Analysis of Longitudinal Stresses in Main Pipelines with a Long Operating Life

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Abstract. With the advent of the possibility of determining the actual bending radius of long-operating main pipelines by pigging inline inspection tools, it became clear that up to 100% of trunk lines cannot provide elastic bend radius within the limits required. Assessing the that requirement for bending radius to be of not more than 1000D, it can certainly be considered justified in relation to construction of new trunk lines, but for most long-operating main pipelines, this requirement conflicts with its actual stress-strain state. Re-ly them for this reason, due to the scale of the problem is not possible. At the same time, a sharp increase in accident rate is also not observed, as a result of which we can conclude that it is necessary to revise the existing regulations for the limiting values of permissible elastic bend radius.

1. Introduction

In 2017 amount of trunk pipelines with a service life of 40 years and more equals to more than 50% of the total. Currently, the main concept for maintaining the reliability of trunk pipelines is operation in technical condition. Assessment of the technical condition is carried out according to the diagnostic data, which is based on in-line diagnostics, the advantage of which is a direct way to detect defects. At the same time, calculations of the stress-strain state of existing pipelines, regardless of the operating life, are carried out according to the regulatory framework intended for the design and construction of a new main pipeline.

2. Theory

Characteristic of the normative calculation of longitudinal stresses. According to [2] for underground rectilinear and elastically bent sections of pipelines, in the absence of longitudinal and transverse movements of the pipeline, subsidence and heaving, the maximum total longitudinal stresses from standard loads and effects - internal pressure, temperature drop and elastic bending are determined by the formula:

\[ \sigma_p^{\alpha} = \mu \sigma_c^{\alpha} - \alpha E \Delta t \pm \sigma_b \]

where: \( \mu \) – Poisson's lateral strain coefficient;
\( \sigma_c^{\alpha} \) – circular stresses from internal gas pressure, MPa;
\( \alpha \) – linear expansion coefficient;
\( E \) – modulus of elasticity of pipe steel, MPa;
\( \Delta t \) – estimated temperature difference assumed to be positive when heated, °C;
σ\textsubscript{b} – elastic bending stress, MPa.

For the calculation of bending stresses in these areas, the recommended formula [2]:

$$\sigma_b = \frac{ED}{2\rho}$$  \hspace{1cm} (2)

where:
- \(E\) – modulus of elasticity of pipe steel, MPa;
- \(D\) – pipe diameter;
- \(\rho\) – radius of elastic bending.

$$\sigma_c = \frac{PD}{2\delta}$$  \hspace{1cm} (3)

where:
- \(P\) is the working gas pressure, MPa;
- \(D\) – pipe inner diameter, cm;
- \(\delta\) – pipe wall thickness, cm.

In formula (1), the classical principle of the independence of the action of forces is used, when the influence of each of the three components is summed up, at the same time this means that the calculation results can be quite conservative, since their interaction is not taken into account.

By the form of the longitudinal stress formula (1), it follows that it is intended in physical terms for the calculation that is pinched at the ends of the pipeline section. In the classical sense, on the linear part of the main pipeline, there are not many pinched sections, tens of km of the route may not have pinched, except for interactions with the surrounding soil. Compensated sections can correspond to compensatory overhead crossings, sections in the immediate vicinity of: cranes with piping, bends, underwater crossings, road crossings, etc. Cold bending bends [3] and steeply bent bends may have a certain pinching and compensating effect.

In formula (1) the necessary conditions “in the absence of longitudinal and transverse movements of the pipeline, subsidence and heaving of the soil”, shows its focus on design, geometrically correct plan and profile, which do not imply a change in the linear-height position. However, the specifics of the construction and operation of the main pipeline is such that “longitudinal and transverse movements” are inevitable.

During designing the linear part of main gas pipelines, sections are provided that are mainly rectilinear, and turns, obstacles, are predominantly laid using cold bends and / or elastic bending, which, in accordance with [4], should not be less than 1000D radius. When designing straight sections, the magnitude of the longitudinal stresses is formed from the influence of the product pressure in the 1st component and the temperature difference in the 2nd component of formula (1).

Calculation of longitudinal stresses from internal pressure looks quite definite. During the construction of the main pipeline, when there is no pressure in the pipeline, circular and longitudinal stresses from them are equal to zero. During operation, the stresses from the gas pressure are zero when the main pipeline stops and increase with increasing product pressure, i.e., during operation, the calculated longitudinal stresses in the pinched area can only be compressive.

**Characteristic of calculating longitudinal stresses from temperature difference.** With stresses from the temperature difference, everything is not so simple.

According to [2, 5, 6], any temperature difference occurs only in the presence of two fixed temperatures, and the first recorded temperature must be subtracted from the second. In [6], it was indicated that “the temperature difference in the metal of the pipe walls should be taken equal to the difference between the maximum and minimum possible wall temperatures during operation and the lowest and highest temperatures at which the design scheme of the pipeline is fixed.”

A significant part in [5, 6] is devoted to the temperature difference \(\Delta t\) at the design and construction stage of the pipeline. In order to reduce longitudinal stresses, it is recommended that this parameter be brought to zero, for example, due to the coincidence of the air temperature during welding of butt joints and the product transportation temperature and (or) lowering the transportation temperature to the same value, etc. Then the calculation, according to formula (1), will be reduced to the calculation of two components of the product pressure and bending radius.
3. Practice

Description of diagnostic tools for detecting bending radii of a section of a trunk pipeline. A breakthrough in the field of in-line diagnostics is the technology for determining the direction and actual bending radius [7] of the examined section, and hence bending stresses according to formula (2). The technology allows, in the process of conducting planned in-line diagnostics, to reliably measure the actual bending radii of the linear part of the surveyed section with a maximum radius of 4000 m over its entire length.

According to [8], repeated attempts were made to endow the in-line diagnostics with the functions of measuring the stress-strain state, but the matter did not advance beyond laboratory achievements.

Pipeline behavior during construction. During construction, the pipeline laid in the trench is filled with loose soil backfill without any compaction along the length, even if it is provided for by the project [6]. The adhesion force between the “soil - insulation, pipeline” pair is a defining characteristic when calculating the resistance of the backfill soil to the longitudinal displacements of the pipeline in the initial period of its operation. The calculated values of the jamming of the pipeline in the soil are determined from the expression:

$$Q_0 = k(\gamma H t g \varphi + c)$$

where:
- $k$ - is the coefficient of reduction of the pinch of the pipeline;
- $\gamma$ – soil density, N/m$^3$;
- $H$ – pipeline filling height with soil, m;
- $\varphi$ – soil internal friction angle;
- $c$ - soil adhesion force, N/m$^2$.

The table provides data on the coefficient of reduction in the amount of jamming of the pipeline, depending on the time of filling the pipeline after construction.

**Table 1.** The value of the coefficient of jamming of the pipeline depending on the time of filling the pipeline.

| Time since filling the pipeline, years | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Coefficient k                         | 0,45| 0,60| 0,70| 0,75| 0,80| 0,85| 0,90| 0,95| 1,0 |

From the above table it follows that the longer the pipeline is in a filled state, the more the soil surrounding it consolidates and turns into a soil mass with a maximum degree of pinching, which prevents longitudinal movement of the pipeline.

It turns out that during the start-up period the pipeline comes into operation with almost zero pinching and has complete freedom of longitudinal (transverse) movements, which can practically be realized in the form of a violation of the straightness of the axis of the pipeline in horizontal (in plan) and in vertical (in profile) planes. The formation of waves of vertical and horizontal “snakes”, incl. can occur in the first years of operation of the pipeline, when the pinching effect of the soil remains at a minimum level [6]. According to [6], at some gas pipelines that have worked for more than a dozen years during opening, cases of a sinusoidal position of the pipeline vertically, over a sufficiently long length, without bulging were revealed. The amplitude of these vertical sinusoids was insignificant (up to 30 cm) and did not interfere with agricultural work. An assessment of the stress-strain state of these main gas pipelines is not given, but it is known that the danger of destruction is characterized not so much by the deflection arrow as by the bending radius, which are interconnected by a differential relationship.

Characterization of the bending radii of the pipeline section. As an example, Fig. 1 shows a graph of the measured (in the bending plane) radii of elastic bending of a rectilinear section of a main gas pipeline with a diameter of 1420 mm, with radii of 1000D or less obtained from the planned in-line diagnostics of the company “NPC In-tube diagnostics” [9]. The abscissa axis is the linear coordinate along the odometer, the ordinate axis is the actual radius of elastic bending in diameters (absolute values).
Figure 1. Graph of the bending radii of a straight section gas pipeline with a diameter of 1420 mm.

It can be seen that in the straight section of the main gas pipeline with a length of 400 m with a life of about 35 years, there are 13 sections with an elastic bend radius of 1000D or less, i.e. there is actual non-compliance with the requirements [4].

It follows from the graph that sinusoidal (when the stress sign changes) can be attributed to the beginning and end of the section (up to 105652 m and after 105980 m), and on the section 328 m long there are 10 waves, less than 1000D, the bending radius of which varies in range 500D ... 1200D without changing the sign, the definition of "snake" is more suitable here [6]. At the same time, it is not clear which longitudinal stresses prevail, tensile or compressive. In favor of compressive ones, the presence of bending radii of less than 1000D, with distances between them from 8 to 90 m.

At the same time, the site may be subject to tensile stresses. Fixed bending radii can arise from many factors, we list some of them: the pipe itself is initially not straightforward; the cut for welding along the perpendicularity and the gap for welding of the joints has a tolerance, as a result, the norms are met, but the pipes are welded at an angle; the bottom of the trench cannot be performed in a straight line, when resting on local hard bumps, the pipe bends under its own and the weight of the soil; fluctuations in the velocity of the in-tube diagnostics shell that distort readings, etc.

There is a possibility that, subject to building and operating standards, even in straight sections, bending radii may be below 1000D.

The situation is much more complicated in areas laid by elastic bending or with cold bending, where there are only a few non-extended places, where the radius.

Figure 2. Graph of the bending radii of the section of the main gas pipeline crossing the ravine, cold bends are highlighted in blue.

It can be seen from the graph that the following values were determined with high accuracy: the minimum bending radius - 276D and the linear coordinate - 89634.5 m, as well as the bending direction - 6.4 hours.

Assessing the requirement 1000D [4], it can certainly be considered justified in relation to new construction, but, by default, it is carried over to the entire life of the main gas pipeline, mainly because the mechanism for controlling this parameter has not existed until recently. In connection with the advent of the technology for detecting the actual radii of elastic and elastic-plastic bending of a main pipeline [8], this requirement conflicts with its actual state.
This situation is typical for the entire linear part of the main pipeline, it can be assumed that in the Russian Federation up to 100% does not meet the standard [4], with a bending radius of 1000D, but there was no increase in accident rate. From which it follows that:

- it is desirable to provide bending radii within the limits of standards, but re-lying the main pipeline for this reason, due to the scale of the problem, is not possible
- it is necessary to revise the existing standards for the scientific justification of the allowable value of the longitudinal stresses of the main pipeline with a long service life.

4. Discussion

Characteristic of the initial data, temperature difference. The temperature difference is the most variable indicator of the calculation of longitudinal stresses.

According to [2, 5, 6], any temperature difference occurs in the presence of two fixed temperatures. Moreover, the first recorded temperature should be subtracted from the second. The standard temperature difference in the pipe wall metal should be taken as the difference between the maximum and minimum temperature during operation and the highest and lowest temperatures at which the design scheme of the pipeline is fixed, i.e. 4 different temperatures must be taken into account.

The temperature difference is determined from the expression:

\[ \Delta T = T_p - T_c \]  

where:

- \(T_p\) - maximum or minimum pipe wall temperature during operation;
- \(T_c\) – the lowest and highest temperatures for fixing the design scheme of the pipeline during construction (welding of overburden).

To determine \(T_p\), no serious obstacles are visible, in [10] the calculation of longitudinal stresses is given, where according to the data of the last 3 years of operation, these figures were 5 ... 26 °C. The number 5° C occurs when the pipeline stops, which is understandable, since the pipe takes the temperature of the soil at a depth of approximately 1.6 m. Figure 3 shows a seasonal graph of the temperature of the soil at this depth, across the territory of the Republic of Bashkortostan.

![Figure 3. Seasonal soil temperature at a depth of 1.6 m in Republic of Bashkortostan.](image)

The graph shows that the minimum soil temperature in March-April is about 30 °C, and the maximum 120 °C in August.

During operation, when the modes of transport of the product change, fluctuations in the stress-strain state are very likely to occur, which will mainly affect the bending radii (bending arrows) of pipes and cold bends. Those. with increasing pressure and temperature, with a corresponding increase in compressive stresses, we can expect, first of all: in the example in Figure 1, a decrease in the bending radius at the minimum bending radius on the linear coordinate 10585 m, in Figure 3, these are both cold bending taps and vice versa.

There are serious doubts about the reliability of the approach to calculations using the principle of independence of the forces. In the example given in the previous paragraph in the calculation according to formula (1), everything is summed up several times (backlog): pressure changes - are taken into account in 1 and 3 components, \(\Delta T\) change - in 1 and 2 components. If, in railway transport, the linear-height position of the rail track is maintained due to the calculated clearances between the rails, then in pipeline transport this is a self-regulating "snake", which in a particular case can take the form of a sinusoid.
This factor does not promise the reliability of the linear part of the pipeline, for various reasons objective (for example, geodynamic), subjective (design errors or deviations from design decisions, rejected construction and installation works, stress corrosion cracking, etc.) that can cause abnormal bending radii.

The “calculations to backlog” approach adopted in [2] is outdated; what was appropriate at the time of the creation of SNiP II-D.10-62 is not actually observed at present. Indeed, the requirements for new construction must be “strict” and it is necessary to correct the deviations for the stress-strain state before putting the main gas pipeline into operation. For example, in [2] there are strict requirements for longitudinal stresses along the inner radius (fiber compressive), in which even the theoretical possibility of corrugation is excluded.

The main gas pipeline with a long service life is quite another matter, the authors are not aware of cases of failures due to corrugation, and accidents due to the appearance of cracks along the outer radius (fiber tensile) occupy a significant place in the statistics [11]. This is taken into account, for example, rejection standards [12], which allow the presence of corrugations, but limited in size.

5. Conclusion
It is necessary to develop a regulatory framework that takes into account the long life of the main gas pipeline. Thus, the main factor that forms the magnitude of the longitudinal stresses of the main gas pipeline with a significant service life is the bending radius, stresses from temperature and pressure are minimal, and in practical calculations can be ignored or taken into account with the coefficient.

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