Analysis of the Stress-Strain State of the Pipeline in the Areas of Frost Heaving of the Soil Using the SCAD Software Package

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Abstract. The article is devoted to the actual problem of construction and operation of pipelines in difficult geological conditions. The paper analyzes the interaction of permafrost soils with underground structures. One of the main problems is considered the soil heaving - the ability of water-saturated soils to increase its volume when frozen. The authors analyzed one of the existing calculation methods for determining the stress-strain state of a pipeline laid on heaving soils; the dependences of the determination of the normal forces of frost heaving have been investigated; calculated the values of stresses and displacements in the SCAD software package. It was revealed that the problems associated with the phenomenon of changes in the volume of soils with temperature drops depend both on the rate of soil freezing and on the length of the heaving section.

1. Introduction
Freezing of moist soils is often accompanied by their heaving - the process of increasing the volume of soils due to the expansion of telluric moisture and pulled up to the freezing front in the process of moisture migration, which is caused by a number of physico-chemical and physico-mechanical processes [1]. The main parameters that determine the frost heaving of soils include: the content of unfrozen water, temperature condition, the depth of seasonal freezing, the rate of freezing of soils, and the thermophysical properties of rocks [2,3].

2. Theoretical part
Consider the stages of the formation of a heaving mound, Figure 1.
The main stages of the formation of a convex heaving mound:

1) uniform soil freezing (a);
2) nonuniform soil freezing and the formation of a lens of thawed moist ground (b);
3) mechanical effects from freezing of mineral soil (c) and gradual swelling of soil and peat;
4) further growth of the mound and degradation of the peat horizon (d);
5) the formed mound, its further growth, the removal of the mineral mass, an increase in the thickness of the peat-mud material between the mounds (e) [5].

The formation of an uneven upper surface of permafrost soils causes an uneven distribution of stagnant ground waters. Water is concentrated in depressions of the upper surface of permafrost. As a result of the freezing of the lens, swelling and cracking of the frozen soil occurs. Due to the fact that the frozen thawed soil has a different thickness, its expansion occurs unevenly: the most powerful sections of the layer expand to a greater extent than low-power [6,7,8,9].

The speed of frost penetration also affects the amount of soil heaving [10]. With rapid freezing, it may turn out that the process of moisture migration to the freezing front, although it does occur, does not fully occur. Therefore, the heaving during rapid freezing of the soil is usually less than during slow freezing [11].

Operation of the pipeline in heaving soils due to soil deformations can lead to a loss of pipeline strength because of the appearance of additional bending stresses in the cross-section of the pipeline [12].

To determine the deformations of the pipeline and its stress state, it is necessary to determine the load on the operated section of the pipeline from the action of heaving forces correctly. Since the heaving forces are self-balanced, they also act on the thawed soil adjacent to the freezing front. When transferring an external load to the ground, heaving decreases [13].

3. Formulation of the problem
In the presented work, the strain-stress state analysis (SSS) of the pipeline is carried out using the SCAD Office software package based on the determination of frost heaving forces by the method of Gorkovenko A.I. [14]. In this case, the pipeline is considered rigidly clamped at the ends of the heaving section of length $2L_0$ and has a deflection described by the function $W(z)$, Figure 2.
1 – nonfrost-susceptible soil, 2 – heaving soil; 
R – balancing resistance of nonfrost-susceptible soil; 
N – longitudinal force in the pipeline wall; 
q(W) – linear value of normal frost heaving forces

Figure 2. Scheme of the pipeline state in the area with heaving.

The calculation was carried out using the initial data given in Table 1.

| Sl.No. | Name of quantity                        | Value  | Unit  |
|--------|----------------------------------------|--------|-------|
| 1      | outside pipeline diameter \(D_0\)      | 1020   | mm    |
| 2      | soil bulk density \(\gamma\)           | 6      | kN/m³ |
| 3      | internal friction angle \(\phi\)       | 17     | angle degree |
| 4      | adhesion \(c_s\)                       | 0.5    | kPa   |
| 5      | depth of freezing \(H_f\)              | 2.2    | m     |
| 6      | the thickness of the frozen soil layer under the pipeline \(h_f\) | 0.5 | m |
| 7      | free heaving \(h_f\)                   | 0.025  | m     |
| 8      | length of soil heaving section \(L_f\) | 30     | m     |

The following relationship for displacements is used as the boundary conditions \(W\):
\[ W(-L_0) = W(L_0) = 0; W(L_0) = W(-L_0) = 0. \] (1)

In accordance with the investigated method, the linear density (standard load) of normal frost heaving forces is calculated in two ways. The choice of the method depends on the type of soil, speed and depth of freezing.

The first of them is described by a linear relationship \(q_n(W)\):
\[ q_n(W) = D_0 \cdot p_{max} \cdot (1 - \frac{W}{h_f}) = q_{max} \cdot (1 - \frac{W}{h_f}). \] (2)

For the initial data presented in Table 1, we obtain:
\[ q_n(W) = 12 \cdot \left(1 - \frac{0.005}{0.025}\right) = 16.4 \, kN/m \]

The second method for determining the load from frost heaving forces is based on a quadratic dependence \(q_n(W)\) or \(W\) [17, 18]:
\[ q_n(W) = D_0 \cdot p_{max} \cdot (1 - \frac{W}{h_f})^2 = q_{max} \cdot (1 - \frac{W}{h_f})^2. \] (3)

Then:
\[ q_n(W) = 12 \cdot \left(1 - \frac{0.005}{0.025}\right)^2 = 13.1 \, kN/m. \]
Soil pressure at freezing depth:

\[ p^o = \gamma \cdot H_f \cdot \tan^2(45 + 0.5 \cdot \varphi_s) \cdot 2 + 2 \cdot \sigma_s \cdot \tan(45 + 0.5 \cdot \varphi_s). \]  

(4)

Similarly:

\[ p^o = 6 \cdot 2.2 \cdot \tan^2(45 + 0.5 \cdot 17) \cdot 2 + 2 \cdot 0.5 \cdot \tan(45 + 0.5 \cdot 17) = 0.02 \text{ MPa}. \]

Figure 3. Dependence of heaving forces on the movement of the pipeline.

Further calculation of the stress state will be performed using the “SCAD Office” software package. Consider the main loads and impacts on the pipeline.

In the initial period of the action of the forces of frost heaving, the calculation scheme is presented in the following form, Figure 4. The calculation scheme in the final period of time, when the load from heaving dies out, is shown in Figure 5.

The difference in the design models occurs due to a decrease in the load from the forces of frost heaving when the pipe moves vertically upwards, and when the pipe moves equal to frost heaving (displacement) at the level of the upper generatrix of the pipe, the load tends to zero \[13,19,20\].

4. Experimental results
The results of calculating the equivalent stresses and displacements of the corresponding sections are shown in Figure 6.
Figure 6. The value of stresses and displacements of the pipeline under the influence of heaving forces 
\( a, c \) – displacements in the initial and final period of time; 
\( b, d \) – stresses in the initial and final period of time.

It should be noted that the design model of the “final period of time” leads to deformations “bottom-up”, which is not true. This means that this design model, built according to the studied method, needs to be improved.

The results of the following calculations of the stress-strain state of the pipeline under the action of frost heaving forces are presented in graphs 7-8. The calculation will be carried out only for the initial stages of the formation of a convex heaving mound, using the design model for the initial period of time.

Table 2. Equivalent stresses in the pipeline depending on displacements in the initial period of time.

| Displacements, mm | 56,435 | 112,871 | 169,306 | 225,741 | 282,176 | 338,612 | 395,047 |
|-------------------|--------|---------|---------|---------|---------|---------|---------|
| Equivalent stresses, MPa | 7,689 | 13,874 | 20,059 | 26,245 | 32,431 | 38,616 | 44,802 |

Figure 7. Graphs of the dependence of the equivalent stresses in the cross-section of the pipeline on displacements for the initial period of time.
5. Conclusion

Despite the small value of stresses relative to the bearing capacity of the pipeline metal, the stresses presented in Table 2 can lead to a loss of strength, since they are additional. To get a complete picture of the stress state of the pipeline, it is necessary to remember the stresses arising from the action of internal pressure and temperature difference. Often, when designing pipeline sections, there is a certain margin of safety, which, as a rule, does not exceed 15% of the yield strength of steel. Therefore, in our opinion, heaving causing a movement of the pipeline section up to 170 mm is permissible, and more can lead to the appearance of plastic deformations.

As already mentioned, the length of the heaving section has a great influence on the stress state. Table 6 shows the result of calculating the equivalent stresses depending on the length of the heaving section at a constant value of the maximum displacement.

Table 3. Changes in stresses in the initial and final period of time depending on the length of the soil heaving section.

| Heaving section length, m | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 | 110 |
|--------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Equivalent stresses in the initial period of time, MPa | 44,80 | 59,42 | 73,78 | 87,79 | 101,42 | 114,57 | 127,19 | 139,21 | 150,55 |

Figure 8. Graph of stress changes with increasing length from 30 to 110 m with a step of 10.

Similarly, the presented results of stresses need to be considered additionally based on the applied strength hypothesis. But, starting from 30 m, the equivalent stresses exceed 40 MPa, which means that, depending on the section of the pipeline on which they act, they can lead either to elastic vertical deformations and, as a consequence, to the loss of stability of the pipeline section, or to plastic deformations, and, then, to break. In the future, attention should be paid to the design of support tools of pipeline stability and its protection against rupture in areas of heaving soils.
6. References

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