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Dynamic behavior of underground viscoelastic pipelines under seismic effect

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ABSTRACT: The article is devoted to the statement of the problem and construction of a mathematical model of seismodynamics of underground polymer pipelines under seismic loading of an arbitrary direction. A system of equations of motion of a linear underground polymer pipeline is derived; to solve the resulting system of equations of motion in a matrix form, the finite difference method with second-order accuracy is used. An algorithm and calculation programshave been developed for studying the stress-strain state of an underground polymer (viscoelastic) pipeline interacting with soil under seismic effects. The values of displacements, stresses, shear forces and bending moments over time and along the pipeline coordinate are obtained. An analysis of the results shows that an account for internal friction associated with the hereditary properties of the pipeline material leads to attenuation of oscillatory process.

KEYWORDS: Seismodynamics, underground polymer pipeline, viscoelasticpipeline, earthquake,soil displacement, stress-strain state, seismic load, variational principle, kinetic and potential energy.

I. INTRODUCTION

In seismically active zones, real soil displacements in the event of possible earthquakes should be taken into account in design and construction of underground structures. The leading role in solving this problem is the development and improvement of methods for calculating underground structures that take into account the real soil-structure interaction under dynamic effect. Actual data on underground structures behavior during strong earthquakes show that the stress-strain state is affected by physical and mechanical properties of soil and structure, the nature of seismic effect, design features, geometric dimensions and the depth of the underground structure [1, 2]. Considering the above, the study of strength properties of underground pipelines, in particular, the ones from polymeric materials, in structurally inhomogeneous and moistened ground conditions of their operation, taking into account the consequences of possible seismic effect, is an important practical problem.
The use of new composite materials in engineering practice, as well as the design and creation of strong, lightweight and reliable structures, requires the improvement of mechanical models of deformable bodies and the development of more advanced mathematical models, their calculation taking into account the real properties of materials and geometry. Therefore, the development of effective algorithms used to solve the problems of underground polymer pipelines is an urgent task.

II. LITERATURESURVEY

In [3], numerical modeling and simulation of experimental tests were given, where the underground pipeline and the surrounding soil were modeled using nonlinear shell elements and elastoplastic springs distributed along the pipeline. The finite element method was used; reasonable forecasts were obtained for the distributions of axial and bending strains measured in tests on a separated platform.

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Constant soil strain poses a serious danger to continuous underground pipelines. The study in [4] presents the results of four tests on a centrifuge designed to study the influence of fault orientation on the behavior of a pipe during the earthquake. The test results show thatthe angle of fault orientation strongly affects the axial strain of the pipe.
Numerical models using the finite element method (FEM) are developed in [5] for the analysis of underground pipelines made of high density polyethylene (HDPE) during fault movements. Numerical results were compared with the results of ASCE and experimental results obtained from tests in a centrifuge. The article focuses on the influence of design parameters, such as the diameter and thickness of the pipe, the depth of the pipeline, the angle of friction and the density of surrounding soil on the maximum bending strain and the distribution of bending strain along the pipeline.
The stress-strain state of underground pipelines under spatial seismic load in the form of a damping sinusoid is described in [6]. The results of changes in normal and tangential stresses, as well as the intensity of normal and tangential stresses over time, coordinate and depending on the earthquake magnitude are presented.
A study of the transverse motion of an underground pipeline located in a water-saturated fine-grained soil using the developed interaction models in the pipeline-soil system was considered in [7]. In the general case, this process is described by a system of nonlinear equations with joint consideration of longitudinal and transverse displacements. To solve the problem, an approximate numerical calculation method was used. The possible rise of pipelines buried in water-saturated soils under longitudinal seismic load was determined and the influence of ground conditions and geometric characteristics of the pipeline on its transverse displacement was shown.
In [8], longitudinal vibrations of underground polymer pipelines under seismic loading were studied. An algorithm and a program for calculating seismic resistance have been developed; viscoelastic properties of the pipeline material were taken into account by applying the Voigt model.
The aim of this work is to study the stress-strain state (SSS) of an underground polymer (viscoelastic) pipeline under seismic effect. A mathematical model of dynamic behavior of a viscoelastic pipeline underseismic loading of an arbitrary direction is developed. The problem is solved by the finite difference method. Changes in displacements, stresses, shear forces and bending moments over time and along the length of the pipeline are obtained. The viscoelastic properties of the pipeline material are described by the Rzhanitsyn – Koltunovthree-parameter kernel; the method described in [9, 10] is used for transformation.

III. METHODOLOGY

This work is devoted to the problem statement and construction of a mathematical model of seismodynamics of underground polymer pipelines under seismic loading of an arbitrary direction based on the T.R.Rashidovseismodynamic theory of underground structures [11], for the case of displacements of the rod points under the combined action of longitudinal, transverse and torsional forces [12]. A system of equations of motion of a linear underground polymer pipeline based on the Hamilton–Ostrogradskyvariational principle for aseismic loading in arbitrary direction is derived. To solve the obtained systems of equations of motion in matrix form, the finite difference method with second-order accuracy is used.
A rectilinear underground polymer pipeline interacting with surrounding soil under seismic effect in arbitrary direction is considered.
To obtain differential equations of underground polymer pipesvibration, the variational Hamilton – Ostrogradsky principle is used [5]

$$\int_t (\delta T - \delta \Pi + \delta A) dt = 0 \,, \tag{1}$$

Where δT and $\delta \Pi$ are the variation of kinetic and potential energy, respectively; δA is the variation of the work of external forces [12].
Based on the assumptions given in [12], the pipeline is modeled as a rod that performs combined longitudinal, transverse and torsional vibrations in the *xy* plane; the displacements are selected as follows:

$$u_1(x,y,t) = u(x,t) - y\alpha_1(x,t),\ u_2(x,y,t) = v(x,t)\,, u_3 = 0 \tag{2}$$

Where u and v are the displacements of the central line of the pipe, α_1 - the angle of inclination of the tangent to the elastic line underpure bending.
The displacement expressions $u_i(x,y,t)$ from (2) are substituted under the variation sign δu_i.
With expression u_i (2), the Cauchy relations take the form

$$\varepsilon_{11} = \frac{\partial u_1}{\partial x} = \frac{\partial}{\partial x}(u - y\alpha_1) = \frac{\partial u}{\partial x} - y\frac{\partial \alpha_1}{\partial x};\ \ \varepsilon_{12} = \frac{\partial u_1}{\partial y} + \frac{\partial u_2}{\partial x} = \frac{\partial}{\partial x}(v) + \frac{\partial}{\partial y}(u - y\alpha_1) = \frac{\partial v}{\partial x} - \alpha_1. \tag{3}$$

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In this case, variations in kinetic, potential energy and work of external forces are presented in the form

$$\int_t \delta T dt = \int_t \int_V \rho\left(\frac{\partial u_1}{\partial t}\cdot\delta\frac{\partial u_1}{\partial t}+\frac{\partial u_2}{\partial t}\delta\frac{\partial u_2}{\partial t}\right)dVdt\,,\quad \int_t \delta\Pi dt = \int_t\int_V\left(\sigma_{11}\delta\varepsilon_{11}+\sigma_{12}\delta\varepsilon_{12}\right)dVdt\,, \tag{4}$$

$$\int_t \delta A dt = \int_t\int_V\left[P_1\delta u_1+P_2\delta u_2\right]dVdt+\int_t\int_S\left[q_1\delta u_1+q_2\delta u_2\right]dSdt+\int_t\int_{S_1}\left[\varphi_1\delta u_1+\varphi_2\delta u_2\right]dS_1 dt\Big|_x\,. \tag{5}$$

From [13] we obtain the relationship between stresses and strains for underground polymer pipelines

$$\sigma_{11}=E\left[\varepsilon_{11}(t)-\int_0^t\Gamma(t-\tau)\varepsilon_{11}(\tau)d\tau\right];\ \sigma_{12}=\frac{E}{2(1+\mu)}\left[\varepsilon_{12}(t)-\int_0^t\Gamma(t-\tau)\varepsilon_{12}(\tau)d\tau\right]. \tag{6}$$

Taking into account the Cauchyrelation (3), the following longitudinal, transverse forces and the bending moment of the underground polymerpipeline are formulated from expression (6):

$$N_{11}(x,t)=EF\left(\frac{\partial u}{\partial x}-\int_0^t\Gamma(t-\tau)\frac{\partial u}{\partial x}d\tau\right);\ \ M_z(x,t)=-EI_z\left(\frac{\partial\alpha_1}{\partial x}-\int_0^t\Gamma(t-\tau)\frac{\partial\alpha_1}{\partial x}d\tau\right);$$

$$Q_{12}(x,t)=GF\left(\left(\frac{\partial v}{\partial x}-\alpha_1\right)-\int_0^t\Gamma(t-\tau)\left(\frac{\partial v}{\partial x}-\alpha_1\right)d\tau\right),$$

where $G=\dfrac{E}{2(1+\mu)}$.

From the variational equation (1) after performing the appropriate operations, taking into account the forces of pipeline-soil interaction [11, 14], we obtain the following systems of differential equations of motion of underground polymer pipeline with corresponding initial and boundary conditions:

$$\begin{gathered}
-\rho F\frac{\partial^2 u}{\partial t^2}+EF\left(\frac{\partial^2 u}{\partial x^2}-\int_0^t\Gamma(t-\tau)\frac{\partial^2 u}{\partial x^2}d\tau\right)-\pi D_H k_x\left(u-u_{0x}\right)=0\\
-\rho F\frac{\partial^2 v}{\partial t^2}+GF\left(\left(\frac{\partial^2 v}{\partial x^2}-\frac{\partial\alpha_1}{\partial x}\right)-\int_0^t\Gamma(t-\tau)\left(\frac{\partial^2 v}{\partial x^2}-\frac{\partial\alpha_1}{\partial x}\right)d\tau\right)+\left(-2p\pi D_H k_x\left(v-u_{0y}\right)\right)=0\\
-\rho I_z\frac{\partial^2\alpha_1}{\partial t^2}+\left(EI_z\frac{\partial^2\alpha_1}{\partial x^2}+GF\frac{\partial v}{\partial x}-GF\alpha_1\right)-\int_0^t\Gamma(t-\tau)\left(EI_z\frac{\partial^2\alpha_1}{\partial x^2}+GF\frac{\partial v}{\partial x}-GF\alpha_1\right)d\tau-\left(q\left(\alpha_1-\frac{\partial u_{0y}}{\partial x}\right)\right)=0
\end{gathered} \tag{7}$$

Natural boundary conditions for underground pipeline are:

$$\begin{gathered}
\left[-EF\left(\frac{\partial u}{\partial x}-\int_0^t\Gamma(t-\tau)\frac{\partial u}{\partial x}d\tau\right)\right]\delta u\Big|_x=0,\ \left[-GF\left(\left(\frac{\partial v}{\partial x}-\alpha_1\right)-\int_0^t\Gamma(t-\tau)\left(\frac{\partial v}{\partial x}-\alpha_1\right)d\tau\right)\right]\delta V\Big|_x=0,\\
\left[EI_z\left(\frac{\partial\alpha_1}{\partial x}-\int_0^t\Gamma(t-\tau)\frac{\partial\alpha_1}{\partial x}d\tau\right)\right]\delta\alpha_1\Big|_x=0.
\end{gathered} \tag{8}$$

Natural initial conditions are:

$$\rho F\frac{\partial u}{\partial t}\delta u\Big|_t=0;\ \ \rho F\frac{\partial v}{\partial t}\delta v\Big|_t=0;\ \ \rho I_z\frac{\partial\alpha_1}{\partial t}\delta\alpha_1\Big|_t=0. \tag{9}$$

We use the Rzhanitsyn-Koltunov weakly singular three-parameter kernelin expressions (7) and (8) [2, 9, 10]

$$\Gamma(t)=\overline{A}_b e^{-\overline{\beta}t}t^{\alpha-1},\ \ 0<\alpha<1,\ \ \left[\overline{\beta}\right]=\mathrm{c}^{-1},\ \ \left[\overline{A}_b\right]=\mathrm{c}^{-\alpha}. \tag{10}$$

The three-parameter kernel (10) has a weak Abel-type singularity. This kind of kernels has a weak feature; to eliminate this, we use transformations in the integrand according to [9]. Therefore, using the replacement of variables $t_n-\tau=z^r$, $r=\alpha_i^{-1}$, we eliminate this feature [10]:

$$\int_0^{t_m}\Gamma_i\left(t_m-\tau\right)T_n\left(\tau\right)d\tau=\frac{A_i}{\alpha_i}\sum_{j=1}^m B_{ij}e^{-\beta_i t_j}T_{n,m+1-j} \tag{11}$$

where

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 6, Issue 8 , August 2019

$$B_{ij} = \frac{\Delta t^{\alpha_i}}{2}\left[(j+1)^{\alpha_i} - (j-1)^{\alpha_i}\right], \quad j = 2, m-1; \quad B_{i1} = \Delta t^{\alpha_i}/2;\ B_{im} = \Delta t^{\alpha_i}\left[m^{\alpha_i} - (m-1)^{\alpha_{i1}}\right]/2$$

Calculation can be carried out with various variations of rheological parameters A_i,α, β.
After some transformations, a system of differential equations of motion, boundary and initial conditions in a general vector form are obtained

$$M\frac{\partial^2 Y}{\partial t^2} + A\frac{\partial^2 Y}{\partial x^2} - \frac{A_b}{\alpha}\sum_{k=1}^{n} B_k^b e^{-\beta t_k} A\frac{\partial^2 Y(t_n - t_k)}{\partial x^2} + B\frac{\partial Y}{\partial x} - \frac{A_b}{\alpha}\sum_{k=1}^{n} B_k^b e^{-\beta t_k} B\frac{\partial Y(t_n - t_k)}{\partial x} + + CY - \frac{A_b}{\alpha}\sum_{k=1}^{n} B_k^b e^{-\beta t_k} DY(t_n - t_k) = Q. \quad (12)$$

Boundary conditions are:

$$\left[\bar{A}\frac{\partial Y}{\partial x} - \frac{A_b}{\alpha}\sum_{k=1}^{n} B_k^b e^{-\beta t_k}\bar{A}\frac{\partial Y(t_n - t_k)}{\partial x} + \bar{C}Y - \frac{A_b}{\alpha}\sum_{k=1}^{n} B_k^b e^{-\beta t_k}\bar{C}Y(t_n - t_k)\right]\delta Y\bigg|_x = 0. \quad (13)$$

Initial conditions are:

$$\frac{\partial Y}{\partial \bar{t}}\delta Y\bigg|_t = 0, \quad (14)$$

where $Q = \left[\frac{l^2 b^2}{a_T^2}\bar{u}_{0x} \quad \frac{q}{EF}\frac{\partial \bar{u}_{0z}}{\partial \bar{x}} \quad \frac{2pl^2 b^2}{a_T^2}\bar{u}_{0z}\right]^T$, $Y = \{u, \upsilon, \alpha_1\}^T$, $M,\ A,\ B,\ C,\ \bar{A}, \bar{B}, \bar{C}$ are the third order matrices.
To solve the problem, the method of finite differences of the second order of accuracy is used.

IV. RESULTS

Consider the problem on the plane*Oxy* when the pipeline is loaded in the plane*xy*, i.e. seismic displacement of soil occurs in a vertical plane at an angle to the longitudinal axis of the pipeline; the ends of the pipeline are fixed. An underground pipelineis fixed at two ends.

$$Y\big|_{x=0} = Y_{0,j} = 0;\ Y\big|_{x=l} = Y_{N,j} = 0. \quad (22)$$

Initial conditions:

$$Y\big|_{t=0} = Y_{i,0} = 0;\ \dot{Y}\big|_{t=0} = \dot{Y}_{i,0} = 0, \quad (23)$$

According to the finite difference scheme are represented as

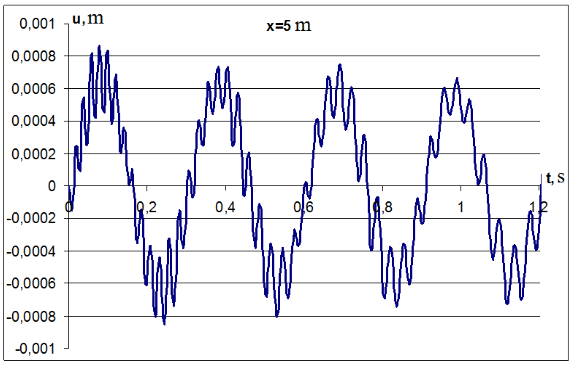
$$\frac{1}{2\tau}(Y_{i,1} - Y_{i,-1}) = 0.$$

Then the initial conditions (23) take the form:

$$Y_{i,-1} = Y_{i,1}. \quad (24)$$

Based on the developed algorithm, the software was created for calculating the underground polymer pipeline under seismic loading.
The task is solved based on the algorithm of computer implementation. Mechanical and geometric parameters are selected as follows: E = 5 10^2MPa; δ = 0.08m; R = 0.2 m; T = 0.2 s; ρ = 940 kg/m^3; A = 0.002 m; D_H = 0.4m; ω = *2π/T*; C_p= 1000 m/s; ε = 0.8;$\mu_{гр}$ = 0.2; μ_{mp} = 0.24; A_b = 0.1; α = 0.25; β = 0.05. The soil motion is set in the form $u_{0x}=A\sin\omega(t-x/C_p)\cos\alpha$, $u_{0z}=A\sin\omega(t-x/C_p)\sin\alpha$. The length of the pipe in question is 10 m, α = 30^0.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 6, Issue 8 , August 2019

a 

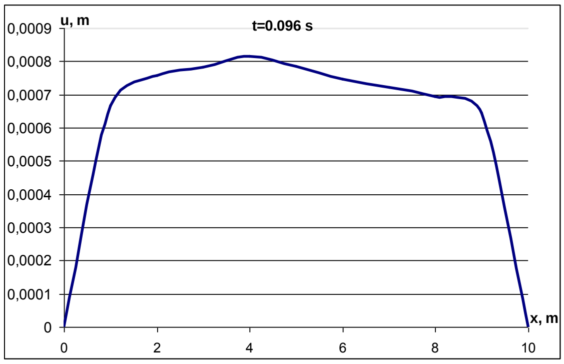
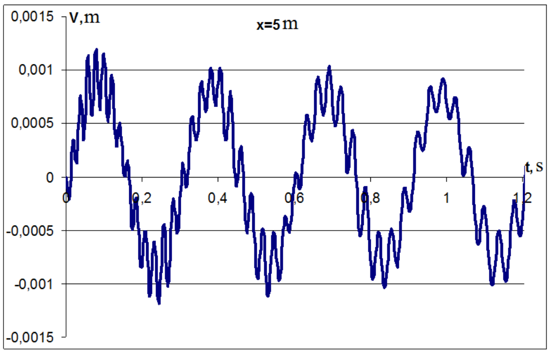
b 

Fig. 1. Change in longitudinal displacement *u* of the pipeline over time at a distance *x=5m* and along the pipeline at a fixed time *t* at $\alpha = 30^0$

a 

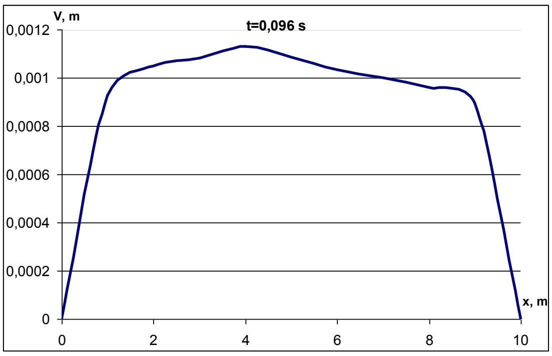
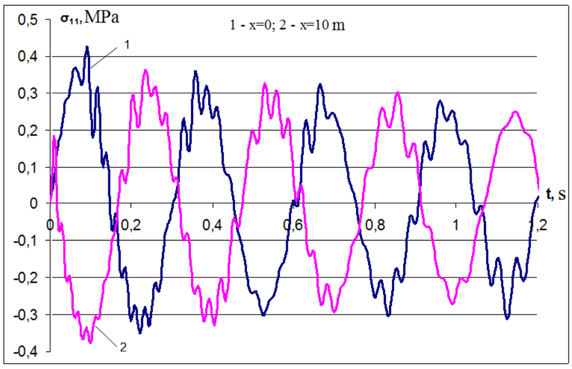
b 

Fig. 2. Change in parameters *V* of underground pipeline under transverse displacement over time at specified points and along the pipeline at a fixed time *t* at $\alpha=30^0$

Figs. 1–2 show the changes in longitudinal and transverse displacements of a polymer pipeline at the point x=5m over time and along the pipeline axis at a fixed time. According to the results of the problem (see Figs. 1–2) at x=5m and set time of displacements (*u*, *V*) along the pipeline axis, the disturbance covers the entire length of the pipeline, the maximum value near the middle of the pipeline, the amplitude of the point oscillations at x = 5m damps over time (Figs. 1–2, a). Here, due to the parameter x/C_p, the amplitudes of displacements oscillations *u* and *V* have bursts. With an increase in amplitude, local bursts increase accordingly (see Figs. 1–2, a).

a 

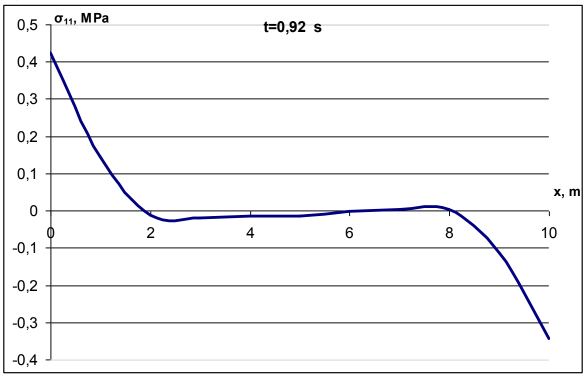
b 

Fig. 4. Change in normal stress σ_{11} of underground pipeline over time at given points and along the pipeline at a set time *t* at $\alpha=30^0$

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Vol. 6, Issue 8 , August 2019

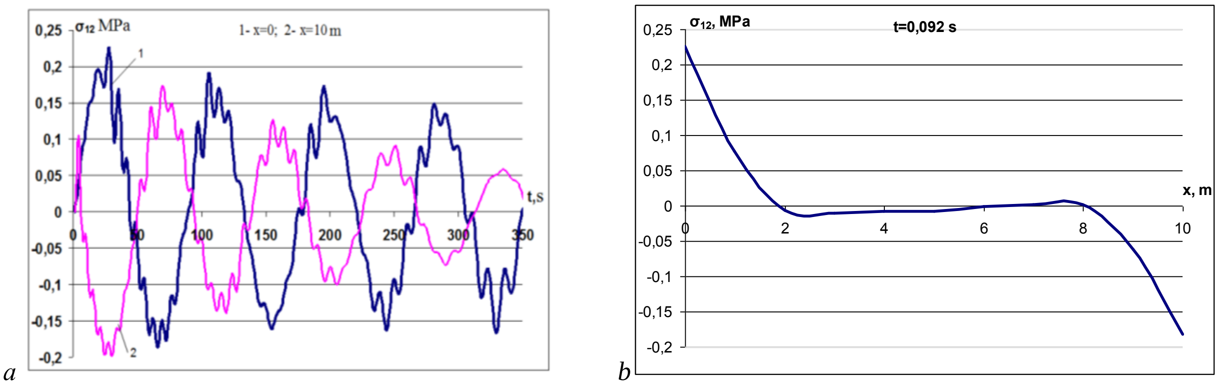

Fig. 5. The change in shear stress σ_{12} of underground pipeline over time at given points and along the pipeline at a set time *t* at $\alpha=30^0$

Graphs of changes in normal stress (Fig. 4) and shear stress (Fig. 5) in the pipeline over time at the fixed end and along the pipeline axis at a set time are presented. From the graphs (Figs. 4 - 5, *a*), an obvious damping of the polymer pipeline oscillations over time follows. In this case, the concentration of normal stress (Fig. 4 - 5, *b*) occurs at the fixed ends of the pipeline.

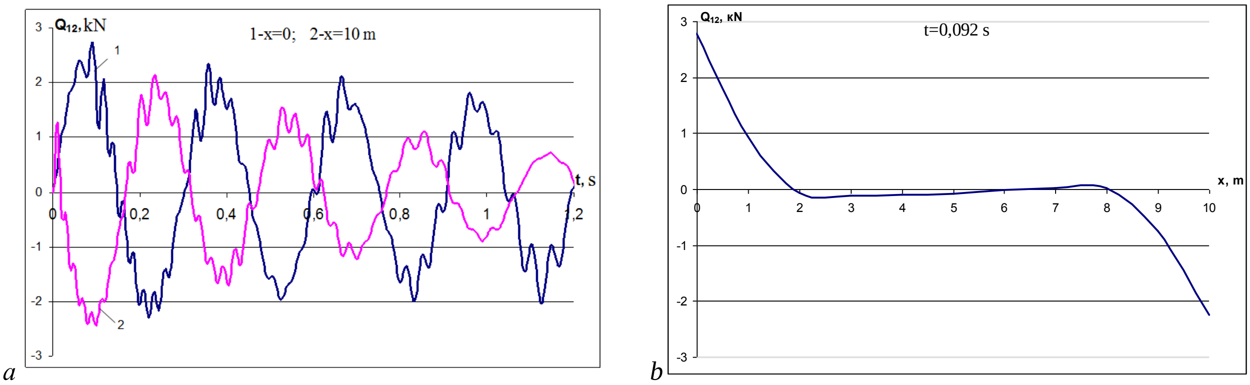

Fig. 6. Change in parameters $Q_{12}$of underground pipeline over timeat given points and along the pipeline at a set time t at $\alpha=30^0$

Fig. 6 shows the change in cutting forces over time and at a set time along the pipeline axis. The transverse force fluctuates with damping and bursts at increasing amplitude (Fig. 6, *a*). The cutting force (Fig. 6, *b*) near the fixed ends has its maximum values.

V. CONCLUSION

Thus, the combined equations of longitudinal and transverse vibrations of the underground polymer pipeline are derived for aseismic loading of arbitrary direction. A computational scheme of the problem is constructed using central finite-difference relations of the finite difference method. The SSS of a polymer pipeline under the influence of a seismic load was investigated. An analysis of the obtained results on combined longitudinal and transverse vibrations of underground polymer pipelines under seismic loading was carried out. An analysis of the above problems showed that the viscoelastic properties of the polymer pipeline contribute to the damping of external seismic effect, which consequently led to less damage and thereby increased the strength and stability of these structures.

All this allows, in perspective, to consider in general terms, the stress-strain state of underground polymer pipeline systems under arbitrary directed seismic effect. This provides for a further deep analysis of the behavior of polymer pipelines based on the calculation results and the actual data of earthquakes occurred in many countries.

The results of the study on adopted model of the polymer pipeline and the nature of external seismic effect allow us to adequately describe its behavior and are in complete agreement with the analysis of the consequences of earthquakes [1, 2] occurred all over the world.

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International Journal of Advanced Research in Science, Engineering and Technology

Vol. 6, Issue 8 , August 2019

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