Numerical methods in the study of seismic dynamics of underground pipelines

Diyorbek Bekmirzaev, Ibrakhim Mirzaev, Nodirakhon Mansurova, Elbek Kosimov and Donitor P Juraev

1Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, 39, st. Kari-Niyazi, 100000, Tashkent, Uzbekistan
2Academy of Sciences of the Republic of Uzbekistan Institute of Mechanics and Seismic Stability of Structures named after M.T. Urazbayev, 31, st. Do’rmon yo’li, 100125, Tashkent, Uzbekistan

E-mail: diyorbek_84@mail.ru

Abstract. A system of equations describing the oscillations of a rectilinear pipeline that interacts with the surrounding soil in the case of seismic action functioning in an arbitrary direction is presented. A numerical implementation of problems related to the determination of the mode of deformation of a pipeline experiencing seismic movement of the soil is performed. The methods of realization of boundary problem of seismodynamics of underground pipelines at arbitrary direction of seismic load are developed, as well as the methods of realization of the problems of seismodynamics of underground pipelines of non-orthogonal configuration, based on Finite difference method.

1. Introduction

In the study of the seismic resistance of underground pipelines [1-15] attention is focused mainly on modeling the interaction in the pipe-soil system. The stress-strain state of life-support systems is determined in terms of the coefficients of interaction of these structures with the surrounding soil, including, the coefficient $k_s$ of uniform shear of a pipeline relative to the soil (coefficient of shear of the pipeline).

Analysis of the consequences of strong earthquakes shows that the seismic resistance of underground structures depends on the direction of the seismic wave. Since during earthquakes underground structures can be exposed to waves from arbitrary directions, a determination of the stress-strain state of underground pipelines in the presence of longitudinal, torsional, and transverse oscillations is relevant and serves to determine the possible seismic hazard [1-8].

Due to the fact that in seismic zones of the Republic gas, oil, petrochemical and other industries are widely developing, it becomes vitally important to ensure the strength to underground structures when exposed to seismic loads. Piping systems for water, gas and oil supply, sewage, liquid fuel, energy and communication lines are important not only in everyday life but also in eliminating the consequences of the earthquakes. Damage of underground piping systems during the earthquakes may seriously endanger social life and property and prolong the time of restoration of the economy after severe earthquakes [1-15].
In works of T. Rashidov, M. Mirsaidov, G.X. Xojmetov, B. Mardonov, K.S. Sultanov, T. Mavlyanov, T. Yuldashev, I. Mirzaev, Sh.M. Mamatkulov, A.A. Haldzhigitov, K.D. Salyamova, B.E. Husanov, M.K. Usarov, A. Yusupov, T.T. Sobirov et al. the use of different mechanical mathematical models was analyzed and a number of urgent problems of underground and ground structures were solved [16-21].

Pipeline life support systems consist of straight-line sections connected by joints and orthogonally and non-orthogonally coupled together. A seismic wave initiated during an earthquake affects such a system of pipelines at an arbitrary angle of attack in space. For an underground system of arbitrarily located pipelines with an arbitrary angle of attack of seismic effect in space, it is necessary to develop new computational mathematical models and software for determining the stress-strain state.

In this paper, we proposed an approach for determining the stress-strain state of a pipeline exposed to an arbitrarily directed plane seismic wave, the normal vector to the wave front with axis Ox makes an angle \( \alpha \), and \( \beta \) is the angle between the projection of this vector on Oyz plane and the pipeline axis Oy [1-3].

2. Methods

The system of differential equations of motion of an underground pipeline with natural boundary and initial conditions in a dimensionless vector form [5-7] has the form

\[
M \frac{\partial^2 U}{\partial t^2} + A \frac{\partial^2 U}{\partial x^2} + B \frac{\partial U}{\partial x} + CU + D \frac{\partial U}{\partial t} = CU_0 + D \frac{\partial U_0}{\partial t},
\]

\[
F \frac{\partial U}{\partial x} + KU + L \frac{\partial U}{\partial t} = KU_0 + L \frac{\partial U_0}{\partial t},
\]

\[
U = 0, \quad \frac{\partial U}{\partial t} = 0, \quad \text{at } t=0,
\]

where \( M, A, B, C, D, F, K, L \) are the sixth-order matrices, \( U \) – pipeline displacements, \( U_0 \) – given ground displacements during an earthquake in the form of seismic waves depending on time and coordinates.

The system of differential equations of motion of a unit with natural initial conditions in a dimensionless vector form is

\[
Q \frac{\partial^2 Y}{\partial t^2} + SY = SY_0,
\]

\[
Y = 0, \quad \frac{\partial Y}{\partial t} = 0, \quad \text{at } t=0,
\]

where \( Q, S \) are sixth order matrices; \( Y_0 \) – ground motion during an earthquake.

As a numerical method for solving the equation of motion (1), (4) taking into account (2) and (3), (5), the finite element method (FEM) in spatial coordinates and the implicit finite difference method (FDM) in time to discretize the problem [22] of the pipeline under arbitrary seismic waves are used.

The stresses in the underground pipeline due to axial force \( N \) and the combined action of the axial force and the moment of force \( M \) under arbitrary action are calculated by the following formulas

\[
\sigma_p = \frac{N}{F},
\]

\[
\sigma^\pm_{y,z} = \frac{N}{F} \pm \frac{M_{y,z} R}{I_{y,z}}.
\]

Consider a non-orthogonally connected piping system. Figure 1 shows a system of pipelines and wells of a non-orthogonal configuration, modeled as a rigid body with rigid joints interacting with soil. The wells have a cylindrical shape, in accordance with which the mass moments of inertia and the coefficients of interaction with soil are calculated. We study the effect of the well mass on the stress state of an underground pipeline under spatial seismic load.
An underground pipeline 172 m long, to which 4 units are connected in sections of 41 m, 85 m, 88 m and 132 m, is shown in figure 1.

Figure 1. Section of a complex system of underground pipelines of non-orthogonal configuration

3. Results and discussions

As an example, consider the following problem. We choose the mechanical and geometrical parameters of the underground pipeline and soil in the following form: 

\[ E = 2 \times 10^5 \text{ MPa}; \]

\[ \rho = 7.8 \times 10^3 \text{ kg/m}^3; \]

\[ D_H = 0.5 \text{ m}; \]

\[ D_B = 0.49 \text{ m}; \]

\[ I_L = \pi (D_H^4 - D_B^4) / 64 \text{ m}^4; \]

\[ I_p = \pi (D_H^4 - D_B^4) / 32 \text{ m}^4; \]

\[ l = 172 \text{ m}; \]

\[ \mu_{\text{soil}} = 0.2; \]

\[ \mu_{\text{pipe}} = 0.3; \]

\[ u_{0x} = u_0 \cos \alpha; \]

\[ u_{0y} = u_0 \sin \alpha \cos \beta; \]

\[ u_{0z} = u_0 \sin \alpha \sin \beta; \]

\[ u_0 = a_0 \sin(t \cdot x / C_p) \cdot H(t \cdot x \cdot \cos \alpha / C_p) + 2 \cdot \pi \cdot \pi \cdot I; \]

\[ a_0 = 0.008 \text{ m}; \]

\[ C_p = 500 \text{ m/s}; \]

\[ k_1 = 1.5 \times 10^5 \text{ kN/m}^3. \]

Well parameters are:

\[ E = 2.5 \times 10^4 \text{ MPa}; \]

\[ \rho = 2.5 \times 10^3 \text{ kg/m}^3; \]

\[ I_L = I_p = m_1 / 12 \cdot H_{ax}^2 + 1 / 2 \cdot m_2 \cdot R_{H}^2 \text{ m}^2; \]

\[ I_{ax} = m_1 / 2 \cdot (R_{H}^2 + R_{B}^2) + m_2 \cdot R_{H}^2 \text{ m}^2; \]

\[ V = \pi \cdot H_{ax} / 4 \cdot (D_H^2 - D_B^2) + 2 \cdot \pi \cdot R_{H}^2 \cdot h_{ax}; \]

\[ k_{ax} = 0.5 \times 10^4 \text{ kN/m}^3; \]

\[ k_{ax}^2 = 1.3 \times 10^4 \text{ kN/m}^3; \]

\[ D_B^2 = 1 \text{ m}; \]

\[ D_B^2 = 0.9 \text{ m}; \]

\[ m_{ax} = V / \rho; \]

\[ m_1 = \pi \cdot H_{ax} / 4 \cdot (D_H^2 - D_B^2) \rho; \]

\[ m_2 = \pi \cdot R_{H}^2 \cdot h_{ax} \rho; \]

\[ H_{ax} = 1 \text{ m}. \]

Consider the effect of arbitrary seismic impact on a complex non-orthogonal underground pipeline at different angles of incidence of seismic wave \( \alpha = 30^\circ, \beta = 30^\circ \). Under the influence of arbitrary seismic loads (including real earthquake records), a complex stress-strain state arises in the sections of the underground pipeline.

Let’s analyze the results. The results of solving the problem are presented in the form of graphs. Figure 2, a, b shows the changes in the values of longitudinal displacement in time in the given sections of the underground pipeline \( x = 41 \text{ m}, x = 81 \text{ m}, x = 85 \text{ m}, x = 92 \text{ m}, x = 132 \text{ m} \) and Fig. 2, c, d shows the changes in the values of longitudinal displacement along the axis of the underground pipeline at a fixed time.

Figure 2. Changes in the values of longitudinal displacement in time in given the sections (a, b) and along the axis of the underground pipeline at a fixed time (c, d)
The graphs show that at longitudinal displacements of the underground pipeline, the influence of the units is slightly noticeable (Figure 2, \(x=41\) m, \(x=85\) m, \(x=88\) m, \(x=132\) m).

Figure 3 shows the changes in the values of transverse displacement in time in the given sections and along the axis of the underground pipeline at a fixed time.

Figure 3. Changes in the values of the transverse displacement in time in the given sections \((a, b)\) and along the axis of the underground pipeline at a fixed time \((c, d)\)

Figure 4 shows the changes in the values of vertical displacement in time in the given sections and along the axis of the underground pipeline at fixed times.

Figure 4. Changes in the values of vertical displacement in time in the given sections \((a, b)\) and along the axis of the underground pipeline at a fixed time \((c, d)\)

Figure 5, \(a, b\) shows the results of a change in the compressive (tensile) stresses in time in the given sections \((x=41\) m, \(x=81\) m, \(x=85\) m, \(x=88\) m, \(x=92\) m, \(x=132\) m) of the underground pipeline. Figure 5,

$c, d$ shows the changes in the values of the compressive (tensile) stresses along the axis of the underground pipeline at a fixed time. The complex non-orthogonal configuration of underground pipelines helps to reduce the longitudinal forces in the underground pipeline near this section to a distance of 15-20 meters. Under compressive (tensile) stresses in complex sections of the underground pipeline, the influence of the unit (Figure 5, $c, d; x=85 \text{ m}, x=88 \text{ m}$) is insignificant. As seen from the graphs under compressive (tensile) stresses of the underground pipeline, the influence of the unit mass is noticeable (Figure 5, $a, b$).

![Graphs showing changes in stresses](image)

**Figure 5.** Changes in the values of compressive (tensile) stresses in time ($a, b$) and along the axis of the underground pipeline at a fixed time ($c, d$)

![Graphs showing changes in total stress](image)

**Figure 6.** Changes in the values of the total stress ($\sigma_y$) in time in the given sections ($a, b$) and along the axis of the underground pipeline at a fixed time ($c, d$)

Figure 6, $a, b$ shows the changes in the values of the total stress ($\sigma_y$) in time in the given sections (the bending relative to the $Oy$ axis) of the underground pipeline. Figure 6, $c, d$ shows the changes in
the values of the total stress ($\sigma_y$) along the axis (the bending relative to the $Oy$ axis) of the underground pipeline at fixed times.

**Figure 7.** Changes in the values of the total stress ($\sigma_y$) in time in the given sections ($a, b$) and along the axis of the underground pipeline at a fixed time ($c, d$)

Figure 7, $a, b$ shows the changes in the values of the total stress ($\sigma_y$) in time in the given sections (the bending relative to the $Oy$ axis) of the underground pipeline. Figure 7, $c, d$ shows the changes in the values of the total stress ($\sigma_y$) along the axis (the bending relative to the $Oy$ axis) of the underground pipeline at fixed times.

**Figure 8.** Changes in the values of the total stresses ($\sigma_z$) in time in the given sections ($a, b$) and along the axis of the underground pipeline at a fixed time ($c, d$)

Figures 8–9, $a, b$ show the changes in the values of the total stresses ($\sigma_z^+$, $\sigma_z^-$) in time in the given sections (the bending relative to the $Oz$ axis) of the underground pipeline. Figures 8–9, $c, d$ show the changes in the values of the total stress ($\sigma_z^+$, $\sigma_z^-$) along the axis (the bending relative to the $Oz$ axis) of
the underground pipeline at fixed times. Here, the units in complex sections of the underground pipeline play an important role, since near the units of the underground pipeline the total stresses increase (see Figures 8–9, a–d; at $x=85$ m and $x=88$ m).

![Figure 9](image-url)

**Figure 9.** Changes in the values of the total stress ($\sigma_z$) in time in the given sections (a, b) and along the axis of the underground pipeline at a fixed time (c, d)

The results show that in the units and complex sections of the underground pipeline (Figures 8–9, c, d), changes in the total stresses along the axis have a complex pattern. This is due to the bending strains. In the future, it is necessary to conduct final assessments of the effect of unit masses on the stress-strain state of the pipeline systems, taking into account their geometrical parameters.

Figure 10 shows the changes of maximum values of longitudinal and transversal displacements, and normal and tangential stresses when the direction of the effect of seismic loads is changing.

![Figure 10](image-url)

**Figure 10.** Change of longitudinal and transversal displacements and normal and tangential stresses at alteration of incidence angle of seismic loads: 1 - Both ends of the pipeline are jammed, 2 - the left end of the pipeline is jammed, the right one is free, 3 - both ends are elastically fixed.
If consider the figures with increasing angle of seismic load effect, maximum values of transversal displacements and tangential stresses are also increasing (Figure 10). It can be concluded that in design of underground pipeline joining parts must be close to elastically fixed conditions. Thus stress-strain state of the pipeline decreases by 20-40% relative to the rigidly fixed boundary conditions.

4. Conclusions

Conducted theoretical and computational-experimental studies solve the problem of assessing the stress-strain state of underground pipelines of complex non-orthogonal configuration under seismic loads directed arbitrary relative to the principal axes of the pipeline.

The work conducted presents a first approximation when considering the complex of problems and it reveals the perspective for the study of pipeline behavior of complex (T-, Г- and V-type) configuration. Presented methods and software provide a complex analysis of the strength of underground pipelines under seismic effects. Besides, they realize the system approach to the determination of earthquake aftermath on SSS of the pipeline and on planning of engineering measures to provide safe and reliable operation of underground pipeline in seismically hazardous zones.

Practical significance of results follows directly from the setting of the problems. That is why, scientific-research works are completed not only by algorithms and PC design programs, but by final practical results. They allow to significantly expand the normative document on seismic engineering of underground pipelines.

The results presented provide a comprehensive analysis of underground pipelines strength during seismic impacts and implement a systematic approach to determining the effect of an earthquake aftermath on the SSS of a pipeline and to planning engineering measures to ensure the safe and reliable operation of an underground pipeline in earthquake-prone areas.

References

[1] Rashidov T R, Yuldashev T and Bekmirzaev D A 2018 Seismodynamics of Underground Pipelines with Arbitrary Direction of Seismic Loading Soil Mech. Found. Eng. 55 243–8
[2] Rashidov T R and Bekmirzaev D A 2015 Seismodynamics of Pipelines Interacting with the Soil Soil Mech. Found. Eng. 52 149–54
[3] Bekmirzaev D A and Rashidov T R 2015 Mathematical Simulation and Solution of the Problem of S Dynamics of Underground Pipelines J. Sib. Fed. Univ. Eng. Technol. 8 1046–55
[4] Bekmirzaev D A and Kishanov R U 2020 Assessment of the Effect of Inertia Forces in Problems of Underground Pipeline Seismodynamics Int. J. Innov. Technol. Explor. Eng. 9 500–3
[5] Rashidov T R and Nishonov N A 2016 Seismic Behavior of Underground Polymer Piping with Variable Interaction Coefficients Soil Mech. Found. Eng. 53 196–201
[6] Rashidov T R and An E V. 2017 Geometrically Nonlinear Buckling Stability Analysis of Axially Loaded Underground Pipelines Soil Mech. Found. Eng. 54 76–80
[7] Rashidov T R and Mubarakov Y 1992 Seismodynamics of underground structures Soil Mech. Found. Eng. 29 213–6
[8] Rashidov T R, Mardonov B M and An E V. 2019 Transverse Vibrations of Buried Pipelines Under Axial Loading Within Geometrically Nonlinear Theory Int. Appl. Mech. 55 229–38
[9] Corrado V, D’Acunto B, Fontana N and Giugni M 2012 Inertial Effects on Finite Length Pipe Seismic Response Math. Probl. Eng. 2012 1–14
[10] Chian S C, Tokimatsu K and Madabhushi S P G 2014 Soil Liquefaction–Induced Uplift of Underground Structures: Physical and Numerical Modeling J. Geotech. Geoenvironmental Eng. 140 04014057
[11] Vazouras P, Dakoulas P and Karamanos S A 2015 Pipe–soil interaction and pipeline performance under strike–slip fault movements Soil Dyn. Earthq. Eng. 72 48–65
[12] Zhuang H, Hu Z, Wang X and Chen G 2015 Seismic responses of a large underground structure in liquefied soils by FEM numerical modelling Bull. Earthq. Eng. 13 3645–68
[13] O’Rourke M J and Liu J 1998 Seismic loading and behavior of buried pipelines Am. Soc. Mech. Eng. Press. Vessel. Pip. Div. PVP

[14] O’Rourke M and Vargas-Londono T 2016 Analytical Model for Segmented Pipe Response to Tensile Ground Strain Earthq. Spectra 32 2533–48

[15] O’Rourke T D, Jung J K and Argyrou C 2016 Underground pipeline response to earthquake-induced ground deformation Soil Dyn. Earthq. Eng. 91 272–83

[16] Mirsaidov M M and Sultanov T Z 2014 Assessment of stress-strain state of earth dams with allowance for non-linear strain of material and large strains Mag. Civ. Eng. 49 73–82

[17] Mirsaidov M, Sultanov T, Yarashov J and Toshmatov E 2019 Assessment of dynamic behaviour of earth dams taking into account large strains ed A Volkov, A Pustovgar, T Sultanov and A Adamtsevich E3S Web Conf. 97 05019

[18] Usarov M, Mamatisaev G, Toshmatov E and Yarashov J 2019 Forced vibrations of a box-like structure of a multi-storey building under dynamic effect J. Phys. Conf. Ser. 1425 012004

[19] Usarov M, Mamatisaev G, Yarashov J and Toshmatov E 2019 Non-stationary oscillations of a box-like structure of a building J. Phys. Conf. Ser. 1425 012003

[20] Khusanov B and Rikhsieva B 2019 Thickness dimensions of the contact layer of soil-rigid body interaction ed A Volkov, A Pustovgar, T Sultanov and A Adamtsevich E3S Web Conf. 97 04040

[21] Mirzaev I, Bekmirzaev D A, Kosimov E A 2019. Formation of Bending Waves in Underground Extended Pipelines under the Action of Seismic Wave. International Journal of Advanced Research in Science, Engineering and Technology 6(8) 10553-10557.

[22] Zienkiewicz O C, and Morgan K, 2000. Finite elements and approximation (University of Wales, Swansea, United Kingdom, Dover Publications Inc) p 352