A study of the cyclic damage to buried pipelines during the passage of seismic waves

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ABSTRACT

THE SEISMIC STRENGTH of underground pipelines is assessed based on the axial stresses on the pipeline from the so-called particular combination of loads and impacts. When calculating the stresses from seismic impact, several standard coefficients are introduced, which assume some damage to the pipeline while ensuring the safety of people and the integrity of equipment. These coefficients also take into account anchoring, which depends on the backfill soil and the degree of pipeline criticality. Permissible stresses are accepted in accordance with regulatory documents for design (SNiP 2.05.06-85). The seismic strength of the pipeline in operation is assessed taking into account the seismic impact intensity which is actually reached during an earthquake, and the loads and impacts which affect a pipeline in an earthquake, as well as any defects present in the pipeline wall.

When a seismic wave passes through an underground pipeline, the girth welds are exposed to an alternating cyclic impact. Here, it is relevant to estimate the fatigue damages accumulated over the course of the earthquake. The magnitude of this damage depends on the intensity of the earthquake, the seismograph of the earthquake, the speed with which the longitudinal seismic wave travels along the longitudinal axis of the pipeline, the degree to which the pipeline is anchored by the soil, and the stress concentration coefficient in any defects.

This article studies the accumulation of cycle-induced damage caused by a longitudinal seismic wave. The results may be applied for evaluations of the cyclic longevity of girth welds with defects in pipelines operating in seismic zones.

Key words: pipeline, strength, stresses, cyclic recurrence, wave, seismicity

1. Introduction

When exposed to seismic impacts, pipelines are subjected to an oscillatory process together with the soil mass. The intensity of the earthquake and the specific way the oscillatory process develops in the ‘pipeline-soil’ system depends significantly on the properties of the soils. Depending on the density and homogeneity of the soil surrounding the pipeline, the presence of frozen earth, and the water and ice content of the soil, differences will be found in the intensity
of earthquake effects, and in the composition of the seismic vibrations, and in the mechanism of interaction between the pipeline and the surrounding soil.

The requirements for ensuring seismic strength in trunk pipelines are determined by the necessity that the main structure of a pipeline system must be in operation during earthquakes and over a certain period afterwards, without any major repair works. As numerous experimental data have shown, as well as the results of inspections, underground pipelines which are laid in soils with average properties in terms of seismic characteristics are strongly bound to the soil mass. Pipeline deformations coincide with deformations in the soil mass, accurate up to a certain coefficient (as a rule, less than one).

It has been established that the degree of damage to the pipeline during an earthquake depends on a whole range of factors: the strength of the seismic impact and the directions in which the seismic waves travel, the geological and hydrological conditions, the operational loads and impacts, the construction of the pipeline and joints, the characteristics of the pipe steel, and the material of the supports, as well as the degree of ‘wear and tear’ in the pipeline. It is not uncommon to see old pipelines fail even after very weak earthquakes, which are barely felt otherwise.

In documents regulating the design of trunk pipelines, regulations are in place for evaluating the seismic strength when a longitudinal seismic P-wave travels along the axis of an underground pipeline. It is accepted that the soil surrounding the pipeline will involve the pipeline in its movement. The soil deformation is calculated, and pipeline deformation can then be taken as equal to the soil deformation, taking into account the coefficient of slippage. The stresses in the pipeline are calculated, given the extension and compression from the seismic wave for a defect-free pipe.

In an operational pipeline there may be defects in girth welds due to faulty fusion, inclusions, and the presence of cracks, etc. Russian researchers have found that after earthquakes the number of accidents on pipelines tends to increase [1]. Taking into account that during an earthquake the girth welds with defects are exposed to alternating loads, it becomes necessary to assess the accumulation of low-cycle damage from seismic impacts.

In order to evaluate this, it is worth examining an infinite straight-line underground pipeline which is anchored by the soil surrounding it, and which has elastic properties. As a result of an earthquake, seismic waves spread through the soil. The pipeline, connected with the soil, is subjected to the oscillatory process. The elastic interaction between the pipeline and the soil is therefore examined. A description of the interaction model is presented in this paper.

As a result of this solution, the relationship has been established between the axial stresses and time for any point on the pipeline. The low-cycle damage accumulated over the period of seismic impact was also calculated according to GOST 52857.6-2007 [2].

2. The model of interaction between the pipeline and the soil

In order to study the characteristics of the seismic impacts on the stress-strain state of the pipeline, a dynamic model has been developed showing the interaction between a linear pipeline and the soil. The longitudinal deformations of an oil pipeline due to a seismic compression-expansion wave (P-wave), which moves along the longitudinal axis of the oil pipeline, are calculated by modelling the process, and is described using differential equations:
\[ at \left| u - u_{gr} (t, x) \right| \leq \frac{t_{pr}}{\pi \cdot D \cdot c_{x0}} \]

\[ EF \frac{\partial^2 u}{\partial x^2} + \pi D c_{x0} \left( u - u_{gr} (t, x) \right) = m \frac{\partial^2 u}{\partial t^2} \]  
\[ (1) \]

\[ at \left| u - u_{gr} (t, x) \right| > \frac{t_{pr}}{\pi D c_{x0}} \]

\[ EF \frac{\partial^2 u}{\partial x^2} + \text{sign} \left( \frac{\partial u}{\partial t} - \frac{\partial u_{gr} (t, x)}{\partial t} \right) t_{pr} = m \frac{\partial^2 u}{\partial t^2} \]  
\[ (2) \]

where:

- \( u_{gr} (t, x) \) is the displacement of soil in the seismic compression-expansion wave (the calculated displacement is used as a function of time for the displacements of soil in the seismic wave), in metres;
- \( t_{pr} \) is the ultimate resistance of the soil to longitudinal displacement of the pipeline (this can be calculated according to [3] taking into account the factor, equaling 1.6-2, which accounts for the increase in the ultimate resistance given dynamic loading), in N/m²;
- \( m \) is the mass of a unit of length of the pipeline with product, taking into account the associated mass of soil (associated mass is taken to be equal to the mass of soil replaced by the pipeline), in kg/m;
- \( F \) is the area of a cross-section of the pipeline, in m²;
- \( E \) is the modulus of elasticity of the steel, in Pa;
- \( u \) is the displacement of the pipeline in a longitudinal direction, in m;
- \( D \) is the external diameter of the pipeline, in m;
- \( c_{x0} \) is a generalized coefficient of tangential resistance of the soil, in Pa/m [4,5].

The initial conditions are taken to be zero, and the boundary conditions may be taken as different — the free ends the displacements of the ends of the section under examination coincide with the displacements of the soil.

As a result of the numerical solution of these equations (for example with the use of a three-layered difference scheme), the maximum longitudinal deformations are calculated for the pipeline from seismic impact \( \varepsilon_s \). This formula also makes it possible to study the behaviour of the pipeline section with a gate valve when a longitudinal seismic wave passes through.

The longitudinal deformation which is transferred to the pipeline from the soil mass under the impact of a longitudinal seismic wave can also be calculated using the formula:

\[ \varepsilon_s = 0.16 m_0 \frac{a_c T_0}{c_p} \]  
\[ (3) \]

where:

- \( m_0 \) is the coefficient of pipeline jamming in the soil (taken based on Table 15 of Ref.6);
- \( a_c \) is the seismic acceleration, which can be calculated according to data from seismic zoning and micro zoning, in m/s²;
$T_0$ is the period of seismic vibrations of the soil mass, as determined from surveys, in secs; $c_p$ is the speed with which the longitudinal seismic wave propagates in the soil mass, and can be calculated from surveys, in m/sec.

It is possible to calculate the coefficient of pipeline anchoring in the soil given seismic impact using the formulas [3, 4]:

$$m_0 = \frac{1}{1 + \left( \frac{2\pi}{T_0 c_p \omega} \right)^2}$$

(4)

$$\omega = \sqrt{\frac{\pi D \epsilon_0}{EF}}$$

(5)

When calculating $\omega$ it is important to account for the increase in the generalized coefficient of tangential resistance of the soil given a dynamic impact, while the coefficient of the increase can be taken as equal to 1.5.

In order to assess the deformation of the pipeline under seismic impact, we can take the elastic model of interaction of the pipeline with the soil, described in Equn 1. Replacing the differential operators in Equn 1 with the ratio of the finite differences, the following are obtained:

$$\frac{\partial^2 u}{\partial x^2} = \frac{u_{k,j+1} - 2u_{k,j} + u_{k,j-1}}{h^2}$$

$$\frac{\partial u}{\partial t} = \frac{u_{k+1,j} - u_{k,j}}{\tau^2}$$

$$\frac{\partial^2 u}{\partial t^2} = \frac{u_{k-1,j} - 2u_{k,j} + u_{k+1,j}}{\tau^2}$$

(6)

where:

$\tau$ is the time increment, in secs;

$h$ is the coordinate $x$-axis increment, in metres;

$k$ is the number of time increments, dimensionless;

$j$ is the number of $x$-axis increments, dimensionless.

After some conversions the following is obtained:

$$u_{k+1,j} = 2u_{k,j} - u_{k-1,j} + \left[ \frac{EF}{m h^2} \left( u_{k,j-1} - 2u_{k,j} + u_{k,j+1} \right) + \frac{\pi D \epsilon_0}{m} \left( u_{k,j} - U_{k,j} \right) \right] \tau^2$$

(7)

Deformations and stresses in the pipeline in a longitudinal direction from the seismic loads can be calculated using the following equations:

$$\varepsilon_{Nk,j} = \frac{u_{k,j} - u_{k,j-1}}{dx}$$

$$\sigma_{Nk,j} = E \varepsilon_{Nk,j}$$

(8)
3. The results of calculating the seismic impact on an underground pipeline

In order to assess low-cycle fatigue damage in a girth weld containing a defect, we calculate the change in longitudinal stress in a cross-section of the pipeline versus time under seismic impact. As an example, we can examine a 1220 x 16 underground pipeline, laid in free-draining sandy soil. The speed of travel of the longitudinal seismic wave $c_p = 150$ m/s. The impact on the underground pipeline is taken for an earthquake rated at 9 points on the MSK-64 scale. The
maximum acceleration of the soil is 4 ms$^{-2}$. The displacement of soil in the seismic wave is determined from the expression:

$$U_g(t, x) = \begin{cases} x > \frac{v_p t}{t}, 0, y_s \left(t - \frac{x}{v_p}\right) \\ 0 \end{cases}$$

(9)

where $y_s(t)$ is the soil displacement versus time given in the seismic log. The seismic log was normalized for a 9-point earthquake. The seismic velocity and acceleration logs of the earthquake are presented in Fig.1.

For this solution, a three-layer difference scheme for time was used, as described above.
The time increment is taken to be $\tau = 2.174 \times 10^{-3}$ secs, and the coordinate increment as $h = 10$ m. The duration of the earthquake is 25 secs and the length of the pipeline section is 3000 m.

By solving Eqsns 7 and 8, the displacements and deformations in the pipeline wall can be calculated. In Fig.2 the displacements and deformations of the soil and pipeline are shown in the seismic wave for the time period 17.4 secs.

Assume that the relevant section is located at the cross-section X, for which it is necessary to determine the deformations and stresses. Deformations in the soil and pipeline in relation to time in the section under examination are presented in Fig.3.

The relationship between the longitudinal stresses and time at the section of the pipeline under examination is presented in Fig.4.

For the following assessment of fatigue damage, a graph showing stress changes versus time drawn. This graph is presented in Fig.4, and was obtained by calculation.

4. An assessment of fatigue damages given seismic impact

In order to assess low-cycle fatigue damage, data for the trend of stress over the time of the earthquake (25 s) were processed using the ‘rain’ method in accordance with GOST 25.101-83 [7]. The low-cycle fatigue damage was assessed using GOST R 52857.6-2007 and the rule of linear addition of damage. The amplitude of stresses, taking into account concentration for the j-th block of loading, is calculated using the formula:

$$\sigma_d (j, \alpha) = 0.5\alpha (\sigma_{maj} - \sigma_{min})$$

(10)

where:

$\sigma_{maj}$ and $\sigma_{min}$ are the maximum and minimum stresses in the j-th block of loading, and $\alpha$ is the coefficient of stress concentration.
The limit number of loading cycles for the j-th block of loading, in accordance with GOST R 52857.6-2007, can be calculated using the formula:

\[ N_{j(a)} = \frac{1}{n_N} \left( \frac{0.99A}{\sigma_{a(j,a)} - \frac{B}{n_\sigma}} \right)^2 \]  

(11)

where:

\[ \sigma_{a(j,a)} = \max \left( \sigma_a(j,a), \frac{B}{n_\sigma} \right) \]  

(12)

\[ A = 0.45 \times 10^5 \text{ MPa} \]
\[ B = 0.4 \sigma_B \]
\[ \sigma_B = 550 \text{ MPa} \]
\[ n_N = 10 \]
\[ n_\sigma = 2 \]

The relationship between the low-cycle fatigue damage and the coefficient of stress concentration in the defect can be calculated according to the formula:

\[ S(\alpha) = \sum_{j} \frac{mn_j}{N(j,\alpha)} \]  

(13)

where \( n_{mj} \) is the number of cycles in the j-th block of loading. The results of the calculation are shown in Fig.5.

It should be taken into account that in a general case the low-cycle fatigue damage given seismic impact will depend on the intensity of the earthquake, the seismic log of the earthquake, the
speed at which the seismic wave travels along the longitudinal axis of the pipeline, the degree of pipeline anchoring in the backfill soil, the stress concentration coefficient in the defect, as well as other factors. In each specific case a separate calculation should be made according to the methodology described above.

5. Conclusion

1. A method has been proposed for evaluating the accumulation of low-cycle fatigue damage from seismic impacts given the presence of defects in a buried pipeline.

2. An example has been presented of calculating low-cycle damage to the underground pipeline containing a defect under seismic impact.

3. Low-cycle damage following seismic impact depends on many factors (the intensity of the earthquake, the soil backfill around the pipeline, the coefficient of concentration in the defect, etc.), which must be taken into account in each situation.

4. When evaluating the safe service life of girth welds with defects in seismically hazardous zones, the damage from seismic loads in the case of an earthquake occurring should be added to the damage from differential temperatures and pressures.

Conflicts of interest

All authors have no conflicts of interest to declare.

References

[6] SNiP 2.05.06-85*: Trunk pipelines.