Study of stress-strain state of pipeline under permafrost conditions

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Abstract. In this paper, the dependences of the stress-strain state and subsidence of pipelines on the dimensions of the subsidence zone are obtained for the sizes of pipes that have become most widespread during the construction of main oil pipelines (530x10, 820x12, 1020x12, 1020x14, 1020x16, 1220x14, 1220x16, 1220x18 mm). True values of stresses in the pipeline wall, as well as the exact location of maximum stresses for the interval of subsidence zones from 5 to 60 meters, are determined. For this purpose, the authors developed a finite element model of the pipeline that takes into account the actual interaction of the pipeline with the subgrade and allows calculating the SSS of the structure for a variable subsidence zone. Based on the obtained dependences for the underground laying of oil pipelines in permafrost areas, it is proposed to artificially limit the zone of possible subsidence by separation supports from the soil with higher building properties and physical-mechanical parameters. This technical solution would significantly reduce costs when constructing new oil pipelines in permafrost areas.

1. Introduction

A gradual decrease in the recovery rate of the hydrocarbon fields commissioned in the middle of the last century in the Tyumen region encouraged the development of the resources of the Arctic region and Eastern Siberia. The construction of oil transport infrastructure facilities in these regions is complicated by the ubiquitous proliferation of permafrost soils, as well as soils with low building properties and physical-mechanical parameters [1-2] due to their excessive water saturation. From the regulatory documents [3], permafrost soils, as a subgrade for engineering structures, can be used according to two principles: I - permafrost soils used in the frozen state preserved during construction and throughout the operation of the structure; II - permafrost soils used in a thawed or thawing state. Article [4] points out the existing contradictions in regulatory documents [3] and [5], which are the main ones in the design of pipeline transport facilities in the permafrost distribution areas. In [3] it was noted that preserving the soil under the structure in the frozen state is expedient at economically justified costs. Otherwise, the use of permafrost soils according to the second principle is recommended. According to [5], the main principle of using permafrost soils as a subgrade under the pipeline is the principle of their preservation in the frozen state. According to [3], main oil pipelines refer to hot pipelines, because they transport oil only at a positive temperature. Thus, in the
construction of main oil pipelines, the fulfillment of the requirements [5] is possible only with the above-ground method of laying. This technical solution leads to an increase in construction costs by a factor of 2.5-4 [4], which in the construction of long-distance facilities significantly reduces the overall profitability of the project. The regulatory document [5] does not provide justification for the necessity of keeping the ground under the oil pipeline in a frozen state [4].

The existing regulator documents [3, 5] do not give clear and justified recommendations on the choice of the method of laying pipelines and the principle of using permafrost soils as their subgrades. In [4], based on the analysis of regulatory documents, it was concluded that during underground laying on permafrost soils, considerable pipe subsidence is expected when soils thaw. In [5], the value of the pipeline subsidence is not limited, but only the stresses arising in the pipeline are regulated. The conducted field studies on oil pipelines laid in the marshy area [4] showed that subsidence can reach 0.5 m during long-term operation without a significant change in the stress-strain state (SSS) of the pipeline.

During underground laying of pipelines on permafrost soils, the most dangerous areas are the areas of the subgrade transition from the soil with a high bearing capacity to thawing soils with low physical and mechanical characteristics. From the scientific and practical point of view, analysis of the change in the SSS of the pipeline in these zones, as well as determination of the maximum values of subsidence depending on the length of the subsidence zone, is of undoubted interest. Proceeding from this, the authors set the following tasks: based on the results of numerical simulation, to obtain the dependences of the effective equivalent stresses in the pipe material on the size of the subsidence zone and to determine the values of the maximum possible sag of the pipeline when the subsidence zone changes. For the finite element analysis, pipes of the following diameters were chosen that have become most widespread during the construction of main oil pipelines: 530х10, 820х12, 1020х12, 1020х14, 1020х16, 1220х14, 1220х16, 1220х18 mm.

According to the design classification, a pipeline is an infinite tubular beam [4], which has zones of elastic pinching along the edges. The authors of the article proposed and implemented a design scheme that takes into account the effect of the hydrostatic load from the transported product, as well as the uniformly distributed load from the weight of the bund on the shell structure of the pipeline as its lateral deformations develop due to the presence of subsidence zones.

2. Methods

Figure 1 shows the design scheme of a pipeline section. The weight of the bund on the pipeline wall is calculated by multiplying the area of curved section $S_1$ by the length of the pipe.

![Figure 1: A design scheme of a pipeline section.](image)

Figure 1. A design scheme of a pipeline section: $L_1$ - zone of elastic pinching of the pipeline by the Winkler model; $L_3$ - free pipeline sagging zone; $\delta$ - pipeline wall thickness, mm; $D_n$ - outside pipeline diameter, mm.

Using software suite ANSYS, a finite element model of a pipeline section was created according to the proposed design scheme. The pipeline was modeled with shell finite elements SHELL181 and is a rotation body. The properties of steel are specified taking into account the nonlinear properties of deformation along the real stress-strain diagram. The boundary conditions are determined by the
elastic-contact interaction of the end sections of the pipeline wall with the ground. The properties of the soil are specified using the coefficient of subgrade reaction by the simplified model, the Winkler hypothesis. It is established that the use of such scheme leads to a satisfactory convergence of the solution, which is confirmed by test calculations. The elastic contact interaction between the wall and the ground is modeled with the help of final element COMBIN14. The hydrostatic load from the pumped product applied to the inner surface of the pipeline and the evenly distributed load from the weight of the bund applied to its outer surface is modeled with elements SURF154. In the proposed model, pipeline subsidence was calculated for the worst case of free sagging at a variable length of the soil zone with poor physical and mechanical characteristics (L3 in Figure 1). The model of the pipeline is broken into a hexagonal grid with a linear size of the edge l = 10 mm. A total of 96 calculations were carried out, in which the following parameters varied: the size of the increment of the subsidence zone is assumed to be 5 meters; thus, an array of data was obtained for changes in pipeline SSS in the range of values of the subsidence zone from 5 to 60 meters; SSS parameters of the whole range of subsidence values were obtained for 8 types of pipes with different diameters and wall thicknesses.

To check the adequacy of the finite-element model, a test calculation of the deflection of a single-span uncompensated beam transition was carried out using a simplified design scheme and a comparison with the known analytical solution was performed. The most suitable model for verification is the design model of a single-span uncompensated beam transition described by A.B. Einbinder and A.G. Kamerstein [6]. The design scheme of the beam transition proposed by them is based on the works of S.P. Timoshenko and supplements them by the fact that, in addition to the operational loads, it takes into account the elastic interaction of the soil with the adjacent underground sections of the pipeline (Figure 2).

![Figure 2. A design scheme of a single-span uncompensated beam transition.](image)

This technique allows determining the value of the arrow of pipeline deflection in the middle of the span:

\[
f = f_1 \frac{qL}{384EI}
\]

(1)

where \(q\) – lateral load; \(L\) – span length; \(EI\) – bending rigidity of the pipeline; \(f_1\) – dimensionless parameter, a function of the value of \(\varphi\) characterizing the relative pinch of the ends of the pipeline [6].

\[
\varphi = \left( \frac{4EI}{D_o \cdot C_y \cdot o_c} \right)^{\frac{1}{2}} \cdot \frac{2}{L}
\]

(2)

\[
f_1 = \frac{1 + 5\varphi + 10\varphi^2 + 12\varphi^3 + 6\varphi^4}{\varphi + 1}
\]

(3)

where \(D_o\) – outside diameter of the pipeline; \(C_y\cdot o_c\) – generalized coefficient of normal ground resistance.

When the model was verified, a hydrostatic load was applied from the transported product to the internal surface of the pipeline without taking into account the weight of the bund. The discrepancy between the analytical solution and the numerical one, the finite element method, was no more than
3%, which is a good result of convergence.

The authors of the article set the task not only to determine the ultimate values of deflections of pipelines of different sizes in the given ranges of the subsidence zone, but also to reveal the exact locations of the zones of increased stresses. The relevance of this approach is confirmed by the fact that in the current regulatory document [5], the limiting parameter of the pipe SSS is effective stresses, the limiting values of displacements are not regulated. With the undoubted advantages of the models of S.P. Timoshenko and [6] and their practical value, these analytical solutions do not allow determining the exact places of stress concentration and their values at any point of the pipeline - both in the longitudinal and annular directions [7, 8].

3. Results and Discussion

Figure 3 shows the results of calculating the stresses in the neutral layer of the pipeline shell with a length of 140 m for various specified parameters in accordance with the accepted design scheme.

The nature of distribution of stresses in the pipeline has various features for a given range of subsidence zones and pipe sizes: if values of subsidence zones are more than 20 meters, the maximum stresses are located on the upper generatrix of the pipe; if the value of the subsidence zone is less than 20 m, then the maximum stresses are concentrated in the middle of the lower generatrix of the
pipeline. Let us note that when assigning boundary conditions for the extent of the subsidence zone, estimates were made at which the moment of the onset of the limiting state was determined, i.e. achieving the value of the yield strength of the pipe material. Modern oil pipelines are made of pipes of strength class not lower than K56. According to [9], strength K56 corresponds to steels with a yield strength of at least 410 MPa. The bending rigidity of the pipeline increases with the increase in the outer diameter, so the limiting stresses in the body of the pipe arise at large values of the subsidence zone. For pipelines with a diameter of 1020 mm, this is 47-50 meters, depending on the wall thickness; for 1220 mm - more than 50 meters. For the pipeline with a diameter of 530 mm, due to less rigidity, the limiting state will arise much earlier. Thus, Figures 4 and 5 summarize the calculations performed and show the dependence of the maximum operating stresses in the metal of the pipelines and their deflections from the size of the subsidence zone.

Article [10] indicates that thermal subsidence of the pipeline of more than 1.0 meters is considered very dangerous and requires carrying out anti-karst procedures. In this regard, this value was taken as the limiting value in determining the values of the pipeline sag, while in the domestic regulatory documentation the criteria for maximum sags of the main pipelines are not presented.

The graphs in Figures 4 and 5 show that with an uneven subsidence of the pipeline, the limiting stresses in the pipe wall at the boundary of soils with different bearing capacity will occur before the pipeline reaches the maximum value of subsidence. In this regard, it is not advisable to take the value of subsidence as a criterion for the safe pipeline operation.

![Figure 4. Change in equivalent stresses in the pipe material when the subsidence zone changes.](image)

![Figure 5. Dependences of the pipeline sag on the size of the subsidence zone.](image)

Thus, the performed calculations taking into account the rigidity of the shell structure of the
pipeline and the properties of the subgrade have shown the possibility of underground laying of oil pipelines in the permafrost distribution areas.

4. Conclusion
The authors have developed a finite element model of the pipeline that takes into account the actual interaction of the pipeline with the subgrade and allows calculating the SSS of the structure for a variable subsidence zone. The properties of the soil are specified using the coefficient of subgrade reaction by the simplified model, the Winkler hypothesis. Conducted model verification with the known analytical solution showed that the discrepancy was no more than 3%. The ANSYS software package is used to implement the finite element model. In this paper, the dependences of the stress-strain state and subsidence of pipelines on the dimensions of the subsidence zone are obtained for the sizes of pipes that have become most widespread during the construction of main oil pipelines (530x10, 820x12, 1020x12, 1020x14, 1020x16, 1220x14, 1220x16, 1220x18 mm). True values of stresses in the pipeline wall, as well as the exact location of maximum stresses for the interval of subsidence zones from 5 to 60 meters, are determined. It is established that if values of subsidence zones are more than 20 meters, the maximum stresses are located on the upper generatrix of the pipe; if the value of the subsidence zone is less than 20 m, then the maximum stresses are concentrated in the middle of the lower generatrix of the pipeline. Studies have shown that it is not advisable to take the value of subsidence as a criterion for the safe pipeline operation, since the limiting stresses occur before the pipeline reaches the maximum value of subsidence. Based on the obtained dependences for the underground laying of oil pipelines in permafrost areas, it is proposed to artificially limit the zone of possible subsidence by separation supports from the soil with higher building properties and physical-mechanical parameters. This technical solution would significantly reduce costs when constructing new oil pipelines in permafrost areas.

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