1 - \chi - \chi') + A}, \tag{15}$$

where: $\chi' = \dfrac{V'_A}{V_K + \Delta V_K}$.

The volume of ice V'_L is evaluated by the formula:

$$V'_L = 0.0136 \cdot \Delta t \cdot V_B, \tag{16}$$

where: VB — volume of the suffusion water; Δt— temperature of suffusion of water.

Having taken in the equation (4) $\chi + \chi' = 1$ and solving it with regard to K, we obtain the formula showing complete freezing of the liquid phase:

$$\frac{r_H}{R_K} \geq \sqrt{1 - \frac{2(P_C - P_0)\cdot(1+\mu)\cdot[1 - \varepsilon + (P_C - P_0)\cdot \beta_l]}{E[\varepsilon - (P_C - P_0)\cdot \beta_l]}} \tag{17}$$

Thus, in the temperature range of frozen rocks from minus 2 to minus 5 ° C, corresponding to the conditions of the Far North of Western Siberia and the taken values: 1.0·103 ≤ E ≤ 2.5·103 MPa; μ = 0.22; ε = 0.083; βl = 1.1·10-4 1/MPa, the following formulas have been obtained:

-for temperature minus 2 °C: $\dfrac{R}{R_K} \geq 0.83$ (18)

-for temperature minus 5 °C: $\dfrac{R}{R_K} \geq 0.52$ (19)

To assess the adequacy of the obtained ratios the experiment was carried out at temperatures of minus 5o and minus 2 ° C in accordance with the technique described in the books [4, 18]. The results are shown in Table. 2.

Table 2. Pressure in freezing water in the enclosed volume .

Factors		Pressure, MPa			
		Results of research in experiments 1, 2, 3			Mean value,
t, °C	$\frac{R}{R_K}$	p_1	p_2	p_3	$\overline{p}$
-.2.0	0.83	0	0	0	0
-2.0	0.50	22.1	22.5	23.0	22.5
-5.0	0.52	17.5	19.8	18.2	18.5
-5.0	0.25	58.4	56.9	57.6	57.6

The results showed that the pressure at minus 2°C and the ratio $R/R_K = 0{,}83$ did not increase, and at minus 5°C and the ratio $R/R_K = 0{,}52$ it did not exceed 20 MPa.

While at lower pressure values *R/R*$_k$ were close to their maximum possible ones evaluated by the formula (1) - 22.9 and 57.4 MPa correspondingly; this indicated the complete phase transition of water into ice in the system simulating the cavity with the boundary conditions (18).

4 Conclusion

Since the actual radius of the cavities generated in the range of occurrence of the frozen rocks is significantly greater, then after refreezing some unfrozen water will always occur in the cavities; in here, the pressure is below the maximum possible value.

References

1. R. Medvedskij, *Stroitel'stvo i jekspluatacija skvazhin na neft' i gaz v vechnomerzlyh porodah* (Nedra, Moscow,1987)
2. V. Kuznecov, PhD Thesis (Tjumen', 1991)
3. N. Weiss, D. Blok, B. Elberling, G. Hugelius, C. J. Jørgensen, M. B. Siewert, P. Kuhry, Sedimentary Geology, **340**, 38-48 (2016)
4. V. Ovchinnikov, D. Gerasimov, N. Aksenov, L. Kamenskij, Burenie i neft', **1**, 42-43 (2012)
5. V. Ovchinnikov, A. Nabokov, O. Danilov, D. Gerasimov, T. Haritonova, *Osnovnye razdely mehaniki sploshnoj sredy i ih prakticheskoe primenenie pri burenii i razrabotke neftjanyh i gazovyh mestorozhdenij. Uchebnoe posobie Tjumen'* (FGBO UVPO», Tjumen' TjumGNGU, 2015)
6. Q. Yu, Z. Zhang, G. Wang, L. Guo, X. Wang, P. Wang, Z. Bao, Cold Regions Science and Technology, **121**, 205-213 (2016)
7. M. Mel'cer, O velichine davlenija pri zamerzanii vody v ogranichennom obeme. (SibNIINP, Tjumen, 2010)
8. Z. Wen, Q. Yu, M. Zhang, K. Xue, L. Chen, D. Li, Cold Regions Science and Technology, **121**, 214-225 (2016)
9. M. Dubina, ZapSibNIGNI, **60,** 90-94 (1984)
10. S. Vjalov, *Reologicheskie osnovy mehaniki gruntov* (Vysshaja shkola, Moscow)
11. L. Guo, Y. Xie, Q. Yu, Y. You, X. Wang, X. Li, Cold Regions Science and Technology, **121**, 187-195 (2016)
12. T. Trofimov, Ju. Badu, G. Dubikov, *Kriogennoe stroenie i l'distost' MMP Zapadno-Sibirskoj plity* (Izd-vo MGU, Moscow. 1980)
13. A. Sel'vashhuk, Neftjanoe hozjajstvo, **5**, 15-19 (1999)
14. Y. Wang, H. Jin, G. Li, Cold Regions Science and Technology, **126**, 10-21 (2016)
15. C. Kneisel, A. Emmert, P. Polich, B. Zollinger, M. Egli, CATENA, **133**, 107-118 (2015)
16. V. Kuznecov, S. Jakubovskaja, D. Gerasimov, Izvestija VUZov «Neft' i gaz», **6**, 31-34 (2002)
17. S. Vjalov, Ju. Zareckij, S. Gorodeckij, *Raschety na prochnost' i polzuchest' pri iskusstvennom zamorazhivanii gruntov* (Strojizdat, Leningrad, 1981)
18. V. Kuznecov, V. Kucherjuk, Izvestija VUZov «Neft' i gaz», **6**, 36-42 (2001)
19. S. Vjalov, Ju. Zareckij, S. Gorodeckij, *Raschety na prochnost' i polzuchest' pri iskusstvennom zamorazhivanii gruntov* (Strojizdat, Leningrad, 1981)
20. M. Dubina, Prognoz davlenij obratnogo promerzanija II In-ta ZapSibNIGNI, **60**, 35-37 (1984)
21. B. Pobedrja, *Mehanika kompozicionnyh materialov* (Izd_VO MGU, Moscow, 1984)
22. A. Vasil'chenko, Fiziko-himicheskij mehanizm razvitija sverh geologicheskih davlenij smjatija obsadnyh kolonn, **981**, 23 (1987)