Theoretical Approbation of the Method for Evaluating Bending Stress of Underground Pipelines from the Ground Surface

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Abstract. The feature of the operation of main underground pipelines in complicated engineering and geological conditions is the need for constant monitoring of their technical condition and the design position of the axis to assess the level of bending stress in order to take preventive measures. The existing methods for monitoring the technical condition of underground pipelines have several disadvantages, for this reason, as a rule, a set of methods is used.

One of the promising methods for assessing the bending stress of underground pipelines is the method of surveying the depth of the pipeline axis from the ground surface. The paper provides dependencies that make it possible to level the errors arising when using this method and to assess the bending stress of an underground pipeline with an error not exceeding the specified one and taking into account the design features of the pipeline and the equipment used.

Comparison of the calculated values of bending stress when using the method of surveying the depth of the axis of an underground pipeline from the ground surface and the values obtained during smart pigging of a section of an underground pipeline is presented. The provisions for determining the optimal shooting step when measuring the depth of the pipeline axis from the soil surface are presented.

1. Introduction

A distinctive feature of the pipeline transport of the Russian Federation is its length, which is a consequence of its crossing of many different climatic and hydrogeological zones with different operational characteristics. This difference in operating conditions leads to the impact on the pipeline of additional loads [1-4], which are force assistance, the economic damage from which can be significant [2].

Due to the fact that these loads have a permanently variable nature, it is practically impossible to take them into account at the design stage of the pipeline. In the simplest case, taking into account these loads and impacts is laid in the pipeline wall thickness [5], however, as practice shows, the values laid down due to the simplification of the design schemes and inaccuracies in the initial data lead to underestimated values of the loads actually acting on the pipeline [6-9].
Thus, the operating conditions in areas with complicated geotechnical conditions cannot be fully taken into account at the design stage and methods are required to monitor the stress-strain state of pipelines in areas with complicated geotechnical operating conditions. External force effects on the pipeline lead to a change in the design height of its laying, as a result of which areas with non-standard radii of curvature are formed, which are places of additional concentrations of bending stress.

Operating conditions also impose additional restrictions on the diagnostic methods used. Since loads are a variable force component, monitoring methods are valuable, which do not require access to the generatrix of the pipeline in order to minimize the cost of work. These methods include monitoring hazardous areas using fiber-optic strain sensors and using data obtained from surveying an underground pipeline from the ground surface to calculate the bending stress of a pipeline.

The method involving the use of fiber-optic sensors is highly accurate and sensitive to changes in the bending radius of the pipeline [10,11]. False positive alarms of the system, indicating the presence of an off-design bend in the test section, are possible when the fiber-optic sensors are mechanically deformed by soil in the process of external forces acting on the pipeline. To supplement the information received from the fiber-optic sensors, it is possible to use the data obtained when surveying the depth of the buried pipeline from the ground surface.

The pipeline survey method is quite simple to implement; however, a number of its disadvantages are known [12-14], which did not allow using this method for a more accurate assessment of bending stress at the test site. In the works [15-17], the authors proposed a mathematical model that allows leveling the errors caused by the error of the route-finding equipment and pre-setting the error limit in determining the bending stress of the pipeline section. Thus, this method can be used both in conjunction with other methods, and separately as a method for monitoring sections of underground pipelines laid in complicated engineering and geological conditions.

The purpose of this study is to test the mathematical model [15,16] based on the data obtained during the smart pigging of the underground main pipeline using the methods of mathematical modeling.

2. Statement of the problem
An underground pipeline D = 1420 mm was taken as the object of research, the length of the test section was 1640 m with known values of bending stress; to simplify the problem, the depth of the pipeline axis along the entire length of the section was assumed to be unchanged h = 3 m (figure 1).

The orange line in the upper graph of Figure 1 corresponds to the stress calculated based on the standard radius of curvature. Thus, there are two areas at the test object with bending stress that go beyond the standard.

It is known that if the depth of the pipeline axis is surveyed from the ground surface without taking into account the structural and design features of the pipeline, then the error arising during the survey will be large enough and will not allow, on the basis of the data obtained, to determine bending stress with a given accuracy [15,16]. Then, it is necessary to limit the maximum error from above and select the step between the measurement points and taking into account the specific operating conditions and parameters of the pipeline so that the following relationship is fulfilled:

\[ \Delta \sigma = |\sigma_{\text{real}} - \sigma_{\text{calc}}| \leq \Delta \sigma_{\text{max}}, \]

where
\( \Delta \sigma \) – maximum calculated error in determining bending stress, MPa;
\( \sigma_{\text{real}} \) – bending stress as per smart pigging;
\( \sigma_{\text{calc}} \) – calculated bending stress;
\( \Delta \sigma_{\text{max}} \) – the maximum error in the calculation of the bending stress.

Given the diameter of the pipeline, the mathematical model [15] for determining optimal measurement step can be simplified to the form:

\[ \Delta \sigma(L) = \frac{a}{L^p}, \]

where
\( \Delta \sigma \) – selected measurement step between points, m;

\( a \) – constant;
\( L \) – selected measurement step between points, m.

2
\( a \) – regression coefficient.

\[ a(h) = k \times h + c, \]  

(3)

where

\( k, c \) – regression coefficients depending on the pipeline diameter;

\( h \) – pipeline laying depth, m.

To solve the problem in equation (1), the authors considered in detail two configurations of the pipeline axis, corresponding to the most conservative options for surveying the depth of the pipeline axis, that is, performed with the maximum error as per figure 2.
3. Discussion

It is known that modern route-finding equipment have an error in determining bending radius no more than $\Delta \pm 5\%$. Let us calculate bending stress at different steps between the measurement points and compare them with the real stress as per smart pigging. The graphical results are presented in figure 3 for the first and in figure 4 for the second point configuration. Accordingly [15,16], with small values of the step between the measurement points, the error in determining the bending stress can be significant, so we will set the minimum step between the measurement points 30 m.

![Figure 2. Outline of an underground pipeline of arbitrary configuration.](image)

![Figure 3. Values of bending stress with the first bent pipe axis configuration.](image)
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Figure 4. Values of bending stress with the second bent pipe axis configuration.

In figures 3 and 4, the red curve corresponds to the stress at the points, calculated by the formula responsible for the maximum value of bending stress taking into account the maximum error of the equipment:

\[ \sigma_I = \sigma_{real} + \Delta \sigma_{max} \]  \hspace{1cm} (4)

Thus, if the curve of the maximum values of bending stress, taking into account the error, intersects the red curve at any point, condition (1) is not met and this step cannot be used to determine bending stress with a given accuracy. Then, with a measurement step between points \( L = 30 \ldots 40 \) m on a given profile, the maximum error in determining bending stress will be higher than that determined in equation (1), taking into account the restrictions from above and below, the optimal steps when surveying the pipeline will be steps \( L = 50 \) and 70 m. Let us compare numerically the obtained values with the smart pigging data.

The maximum error in determining bending stress between the real values (according to smart pigging) and the values at a certain step will be determined as the difference between the real values and the maximum value of the two point configurations (figure 2) at the selected step according to the equation:

\[ \sigma_{max}^{exp}(L) = |\sigma_{real} - \sigma_{calc}(max(L(N = 1; N = 2)))|, \]  \hspace{1cm} (5)

where

\( \sigma_{calc} \) – calculated bending stress with the given measurement step;
\( N \) – axis configuration number.

The absolute excess of \( \sigma_{max}^{exp} \) over the values of the mathematical model in equation (2) will be determined by the equation:

\[ \sigma_{abs}(L) = |\sigma_{max}^{calc}(L) - \Delta \sigma(L)| \]  \hspace{1cm} (6)

Let us calculate the values of the maximum error in determining bending stress according to the mathematical models in equations (2) and (3). The coefficients of the regression equation for the pipeline \( D = 1420 \) mm at the depth of the axis \( h = 3 \) m are:

\( k = 29782; \)
\( c = 254 \) [14, 15].

The values of the coefficient "a" are:

\( a(3) = 29782 \times 3 + 254 = 89600 \)
The maximum errors at steps $L = 50$ and $70$ m for this pipeline are:

$$
\Delta \sigma(50) = \frac{89600}{50^2} \approx 36 \text{ MPa}
$$

$$
\Delta \sigma(70) = \frac{89600}{70^2} \approx 18 \text{ MPa}
$$

Comparison of the values of the maximum error in the determination of bending stress according to mathematical models in equations (2) and (3) with a selected step between the measurement points with the values obtained in the study of the pipeline using the smart pigging are presented in table 1. For clarity, only those results are displayed in which the error values exceed the values of the mathematical model.

**Table 1. Results of comparison of mathematical models with smart pigging data.**

| Measurement point (m) | Real stress (MPa) | Evaluate stress $(\max(L/N=1, N=2)$ | Maximum experimental stress $L=50$ (MPa) | Absolute error stress $L=50$ (MPa) | Maximum experimental stress $L=70$ (MPa) | Absolute error stress $L=70$ (MPa) |
|-----------------------|------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 107570                | 18.4             | 54.6                                     | 37.7                                     | 36.2                                     | 0.2                                      | 19.2                                      | 1.2                                      |
| 107730                | 9.9              | 46.3                                     | 30.1                                     | 36.4                                     | 0.4                                      | 20.3                                      | 2.3                                      |
| 107770                | 30.2             | 69.2                                     | 56.1                                     | 38.9                                     | 2.9                                      | 25.9                                      | 7.9                                      |
| 108050                | 71.0             | 111.5                                    | 94.7                                     | 40.5                                     | 4.5                                      | 23.7                                      | 5.7                                      |
| 108130                | 7.9              | 45.3                                     | 29.6                                     | 37.4                                     | 1.4                                      | 21.7                                      | 3.7                                      |
| 108170                | 24.7             | 62.8                                     | 47.7                                     | 38.1                                     | 2.1                                      | 22.9                                      | 4.9                                      |
| 108290                | 24.3             | 62.8                                     | 49.1                                     | 38.5                                     | 2.5                                      | 24.9                                      | 6.9                                      |
| 108370                | 21.6             | 59.5                                     | 43.9                                     | 37.9                                     | 1.9                                      | 22.3                                      | 4.3                                      |
| 108450                | 46.7             | 84.0                                     | 67.9                                     | 37.2                                     | 1.2                                      | 21.2                                      | 3.2                                      |
| 108610                | 37.4             | 76.6                                     | 62.6                                     | 39.3                                     | 3.3                                      | 25.3                                      | 7.3                                      |
| 108650                | 39.3             | 77.1                                     | 62.2                                     | 37.8                                     | 1.8                                      | 22.9                                      | 4.9                                      |
| 108730                | 14.9             | 50.5                                     | 40.2                                     | 35.6                                     | 0.4                                      | 25.3                                      | 7.3                                      |

Table 1 shows that for some points there is an excess of the maximum error values over the mathematical model. This is due to the fact that the methods for measuring bending stress using smart pigging also have some component of the hardware error, while the mathematical model is built on the basis of geometric positions that are accurate. The maximum difference between the experimental data and the data of the mathematical model is 7.9 MPa, thus, the mathematical model based on real data works quite accurately and can be applied to determine the optimal parameters for surveying the depth of the buried pipeline from the ground surface for subsequent use of the obtained data in the calculation of bending stress.

4. Conclusions to work

The method of calculating bending stress based on the data of surveying the depth of the buried pipeline from the ground surface can be used as an additional monitoring method in case of suspicion of mechanical damage to other monitoring systems or to supplement information on the state of the pipeline at the inspection site (for example, based on fiber-optic sensors deformation), and as the main method of control of the pipeline section.
A comparison is made of the values of bending stress obtained according to the smart pigging data with the values of bending stress that can be obtained when examining the pipeline with route finding equipment from the ground surface at different steps of the study. The error between the obtained data is estimated. The conclusion is made about the possibility of using the mathematical model in equation (2) on real objects of the main pipeline with a careful selection of the research step. It is shown that when using the mathematical model in equation (2), it is possible to measure bending stress of a section of an underground pipeline with an error not exceeding a specified one.

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