Simulation of Dynamic Effects on Trunk Pipelines Laid in Difficult Engineering and Geological Conditions

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Abstract. In this paper, we conduct an experimental study of pipeline deformation together with soil to analyze the stress-strain state of the pipeline and compare it with the results of computer simulation. The experimental setup is a box of OSB panels, which is filled with soil. A polypropylene pipe is laid in the ground, onto which strain gauges are attached, which transmit strain measurements to the computer. At the bottom of the box is a board that drives the ground with a jack. The dependence of stresses in the pipe on soil displacements is constructed first for a polypropylene pipe, then the stresses are converted to a steel pipe and compared with the results of computer simulation in Ansys. The discrepancy between the results is small, due to inaccuracy in the selection of models of soil behavior. Further refinement of mathematical models is planned.

1. Introduction. Relevance of the issue
For a long time in Russia, trunk pipelines have been constructed without taking into account the influence of geodynamic zones on the position of the pipeline.

A change in the position of the pipeline in geodynamic zones may occur due to seismic activity, landslides, karst or on the boundaries of tectonic faults. The most common primary movements along faults are shifts, upthrow and downthrow, as well as the simultaneous joint effects of these movements. A local change in the position of the pipeline that occurs under these effects causes additional stresses from its bending, and the overall stress-strain state worsens, which can lead to the destruction of the pipeline and accidents.

2. Statement of the problem
The objective of this study is to determine the extent to which local ground movements affect the stress-strain state of a pipeline.

Local movement of the soil is considered on the example of a shift of rocks in the zone of active tectonic faults.

In [1], using the Ansys software package, a 36 m long pipeline section with a diameter of D = 1220 mm in soil was simulated. The soil is modeled as an elastic medium and consists of three parts, one of which (horizontal) is attached to a horizontal displacement.

In this paper, which is a continuation of the aforementioned work, an experimental study of pipeline deformation is carried out together with soil to analyze the stress-strain state of the pipeline and compare it with the results of computer simulation.
3. Description of the experimental setup and the progress of the experiment
To carry out the experiment, a box of OSB panels with dimensions of 80×80×60 cm³ was assembled, which was installed on wooden supports 30 cm above the ground level to be able to work with the jack (Figure 1).

![Figure 1. Appearance of the experimental setup.](image1)

![Figure 2. Laying the pipe in the trench.](image2)

In the center of the bottom of the box there is an opening for a block connected to a board lying on the bottom of the box. The box is filled with soil to a height of 30 cm. After soil compaction, a trench is dug in it under the pipeline, 15 cm deep, perpendicular to the board located at the bottom of the box (Figure 2). After laying the pipeline, the trench is buried, the soil is compacted again. Using a jack, the whetstone with the board is brought into vertical movement together with soil located above the board (Figure 3).

![Figure 3. The experimental setup.](image3)

In the pipeline, represented by a polypropylene pipe 70 cm long with a diameter of 20 mm and a wall thickness of 2 mm, bending stresses occur. The deformation of the pipe material is recorded by foil strain gauges glued with epoxy glue to the pipe in four places: two in the middle of the pipe and two at a distance of 10 cm from the middle. One of each pair of sensors is located in the upper part of
the pipe and fixes the tensile stresses of the pipe material, the other in the lower part and fixes the compressive stresses (Figure 4) [2].

![Figure 4. Arrangement of strain gauges on the pipe.](image)

The signal from the load cells is transmitted through an Arduino board to a personal computer via an electric cable, where it is recorded and processed (Figure 5).

![Figure 5. Transmission of a signal to a computer.](image)

4. Processing of experimental data and comparison with the results of mathematical modeling

To calibrate the load cells, a load of 1 kg was applied to the center of the pipe, the ends of which were mounted on the supports [3]. A pipe deflection of 2 cm corresponds to a bending radius of 3.07 m. The longitudinal stresses of a polypropylene pipe from its bend during calibration \( \sigma_{1C} \) were [4]

\[
\sigma = \pm \frac{E \cdot D}{2 \cdot R} \\
\sigma_{1C} = \pm \frac{E_1 \cdot D_1}{2 \cdot R_1} = \pm \frac{1.2 \cdot 10^9 \cdot 0.02}{2 \cdot 3.07} = \pm 3.9 \text{ MPa},
\]

where \( E_1 \) - the modulus of elasticity of the material of the polypropylene pipe, Pa;

\( D_1 \) - the outer diameter of the polypropylene pipe, m;

\( R_1 \) - bending radius of a polypropylene pipe, m.

At this bend, strain gauge readings were recorded and scaled measurement coefficients were calculated [5]. The calibrated readings of the strain gauges during the experiment are presented in table 1.
Table 1. Experimental data.

| Shift, cm | Clay Stress, MPa | Sand Stress, MPa |
|-----------|------------------|------------------|
| Sensors in the middle of the pipe | Sensors away from the middle of the pipe | Sensors in the middle of the pipe | Sensors away from the middle of the pipe |
| Sensor from above | Sensor from below | Sensor from above | Sensor from below | Sensor from above | Sensor from below | Sensor from above | Sensor from below |
| 1 | 1,75 | 1,64 | 1,48 | 1,40 | 1,24 | 1,54 | 1,14 | 1,08 |
| 2 | 3,22 | 2,77 | 2,11 | 1,94 | 1,90 | 2,47 | 1,70 | 1,64 |
| 3 | 4,52 | 3,55 | 2,46 | 2,31 | 2,52 | 3,08 | 2,15 | 2,00 |
| 4 | 5,71 | 3,98 | 2,68 | 2,52 | 2,89 | 3,54 | 2,50 | 2,30 |
| 5 | 6,52 | 4,29 | 2,84 | 2,62 | 3,11 | 3,81 | 2,77 | 2,46 |
| 6 | 6,77 | 4,45 | 2,89 | 2,71 | 3,33 | 3,99 | 2,94 | 2,60 |

From table 1 it is seen that the maximum stresses occur in the middle section of the pipe, and when filling the box with clay, the stress in the pipe is greater than when filling with sand.

Since the height of the filling of the pipeline in the experiment is small, and also due to the flow of soil around the pipeline during shear, the increase in stress in the pipe decreases with an increase in shear [6], and with a shear of more than 6 cm, the stress value remains practically unchanged (in figure 6, the numbering of the dependence curves corresponds to the serial number of the column in the table 1).

Therefore, to compare the results of the experiment with the results of computer simulations, we assume that the stresses in the pipe grow linearly and in proportion to the increase in stresses during shear in the experiment from the initial position by 1 cm. Let us take stresses in the polypropylene pipe when the soil is shifted by 1 cm $\sigma_1 = 1.75$ MPa as maximum during the experiment [7].

To translate the stresses arising in the polypropylene pipe $\sigma_1$ into stresses in the steel pipe $\sigma_2$, we use the similarity theory [8].
According to formula (1), bending stresses depend on three quantities: we introduce three similarity coefficients \( k_1, k_2, k_3 \)[9].

\[
\begin{align*}
  k_1 &= \frac{E_2}{E_1} = \frac{200 \cdot 10^9}{1,2 \cdot 10^9} = 166,6, \\
  k_2 &= \frac{D_2}{D_1} = \frac{1,22}{0,2} = 61, \\
  k_3 &= \frac{R_2}{R_1} = \frac{1800}{3,07} = 586,32,
\end{align*}
\]

where \( E_2, D_2, R_2 \) - modulus of elasticity, outer diameter, bending radius of the steel pipe.

To determine \( R_2 \), we use the conditions specified in [1], where the width of the zone of soil shear is \( b = 12 \) m. We define \( R_2 \) when the pipe bends (soil shear) \( h = 1 \) cm (Figure 7).

![Figure 7](image)

By the property of intersecting chords [10]

\[
2R_2 - h = \frac{0,5b \cdot 0,5b}{h},
\]

where from

\[
R_2 = \frac{0,25b^2}{2h} + \frac{h}{2} = \frac{0,25 \cdot 12^2}{2 \cdot 0,01} + \frac{0,01}{2} = 1800 \text{ m}.
\]

Longitudinal stresses from bending in a steel pipe when the soil is shifted by 1 cm according to the theory of similarity [11]

\[
\sigma_2 = \frac{\sigma_1 \cdot k_1 \cdot k_2}{k_3} = \frac{1,75 \cdot 166,6 \cdot 61}{586,32} = 30,33 \text{ MPa}.
\]

Let us construct an experimental dependence and compare it with a computer one (Figure 8) [12].
5. Conclusions
According to the experiment, the steel pipeline laid in clay will reach the maximum allowable stresses exceeding the tensile strength of the soil displacement by 17 cm, when computer simulation yields a result of 28 cm. The discrepancies in the results are caused by a small discrepancy in the soil behavior models, and these models will be further developed [13].

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