Analysis of the stressed-deformed state of a pipeline with curved line parts in frozen soil

P A Kulakov, A V Rubtsov Z R, Afanasenko V G, Mukhametzyanov and M I Bayazitov

Ufa State Petroleum Technological University, 1, Kosmonavtov street, Ufa, 450062, Russia

E-mail: kulakov.p.a@mail.ru

Abstract. The paper presents a methodology for calculating the stress-deformed state of the pipeline. All dimensions required for calculations are given. The object of research is a section of an elevated trunk pipe with curved sections transporting oil. The stress-deformed state of the pipeline was calculated considering and without considering soil conditions using the SolidWorks PC. According to the results of all the calculations of the stress-deformed state of the pipe with curved sections, the dependence of the stress distribution over the zones of the pipeline on the strength of frost heaving of the soil is derived.

1. Introduction

The development of the oil, gas and other industries depends on improving the work and technical supply of gas and oil transportation systems from remote and poorly developed industrial regions. The optimal operation is called the operation in which, first of all, the maximum use of pipeline capacity occurs with minimal economic investment.

Pipelines during operation are subject to significant loads - axial expansion or compressive stress, pressure inside the pipeline, backfill load, variable temperature changes.

The presence of these many factors contributes to the emergence and further development of corrosion outside and inside the main pipeline, thus contributing to the appearance of leaks on the walls of the pipeline and therefore to accidents. To avoid these complications, much attention is paid to the reliability and effectiveness of the main lines at the design stage.

Reliable operation of trunk pipelines operating in complicated non-standard and geological criteria, largely depends on the regularity of soil phenomena. Landslides and soil displacements can be these phenomena [1]. In such places, auxiliary stresses arise on the example of bending moments, compressive forces and tensile stresses, which have all chances to lead to overstrain of some unstable sections of the pipeline [2]. There is a great danger of pipeline destruction if the hazard coefficient increases, which can happen if there are all kinds of stress concentrators in high voltage zones (welds obtained with deviations from the standards, unreliably fabricated structure, defective pipeline elements).

To increase the reliability and efficiency of the main pipeline lines, a methodology has been developed for calculating the stress-strain state of pipelines with curved sections laid in frozen ground on heavily flooded sections of the route. The technique can be applied in the design of trunk pipelines operating in frosty heaving conditions, in determining their strength and reliability.
The object of research is a section of an elevated trunk pipeline with curved sections transporting oil under a pressure of 3 MPa.

2. The research part

The total length of the pipeline is 63 m, with an outer diameter of 1020 mm, having a wall thickness of 16 mm. The pipeline has 4 bent bends with an outer diameter of 1530 mm, having a wall thickness of 16 mm with a radius of curvature of 1.5 D.

The pipeline is made of pipe steel grade 09G2S GOST 4543-71 (table 1).

Table 1. Steel grade characteristics of the pipeline.

| Name of characteristic                      | Value        |
|---------------------------------------------|--------------|
| Yield strength, MPa                         | 295          |
| Normal modulus of elasticity, MPa           | 200000       |
| Poisson's ratio                             | 0,3          |
| Density, kg / m³                            | 7850         |
| Linear expansion temperature coefficient, 1 / C | 0,000012     |
| Thermal conductivity, W / (m * C)            | 1            |
| The limit of compressive strength, MPa      | 410          |
| Fatigue strength, MPa                       | 209          |
| Tensile strength at torsion, MPa             | 139          |

The pipeline is laid in clay soil at a height of 0.5-1.4 m from the earth's surface.

The internal pressure in the pipe is 5 MPa. The cork closure temperature is minus 5 °C and the product temperature is 20 °C.

The main load in this plug is the pressure load caused by the flow of fluid in the pipe. The design scheme of the pipeline indicating the types of supports is shown in figure 1.

The force of frost heaving raising the pipeline from the design location creates stresses in the material of its wall [3]. The ductile material begins to damage in places where the von Mises stress becomes equal to the ultimate stress. In most cases, the yield strength is used as the ultimate stress.

Frosty heaving is an increase in soil volume at negative temperatures. This is due to the fact that the moisture contained in the soil, when frozen, increases in volume. The density of water is 1000 kg / m³, the density of ice is 916 kg / m³, which means that with the same mass, ice will occupy a larger volume than water by about 9%. In winter, the water contained in the soil turns into ice, increasing in volume, and thereby creates pressure on the soil [4]. Under the influence of this pressure, the soil begins to move. This pressure cannot push deep-seated lower dense layers of soil, therefore it squeezes the soil up, and with it the pipeline.

Figure 1. The general scheme of the pipeline with the location of the supports.
Analysis of the stress-strain state of a pipeline with curved sections in frozen soil begins with the construction of a three-dimensional model.

Next, to calculate the stress-strain state taking into account soil heaving, we use the SolidWorks library. We create an object under the given conditions: the temperature of the transported product is 20 °C, steel grade 09G2S with a yield strength of 295 MPa. We apply the pressure of the pipeline product equal to 5 MPa [5-8]. Figure 2 shows a sectional pipeline with marked walls for applying product pressure.

![Figure 2. The pipeline in the cut.](image)

We analyze the stress-deformed state of the pipeline along the zones of the pipeline [9-12] (figure 3).

![Figure 3. Division of the pipeline into zones for fixing stresses.](image)

3. **Research results**

The procedure for calculating the SDS of a pipeline section with curved sections without taking into account soil heaving. We calculate the SDS by setting only in this case the internal pressure and gravity (figures 4-5) [13-16].

![Figure 4. Stresses in the zones of the pipeline without taking into account soil heaving.](image)
The graph below shows the displacement of the pipeline according to certain zones (figure 6).

![Graph showing displacement](image)

**Figure 6.** Displacement without exposure to heaving pressure.

Next, we calculate the stress-strain state (SDS) of the pipeline, taking into account the pressure of frost heaving of the soil of various sizes in the range from 2.5 to 15 MPa.

The stresses observed under the pressure of frost heaving in the areas of the pipeline are shown in table 2.

| The zone number | 11   | 22   | 33   | 44   | 55   | 66   | 77   |
|-----------------|------|------|------|------|------|------|------|
| Stresses in the pipeline zones from the pressure of frost heaving of the soil of various sizes in the range from 2.5 to 15 MPa, MPa | 22,5 | 22,39| 37,6 | 46,9 | 47,6 | 53,4 | 39,5 | 77,2 |
|                 | 44,5 | 113,8| 776,4| 884,9| 994,2| 882,7| 669,1| 22,34|
|                 | 110  | 44,63| 1174 | 1186 | 2208 | 1191 | 1174 | 99,25|
|                 | 115  | 111,4| 2265 | 2281 | 3312 | 2289 | 2243 | 55,04|

Displacements observed under the pressure of frost heaving in the areas of the pipeline are given in table 3.

| The zone number | 11   | 22   | 33   | 44   | 55   | 66   | 77   | 88   |
|-----------------|------|------|------|------|------|------|------|------|
| At frost heaving pressure in the range from 2.5 to 15 MPa, the following | 22,5 | 22,95| 119,7| 443,8| 665,3| 669,3| 445,6| 00,713|
|                 | 44,5 | 22,07| 993,5| 1176 | 2264 | 2239 | 1180 | 887,3 | 55,04|
|                 | 110  | 117,6| 1138 | 3302 | 4444 | 4413 | 3319 | 1168 | 44,03|

**Figure 5.** Pipeline movements without soil heaving.
movements are observed in the pipeline zones, mm

| Characteristic of SDS | The magnitude of the forces of frost heaving, affecting the pipeline, MPa |
|---------------------|---------------------------------------------------------------|
|                     | 2.5               | 4.5               | 10                  | 15                  |
| Mises equivalent stress, MPa | 53.4               | 95                | 208                 | 312                 |
| Total linear displacement, mm | 69.3               | 268               | 444                 | 777                 |

The results of all calculations of the stress-strain state of the pipe with curved sections, taking into account the pressure of frost heaving of the soil, with a voltage in the range from 2.5 to 15 MPa are summarized in table 4.

Table 4. Pipeline SDS results.

Using all the results of stress calculations, we plot diagrams in the zones of the pipeline at a soil heaving pressure in the range from 2.5 to 15 MPa (figure 7).

Also, based on all the calculation results, we build the dependence of the elevation of the zones of the pipeline on the design position under the influence of frosty soil pressure in the range from 2.5 to 15 MPa (figure 8).

Figure 7. Plots of stresses in the zones of the pipeline at a pressure of heaving of the soil in the range from 2.5 to 15 MPa.

Figure 8. The lifting height of the pipeline zones from the design position under the influence of pressure of frost heaving of the soil of various sizes.
Accordingly, the more forces of frost heaving of soils act on a pipeline with curved sections, the more uneven the distribution of stresses over its zones is observed [7]. In this case, stresses above the yield strength of 295 MPa of the 09G2S pipe material arise with a frost heaving force of the soil equal to and above 15 MPa.

4. Conclusion
The revealed dependence of the thickness of deposits on the voltage at the thermoelectric module allows us to develop a method for determining the planned repair time for the operation of heat exchange equipment and, on this basis, to develop an optimal program for the maintenance and repair of laminate heat exchangers.

The revealed dependence of the Mezes stress and the magnitude of the rise of the pipeline on the magnitude of the soil pressure allows us to develop a method for assessing the technical condition of the facility and determining the repair time for the operation of pipeline transport.

References
[1] Borodavkin P P (1973) Underground pipelines (Moscow: Nedra)
[2] Valarezo D, Mendieta G, Quiñones-Cuenca M, Quiñonez V and Soto J (2020) Advances in Intelligent Systems and Computing 1099 257-69
[3] Zheng Y, Chen C, Liu T, Sun C and Chen L. (2020) Environmental Earth Sciences 79(1) 21
[4] Duong N T and Suzuki M (2020) Lecture Notes in Civil Engineering 62 985-92
[5] Wang C, Hawlader B, Islam N and Soga K (2019) Soil Dynamics and Earthquake Engineering 127 105824
[6] Tsapurin K A, Skvortsov Yu V and Glushkov S V (2012) Engineering sciences: theory and practice 1 98-105
[7] Edigarov S G and Bobrovsky S A (1973) Design and operation of oil depots and gas storages (Moscow: Nedra)
[8] YuFin V A, Krivoshein B L and Agapkin V N (1974) Influence of thermophysical characteristics of soils on operating modes of main pipelines VNIIgazprom, Moscow 69
[9] Ostaeva F D (1982) Issues of pipeline strength: Sat. scientific VNIIST, Moscow
[10] Korshak A A and Nechval A M (2005) Pipeline transport of oil, petroleum products and gas: A manual for the system of continuing professional education Design PoligrafServis, Ufa
[11] Kuzeev I R, Naumkin E A, Pankratiev S A and Tlyasheva R R (2018) Solid State Phenomena 284 587-92
[12] Tyusenkov A S, Rubtsov A V and Tlyasheva R R (2017) Solid State Phenomena 265 868-872.
[13] Mukhametzyanov Z R, Rubtsov A V and Valiev A S (2019) Lecture Notes in Mechanical Engineering 0(9783319956299) 1999-2006
[14] Kulakov P A, Galyautdinov D D and Afanasenko V G (2020) Lecture Notes in Mechanical Engineering 1 753-763
[15] Naumkin E A, Rubtsov A V, Kulakov P A, Usachev K A (2019) Journal of Physics: Conference Series 1399(5) 055054
[16] Kuzeyev I R, Naumkin E A, Kudashev R R, Ryabov A A and Konovalov B B (2015) SOCAR Proceedings 2 47-53