Behaviour and Calculation of Polymer Pipelines Under Real Earthquake Records

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Abstract. The effect of real records of several earthquakes on polymer pipeline vibrations are studied and analyzed in the paper. Longitudinal vibrations of straight end section of the underground pipeline are considered using the Kelvin-Voigt model. To solve the equation, the method of finite differences of the second order of accuracy is used. An algorithm has been compiled and on its basis a software product has been developed for the numerical calculation of an underground polymer pipeline under the effect of real seismograms recorded in different cities of the world. The stress-strain state (SSS) of polymer pipelines is determined under various boundary conditions.

1. Introduction

Problems of seismic safety of pipelines operation in various branches of industry and construction are of great relevance. The main accidents in pipelines are due to corrosion of metal pipes. An improvement of durability and reliability of pipelines is associated with the use of pipes made of polymer materials. The widespread use of such pipes aims to increase the service life of pipelines, reduce operational, resource, financial costs and reduce damage in case of possible earthquakes.

In seismically active areas, the design and construction of underground structures should take into account real soil displacements in the event of possible earthquakes. The leading role in solving this problem is the development and improvement of the methods for calculating underground structures that take into account the real structure – soil interaction under dynamic impacts. Actual data on the behavior of underground structures during strong earthquakes show that the stress-strain state is affected by physical and mechanical properties of soil and structure, the nature of seismic effects, design features, geometrical dimensions and the depth of the underground structure. The study of earthquake resistance of underground structures, taking into account all these factors in a complex, predetermines the use of numerical calculation methods oriented to the use of computing tools.

The degree of pipelines damage during an earthquake depends on a number of factors: the intensity of seismic impact, geological and hydrogeological conditions, operational and technological loads and impacts, the pipeline design, the characteristics of the pipe material and its operation time.

In [1-4] T.Rashidov, O’Rourke, and other researchers summarized the data available in the literature on seismic resistance of straight pipelines. Their studies deserve a special attention from the
point of view of the generalization of data related to the specific accident rate of pipelines built of various materials during earthquakes.

Distinctive properties of polymer pipelines reliability, due to their elasticity, confirm the results of damage analysis of gas, water and sewer pipelines during the earthquakes in Kobe (Japan), 1995 and Christchurch (New Zealand), 2011. Plastic materials and flexible piping systems, made on a high-quality basis from PVC and PE, were damaged several times less than the pipes made from traditional materials [5-7].

Based on the analysis of the effect of earthquakes on underground structures [8–14], a classification of underground pipelines has been developed, a forecast of their damageability and specific accident rate under seismic impacts has been formulated. However, during an earthquake, a seismic load acts on the pipeline system at an arbitrary angle of attack, and from a review of the effects of strong ground motion it was found that the seismically stressed state of an underground structure substantially depends on the properties of surrounding soil [11–14]. The most unfavorable factors are the pipelines embedment in soils with different properties along the axis, active faults, areas with landslides, caving-ins, cracks, liquefaction zones, flooding and water-saturated soils when their condition is close to the loss of bearing capacity, as well as soils with high corrosion properties. Based on the latest conclusions from the practice of pipelines construction and operation, it is recommended, first of all, to use pipes made of composite materials when laying the water supply and sewage networks, especially in saturated ground conditions.

An analysis of foreign publications has been carried out, and in a complex with the previously fulfilled studies, it has been revealed that the following problems are relevant today: 1) to study the SSS of underground piping system with an arbitrary direction of seismic impact propagation; 2) to consider the SSS of underground pipelines buried in soils with different properties along the axis, that is, when various laws of interaction in the pipe – soil system are taken on the contact surface, which consider the above complicated conditions for laying pipelines in seismic regions [15–17].

Continuum plate model in the form of a cantilever anisotropic plate developed in the framework of the bimoment theory of plates describing seismic oscillations of buildings is proposed in the paper [18] as a dynamic model of a building.

Soils surrounding underground pipelines are not only a source of seismic impact, but participate in the oscillatory process together with the pipeline. Depending on the homogeneity and density of the soil surrounding the pipeline, the degree of watering, the earthquake intensity and the mechanism of structure - soil interaction differ [1, 11, 19]. Because of this, empirical and experimental studies on the analysis of actual data on the behavior of underground and elevated pipelines under seismic effect are of great importance. The stress-strain state, dynamic behavior and wave phenomenon in various systems were studied in [20-23], taking into account the features of various structures.

To assess and reduce seismic risk, preliminary assessment of the hazard from earthquakes and timely consideration of appropriate measures are of great importance. Thus, it is necessary to ensure the strength and stability of above-ground and underground structures under seismic loads in the form of seismograms, velocigrams and accelerograms.

2. Materials and methods

In [17, 19], attention is, first of all, drawn to the study of the interaction of structures with surrounding soil under their relative motion; the issues of the influence of complex units in the systems of branched underground pipelines when connected to the wells or to each other are studied. In the seismodynamic theory of underground structures, research related to the problem of the “underground structure – soil” interaction is at the forefront. So, various laws of interaction between the structure and soil are being developed, taking into account the parameters characterizing the process of contact interaction of deformable rigid bodies with soil [16, 24].

Longitudinal vibrations of underground polymer pipelines under seismic loading in harmonic form were studied in [24]. An algorithm and a seismic stability calculation program have been developed; viscoelastic properties of the pipeline material were taken into account using the Voigt model. To
develop this calculation, we consider the longitudinal vibrations of underground viscoelastic pipelines on the effect of real earthquake records.

Consider the longitudinal vibrations of the straight end section of an underground pipeline using the Kelvin – Voigt model. In this case, the relationship between stresses and strains is

$$\sigma = E \varepsilon + \eta \frac{\partial \varepsilon}{\partial t}. \quad (1)$$

Considering relation (1), the general differential equation of longitudinal vibrations of the underground polymer pipeline takes the form

$$\rho \frac{\partial^2 u}{\partial t^2} = E \frac{\partial^2 u}{\partial x^2} + \eta \frac{\partial^3 u}{\partial x^2 \partial t} - \frac{2R}{(R^2 - r^2)} k_s(x)(u - u_0). \quad (2)$$

where $E$ is the modulus of elasticity; $\eta$ is the viscosity coefficient; $R$ is the outer radius of the pipeline; $r$ is the inner radius of the pipeline; $u_0$ is the soil displacement.

Introduce the following dimensionless quantities $x = lx$, $\bar{u} = 2Ru$, $\bar{t} = t_0 \cdot t$. Given the dimensionless travel time and coordinates, equation (2) is formulated in the following dimensionless form:

$$\frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial x^2} + \varphi \frac{\partial^3 u}{\partial x^2 \partial t} - D k_s(x)(u - u_0). \quad (3)$$

Here $D = \frac{2Rl^2}{E(R^2 - r^2)}$, $\varphi = \frac{\eta}{Et_0}$.

Consider the case of satisfying the boundary conditions when both ends of the pipe are fixed:

$$u(0,t) = 0, \quad \frac{\partial u}{\partial x} \bigg|_{x=0} = 0. \quad (4)$$

Initial conditions are

$$u \big|_{t=0} = u_0, \quad \dot{u} \big|_{t=0} = \dot{u}_0 = 0. \quad (5)$$

The relation describing the soil displacement along the pipeline axis can be set in an arbitrary form, for example, in the form of a harmonic and damping harmonic load, a traveling wave of variable intensity, an impulse load, and also in the form of seismograms of real earthquake records [18].

This equation may be solved using the second-order finite difference method. Taking into account the initial conditions (5), the equation is solved using direct and reverse sweeps at each time step $\tau (0 < j < M)$. With a change in the boundary conditions at $i=1$ and $i=N$ and the initial conditions for $j = 0$, the above algorithms change accordingly.

3. Results and Discussion

Consider an underground polymer pipeline interacting with soil under seismic motion in the form of real earthquake records. The geometrical, physical and mechanical parameters of the polymer pipe and soil are as follows: $E = 5 \cdot 10^8$ Pa, $\rho = 940$ kg/m$^3$, $l = 20$ m, $R_c = 0.110$ m, $R_0 = 0.1037$ m, $\eta = 7.7 \cdot 10^5$ Pa·s, $a_0 = 5.2 \cdot 10^3$ m, $k_s = 8 \cdot 10^4$ kN/m. Seismic displacement of soil along the pipeline axis is taken in the form of a seismogram. The results of numerical implementation are shown in figures 1 - 4 in the form of a
change in longitudinal displacement and stress along the pipeline axis at a given time and over time in pipeline sections under the effect of a real earthquake record.

**Figure 1.** A real record of soil longitudinal displacement over time during an earthquake recorded in Chile on 02.27.2010; 
\[ u_{\text{soil, max}} = 7.046 \text{ cm, } t = 50.17 \text{ s} \]

**Figure 2.** The change in the longitudinal displacement \( u \) of the pipeline over time under the action of a real earthquake record \( x = 1 \text{ m} \) (Chile, February 27, 2010)

Figures 1 and 2 show the graphs of changes in the values of soil and pipeline displacements over time and along the pipeline axis at a given time. Longitudinal vibrations of the pipeline and soil coincide in phase, but in the pipeline the displacements are two times less than in soil. The amplitude of the pipeline and soil oscillations at \( t = 50.17 \text{ s} \) reaches its maximum value \( u_{\text{max}} = 2.6 \text{ cm} \) and \( u_{\text{soil,max}} = 7.046 \text{ cm} \). At \( t = 50 \text{ s} \), the moment of time, the stresses at the fixed ends of the pipeline reach their maximum value \( \sigma = \pm 60 \text{ MPa} \) (see figure 3).

**Figure 3.** Change in pipeline stresses over time under the effect of a real earthquake record \( x = 0 \text{ m} \)

**Figure 4.** Change in stresses along the pipeline axis at a given time \( t = 50 \text{ s} \)

As the graphs in figures 3–4 show, the stresses of the pipeline coincide with the given record of a real earthquake, and figure 3 shows the maximum stress values at \( t = 50.17 \text{ s} \), it is seen here that the maximum stress values occur at the fixed ends of the pipeline.

Figure 5 shows a change in the values of soil and pipeline displacements over time and along the pipeline axis at a given time; a comparison of results of soil and pipeline displacements is also shown. Longitudinal vibrations of the pipeline and soil coincide in phase, but in the pipeline the displacements are two times less than in soil.
**Figure 5.** Change in longitudinal displacement $u$ over time: 1 - soil; 2 - pipeline $x=1$ m  
(L’Aquila Italy Earthquake, April 6, 2009)

**Figure 6.** Change in longitudinal stress of the pipeline over time in the section $x=0$

**Figure 7.** Change in the maximum stress of the pipeline at a given time $t=17.91$ s

From the graphs in figures 6 - 7, it can be seen that the stresses of the pipeline coincide with the given record of a real earthquake, and figure 5 shows that at the fixed ends of the pipeline, the stresses reach maximum values at $t = 17.91$ s.

### 4. Conclusion

1. Thus, the SSS of polymer pipelines is determined under various boundary conditions, i.e. under conditions of fixing of both ends of the pipeline, under yield fixing of the left end and the free right end of the polymer pipeline, taking into account real records of earthquake seismograms.

2. Unlike steel pipelines, in polymer pipelines the stresses are an order of magnitude less than under the action of real seismic loads. At rigid fixing of the pipeline end to a stationary object, the stresses near the fixing point is approximately two times greater than under the yield fixing.

3. Calculation of an underground structure under the influence of recorded real seismograms takes into account all the features of seismic process contained in the seismograms, and therefore more objectively characterizes the behavior of the structure under seismic effect, allows calculating the true stresses occurring in the body of the object under study. This provides the opportunity to conduct more accurate calculations of the maximum stresses in the underground pipeline and formulate a more reliable conclusion about the earthquake resistance of a particular pipeline under soil conditions at the construction site, as well as to offer to designers and builders the ways to ensure the earthquake resistance of the objects under consideration.
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