Comparison of the impacts of harmonic and seismic waves on an underground pipeline during the Gazli earthquake

Elbek Kosimov, Ibrakhim Mirzaev and Diyorbek Bekmirzaev

Academy of Sciences of the Republic of Uzbekistan Institute of Mechanics and Seismic Stability of Structures named after M.T. Urazbayev, 33, st. Do’rmon yo’li, 100125, Tashkent, Uzbekistan

E-mail: diyorbek_84@mail.ru

Abstract. The paper considers a class of problems of the dynamics of spatial systems of underground pipelines under the action of three-component seismic waves propagating in soil based on instrumental records of real earthquakes. A comparison was made of the impacts of harmonic and seismic waves on an underground pipeline during the Gazli earthquake. A graphical method for determining the dominant period to be used in calculations for harmonic impact was given.

1. Introduction
As is well-known, the degree of pipelines damage during an earthquake depends on a number of factors: the strength of seismic impact, the direction of seismic wave propagation, geological and hydrogeological conditions (specific gravity of soil base and the degree of pipeline fixing in soil), the pipeline depth, operational and technological loads and impacts, the design of the pipeline sections and its joints, the material characteristics of the pipes and supports, the degree of pipeline elements wear [1-2].

The study of dynamic processes in underground structures (spatial pipeline systems, subway tunnels, and structure foundations), occurring when subjected to seismic waves, can be conducted using hypotheses, equations, and methods of the mechanics of a rigid body.

Computational experiments for the structure calculation using a set of selected seismograms were conducted under different boundary conditions, taking into account the interaction in the pipe-soil system. As a result, it became possible to obtain the maximum stresses and other values (stress intensity, damage accumulation function) to test the seismic stability criterion of a structure [3-6].

Seismic waves are complex in nature, they are nonstationary, differ in the spectrum of frequencies, maximum amplitudes of oscillations, and the impact duration (from several seconds to several minutes). The amplitude-frequency response of the seismogram of the earthquake, the epicenter of which located too close to the object, depends on the focal depth, the amount of released energy, the soil structure from the focus to its surface, and other factors [1-2].

2. Methods
The paper considers a class of problems of the dynamics of spatial systems of underground pipelines under the three-component seismic waves propagating in soil based on instrumental records of real earthquakes. Let us assume that the propagating seismic wave specified and reflected from the...
pipeline system does not affect the displacement field in soil. Since the seismic wavelength is greater than the pipeline diameter, a rod under tension-compression, torsion, and bending models the pipeline considering shear strain; its interaction with surrounding soil is modeled according to various simplified models. Seismic action propagating in soil is transferred to the pipeline through a combination of elastic and viscous contact elements. The boundary conditions at the ends of the pipeline system can be as follows: the condition of rigid fixing; anchoring to soil, i.e. when a pipeline moves with soil; with given forces and moments; the condition of complete or partial stress-free; viscoelastic condition [4-15].

The spatial system of underground pipelines interacting with soil can be divided into linear sections of the pipeline, massive nodes and butt joint contacts [3]. The butt joint contacts can be rigid or flexible. A finite-difference method for solving the seismodynamics problems was proposed for such structures [4-8].

The studies in [16-17] presented the mass and stiffness matrices for spatial rod systems. The underground structure was divided into finite elements, the mass and stiffness matrices were constructed for the linear finite element, the nodal element, and for the underground structure, as a whole. By replacing a rod finite element with the finite element of a pipe, we can build the mass and stiffness matrices of the pipeline itself, its joints, interaction rigidity and viscosity. Moreover, each pipeline, its joints and nodal elements can have their own mass, rigid and viscous parameters. In joint pipelines, consisting of pipe sections, it is necessary to take into account the geometrical and mechanical characteristics of the flexible joint. To simulate a flexible joint, we neglect its mass and represent the joint as a spring and a viscous element.

To obtain the stiffness and mass matrices, we use the principle of virtual displacements. For each type of finite element, from the principle of virtual displacements, we have

$$\delta A - \delta A_1 - \delta A_2 = 0$$  \hspace{1cm} (1)

where $\delta A$, $\delta A_1$, $\delta A_2$ is the virtual work of elastic forces of the pipeline or its butt end elements; virtual work of distributed inertial forces, forces of interaction with soil and external distributed forces; virtual work of response forces at the ends of the pipeline finite element.

Consider the pipe element connection to a node element. When they are rigidly connected, the generalized displacements of the end of the pipeline element and the point of the node to which this end of the pipeline element is connected will be similar. In the case of a hinged joint, the generalized displacements of the node and the corresponding butt end of the pipeline element have different values. Hence follows the problem of expressing the generalized displacements of the pipeline end element through the generalized displacements of the nodal element, and building the mass and stiffness matrices in the presence of hinge links. The connection to the eccentricity could be also realized through the appropriate transformations. The formulas for these transformations were given in [16-17].

Pipeline systems may contain the parts modeled as a concentrated mass interacting with soil. In this case, the concentrated mass is combined with the node of the finite element, called the nodal element. The nodal element is characterized by the coordinates of the center of mass, the mass $m$ and the moments of inertia $J_{xx}$, $J_{yy}$, $J_{zz}$, $J_{xy}$, $J_{yz}$, $J_{zx}$, $J_{zy}$, $J_{zx}$ [18].

The mass of the nodal element has a certain surface that interacts with soil [18]. This interaction is expressed by the interaction matrix in the global coordinate system.

From the above-mentioned finite elements of rod, butt joint and a nodal element interacting with soil, it is possible to build a spatial system of an underground pipeline of any complexity. The boundary conditions at the end points of the pipeline system can specify the conditions for its fixing to soil or other set values of displacements, stress-free conditions, viscoelastic interaction with soil. These conditions are also covered by the given finite elements.

The system of equations of motion of the underground pipeline system after finite element discretization has the form
\[
\begin{bmatrix}
M_p
\end{bmatrix}\ddot{U} + \begin{bmatrix}
C_p
\end{bmatrix}\dot{U} + \begin{bmatrix}
K_p
\end{bmatrix}U + \begin{bmatrix}
C_u
\end{bmatrix}(U - \{U0\}) + \begin{bmatrix}
K_u
\end{bmatrix}(U - \{U0\}) = \{F(t)\}.
\]

Here \([M_p]\) is the mass matrix, \([K_p]\) is the stiffness matrix, \([C_p]\) is the damping matrix, \([K_u]\) is the interaction matrix, \([C_u]\) is the viscous interaction matrix, \([F]\) is the impact vector, \([U0]\) is the seismic wave in the form of seismograms of real earthquake records, coordinate- and time-dependent. The damping matrix is constructed as \([C_p] = \alpha[M_p] + \beta[K_p]\) [16-17]. The coefficients \(\alpha\) and \(\beta\) are determined based on experimental data by the following relations:

\[
\beta\omega_1^2 + \alpha = \gamma\omega_1; \quad \beta\omega_2^2 + \alpha = \gamma\omega_2; \quad \gamma = \frac{\delta}{\pi},
\]

where \(\delta\) is the logarithmic decrement of the structure vibration damping; \(\omega_1, \omega_2\) are the frequencies of two characteristic modes of vibrations.

The initial conditions are

\[
\{U\}^0 = \{U_{CT}\}, \quad \{\dot{U}\}^0 = 0,
\]

where \(\{U_{CT}\}\) is the solution to the static problem.

To determine the initial conditions, the statics problem is solved for given external forces and displacements of certain nodes

\[
\begin{bmatrix}
K_p
K_u
\end{bmatrix}\{U_{CT}\} = \{F\}.
\]

To solve this system of algebraic equations, the Cholesky method was applied with the profile storage of the stiffness matrix of the underground pipeline spatial system [19].

Further, the system of ordinary differential equations was approximated by an implicit difference scheme; the displacements and rotations at the nodal points, then the forces and moments in the finite elements were calculated by the Cholesky method stepwise in time.

3. Results and discussions

In practical calculations [building standards KMK, SNiP], a harmonic function with an appropriate amplitude and frequency was usually used as a seismic impact. For extended underground structures, it is required to consider the seismic impact in the form of a seismic wave [18]. Below we present the definition of the amplitude and frequency of the displacement wave in the form of a sinusoid based on real records of the Gazli earthquake on May 15, 1976 [20]. During this earthquake, a straight section of a steel water pipe of a diameter of 1.02 m and a thickness of 0.008 m was destroyed at a point of the welded joint. In the calculations, the origin of coordinates lies on the left end of the pipeline and is directed along the pipeline axis.

Table 1 shows a comparison of the values of the maximum stress given in [18] calculated by the finite element method and an implicit finite-difference scheme based on instrumental recording of longitudinal wave.

The boundary conditions at the pipeline ends are specified as anchorage to soil, i.e. the ends of the pipeline move together with soil. Since the elastic limit of steel is 180 MPa, the stress values calculated for the linear problem by the numerical method based on instrumental recording allow us to conclude that the pipeline may fail during the earthquake, as it was in reality.

| No | Pipe length (m) | Seismic wave propagation in soil (m/s) | Maximum stress calculated according to [7] \(\sigma_{max}\) (MPa) | Maximum stress calculated by direct method based on real records \(\sigma_{max}\) (MPa) |
|----|----------------|-------------------------------------|-------------------------------------------------|-------------------------------------|
| 1  | 50             | 500                                 | 167                                             | 214                                 |
| 2  | 100            | 500                                 | 83.5                                            | 209                                 |
Table 2 shows a comparison of the calculated maximum stress values at different pipeline lengths, propagation velocities and angles of incidence of seismic wave. The values of the maximum stresses are calculated in the middle of the pipeline length.

The change in the pipeline length has little effect on the values of the maximum stress in the middle of the pipeline; this is because the boundary conditions have a significant influence on the process to a distance of 20-25 m from the ends.

The higher the wave propagation in soil, the lower the value of the maximum stress, due to a decrease in soil strain with an increase in wave propagation under constant amplitude. The greater the angle of incidence of the seismic wave with respect to the pipeline axis, the lower the maximum stress.

| No | Pipe length (m) | Seismic wave propagation in soil (m/s) | Maximum stress calculated according to [7] \( \sigma_{\text{max}} \) (MPa) | Maximum stress calculated by direct method based on real records \( \sigma_{\text{max}} \) at a wave incidence angle of 0° \( \sigma_{\text{max}} \) (MPa) | Maximum stress calculated by direct method based on real records \( \sigma_{\text{max}} \) at a wave incidence angle of 30° \( \sigma_{\text{max}} \) (MPa) |
|----|----------------|---------------------------------------|----------------------------------|-----------------------------------|-----------------------------------|
| 1  | 50             | 200                                   | 167                              | 473                               | 341                               |
|    |                | 500                                   |                                  | 214                               | 150                               |
|    |                | 1000                                  |                                  | 116                               | 84.3                              |
|    |                | 200                                   |                                  | 455                               | 337                               |
| 2  | 100            | 500                                   | 83.5                             | 209.1                             | 147                               |
|    |                | 1000                                  |                                  | 110                               | 78.7                              |
|    |                | 200                                   |                                  | 452.1                             | 336                               |
| 3  | 400            | 500                                   | 21.1                             | 206                               | 147                               |
|    |                | 1000                                  |                                  | 113                               | 79                                |

Figure 1 shows the graphs of the longitudinal component of seismic waves. The upper plot shows the ground acceleration and the lower plot shows the ground displacement in time.

**Figure 1.** Determination of the dominant period of seismic waves

From the graph of ground acceleration, we select its maximum value and set the value of the time passage of this value, then, from the graph of displacements we measure the time interval of one full-wave oscillation of displacement at the set time value, as shown in Figure 1. The measured time interval is called the dominant period of seismic wave. In our case, the maximum ground acceleration...
is 6.67 m/s$^2$, the time passage of this maximum is 14.59 s, and the dominant period is 0.63 s. It should be noted that it is difficult to determine the dominant period for the most of earthquake records.

Figure 2 and Figure 3 show the time variation of stress at the point $x=0.5$ m of the pipeline sections 50 m and 100 m long, respectively, when the propagation direction of a real seismic wave coincides with the pipeline axis. The graph in Figure 2 shows the high-frequency components at low amplitude associated with the wave reflection in a 50 m long pipeline. The maximum stress is 264 MPa. This effect is hardly noticeable in a pipe 100 m long, in this case the maximum stress is 201 MPa. The maximum stress for a 50 m long pipeline is 31 % higher than the maximum stress for a 100 m long pipeline.

Figure 2. Stress change in time near the left end of the pipeline 50 m long

Figure 3. Stress change in time near the left end of the pipeline 100 m long

Figure 4 and Figure 5 show the comparison of stresses under a sinusoidal wave parallel to the pipeline axis with the calculated characteristics (Figure 1) and the wave calculated by a real record of the earthquake at the point $x=0.5$ m of the pipeline sections 50 m and 100 m long, respectively. Figure 4 shows that the maximum stress values in the pipeline for two types of impact are close. This is not observed for a 100 m long pipeline. The same comparisons are shown in Figure 6 and Figure 7 for the midpoints of the pipelines. As noted above, the type of boundary conditions has almost no effect on the process, as is evident from the graphs similarity in Figure 6 and Figure 7.
Consider now the effect of the angle between the propagation direction of the longitudinal component of earthquake record and the pipeline axis. Let us analyze the influence of the wave propagation velocity in soil on the process.
Figure 7. Comparison of stresses under the action of a harmonic wave and a wave according to a real record of an earthquake in the middle of a 100 m long pipeline

Figure 8 shows the graphs of the stress change at an angle of 0° at the left end of the pipeline 400 m long at various propagation velocities of the longitudinal seismic wave; the greater velocity, the lower the maximum stress. Figure 9 shows the same graph for an angle of 30° between the propagation direction of the longitudinal component of the earthquake record and the pipeline axis; however, in this case the stresses are much less than at an angle of 0° (see Table 2).

Figure 8. Comparison of stresses in a pipeline 400 m long under the action of a wave according to a real record of an earthquake, when the propagation direction coincides with the pipeline axis

Figure 9. Comparison of the maximum stresses in the cross-section of a pipeline 400 m long under the action of a wave according to a real record of an earthquake, when the propagation direction is at an angle of 30° to the pipeline axis

Figure 10 shows the graphs of stress changes along the length of the pipeline at time point 14 s at different angles of incidence of a three-component seismic wave. Figure 11 shows the same changes in time for the middle of the pipeline. The stress distribution pattern changes with the change in this angle.
Figure 10. Comparison of the maximum stresses in the cross-section of a pipeline 400 m long under different wave angles according to a real earthquake record

Figure 11. Comparison of the maximum stresses in the cross-section of the middle of a 400 m long pipeline under different wave angles according to a real earthquake record

4. Conclusions
The study showed that the choice of the amplitude and frequency values of a harmonic wave to be used in calculations of the real earthquake record is difficult and can often lead to gross errors. When calculating the impact according to real earthquake records, it is necessary to take into account the ground and other conditions, including the wave propagation velocity. The maximum stresses arise when the direction of seismic wave propagation coincides with the direction of the pipeline axis.

References
[1] Ishihara K 2006 Liquefaction of Subsurface Soils During Earthquakes J. Disaster Res. 1 245–61
[2] Khachiyan E E 2015 On the possibility of predicting seismogram and accelerogram of strong motions of the soil for an earthquake model considered as an instantaneous rupture of the Earth’s surface Seism. Instruments 51 129–40
[3] Rashidov T R and Mubarakov Y 1992 Seismodynamics of underground structures Soil Mech. Found. Eng.
[4] 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
[5] Rashidov T R and Bekmirzaev D A 2015 Seismodynamics of Pipelines Interacting with the Soil Soil Mech. Found. Eng. 52 149–54
[6] Bekmirzaev D A and Mirzaev I 2020 Dynamic processes in underground pipelines of complex orthogonal configuration at different incidence angles of seismic effect Int. J. Sci. Technol. Res. 9 2449–53
[7] Bekmirzaev D, Mansurova N, Nishonov N, Kosimov E and Numonov A 2020 Underground pipelines dynamics problem solution under longitudinal seismic loading IOP Conf. Ser. Mater. Sci. Eng. 883 012045
[8] Nishonov N, Bekmirzaev D, An E, Urazmukhamedova Z and Turajonov K 2020 Behaviour and
Calculation of Polymer Pipelines Under Real Earthquake Records *IOP Conf. Ser. Mater. Sci. Eng.* **869** 052076

[9] Stewart H, O’Rourke T, Ha D, Abdoun T, O’Rourke M and Van Laak P 2006 Split-containers for centrifuge modeling of permanent ground deformation effects on buried pipeline systems *Physical Modelling in Geotechnics* (Taylor & Francis)

[10] Fard S S, Nekooei M, Oskouei A V and Aziminejad A 2019 Experimental and numerical modeling of horizontally-bent buried pipelines crossing fault slip *Lat. Am. J. Solids Struct.* **16**

[11] Valeev A R, Yalalov D V 2017 Analysis of methods of seismic protection of main pipelines *Transport and storage of oil products and hydrocarbons* **3** 38-42

[12] Rashidov T R, Bekmirzaev D A 2015 Seismodynamic problems of complex underground pipelines *J. Seismic stability. Safety of structures* **3** 33–37.

[13] Bekmirzaev D, Mirzaev I, Mansurova N, Kosimov E and Juraev D P 2020 Numerical methods in the study of seismic dynamics of underground pipelines *IOP Conf. Ser. Mater. Sci. Eng.* **869** 052035

[14] Saberi M, Behnamfar F and Vafaeian M 2015 A Continuum Shell-beam Finite Element Modeling of Buried Pipes with 90-degree Elbow Subjected to Earthquake Excitations *Int. J. Eng.* **28**

[15] Saberi M, Arabzadeh H, Keshavarz A 2011 Numerical Analysis of Buried Pipelines with Right Angle Elbow under Wave Propagation *J. Procedia Engineering* **14** 3260-67

[16] Bekmirzaev D A, Kishanov R U and Mansurova N S 2020 Mathematical Simulation and Solution of the Problem of Seismo–Dynamics of Underground Pipelines *Int. J. Emerg. Trends Eng. Res.* **8** 5028–33

[17] Myachenkov V I 1970 The stability of cylindrical shells under axisymmetric transverse pressure *Sov. Appl. Mech.* **6** 19–23

[18] 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

[19] Rashidov T R, Khozhmetov G Kh 1985 *Seismic resistance of underground pipelines* (Tashkent: FAN) p 152

[20] George A, Liu J 1984 Numerical solution of large sparse systems of equations (M.: Mir) p 333

[21] Gazli earthquakes in 1976. 1982 *Engineering analysis of aftermath* (M.: Nauka) p 196