Analysis of the General Stability of Buried Pipelines in the Longitudinal Direction Taking into Account the Peculiarities of Their Construction and Operation

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Abstract. Main oil and gas pipelines should be checked for overall longitudinal stability. In this case, the longitudinal compressive force in the cross-section of the pipeline, leading to the loss of its stability, is determined by the effect of a positive temperature difference in the metal of the pipes and the working pressure in its cavity. The longitudinal critical force, at which the loss of longitudinal stability of the pipeline occurs, is determined according to the rules of structural mechanics in the plane of the least bending stiffness of the system taking into account the constructive solution of its laying. The value of the longitudinal critical force of a buried pipeline depends on the geometric characteristics of the pipe, its weight with the pumped product, the parameters of curvature of the longitudinal axis of the pipeline when it is laid along the terrain, and the resistance of the soil to its longitudinal and transverse displacement. During operation, due to a decrease in the resistance of the soil surrounding the pipeline to its movements for various reasons, a decrease in the critical force occurs. Loss of stability of a buried pipeline occurs in the plane with the least bending stiffness of the system. With the help of theoretical studies of the general stability of buried pipelines, analytical dependences of the longitudinal critical force for a buried pipeline were obtained on the basis of taking into account the curvature of the longitudinal axis of the pipeline during construction and reducing the resistance to displacement of the pipeline during its operation for 5 different design schemes.

1. Introduction

In accordance with the requirements of the set of rules [1], buried oil and gas pipelines, constructed in conditions of negative air temperatures, are exposed to significant longitudinal compressive forces [1-7]. So, for example, at a temperature difference (the temperature difference between the pipe metal during operation and construction) + 10°C in a buried stationary pipeline with a diameter of 1020 mm and a wall thickness of 11 mm, a longitudinal compressive force equal to 87.95x10⁴ N. In conditions of a sufficiently high temperature of the pumped product in pipeline sections built at negative ambient temperatures, after oil and gas pumping stations, a positive temperature difference can reach values of up to 50°C. When pumping oil and oil products with heating the temperature difference is up to 80°C [8]. Operational experience, well-known studies of the stress-strain state of pipelines under the action of high longitudinal compressive forces and some special technical solutions for laying a pipeline confirm the existence of real conditions for the loss of the overall stability of pipelines in the longitudinal direction. Loss of stability is characterized by a large deflection, usually exceeding the
depth of the buried pipeline, the occurrence of excessively high stresses in the pipeline and damage to the structure. And therefore, the loss of the overall stability of the pipeline is unacceptable.

Therefore, the following should be noted: an analysis of the stability of buried pipelines according to known design formulas shows that at the above values of the positive temperature difference of 50°C and 80°C, stability loss occurs mainly in pipelines of relatively small diameters, laid in weakly bearing soils. Loss of stability mainly occurs with pipeline deflection in the vertical plane. Let us show this with specific examples.

The longitudinal critical force, at which there is a loss of longitudinal stability, for straight pipelines is determined by the formula obtained by Professor E.M. Yasin:

\[ N_{cr} = 4.09 \times 10^3 \sqrt{p_s q F^2 E I}, \]  

(1)

where \( p_s \) and \( q \) — resistance to longitudinal and lateral upward movement of the pipeline respectively, \( F \) — cross-sectional area of the pipe; \( I \) — moment of inertia of the cross-section of the pipe; \( E \) — modulus of elasticity of the pipe metal.

Resistance to longitudinal and transverse movements of a buried pipeline \( p_s \) and \( q \) include the weight of the pipeline with the pumped product and the resistance of the soil to displacements of the pipeline, determined depending on the properties of the soil (volumetric weight, adhesion and angle of internal friction) and the depth of the pipeline [4]. Taking according to [9,10] geometric characteristics and values \( E \) for the metal of oil pipeline pipes with a diameter of 1020 mm, a wall thickness of 11 mm and the type of loam soil when the pipeline is buried by 1 meter, are calculated \( q = 27200 \text{N/m} \) and \( p = 15300 \text{N/m} \). Then, by (1), we have \( N_{cr} = 12.34 \text{MN} \).

Based on the requirements [1], the condition for ensuring longitudinal stability is

\[ S \leq \frac{m}{1.1} \cdot N_{cr}, \]  

(2)

where \( S \) — equivalent longitudinal force and \( m \) — the coefficient of the pipeline operating condition.

For pipeline with a diameter of 1020 mm and a wall thickness of 11 mm at operating pressure \( p = 4.0 \text{MPa} \) and \( m = 0.99 \) condition (2) is provided at a positive temperature difference of 110°C or less. For a pipeline with a diameter of 325 mm and a wall thickness of 9 mm, with the above initial data, we have \( q = 7800 \text{N/m} \), \( p_s = 2800 \text{N/m} \), \( N_{cr} = 12.16 \text{MN} \). Condition (2) for this pipeline is provided at a positive temperature difference of 80°C or less.

A decrease in the numerical characteristics of soil properties, pipeline burial and the weight of the pipeline with the product significantly reduce the critical longitudinal force and the permissible positive temperature difference, at which the overall stability of the underground pipeline in the longitudinal direction is ensured. Laying the pipeline along the terrain on convex curved sections also leads to a decrease in the longitudinal critical compressive force.

2. Methods
Following the recommendations of the works of Professor E.M. Yasin, we determine the decrease in the value of the critical effort for some design schemes that take into account the parameters that affect the value of the critical effort. In this case, a fourth-order differential equation of the pipeline bending was used, containing the longitudinal compressive force \( N \) on a curved section, resistance forces to pipeline displacements \( p_s \) and \( q \), its bending stiffness \( EI \) [5].

By solving the differential equation of bending on the basis of the above conditions, analytical relationships were obtained between the loads acting on the pipeline, the geometric characteristics of the pipeline and its displacement.

Such an analytical dependence for various design schemes of the pipeline is obtained in the form
where \( A \) – dimensionless parameter characterizing the features of design schemes for the loads acting on the pipeline and geometric parameters; \( a \) – dimensionless parameter characterizing pipeline bending.

Parameter values \( A \) for the design schemes considered in this work are determined by the formulas given in Table 1.

**Table 1.** Design formulas for calculating the parameter \( A \) with different design schemes.

| Design scheme number | Name of the design scheme                                                                 | Parameter \( A \)                                                                 |
|----------------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| 1 (figure 1, a)      | Buried straight pipeline                                                                  | \( A = 0 \)                                                                      |
| 2 (figure 1, b)      | Opened section of a buried straight pipeline                                             | \( A = \frac{q_p}{q_p} \left[ \tan \alpha - \tan \alpha \cos (a - b_0) + \sin (a - b_0) - a + b_0 \right] \) |
| 3 (figure 1, c)      | An underground curved section of a pipeline with a bent branch in bold terrain relief     | \( A = B_3 \left[ a_0^3 + a_0^2 \cdot \sin (a - a_0) - a_0^2 \cdot \tan \alpha \cdot \cos (a - a_0) \right] \) |
|                      | A buried pipeline with a section of elastic bend in bold terrain relief at \( l \geq l_0 \) | \( B_3 = \frac{EI}{qR \tan^2 \varphi} \)                                         |
| 4 (figure 1, d)      | A buried pipeline with a section of elastic bend in bold terrain relief at \( l \geq 1 \) | \( A = \frac{B_4 a_0^4 \cos (a - a_0)}{\left( \pi^2 - a_0^2 \right)} \left[ \tan \alpha - a_0 \tan \alpha \right] ; \) |
|                      |                                                                                        | \( B_4 = \frac{8EI}{q \rho l_0^2} \)                                              |
| 5 (figure 1, e)      | A buried pipeline with a section of elastic bend in bold terrain relief at \( l \leq l_0 \) | \( A = \frac{B_5 a_0^4 \cos \left( \frac{\pi a}{a_0} \right)}{\left( \pi^2 - a_0^2 \right)} \left[ \pi \tan \alpha - a_0 \frac{\tan \alpha}{a_0} \right] ; \) |
|                      |                                                                                        | \( B_5 = \frac{8EI}{\pi q \rho l_0^2} \)                                          |

**Figure 1.** Design schemes: a) the first design scheme; b) the second design scheme; c) the third design scheme; d) the fourth design scheme; e) the fifth design scheme.
In the formula (3) and Table 1 are indicated: \( a = \frac{kl}{2} \); \( k = \sqrt{\frac{N}{EI}} \). Here \( l \) – the length of the bent section of the pipeline with a loss of longitudinal stability and \( N \) – longitudinal compressive force acting in the pipeline in the curved section.

In addition, the following conventions are adopted in Table 1. Parameters \( q_{p}, q_{s} \) – the weight of the pipeline with the pumped product and the force of soil resistance to the deflection of the pipeline in the vertical plane respectively. The values \( q_{p}, q_{s} \) are determined in accordance with the recommendations [4, 7]. Parameter \( h_{0} = 0.5kb \), where \( b \) – the length of the exposed section of the pipeline to its lower generatrix. An opening of a buried pipeline can occur for various reasons - repair of an existing pipeline, erosion of soil above the pipeline, and so on. In these areas, the resistance of the soil to the movements of the pipeline and pipelines is significantly reduced; it can lose longitudinal stability with bending in the vertical plane, which has the lowest bending stiffness. In the third calculation scheme \( a_{0} = kRtg\varphi \), where \( R \) – radius of curvature of the bent branch, \( \varphi \) – half the angle of rotation of the pipeline at its top in the vertical plane, \( q \) – the sum of the weight of the pipeline with the product \( q_{p} \) and the resistance of the soil to the deflection of the pipeline \( q_{s} \). In the fourth and fifth design scheme \( a_{0} = \frac{kl_{0}}{2} \), where \( l_{0} \) – the wavelength of the bending of the pipeline in the vertical plane when it is laid during construction along the terrain. Therewithal \( \rho \) is the minimum radius of elastic bend of the pipeline, which occurs at the apex of the angle of rotation.

The solution of equation (3) makes it possible to find the first nonzero minimum value of the parameter \( a \), denoted by us as \( a_{m} \), with the given initial data: \( q_{p}, q_{s}, b \) for the second design scheme; \( E, I, q, R, \varphi \) for the third design model and \( E, I, q, l_{0}, \varphi \) for the fourth and fifth design schemes. Then the following will be obtained:

\[
N = \left( \frac{2a_{m}}{l} \right)^{2} EI. \tag{5}
\]

In the process of bending the pipeline under the action of the longitudinal compressive force, the value of the longitudinal compressive force decreases from the initial \( N_{0} \) (in the absence of movement) to \( N \). Relationship between longitudinal forces \( N_{0} \) and \( N \) has the form

\[
N_{0} = N + 0.5p_{l}\left[ \frac{4EFc}{p_{s}l^{2}} + 1 \right], \tag{6}
\]

where \( F \) – cross-sectional area of the pipe; \( c \) – an increase in the length of the pipeline from its stationary state during its bending under conditions of loss of longitudinal stability, equal to the difference in the lengths of the bent section of the pipeline with a loss of stability and this section of the pipeline before its bending under the action of longitudinal compressive forces.

Increase in length \( c \) pipeline is determined by the formula

\[
c = \frac{\pi^{2}v_{0}^{2}}{4l}, \tag{7}
\]
where \( v_0 \) — the greatest deflection of the pipeline at loss of stability, calculated by the formula

\[
v_0 = \frac{q}{EI} \left( \frac{l}{2a_m} \right)^4 v_0,
\]

where \( q = q_s + q_p \) for design models 1, 3, 4, 5, for design model 2 we have \( q = q_p \).

Dimensionless parameters \( \bar{v}_0 \) are calculated using the following formulas:

a) for design scheme 2

\[
\bar{v}_0 = 1 + \frac{a_m^2}{2} - \frac{1}{\cos a_m} \cdot \frac{q_s}{q_p} \left[ \cos \left( a_m - b_{om} \right) + \frac{(a_m - b_{om})^2}{2} \right],
\]

b) for design scheme 3

\[
\bar{v}_0 = \frac{4Et}{qRl^2} \left[ \cos \left( a_m - a_{om} \right) - 1 \right] + \frac{a_m^2}{2} + \frac{8Et \varphi}{q} \cdot \frac{a_m^4}{l^2} \left[ 1 - \frac{Rt \varphi}{l} \right],
\]

c) for design scheme 4

\[
\bar{v}_0 = 1 + \frac{a_m^2}{2} - \frac{1}{\cos a_m} \cdot \frac{2EI}{qRl^2 \left( \frac{2a_m a_{om}}{\pi} \right)^2} + \frac{EI}{qRl^2 \left( \pi^2 - a_0^2 \right)^2} \left( \frac{2a_m a_{om}}{a_{om}} \right) \left[ 1 + \left( \frac{\pi}{a_{om}} \right)^2 \cdot \frac{\cos \left( \frac{a_m}{a_{om}} \right)}{\cos a_m} \right],
\]

d) for design scheme 5

\[
\bar{v}_0 = 1 + \frac{a_m^2}{2} - \frac{1}{\cos a_m} \cdot \frac{2EI}{qRl^2 \left( \frac{2a_m a_0}{\pi} \right)^2} + \frac{EI}{qRl^2 \left( \pi^2 - a_0^2 \right)^2} \left( \frac{2a_m a_0}{a_0} \right) \left[ 1 - \left( \frac{\pi}{a_0} \right)^2 \cdot \frac{\cos \left( \frac{a_m}{a_0} \right)}{\cos a_m} \right].
\]

In the calculation formula (9), the parameter

\[
b_{om} = a_m \cdot \frac{b}{l},
\]

In formula (10)

\[
a_{om} = \frac{2a_m}{l} \cdot Rt \varphi.
\]

In formulas (11), (12)

\[
a_{om} = a_m \cdot \frac{l}{l}.
\]

Solving together equations (4) - (6), the analytical dependence of the longitudinal compressive force on the geometric characteristics and properties of the soil for the equilibrium state of a bent pipeline under conditions of loss of longitudinal stability was obtained.
Minimization of analytical expression (16) with respect to \( l \) allows us to get the lower critical force \( N_{cr} \), at which there is a loss of overall stability of the underground pipeline in the longitudinal direction.

3. Results
As an example, using the given design formulas and calculation methodology, the lower critical force for an underground pipeline with a diameter of 325 mm and a wall thickness of 9 mm at \( q = 7800 \text{N/m} \) and \( p_s = 2800 \text{N/m} \) was determined. As a result, the following was obtained for the design schemes:

- for the second one \( b_0 = 0.75a, \frac{q_s}{q_p} = 4.82 \) value \( N_{cr} = 1.86 \text{MN} \);
- for the third one \( R = 5 \cdot D_{outer} = 1.625 \text{m}, \varphi = 10^\circ \) value \( N_{cr} = 1.52 \text{MN} \);
- for the fourth one \( a_0 = 0.75a \) value \( N_{cr} = 1.78 \text{MN} \);
- for the fifth one \( a_0 = 1.25a, \rho = 350 \text{m} \) value \( N_{cr} = 1.64 \text{MN} \).

Condition (2) is satisfied for the considered design schemes:

- for the second one if \( \Delta t \leq 69^\circ \text{C} \);
- the third one if \( \Delta t \leq 55^\circ \text{C} \);
- the fourth one if \( \Delta t \leq 65^\circ \text{C} \);
- the fifth one if \( \Delta t \leq 60^\circ \text{C} \).

Based on the results of the calculation, it can be concluded that the presence of areas exposed from the ground and curvatures of the longitudinal axis of the buried pipeline lead to a decrease in the values of the lower critical force. In this regard, in conditions of a positive temperature difference on the pipeline, it is necessary to take the parameters of the longitudinal axis curvature during construction and the length of the opening during maintenance and repairs on the basis of calculations for the overall longitudinal stability of the pipeline.

4. Conclusions
- Calculation formulas are obtained and an algorithm is given for determining the longitudinal critical force in the presence of curvatures of the longitudinal axis of a buried pipeline when it is laid along the terrain.
- Problems for the conditions of constructive performance of longitudinal axis curvatures by elastic bending of pipes and the use of bent branches are solved.
- A study of the effect of soil opening of a buried pipeline on the critical longitudinal force during maintenance and repair of pipes was carried out, and calculation formulas were obtained for calculating the longitudinal critical force.
- Some calculations have been made to determine the critical longitudinal force in the conditions of laying the pipeline by elastic bending of pipes and with using bent branches. Calculations were also made to assess the impact of opening a buried pipeline for its maintenance and repair on its overall stability under the influence of a positive temperature difference.
- A recommendation is given on the need to check the overall longitudinal stability when choosing the design of bent sections of buried pipelines and the length of the opening of the existing oil and gas pipeline under the influence of a positive temperature difference.
5. References

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