Transverse Vibrations of Underground Pipelines with Different Interaction Laws of Pipe with Surrounding Soils

Batir Mardonov[1], *Ekaterina* An[1*], *Shuhrat* Shojalilov[2], *Yakutxon* Khakimova[2], and *Gulchexra* Ismoilova[2]

[1]Academy of science of the Republic of Uzbekistan Institute of Mechanics and Seismic Stability of Structures named after M.T. Urazbaev, Tashkent, Uzbekistan
[2]Tashkent State Transport University, Tashkent, Uzbekistan

Abstract. Studies on the effect of changing the stiffness coefficient along the length of the pipeline on its resonant vibration mode are considered in the paper. A computational model of transverse vibrations of the pipeline located in soil with different properties is created. Theoretical and computational studies to solve the problems of stability of underground pipelines located in the soils with different properties under seismic effects are carried out. It is revealed that the vibratory process of the pipeline can be realized at frequencies close to resonance. The results of the study are presented as curves of distribution of displacements of pipeline sections along the length at dimensionless frequencies. When the pipeline vibrates with a frequency close to the resonant frequency, the displacements of pipeline sections can take very large values. It is shown that at frequencies close to resonance, the values of moments can be large in the pipeline sections, which are the reasons for the loss of pipeline stability.

1 Introduction

At present time pipelines are used to deliver water, oil, gas and etc. Underground pipelines are buried in the ground, and they stretch over large areas, where they interact with soils of different physical and mechanical properties. It significantly increases their exposure to damage from all sorts of sources, in particular during seismic activity.

Therefore, the study of the stability of underground pipelines during earthquakes is relevant. The solution of the problem of seismodynamics of underground pipelines, taking into account the intersection of soils with different properties along the pipe axis, serves to determine the possible seismic hazard.

To date, in domestic and foreign science, there are theoretical and experimental studies for determining the stress-strain state [1-16] and stability [17-24] of underground pipelines interacting with the surrounding soil under seismic effects. A theory of propagating seismic waves in an underground pipeline and surrounding soil called the wave theory of seismic resistance of underground pipelines is proposed in [12]. According to linear and nonlinear

* Corresponding author : ekaterinaan@mail.ru

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

laws, this theory is used to analyze only longitudinal vibrations of a pipeline interacting with homogeneous soil. In all the above investigations, when considering the interaction of the underground pipeline with the surrounding soil, the variability of the interaction parameters along the length of the pipeline is not considered. This is especially important for long pipelines buried in the ground and stretched over large areas, where soil conditions change significantly. In this case, the behavior of the pipeline mainly depends on the choice of the law of its interaction with the surrounding soil, which in the simplest cases is characterized by the interaction coefficients determined from experiments [5, 7, 11, 12].

Transverse vibrations are of interest for long pipelines because they cause a loss of stability and such a phenomenon as buckling of pipelines. A methodology for the study of transverse vibratory processes in underground pipelines is developed in this paper when considering the variability of the interaction parameters along the length of the pipeline to establish the cause of the loss of stability of underground pipelines.

2 Methods

Let us consider the case when the pipeline contacts the surrounding soil at two interaction areas k_1 ($0<x<l_1$) и k_2 ($l_1<x<l$), where l is the total length of the pipeline. Set the origin in the initial section of the pipeline and direct the axis x along the pipeline axis. When the time $t_1=(H-2R)/c$ (where R is the depth of the pipe; c is the speed of the wave propagation) a wave formed at the depth $Z=H$ falls on the pipeline. The wave front is perpendicular to the pipeline axis. If we do not consider the time of the wave flow around the pipeline and the secondary waves of reflection and diffraction, then at time $t\geq t_1$ the distributed load will act along the length of the pipeline k_1 (w_1-u_0) when $0<x<l_1$ and k_2 (w_2-u_0) when $l_1<x<l$, where $w_1(x,t)$, $w_2(x,t)$ are the transverse displacements of pipeline sections, $u=u_0(t)=u_{00}(c_t-H+2R)$ is the displacement of soil particles behind the wave front in the plane $Z=H-2R$.

The equations of transverse vibrations of the pipeline for each section have the form

$$EI\frac{\partial^4 w_1}{\partial x^4}+m\frac{\partial^2 w_1}{\partial t^2}+k_1(w_1-u_0)=0 \quad (0<x<l_1) \tag{1}$$

$$EI\frac{\partial^4 w_2}{\partial x^4}+m\frac{\partial^2 w_2}{\partial t^2}+k_2(w_2-u_0)=0 \quad (l_1<x<l) \tag{2}$$

where EI is bending rigidity of the pipeline; m is the linear mass.
Equations (1) and (2) satisfy the boundary conditions

$$w_1=0 \quad \frac{\partial^2 w_1}{\partial x^2}=0 \quad for\ \ x=0, \tag{3}$$

$$w_2=0 \quad \frac{\partial^2 w_2}{\partial x^2}=0 \quad for\ x=l\,. \tag{4}$$

Also, it is necessary to satisfy the conditions of continuity of displacements, angles of rotation, moments and shearing forces at the transition boundary

$$w_1=w_2,\quad \frac{\partial w_1}{\partial x}=\frac{\partial w_2}{\partial x},\ \frac{\partial^2 w_1}{\partial x^2}=\frac{\partial^2 w_2}{\partial x^2},\quad \frac{\partial^3 w_1}{\partial x^3}=\frac{\partial^3 w_2}{\partial x^3} \qquad for\ \ x=l_1\,. \tag{5}$$

Consider the case $u_0 = A\sin[\omega(ct - H + 2R)] = A\sin\left(\dfrac{2\pi(ct - H + 2R)}{\xi_R}\right)$,

where ξ_R is the wave length; A is the amplitude of the vibrations.
The process is considered to be steady, then the solutions of equations (1) and (2) have the form

$$w_1 = X_2(x)\sin(\omega t + \alpha), \;\; w_2 = X_2(x)\sin(\omega t + \alpha),$$

where $\omega = \dfrac{c}{\xi_R}$; $\alpha = -\dfrac{2\pi(H - 2R)}{\xi_R}$.
The functions $X_1(x)$ and $X_2(x)$ satisfy the equations

$$X_1^{IV} - \lambda_1^4 X_1 = c_1, \quad X_2^{IV} - \lambda_2^4 X_2 = c_2, \quad \text{for } \omega^2 > \frac{k_{01}}{m}$$

$$X_1^{IV} + \lambda_1^4 X_1 = c_1, \quad X_2^{IV} + \lambda_2^4 X_2 = c_2, \quad \text{for } \omega^2 < \frac{k_{02}}{m}, \qquad 6)$$

where $k_{01} = \max(k_1, k_2)$, $k_{02} = \min(k_1, k_2)$, $\lambda_1^4 = \dfrac{m\omega^2 - k_1}{EJ}$, $\lambda_2^4 = \dfrac{m\omega^2 - k_2}{EJ}$, $c_i = Ak_i / EJ$.

1. Consider the case $\omega^2 > k_{01}/m$.
Then the solutions of equations (1) and (2) can be represented in the form:

$$X_1 = A_1Y_1(\lambda_1, x) + A_2Y_2(\lambda_1, x) + A_3Y_3(\lambda_1, x) + A_4Y_4(\lambda_1, x) - \frac{c_1}{\lambda_1^4}$$

$$X_2 = B_1Y_1(\lambda_2, x) + B_2Y_{21}(\lambda_2, x) + B_3Y_{31}(\lambda_2, x) + B_4Y_4(\lambda_2, x) - \frac{c_1}{\lambda_2^4},$$

where A_i, B_i are arbitrary constants; $Y_i(z)$ are Krylov functions

$$Y_1(z) = \frac{chz + \cos z}{2}, \quad Y_2(z) = \frac{shz + \sin z}{2}, \qquad (7)$$

$$Y_3(z) = \frac{chz - \cos z}{2}, \quad Y_4(z) = \frac{shz - \sin z}{2}. \qquad (8)$$

Taking into account the boundary conditions (3), the displacement $X_1(x)$ has the form

$$X_1 = \frac{c_1}{\lambda_1^4}Y_1(\lambda_1, x) + A_2Y_2(\lambda_1, x) + A_4Y_4(\lambda_1, x) - \frac{c_1}{\lambda_1^4}, \quad 0 \prec x \prec l_1 \qquad (9)$$

We put the function $X_2(x)$ in the following form:

$$X_2 = B_1 Y_1[\lambda_2,(x-l_1)] + B_2 Y_2[\lambda_2,(x-l_1)] + B_3 Y_3[\lambda_2,(x-l_1)] +$$
$$+ B_4 Y_4[\lambda_2,(x-l_1)] - \frac{c_1}{\lambda_2^4}, \qquad l_1 < x < l \,. \tag{10}$$

From conditions (5) it follows

$$B_1 = A_2 Y_2(\lambda_1 l_1) + A_4 Y_4(\lambda_1 l_1) + \frac{c_1}{\lambda_1^4}\left[Y_1(\lambda_1 l_1) - 1\right] + \frac{c_1}{\lambda_2^4},$$

$$B_2 = \beta\left[A_2 Y_1(\lambda_1 l_1) + A_4 Y_3(\lambda_1 l_1)\right] + \frac{c_1}{\lambda_1^3 \lambda_2} Y_4(\lambda_1 l_1),$$

$$B_3 = \beta^2\left[A_2 Y_4(\lambda_1 l_1) + A_4 Y_2(\lambda_1 l_1)\right] + \frac{c_1}{\lambda_1^2 \lambda_2^2} Y_3(\lambda_1 l_1),$$

$$B_4 = \beta^3\left[A_2 Y_3(\lambda_1 l_1) + A_4 Y_1(\lambda_1 l_1)\right] + \frac{c_1}{\lambda_1 \lambda_2^3} Y_2(\lambda_1 l_1),$$

where $\beta = \frac{\lambda_1}{\lambda_2}$.

Substituting the expressions B_i into formula (10), we obtain

$$X_2 = A_2 F_2(x) + A_4 F_4(x) + F_0(x), \tag{11}$$

Where

$$F_2 = Y_2(\lambda_1 l_1) Y_1\left[\lambda_2(x-l_1)\right] + \beta Y_1(\lambda_1 l_1) Y_2\left[\lambda_2(x-l_1)\right] +$$
$$+\beta^2 Y_4(\lambda_1 l_1) Y_3\left[\lambda_2(x-l_1)\right] + +\beta^3 Y_3(\lambda_1 l_1) Y_4\left[\lambda_2(x-l_1)\right],$$
$$F_4 = Y_4(\lambda_1 l_1) Y_1\left[\lambda_2(x-l_1)\right] + \beta Y_3(\lambda_1 l_1) Y_2\left[\lambda_2(x-l_1)\right] +$$
$$+\beta^2 Y_2(\lambda_1 l_1) Y_3\left[\lambda_2(x-l_1)\right] + +\beta^3 Y_1(\lambda_1 l_1) Y_4\left[\lambda_2(x-l_1)\right],$$

$$F_0(x) = \left\{\frac{c_1}{\lambda_1^4}\left[Y_1(\lambda_1 l_1) - 1\right] + \frac{c_2}{\lambda_1^4}\right\} Y_1\left[\lambda_2(x-l_1)\right] + \frac{c_1}{\lambda_1^3 \lambda_2} Y_4(\lambda_1 l_1) Y_2\left[\lambda_1(x-l_1)\right] +$$
$$+ \frac{c_1}{\lambda_1^2 \lambda_2^2} Y_3(\lambda_1 l_1) Y_3\left[\lambda_2(x-l_1)\right] + \frac{c_1}{\lambda_1 \lambda_2^3} Y_2(\lambda_1 l_1) Y_4\left[\lambda_2(x-l_1)\right].$$

According to conditions (4), we put

$$X_2(l) = 0, \quad X_2''(l) = 0 \,.$$

Using these conditions, we will compose an equation to determine the constants A_2 and A_4

$$A_2F_2(l)+A_4F_4(l)=-F_0(l),$$
$$A_2F_2''(l)+A_4F_4''(l)=-F_0''(l).$$

From this system, we find the constants A_2 and A_4

$$A_2=\frac{F_0''(l)\,F_4(l)-F_0(l)F_4''(l)}{F_2(l)F_4''(l)-F_2''(l)F_4(l)},\quad A_4=\frac{F_2''(l)\,F_0(l)-F_4''(l)F_2(l)}{F_2(l)F_4''(l)-F_2''(l)F_4(l)}.$$

Substituting the expressions for the constants A_2 and A_4 into formulas (9) and (11), we finally obtain problems solutions where the frequency of vibrations of the external action satisfies the condition $\omega_2>k_{02}/m$.

2. Consider the case $\omega^2<\dfrac{k_{02}}{m}$. Functions X_1 and X_2 satisfy the equations:

$$X_1^{IV}+4\gamma_1^4X_1=c_1,\quad X_2^{IV}+4\gamma_2^4X_2=c_2, \tag{12}$$

where $\gamma_1^4=-\dfrac{\lambda_1^4}{4}=\dfrac{k_1-m\omega^2}{4EI},\quad \gamma_2^4=-\lambda_2^4=\dfrac{k_2-m\omega^2}{4EI}$.

The solutions of equations (12) we represent in the form

$$\begin{gathered}X_1=A_1Z_1(\gamma_1x)+A_2Z_2(\gamma_1x)+A_3Z_3(\gamma_1x)+A_4Z_4(\gamma_1x)+\frac{c_1}{4\gamma_1^4},\\ X_2=B_1Z_1[\gamma_2(x-l)]+B_2Z_2[\gamma_2(x-l)]+B_3Z_3[\gamma_2(x-l_1)]+B_4Z_4[\gamma_2(x-l_1)]+\frac{c_2}{4\gamma_2^4},\end{gathered} \tag{13}$$

where $Z(z)$ are represented through functions of the Krylov type:

$$Z_1=ch\gamma z\cos\gamma z,\quad Z_2=sh\gamma z\cos\gamma z+ch\gamma z\sin\gamma z,$$
$$Z_3=sh\gamma z\sin\gamma z,\quad Z_4=sh\gamma z\cos\gamma z-ch\gamma z\sin\gamma z.$$

For derivatives of these functions, we have the dependencies

$$\begin{aligned}
&Z_1^I=\gamma Z_4,\ Z_1^{II}=-2\gamma^2Z_3,\ Z_1^{III}=-2\gamma^3Z_2,\ Z_1^{IV}=-4\gamma^4Z_1,\\
&Z_2^I=\gamma Z_1,\ Z_2^{II}=2\gamma^2Z_4,\ Z_2^{III}=-4\gamma^3Z_3,\ Z_2^{IV}=-4\gamma^4Z_2,\\
&Z_3^I=\gamma Z_2,\ Z_3^{II}=2\gamma^2Z_1,\ Z_3^{III}=2\gamma^3Z_4,\ Z_3^{IV}=-4\gamma^4Z_3,\\
&Z_4^I=-2\gamma Z_3,\ Z_4^{II}=-2\gamma^2Z_2,\ Z_4^{III}=-4\gamma^3Z_1,\ Z_4^{IV}=-4\gamma^4Z_4.
\end{aligned}$$

It is seen that all functions Z_i satisfy the equation

$$X_i^{IV}+4\gamma^4X_i=0\,.$$

From boundary conditions (4), it follows

$$X_1 = \frac{c_1}{4\gamma_1^4}[1 - Z_1(\gamma_1 x)] + A_2 Z_2(\gamma_1 x) + A_4 Z_4(\gamma_1 x).$$

Conditions (5) give

$$B_1 = \frac{c_1}{4\gamma_1^4}\left[1 - Z_1(\gamma_1 l_1)\right] + A_2 Z_2(\gamma_1 l_1) + A_4 Z_4(\gamma_1 l_1) - \frac{c_1}{4\gamma_2^4},$$

$$B_2 = \alpha\left[A_2 Z_1(\gamma_1 l_1) - 2A_4 Z_3(\gamma_1 l_1)\right] - \frac{c_1}{4\gamma_1^3\gamma_2} Z_4(\gamma_1 l_1),$$

$$B_3 = \frac{\alpha^2}{2}\left[A_2 Z_4(\gamma_1 l_1) - 2A_4 Z_2(\gamma_1 l_1)\right] + \frac{c_1}{4\gamma_1^2\gamma_2^2} Z_3(\gamma_1 l_1),$$

$$B_4 = \frac{\alpha^3}{2}\left[-A_2 Z_3(\gamma_1 l_1) - 2A_4 Z_1(\gamma_1 l_1)\right] - \frac{c_1}{4\gamma_1\gamma_2^3} Z_2(\gamma_1 l_1).$$

Substituting expressions B_i into formulas (5), we establish the form of the function $X_2(x)$

$$X_2 = A_2 R_2(x) + A_4 R_4(x) + R_0(x),$$

where

$$R_2 = Z_2(\gamma_1 l_1) Z_n\left[\gamma_2(x - l_1)\right] + \alpha Z_1(\gamma_1 l_1) Z_2\left[\gamma_2(x - l_1)\right] +$$

$$+\frac{\alpha^2}{2}\cdot Z_2(\gamma_1 l_1)\cdot Z_3\left[\gamma_2(x - l_1\right] - \frac{\alpha^3}{4} Z_3(\gamma_1 l_1) Z_4\left[\gamma_2(x - l_1)\right],$$

$$R_4 = Z_4(\gamma_1 l_1) Z_1\left[\gamma_2(x - l_1)\right] + 2Z_3(\gamma_1 l_1) Z_2\left[\gamma_2(x - l_1)\right] +$$

$$+\alpha^2\cdot Z_2(\gamma_1 l_1)\cdot Z_3\left[\gamma_2(x - l_1\right] - \frac{\alpha^3}{4} Z_1(\gamma_1 l_1) Z_4\left[\gamma_2(x - l_1)\right],$$

$$R_0(x) = \frac{c_1}{4\gamma_1^4}\left[1 - Z_1(\gamma_1 l_1)\right] Z_1\left[\gamma_2(x - l_1)\right] - \frac{c_1}{4\gamma_2^4} Z_1\left[\gamma_2(x - l_1)\right] -$$

$$-\frac{c_1}{4\gamma_1^3\gamma_2} Z_4(\gamma_1 e_1) Z_2\left[\gamma_2(x - l_1\right] - \frac{c_1}{4\gamma_1^2\gamma_2^2} Z_3(\gamma_1 l_1) Z_3\left[\gamma_2(x - l_1)\right] +$$

$$+\frac{c_1}{4\gamma_1\gamma_2^3} Z_1(\gamma_1 l_1) Z_4\left[\gamma_2(x - l_1)\right], \ \alpha = \gamma_1/\gamma_2.$$

Using the boundary conditions (5), we compose equations for determining the constants A_2 and A_4

$$A_2 R_2(l) + A_4 R_4(l) = -R_0(l), \quad A_2 R_2^{II}(l) + A_4 R_4^{II}(l) = -R_0^{II}(l).$$

From this system, we determine A_2 and A_4.

3 Results and Discussion

Consider the results of calculations. Figures 1 – 3 show the curves of the distribution of deflections (referred to the value A) and moments (referred to the value of EJl^2/A) along the pipeline axis x/l in the case of $\omega^2 > k_{02}/m$ depends on various frequency ratios $\overline{\omega}_1 = \frac{1}{\omega}\sqrt{k_1/m}$, $\overline{\omega}_2 = \frac{1}{\omega}\sqrt{k_2/m}$.

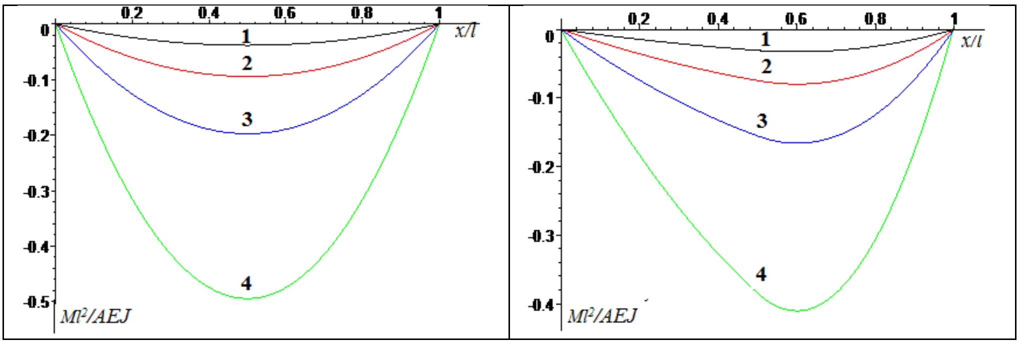


Fig. 1. Distribution of the moment $\overline{M} = Ml^2 / AEJ$ along the pipeline length x/l at frequencies close to the first resonance frequency $\overline{\omega} = 3.15$ depends on various frequencies $\overline{\omega} = \sqrt[4]{\frac{m\omega^2 l^4}{EJ}}$: *1* – $\varpi = 5$, *2* – $\varpi = 4.5$, *3* – $\varpi = 4$, *4* – $\varpi = 3.5$

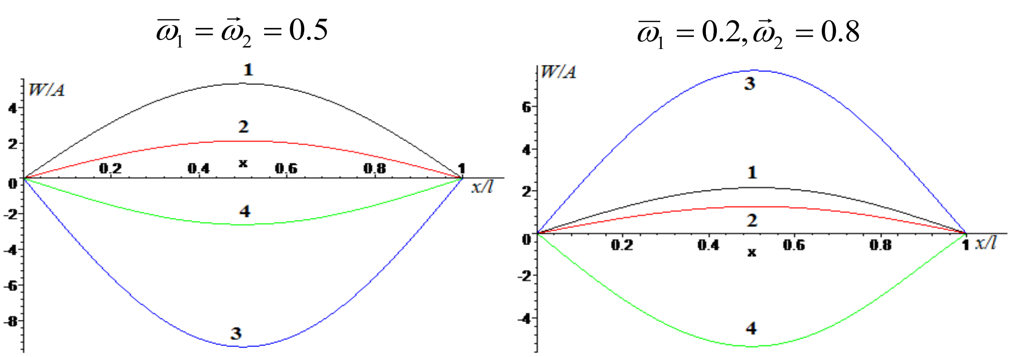
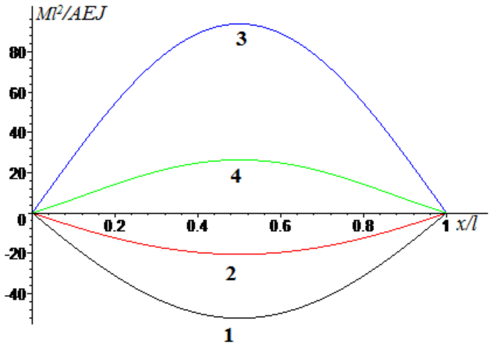


Fig. 2. Distribution of pipeline deflections along the pipeline length x/l at frequencies close to the first resonance frequency $\overline{\omega} = 3.15$: 1 – $\varpi = 5$, 2 – $\varpi = 4.5$, 3 – $\varpi = 4$, 4 – $\varpi = 3.5$

https://doi.org/10.1051/e3sconf/202126402035



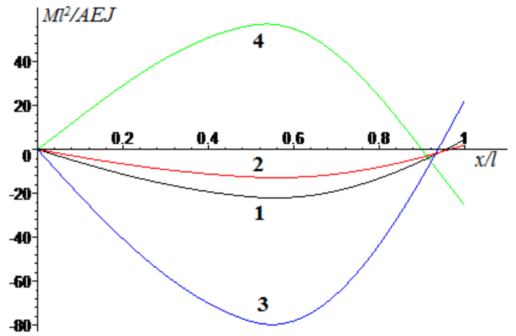


Figure 3. Distribution of the moment $\overline{M} = Ml^2 / AEJ$ along the pipeline length *x/l* at frequencies close to the first resonance frequency $\varpi = 3.15$: 1 – $\varpi = 5$, 2 – $\varpi = 4.5$, 3 – $\varpi = 4$, 4 – $\varpi = 3.5$

The vibratory process of the pipeline can be realized at frequencies close to the roots of the equation, at which the denominators for the functions $X_1(x,\omega)$ and $X_2(x,\omega)$ equal to zero. In figure 2 shows the curves of the distribution of displacements (referred to the value A) of pipeline sections along the length at dimensionless frequencies close to two resonance frequencies depends on various values of the ratios ω_1/ω and ω_2/ω ($\omega_i^2 = k_i / m$). In the calculations, it was assumed that l_1/l=0.5. When the pipeline vibrates with a frequency close to the resonant frequency, the displacements of pipeline sections can take very large values. In the case under consideration, the presence of a section with different stiffness coefficients doesn't significantly affect the resonant vibration mode. Similar curves for moments are shown in figures 1 and 3. It can be seen that at frequencies close to the resonance, the values of moments can be large in the pipeline sections, which are the reasons for the loss of pipeline stability.

4 Conclusions

The results obtained when studying vibratory processes in underground pipelines using the developed software product allow us to recommend them for specific calculations and design of underground pipelines under seismic conditions. A number of numerical results were obtained depending on the frequencies close to two resonance frequencies. So, we can conclude that at pipeline vibrations close to the resonance, the displacements of pipeline sections can take very large values. The values of moments can be large in the pipeline sections, which are the reasons for the loss of pipeline stability.

The obtained results and conclusions on them are in satisfactory agreement with the results of observations of the behavior of pipelines in real conditions, which have been observed repeatedly, especially recently during strong earthquakes.

The results presented provide the analysis of the behavior of underground pipelines during seismic impacts and allow developing effective methods for studying the effects of an earthquake on the stability of the underground pipeline in seismic areas.

References

1. Vazouras P, Karamanos S.A., and Dakoulas P. Finite element analysis of buried steel pipelines under strike-slip fault displacements *Soil Dyn. Earthq. Eng.* **30**, pp.1361–1376 (2010)
2. Toprak S, Nacaroğlu E and Koç A.C. Seismic Response of Underground Lifeline Systems *Geotechnical, Geological and Earthquake Engineering* pp. 245–263, (2015)
3. O'Rourke T D, Jeon S-S, Toprak S, Cubrinovski M, Hughes M, van Ballegooy S and Bouziou D Earthquake Response of Underground Pipeline Networks in Christchurch, NZ *Earthq. Spectra* **30**, pp. 183–204, (2014)
4. Corrado V, D. Acunto B., Fontana N. and Giugni M. Inertial Effects on Finite Length Pipe Seismic Response *Math. Probl. Eng,* pp.1–14, (2012)
5. Chen Y, Liu Z, Liu X, Yang M and Jiang L. Experimental Study on Strain Properties of Buried Steel Pipeline Joint under Strike-slip Faults *Shenyang Jianzhu Daxue Xuebao (Ziran Kexue Ban)/Journal Shenyang Jianzhu Univ. (Natural Sci.)*, (2017)
6. Kachadoorian R. Earthquake: Correlation Between Pipeline Damage and Geologic Environment *J. Am. Water Works Assoc.* **68**, pp. 165–167, (1976)
7. Lin T J, Liu G Y, Chung L L and Chou C.H. Verification of Numerical Modeling in Buried Pipelines under Large Fault Movements by Small-Scale Experiments *15 WCEE,* (2012)
8. Israilov M.S, Mardonov B., and Rashidov T.R. Seismodynamics of an underground pipeline in nonideal contact with soil: Effect of sliding on dynamic stresses *J. Appl. Mech. Tech. Phys.* **57** 1126–1132, (2016)
9. Jeon S-S and O'Rourke T D. Northridge Earthquake Effects on Pipelines and Residential Buildings *Bull. Seismol. Soc. Am.* **95** 294–318, (2005)
10. Rashidov T.R. *Dynamic theory of earthquake resistance of complex systems of underground structures* (Tashkent: "Fan"), (1973)
11. Rashidov T.R and Khojmetov G.X. *Earthquake resistance of underground pipelines* (Tashkent: "Fan"), (1985)
12. Sultanov K.S and Vatin N.I. Wave Theory of Seismic Resistance of Underground Pipelines *Appl. Sci.* **11** 1797, (2021)
13. Bekmirzaev D.A., Kishanov R.U. and Mansurova N.Sh. Mathematical Simulation and Solution of the Problem of Seismo–Dynamics of Underground Pipelines *Int. J. Emerg. Tr. Eng. Res.* **8** 5028–5033, (2020)
14. Bekmirzaev D.A, Mansurova N.Sh, Nishonov N.A., Kosimov E.A. and Numonov A Underground pipelines dynamics problem solution under longitudinal seismic loading *IOP Conf. Ser. Mater. Sci. Eng.* 883 012045, (2020)
15. Nishonov N.A., Bekmirzaev D.A., An E V, Urazmukhamedova Z and Turajonov K Behaviour and Calculation of Polymer Pipelines Under Real Earthquake Records *IOP Conf. Ser. Mater. Sci. Eng.* **869** 052076, (2020)
16. Kosimov E A, Mirzaev I and Bekmirzaev D A 2021 Comparison of the impacts of harmonic and seismic waves on an underground pipeline during the Gazli earthquake *IOP Conf. Ser. Mater. Sci. Eng.* 1030 012082
17. Wakamatsu K and Yoshida N. Ground failures and their effects on structures in Midorigaoka district, Japan during recent successive earthquakes *Earthquake Geotechnical Case Histories for Performance-Based Design* (CRC Press) 159–176, (2009)
18. Azadi M and Mir Mohammad Hosseini S.M. The Uplifting Behavior of Shallow Tunnels within the Liquefiable Soils under Cyclic Loadings *Tunn. Undergr. Sp. Technol.* **25**, pp. 158–167, (2010)

19. Chian S C and Madabhushi S P G Effect of buried depth and diameter on uplift of underground structures in liquefied soils *Soil Dyn. Earthq. Eng.* **41**, pp.181–190, (2012)
20. Saeedzadeh R and Hataf N Uplift Response of Buried Pipelines in Saturated Sand Deposit under Earthquake Loading *Soil Dynamics and Earthquake Engineering* **31** pp. 1378–1384, (2011)
21. Uno H, Oka F, Tanizaki S and Tateishi. A Centrifuge Model Tests on the Uplift Behavior of an Underground Structure during Liquefaction and its Numerical Modeling *Earthquake Geotechnical Case Histories for Performance-Based Design* (CRC Press), pp. 1041–1049, (2009)
22. Rashidov T R, Mardonov B.M., and An E V. Transverse Vibrations of Buried Pipelines Under Axial Loading within Geometrically Nonlinear Theory *Int. Appl. Mech*. **55** pp. 229 – 238, (2019)
23. An E.V., and Rashidov T.R. Seismodynamics of Underground Pipelines Interacting with Water-Saturated Fine-Grained Soil *Mech. Solids*, **50**, pp. 305–317, (2015)
24. Rashidov T R and An E V. Geometrically Nonlinear Buckling Stability Analysis of Axially Loaded Underground Pipelines *Soil Mech. Found. Eng.* **54**, pp. 76–80, (2017)