Construction of a mathematical model of the vibrational process of pipelines under internal and external loads

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Abstract. The article proposes a modal analysis of the natural vibrations of polyethylene pipelines, which is a calculation of the vertical and lateral pressure exerted by the soil on the pipelines, on the basis of which an oscillation study was conducted in the Ansys software package. The results of modal analysis for polyethylene pipes are presented for a laying scheme with inclined walls and various soils.

1. Soil pressure on underground pipelines

Before the development and before the construction of the underground pipeline into the soil in an unlimited array is in a state of natural or geostatic equilibrium under its own weight. At the same time, compressive stresses (pressures) act on the depth \( H \) in the soil mass (figure 1): vertical and horizontal [1-3].

![Figure 1. Underground pipeline in the ground](image)

The soil pressure on underground structures is different than the pressure in an untouched massif at the same depth, because: firstly, the structures have a different rigidity than the soil, and secondly, the movement of the soil has time to occur in the period between the development of the soil and the construction of the structure finally, thirdly, there are gaps between the structure and the massifs that allow some movement of the soil [4-5].

The pressure exerted by the soil on the structure depends on the depth of laying and rigidity of the latter; humidity and the degree of compaction of the soil above the structure and especially next to it...
and the method of construction of the structure. Three main cases of building construction should be distinguished:

- a structure in the embankment (Figure 2, a) erected or laid directly on the surface of the earth or in a very small recess compared to the width of the recess, followed by backfill; this is how culverts are usually constructed under road embankments;

- a structure in a recess or trench (Figure 2, b), when it is erected or laid in an open pit having a width that is small compared to depth and limited by more or less solid walls; the space near the structure and above it is filled with soil; water pipelines, sewers, drains, etc. are usually laid in this way;

- a structure constructed in a closed way (Figure 2, c), in which the soil mass is not disturbed from the surface, this method is used in the construction of tunnels and in trenchless laying of pipelines [6-7].

![Figure 2. Methods for the construction of pipelines in the soil.](image)

The soil pressure on the underground structure does not remain constant, but changes due to changes in temperature and humidity conditions and creep of the soil. In most cases, the pressure on the structure gradually increases over time, reaching its maximum value over a certain period of time, with a subsequent decrease sometimes [8].

2. **Analysis of natural vibrations of polyethylene pipelines**

For the analysis, 5 polyethylene pipes with the following characteristics were modeled: 125x3,1; 180x4,4; 250x6,2; 355x8,7 and 630x15,4 [9].

The pipeline is fixed on both sides at a distance of 0,22L (Figure 3).

The study was conducted for pipelines laid in a trench with inclined walls. Laying a slope on a flat base at a depth of 2,5 m in sandy soil (G-I) and heavy clay (G-VI). The specific gravity of the soil is 16,7kN/m³ and the soil deformation modulus is 1,1 MPa.

![Figure 3. The design scheme of the pipe line, fixed on both sides at a distance of 0,22L](image)
The analysis is shown in detail on the example of a polyethylene pipeline with an outer diameter of 180 mm.

To find the pressure exerted by the soil on the pipeline, we determined the vertical and lateral pressure of the soil on the pipeline with a pipe wall thickness of 4.4 mm [10-12].

Vertical soil pressure on a polyethylene pipe:

\[ Q_s^v = n\gamma HD_{out}K_{out}, \]  

where \( n \) – load factor for external, permanent and temporary loads;  
\( \gamma \) – specific gravity of soil, kN/m\(^3\);  
\( D_{out} \) – pipe outer diameter, m;  
\( K_{out} \) – backfill soil concentration concentration coefficient when laying pipes on undisturbed soil in the embankment.

Lateral soil pressure on a polyethylene pipe:

\[ Q_s^h = n\gamma(H + \frac{D_{out}}{2})D_{out}\lambda_{out}, \]  

where \( H \) – pipeline immersion depth, m;  
\( \lambda_{out} \) – coefficient at normal degree of compaction of the backfill.

Based on the data obtained, the pressure exerted by the soil on the pipeline was determined (Table 1):

\[ q = \frac{Q_{eq}}{D_{Hout}}, \]  

\[ q = \frac{8.8435}{0.180} = 49.1286 \text{ kN/m}^2 \]

\( Q_{eq} \) - calculated linear reduced equivalent load, kN/m.

**Table 1.** Soil pressure on a pipeline laid in a trench with inclined walls.

| Soil category | Name of soil | Soil pressure, kN/m\(^2\) |
|---------------|--------------|--------------------------|
| G-I           | Sands are gravelly, large and medium-sized | 49.1724643 | 49.1286035 | 49.0739973 | 48.9908462 | 48.7741223 |
| G-VI          | Heavy clay   | 59.0183263 | 59.0018084 | 58.9809835 | 58.9495442 | 58.8673744 |
Then a modal analysis was carried out in the Ansys software package, based on which the results were obtained for 100 waveforms (Table 2, Table 3).

### Table 2. Analysis results.

| Mode | Meter pipeline |
|------|----------------|
|      | 125x3,1        | 180x4,4       | 250x6,2       |
|      | G-I  | G-VI | G-I  | G-VI | G-I  | G-VI |
| 1    | 49,488 | 47,486 | 47,021 | 50,137 | 48,768 | 48,461 | 26,533 | 25,463 | 25,208 |
| 2    | 119,18 | 112,26 | 110,64 | 119 | 114,88 | 113,97 | 69,424 | 63,89 | 62,588 |
| 3    | 142,65 | 133,81 | 131,78 | 134,36 | 129,08 | 127,92 | 78,846 | 72,211 | 70,731 |
| 4    | 154,41 | 152,1 | 151,51 | 151,95 | 150,05 | 149,61 | 122,81 | 116,99 | 115,62 |
| 5    | 160,78 | 161,02 | 161,06 | 206,96 | 207,26 | 207,31 | 157,75 | 155,75 | 153,37 |
| ...  | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 95   | 2114,6 | 2108,7 | 2107,5 | 1975 | 1973,3 | 1972,9 | 1577,1 | 1572 | 1572 |
| 96   | 2127,9 | 2123,6 | 2122,7 | 2001,7 | 1996,1 | 1995 | 1587,6 | 1586,8 | 1586,6 |
| 97   | 2144,6 | 2134,6 | 2132,5 | 2011,3 | 2009,6 | 2009,2 | 1595,8 | 1593,3 | 1592,8 |
| 98   | 2163,5 | 2153,3 | 2150,6 | 2016,4 | 2013,8 | 2013,2 | 1612,4 | 1608,4 | 1607,6 |
| 99   | 2172,6 | 2165,7 | 2164,7 | 2038,9 | 2032,5 | 2031,3 | 1636,3 | 1634,3 | 1633,8 |
| 100  | 2186,8 | 2183,2 | 2182 | 2051,5 | 2049,1 | 2048,5 | 1641,6 | 1639,5 | 1639 |

### Table 3. Analysis results.

| Mode | Meter pipeline |
|------|----------------|
|      | 355x8,7        | 630x15,4      |
|      | G-I  | G-VI | G-I  | G-VI | G-I  | G-VI |
| 1    | 12,608 | 11,096 | 10,598 | 4,6314 | 0 | 0 |
| 2    | 34,119 | 27,132 | 25,104 | 12,447 | 0 | 0 |
| 3    | 37,954 | 28,302 | 25,867 | 15,101 | 6,8391 | 4,4181 |
| 4    | 67,465 | 56,796 | 54,254 | 26,596 | 16,143 | 12,462 |
| 5    | 78,019 | 65,328 | 62,44 | 29,104 | 16,926 | 13,932 |
| ...  | ... | ... | ... | ... | ... | ... |
| 95   | 1128,8 | 1129,1 | 1129,2 | 646,88 | 643,05 | 642,23 |
| 96   | 1138 | 1136,8 | 1136,6 | 651,39 | 647,51 | 646,72 |
| 97   | 1142,8 | 1139,2 | 1138,5 | 659,82 | 655,48 | 654,11 |
| 98   | 1157,8 | 1152,1 | 1150,9 | 665,69 | 657,45 | 656,13 |
| 99   | 1169,7 | 1165,1 | 1164,1 | 670,93 | 663,27 | 661,74 |
| 100  | 1192,8 | 1189,9 | 1188,9 | 678,47 | 676,49 | 676,09 |

### 3. Construction of indicative graphs of changes in the natural frequencies of pipeline oscillations

Based on the calculation results, histograms of the dependence of the change in the natural frequencies of pipeline oscillations on the type of soil in which they are located were constructed. Figure 4 (a-e) shows graphs for 50 waveforms [13-18].
Figure 4. Graphs of natural frequencies of oscillations of 5 types of pipelines

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