To the question of determining bending stress of a buried pipeline from the ground surface

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Abstract. The laying of buried pipelines in difficult engineering and geological conditions is associated with the need to take into account a large number of factors affecting the process of pipeline operation. It is practically impossible to take into account all these factors at the design stage. In this regard, methods that make it possible to assess the technical condition of the pipeline at a specific point in time acquire particular relevance. One of the promising methods for assessing the technical condition of underground pipelines is to survey the depth of the axis of the underground pipeline from the ground surface with subsequent use of the data obtained to assess the level of bending stress. The low popularity of this method lies in the large errors obtained in the calculations according to the developed methods. In the work, the reasons for the occurrence of significant errors in determining bending stresses when using survey data were analyzed, mathematical dependencies were proposed that make it possible to evaluate bending stress based on the data obtained with the accuracy specified at the design stage of the experiment. Calculations are provided that confirm the adequacy of the proposed mathematical models.

1. Introduction
The experience of operation and construction of main pipelines in harsh engineering and geological conditions shows that the formation of sections of the pipeline with a non-standard bending radius [5,10,12,14] occurs under the influence of several factors [2,12,14-15]. Such sites are dangerous due to the risk of accidents and incidents [5,9].

The impact of negative factors during the operation of the buried pipeline leads to a change in the design depth [2,11,12,14]. As a result, sections with increased bending stress are formed, which makes a significant contribution to the stress-strain state of the pipeline.

Despite many existing methods for assessing and monitoring the technical condition of main the pipelines [1,3,6–8,15], many of them are not applicable due to the conditions described above. Thus, the cost and complexity of smart pigging do not allow widespread use of this type of diagnostics to monitor hazardous areas. Physical methods require access to the generatrix of the pipe, which is a complex and expensive operation.

A prospect in this regard is the survey of the depth of the buried pipeline from the ground surface with the subsequent use of the data to assess its technical condition. The low popularity of this method is due to the poor development of scientific, technical and methodological provisions. For example, according to [4,11,13-15], the error in determining bending stresses based on survey data can reach...
50%. Thus, measurements taken without first evaluating the maximum error cannot be used to further evaluate the stress-strain state of the pipeline.

The normative and technical documentation for surveying the depth of the axis of the pipeline from the ground surface and interpreting the obtained data does not allow us to estimate the bending stresses with sufficient accuracy for engineering calculations due to insufficient elaboration of the methodology.

The standards WFD 39-1.10-026-2001 and R-352-79 do not allow the determination of the error of measurement of the radius of curvature caused using search and navigation equipment. Also, the proposed mathematical relations for calculating the radius of curvature have rather conservative measurement requirements, which are practically impossible when experiment running in the field. These restrictions and assumptions can cause large inaccuracies in the calculation according to the standards of WFD 39-1.10-026-2001 and R-352-79.

The purpose of this study is to improve the methodology for assessing the bending stress of a buried pipeline based on surveying the depth of the pipeline axis from the ground surface.

2. Statement of the problem
Since a detailed account of all these factors at the design stage is practically impossible, methods based on surveying the position of the axis of the pipeline from the ground surface become relevant. The only documents regulating the interpretation and progress of determining the radius of elastic bending from the soil surface is the WFD 39-1.10-026-2001. However, this technique has several limitations and does not allow us to judge the adequacy of the data obtained after measurement. Besides, the methodology does not provide the necessary information about the process of the survey itself: for example, the step size when measuring the depth of a buried pipeline from the ground surface, taking into account the error of the equipment during the measurement data, the methodology for estimating the bending stress based on the data obtained. Similar standards in the countries of the European Union are not developed now. Figure 1 shows an abstract profile of an underground pipeline.

In [9], a rationale is presented for the possibility of calculating the radius of curvature of a pipeline section at three points based on geometric positions.

The black line indicates the profile of a buried pipeline with a bending radius $\rho_{\text{real}}$. Since the device for measuring the depth has a measurement error, it cannot be stated at what distance from the pipeline axis the measured point is located. Thus, we will keep in mind that the measurement result is not a point, but a certain range $h \pm \Delta$, where $h$ is the depth of the pipeline, m, $\Delta$ is the error of the device, % (Figure 1).

Figure 1. Outline of an underground pipeline of arbitrary configuration.
Due to the lack of access to the generatrix of the pipe during the survey, it is necessary to consider the most conservative version of the location of the measurement points. This option involves two possible options for the configuration of points with maximum errors $h \pm \Delta$ at three points per figure 1.

We consider the problem in a flat coordinate system: $L$ is the distance between the measurement points, $h$ is the depth of the axis of the pipeline. To assess the most conservative conditions, the depth of the pipeline will be $h = 3$ m, the error of the device for determining the depth of the axis of the pipeline is $\Delta \pm 5\%$, the measurement step between points $L = 10$, 20 . . . 100 m. A number of nominal diameters $D = 1420$, 1220, 1020, 820 mm.

To determine the bending stresses, the classical formula is used:

$$\sigma_i = \frac{E_d a}{2\rho_i^2},$$

(1)

The bending radius of the pipeline $\rho$ at three points is calculated by the formula [9]:

$$\rho_i = \frac{a_i b_i c_i}{\sqrt{(a_i+b_i+c_i)(-a_i+b_i+c_i)(a_i-b_i+c_i)(a_i+b_i-c_i)}};$$

(2)

$$a_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2};$$

(2.1)

$$b_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2};$$

(2.2)

$$c_i = \sqrt{(x_{i+1} - x_{i-1})^2 + (y_{i+1} - y_{i-1})^2};$$

(2.3)

where

$x_i, x_{i-1}, x_{i+1}$ – distance between measuring points; $y_i, y_{i-1}, y_{i+1}$ – pipeline depth at these measurement points.

The error in determining the bending radius is calculated by the formula:

$$\Delta \rho = |\rho_{real} - \rho_{calc}|,$$

(3)

where

$\rho_{real}, \rho_{calc}$ – real and calculated bending radius of the section, m.

Error in the determination of bending stress $\Delta \sigma$:

$$\Delta \sigma = |\sigma_{real} - \sigma_{calc}|,$$

(4)

where

$\sigma_{real}, \sigma_{calc}$ – real and calculated bending stress, MPa.

In connection with the foregoing, it is necessary to analyze the influence of the error of the device and the measurement step between points on the values of the calculated bending stresses and evaluate the error of these values.

3. Methodology

3.1. The first bent pipe axis configuration (bending radius)

The presence of the error of the device introduces some error in the calculated values of the radius of curvature. By the formula (2), the calculated bending radius is determined for given boundary conditions.

Figure 2 shows the dependence of the calculated radius of the curvature of the pipeline section on the step between the measurement points. The dashed lines in the graph indicate the real (actual) radius of the pipeline corresponding to the diameters in accordance with figure 1. According to the graph, at small steps, the difference between the calculated and actual values of the calculated bending radius does not allow estimating the bending stresses with sufficient accuracy.
Figure 2. The influence of the step between points on the calculated bending radius.

The error $\Delta$ also affects the calculated values. To determine the effect of the equipment error on the calculation result, a graph was constructed reflecting the influence of various error values $\Delta$ and the measurement step $L$ on the calculated bending radius for the pipeline $D_n = 1420$ mm (Figure 3). This graph will be a surface, each point of which corresponds to three given parameters: the calculated bending radius $\rho_{calc}$, the error of the device $\Delta$, and the step between the measurement points $L$.

![Figure 3.](image)

Figure 3. Dependence of the calculated bending radius on the error of the device and the measurement step between points for the pipeline $D_n = 1420$ mm.

3.2. The second bent pipe axis configuration (bending radius)

To assess the effect of the distance between the points with consideration with a constant error of $\Delta = \pm 5\%$, a graph was also plotted of the calculated bending radius of the pipeline versus the measurement step (Figure 4).
Analyzing the graph, we can conclude that the values of the calculated bending radius in this configuration of points are abnormally high, which is associated with the bending of the pipeline in the opposite plane relative to the true one. However, it is also noticeable that they arise only at small measurement steps between points.

The results: before measuring the depth of the axis of the pipeline, it is necessary to determine the measurement step between the points at which it is possible to determine the bending stresses with sufficient accuracy.

By modernizing formula (4), we obtain a criterion for determining the optimal, taking into account the hardware error of the search and navigation equipment and allowing calculation with a given measurement accuracy:

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

where

\( \Delta \sigma_{\text{max}} \) – the maximum error in the calculation of the bending stress of the pipeline section, MPa.

Thus, taking into account the depth of the axis of the pipeline, the diameter of the pipeline, and the error of the device, it is necessary to choose a step between the measurement points at which relation (5) will be satisfied.

3.3. The first bent pipe axis configuration (bending stress)

Let's consider \( \Delta \sigma_{\text{max}} = 50 \) MPa. We will try to evaluate at what measurement step between points the relation (5) is fulfilled for a pipeline depth \( h = 3 \) m and an error \( \Delta = \pm 5\% \) for various pipeline diameters (Figure 5).
Figure 5. The dependence of the difference in bending stress on the measurement step.

The smaller the diameter of the pipeline, the faster the curve crosses the set value of the maximum error $\Delta \sigma = 50$ MPa. In general, the obtained step values between the points at which relation (5) is satisfied are $L \geq 43$. Numerically, these values are equal to the minimum step for the first configuration of the pipeline axis.

3.4. The second bent pipe axis configuration (bending stress)

Next, we will estimate at what measurement step between points the relation (5) is fulfilled with a pipeline laying depth $h = 3$ m and an error $\Delta = \pm 5\%$ for various diameters (Figure 6).

Figure 6. The dependence of the difference in bending stress on the measurement step.

The results showed that the error in the determination of bending stresses depends on the error of the equipment used, as well as the distance between the measurement points. For pipelines $D \leq 1420$ mm, equipment error values $\Delta \leq \pm 5\%$, you can take a step $L \geq 50$ m, at which you can guarantee the obtained values $\Delta \sigma_{\text{max}} \leq 50$ MPa.
4. Discussion
Before performing a survey of the depth of the axis of the buried pipeline, it was found that the error in determining bending stress during the first configuration of the axis of the bent section of the pipeline is an upper estimate for the second configuration, thus, when developing a mathematical model, we will use the data of the first configuration of the axis of the bent section, as the most conservative.

The dependence of the error in the determination of the bending stresses $\Delta \sigma$ on the measurement step $L$ is an inverse proportion function, which can be described with the introduction of empirical coefficients. The function of the dependence of the error of bending stresses on the step between the measurement points is the function (6):

$$\Delta \sigma(L) = \frac{a}{L^2}$$

where

$L$ – selected measurement step between points, m;
$a$ – regression coefficient.

The search for the coefficient “$q$” in equation (6) is reduced to solving the problem of minimizing the mean-square error of function (7):

$$Q(L, X) = \frac{1}{l} \sum_{i=1}^{l} (\Delta \sigma(L) - y_i)^2 \rightarrow \min,$$

where

$X$ – data sampling;
$y_i$ – response to a specific object;
$l$ – the number of elements in the data sample.

The data sample is a matrix with a size of 1000 rows by 2 columns, where each step value between points - $L$ corresponds to the value of the error in determining bending stress – $\Delta \sigma$.

$$X = (L_i; \Delta \sigma_i),$$

where

$L_i$ – selected measurement step between points;
$\Delta \sigma_i$ – error in determining bending stresses at this step.

The solution to the optimization the problem (7) (that is, finding the minimum of the objective function) is a classical problem in mathematics. To solve problem (7) in this work, the nonlinear least-squares method, the Levenberg-Marquardt algorithm, was used.

Figure 7 presents the results of searching for the minimum of the function (7) using the Levenberg-Marquardt algorithm for a pipeline $D_n = 1420$ mm located at a depth of $h = 3$ m. Let the maximum error in determining bending stress be $\Delta \sigma_{\text{max}} = 50$ MPa.

The black dots indicate the values of the X data sample, because of its large dimensionality, the dots represent a solid line. The orange line is a function selected by solving the problem (7). As can be seen, the mathematical model (6) made it possible to describe the dependence of the difference in bending stress on the step between the measurement points almost perfectly, the determination coefficient is 0.99. Thus, in the mathematical model (6) there is practically no proportion of the unexplained variance. It was also found that by solving the problem (7), model (6) allows one to obtain a dependence for a pipeline of an arbitrary diameter and depth.
The values of the coefficient "q" for pipelines of the conditional diameter $D_n = 1420 \div 820$ mm are presented in table 1.

Table 1. The values of the coefficient "q" in formula (6).

| Diameter (mm) | 3.0  | 2.5  | 2.0  | 1.5  | 1.0  |
|---------------|------|------|------|------|------|
| 1420          | 89420| 74586| 59739| 44882| 30014|
| 1220          | 76804| 64065| 51327| 38571| 25807|
| 1020          | 64189| 53543| 42897| 32251| 21605|
| 820           | 51551| 43011| 34471| 25931| 17391|

When analyzing the graph in Figure 8, it can be noted that the difference in bending stresses (the error in determining bending stress) is high for small values of the step between points and tends to exponentially decrease with the increasing step. Thus, the value of the measurement step between the points introduces a significant error in determining the calculated value of bending stresses. However, after $L > 40$ m, the graph of the dependence of the error of bending stresses on the measurement step crosses the maximum value of the specified error. Thus, at a measurement step between points $L > 40$ m, the error in determining bending stresses is $\Delta \sigma \leq 50$ MPa.

The value of the coefficient "q" in the regression equation (6) also represents a regression dependence, in this case linear, in accordance with the following model:

$$ q(h) = p \times h + g, \tag{9} $$

where

$p, g$ – regression coefficients depending on the diameter of the pipeline;

$h$ – depth of the pipeline, m.

Regression models for each for pipelines of conditionally diameter $D = 1420 \div 1020$ mm are presented in table 2.

Table 2. The results of the solving problem (9).

| Pipeline diameter (mm) | Regression coefficients values |
|------------------------|-------------------------------|
|                        | $p$                           | $g$                           |
It is necessary to note the question of determining the maximum step when conducting a survey of the depth of the pipeline from the ground surface. Its value should be established based on the calculation scheme presented above in Figure 1 - at least three measurement points must be present on a section of the same curvature. This condition can be fulfilled if the maximum step between the measurement points satisfies the following relation:

\[ l_{\text{max}} \leq \frac{2 \cdot \rho_{\text{min}}}{4} = \frac{\rho_{\text{min}}}{2}, \]  

where

\( \rho_{\text{min}} \) – the minimum radius of curvature of the pipeline section, at which the reliability condition is fulfilled, that is, the pipeline is not subjected to stresses that cause irreversible plastic deformations.

We illustrate the operation of this mathematical model by the example of solving the problem of determining the optimal measurement step. We set the following parameters of the pipeline and route-finding equipment: pipeline diameter \( D_n = 1420 \text{ mm} \), the maximum depth of the pipeline \( h = 3 \text{ m} \), the error of the route-finding equipment \( \Delta = \pm 5\% \), the maximum allowable error in determining the bending stresses of the pipeline section \( \Delta \sigma_{\text{max}} = 50 \text{ MPa} \). It is necessary to choose a step satisfying (5).

Initially, we determine the value of the coefficient “\( q \)” in the regression equation (6) by substituting the depth of the pipeline and the coefficients “\( g \)” in equation (9) according to Table 2, depending on the diameter of the pipeline:

\[ q(3) = 26299 \times 3 + 323 = 89420. \]

The next step is to calculate the error value of bending stresses depending on the step according to the developed mathematical model (6) and check the condition (5). The calculation results are shown in Table 3.

Thus, the measurement step between points, which satisfies the boundary conditions, is \( L \geq 50 \text{ m} \). The results of the calculations in Table 3 indicate the high accuracy of the selected mathematical model and its regression coefficients.

**Table 3.** The results of the calculation.

| Measurement step (m) | \( \Delta \sigma \), according to the mathematical model (MPa) | \( \Delta \sigma_{\text{real}} \), according to the data (MPa) | Absolute error (MPa) |
|----------------------|-------------------------------------------------|-------------------------------------------------|-------------------|
| 20                   | 222.6                                           | 222.8                                           | 0.2               |
| 30                   | 98.4                                            | 98.7                                            | 0.4               |
| 40                   | 54.9                                            | 55.3                                            | 0.4               |
| 50                   | 34.8                                            | 35.2                                            | 0.4               |
| 60                   | 23.8                                            | 24.3                                            | 0.4               |

5. Conclusions

The paper presents the provisions proving the need to determine the optimal step between the measurement points, taking into account the specific operating conditions of the buried pipeline before surveying the depth of the pipeline axis from the ground surface. The maximum error in determining bending stress from the data obtained, with this approach, will not exceed a predetermined value.
The developed mathematical models make it possible to determine the optimal step between the measurement points, which will guarantee the upper estimate for the real values of bending stress. The simplicity and accuracy of the method allow it to be used as one of the methods for monitoring buried sections of main pipelines laid in complicated engineering and geological conditions.

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