


Investigation of the Dynamic Behavior of Buried Natural Gas Pipe System

Kaşif Furkan Öztürk 

Gümüşhane University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Gümüşhane, Türkiye, kasiffurkan.ozturk@gumushane.edu.tr, ror.org/00r9t7n55

ARTICLE INFO

ABSTRACT

Keywords:

Equivalent spring-dashpot model

FEM

Frequency content of earthquake

Soil-pipe interaction

Article History:

Received: 30.01.2025

Revised: 01.07.2025

Accepted: 08.08.2025

Online Available: 28.08.2025

Natural gas pipelines are important infrastructure elements that are often designed to be buried and can cross very long distances, both on the mainland and on the ocean seabed. In this context, researches on the safety of these structures, which are known to cause significant economic losses if damaged, still maintains its importance. From this point of view, the dynamic behavior of a buried pipe system modeled using the equivalent spring-dashpot approach is investigated for three different soil systems and two earthquake records with three different frequency contents. The research shows that while the peak von mises stress of the pipe system can generally decrease depending on decrease in soil stiffness, the peak lateral displacements of the pipe system can generally increase depending on the decrease in soil stiffness. Furthermore, the results point out that the peak von mises stresses and the lateral displacements of the pipe system can significantly increase from high frequency content to low frequency content depending on the frequency content of earthquake.

1. Introduction

Natural gas pipelines are infrastructure systems that provide safe, economical and efficient transportation of natural gas from production sites to final consumption points. These pipelines are usually made of durable materials such as steel or high-density polyethylene (HDPE) and are designed to withstand high pressure. Their main function is to transport natural gas from production facilities to distribution networks, power plants, industrial facilities and residences. Natural gas pipelines can transport not only natural gas, which is its main component such as methane, but also various hydrocarbon gases such as ethane, propane and butane. In some cases, pipelines also have the capacity to transport other gases such as carbon dioxide or hydrogen, which are transported in gasified form. These systems play a critical role in meeting energy needs and are one of the basic elements of modern life. Considering the reasons stated and the prevalence of their usage areas, damage to these structures, especially in natural disasters

such as earthquakes, can cause significant economic losses and even loss of life. In this context, damage to such structures under earthquakes can occur depending on many mechanisms such as earthquake-triggered liquefaction, lateral spread, high peak ground acceleration, surface rupture, landslide [1].

The dynamic behavior of buried pipelines can be investigated using analytical and numerical methods [2]. Basically, the models developed in this context aim to analyze the dynamic behavior of the pipe or pipeline system under dynamic loadings [2–5]. On the other hands, when literature is investigating, it is seen that some researchers have focused on the effects of fault movement [6–9]. When investigating wave propagation effects, the modeling approaches using finite element or finite difference methods can be examined under two main headings [2].

The first of these is two dimensional (2D) models created by taking into account the plane deformation state, which is well known and

frequently used in numerical solutions. The second of these is the soil-pipe models, which are created by taking into account the plane stress condition and are often created from plane-spring-dashpot elements that can be considered numerically. These modeling approaches mentioned have significant advantages over three-dimensional (3D) modeling approaches in terms of practicality and time consuming but it is important to remember that 3D models may be necessary depending on the loading conditions, boundary conditions or/and the problem at hand [10]. Researchers point out that structures such as tunnels and pipelines with very long dimensions may develop significantly different behaviors than wave movements considered as uniform, depending on the spatially changing wave effects [11–13].

The effects of earthquake loadings on the dynamic behavior of aboveground structures and partially embedded some structures have been investigated by many researchers depending on earthquake characteristics such as frequency content ratio, near and far-fault effect. Kianoush and Ghaemmaghami [14] investigated the dynamic behaviors of varied concrete rectangular liquid tanks using different earthquakes classifying depending on frequency content ratios (Peak Ground Acceleration (PGA)/Peak Ground Velocity (PGV)). Cakir [15] showed changes that may occur in the dynamic responses of cantilever retaining wall under earthquake loadings with different frequency content ratios, taking into account different soil conditions.

Nguyen et al. [16] showed the effects of the earthquake frequency content on the dynamic responses of the nuclear reactor building for different subsoil conditions considering soil-structure interaction (SSI). Araz et al. [17] investigated changes in dynamic behaviors of ten and forty-story building with and without tuned mass damper under earthquakes with different frequency content ratios. Ozturk et al. [18] investigated the changes in the dynamic behavior of the wing wall system by considering the box culvert-wing wall-backfill-foundation soil interaction system under earthquake loadings with different frequency contents. Ozturk et al. [19] showed the changes of the dynamic responses of cantilever retaining walls with three

different configurations in four different foundation soil system under earthquakes with different frequency content ratios. On the other hand, when the literature is examined, it is understood that the investigations of these effects on buried structures are still significantly limited. It is also worth emphasizing here that in all of the above-mentioned studies, frequency content definitions of earthquake loadings have been discussed under three main group which defined as high ($PGA/PGV > 1.2$), intermediate ($1.2 \geq PGA/PGV \geq 0.8$), low ($0.8 > PGA/PGV$) depending on earthquake frequency content ratio. Also, the frequency content ratio expressed here have been defined as the ratio of PGA to PGV.

In light of the above-mentioned information, the dynamic behaviors of the natural gas pipe system have been investigated for three different soil conditions and two earthquakes. For this purpose, a steel pipe system has been considered and the soil-pipe interaction system has been developed by adopting two-dimensional modeling approach for plane stress analysis with the help of plane element and spring-damper elements. Soil systems have been subjected to 1D site analysis using earthquakes scaled to 0.5g at the bedrock level. Then, the acceleration and velocity contents of the earthquake records have been obtained from the 1D analyses at the pipe center level. These acceleration-time histories obtained in site analyses have been used in full transient parametric analyses performed for finite element model modeled using the spring-dashpot approach. Results of the dynamic analyses have been comparatively discussed in terms of displacement and peak von-mises stresses obtained on the pipe depending on different soil conditions and earthquake frequency contents.

2. Finite Element Model Proposed for Soil-Pipe Interaction System

The soil-pipe interaction system has been created considering the spring-dashpot system. For this purpose, has been utilized from ANSYS finite element package program [20]. While pipe system has been modelled using plane element (PLANE182), properties of springs and dashpots have been defined using COMBIN14 type element. While one end of the spring and dashpot

elements have been connected to pipe system, the other ends have been fixed.

API 5L grade X65 steel pipe within the scope of this study is used. Wall thickness and outer diameter (D) of pipe system is 0.0127 m and 0.9144 m, respectively. In addition, the nonlinear behavior of pipe in the dynamic analyses have been considered using bilinear isotropic hardening material model. Density, Young's modulus and Poisson's ratio of pipe system have been considered 7850 kg/m³, 210000 MPa and 0.3, respectively. Also, the bilinear isotropic hardening material model for nonlinear behavior of the steel pipe system has been taken into

consideration. This model is convenient to capture the nonlinear behavior of the pipe system [11, 21]. The yield stress of the pipe system for this material model has been considered as 448 MPa. Furthermore, pipe system has been located in a soil layer on the bedrock. Thickness of soil layer is 30 m and the distance from soil surface to center of pipe system is 1 m. It is also worth emphasizing here that the geometric properties and burial depth of the steel pipe considered in the study have been selected based on the literature [22–24]. The scenario of soil-pipe interaction system considered in parametric analyses have been schematically shown schematically in Figure 1.

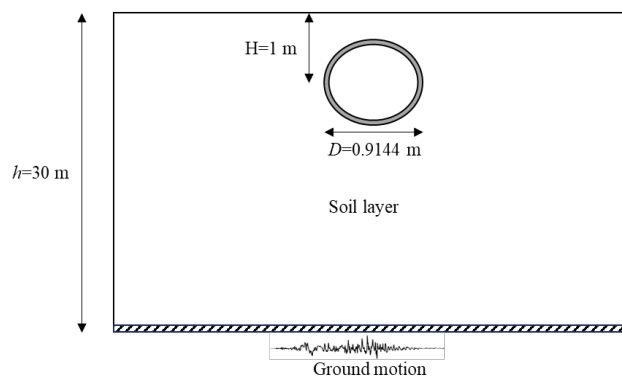


Figure 1. Soil-pipe interaction system

Properties of the spring, dashpot and pipe system have been tabulated in Table 1. The lateral stiffness and damping values have been defined as following [2, 3]:

$$K_s = \rho V_s^2 S_u l \quad (1)$$

$$C_s = C_v = \rho V_s S_{uv(vv)} R l \quad (2)$$

Where K_s , C_s and C_v terms define lateral stiffness, lateral and vertical damping values, respectively. In addition, ρ , V_s , S_{uv} , S_{vv} , R and l terms define density, shear wave velocity of soil, dimensionless lateral and vertical damping coefficients, outer radius and pipe length, respectively. In addition, the modulus of the subgrade reaction (Winkler spring stiffness) (K_v) for the vertical direction is considered as following [25]:

$$K_v = \frac{2\pi}{(1-\nu)} G \frac{D}{\lambda} \quad (3)$$

Where λ defines the idealized wavelength. This function can be found as following:

$$\lambda = TV_s = 4h \quad (4)$$

Where T and h define period and thickness of the soil layer, respectively.

Spring stiffness and damping expressions determined based on the equations defined above are defined in accordance with the relevant spring elements in the developed finite element model. For this purpose, the finite element model developed by taking into account the spring-dashpot approach is shown in Figure 2.

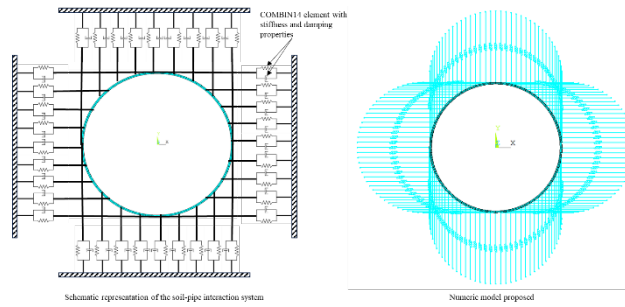


Figure 2. Finite element model developed using spring-dashpot elements for soil-pipe interaction system

3. Modal Analysis and Verification of the Proposed Model

The modal analyses of the proposed finite element model have been carried out using the Block Lanchoz approach. Fundamental mode frequencies in S1, S2 and S3 soil systems at x-direction (horizontal direction) have been obtained as 172.43, 121.93, 86.22 Hz, while the fundamental mode frequencies in same soil systems at y-direction (vertical direction) have been obtained as 26.62, 18.82 and 13.31 Hz. As can be seen, the decrease in soil stiffness can cause significant decreases in frequency values.

These fundamental mode frequencies have a significant effect on the dynamic behavior of the finite element model. In this context, the accuracy of the finite element model can be considered through the accuracy of these mode frequencies. To verify the model, the lumped mass approach can be used. For this aim, by using the lateral and vertical stiffness terms taken into account in the finite element model, the equivalent fundamental mode frequencies of the soil-pipe interaction system can be obtained. For such an approach, the stiffness of the pipe system in horizontal and vertical directions can be calculated with the following equation:

$$K_p = \frac{192EI}{H^3} \tag{5}$$

Where E, I and H define the young modulus of steel, the moment of inertia and l m, respectively. Then, considering that the pipe system is connected to the soil system from its center, equivalent stiffness expressions can be obtained as follows:

$$K_{eqs} = \frac{K_p K_s}{K_p + K_s}; K_{eqv} = \frac{K_p K_v}{K_p + K_v} \tag{6}$$

Where K_{eqs} and K_{eqv} define the equivalent stiffnesses in horizontal and vertical directions. The fundamental frequencies of the equivalent system can be found with the help of the following equations.

$$f_{eqs} = \frac{1}{2\pi} \sqrt{\frac{K_{eqs}}{m_p}}; f_{eqv} = \frac{1}{2\pi} \sqrt{\frac{K_{eqv}}{m_p}} \tag{7}$$

Where m_p , f_{eqs} and f_{eqv} define the mass of the pipe system, equivalent frequencies of soil-pipe interaction system for the horizontal and vertical directions, respectively. In this context, the equivalent frequencies obtained using this approach are 172.15, 121.80 and 86.15 Hz for the horizontal direction in the S1, S2 and S3 soil systems, while the same values for vertical direction are 26.60, 18.81 and 13.30 Hz. As can be easily understood, the fundamental mode frequencies obtained from the finite element model and the equivalent mode frequencies obtained by adopting the lumped mass approach overlap significantly. This indicates the accuracy of the proposed finite element model.

4. Dynamic Analysis of Equivalent Spring-Dashpot Model

The parametric analyses have been carried out in time domain for three different soil system. Properties of soil system considered in analyses have been tabulated in Table 2. In addition, two different earthquake record with different frequency content have been considered, as shown in Table 3. The records considered have been scaled to 0.5g at the bedrock level to take into account possible soil amplification effects and clearly to observe response changes. In addition, obtaining the dynamic responses of buried structures can be possible by obtaining the ground acceleration that varies depending on the earthquake wave propagating from the bedrock

at the pipeline level. For this purpose, DEEPSOIL program, which this program is 1-D site analysis program and can perform the equivalent-linear analysis in frequency domain, is used. The variations of accelerations obtained from the 1-D site analysis are shown in Figure 3. These acceleration-time histories of earthquakes have been obtained at 1m depth from surface. As can be seen from Table 3, the PGA/PGV characteristics of these earthquake records can vary significantly compared to original ground motion records considered at bedrock level. For

this reason, the earthquake records classified based on frequency content ratio at the bedrock level have been reclassified at 1 m level below the surface. In this context, it is understood that the frequency contents obtained in S1, S2 and S3 soil systems for Northridge loading are intermediate (I-1), high (H-2), high (H-3), respectively, while the frequency contents obtained in the same soil systems for Kocaeli earthquake are obtained as low (L-1), low (L-2) and low (L-3), respectively (Table 4).

Table 1. Pipe properties and dimensionless coefficients considered in the study

R (m)	t (m)	R/t (-)	H (m)	H/R (-)	S_u (-)	S_{uu} (-)	S_{vv} (-)
0.4572	0.0127	36.00	1.00	2.19	2.87	6.52	6.52

R: Outer diameter of pipe system, t: thickness of pipe wall, H: embedment depth (from soil surface to center of pipe system), S_u : dimensionless lateral stiffness coefficient, $S_{uu}=S_{vv}$: dimensionless lateral/vertical damping coefficient

Table 2. Soil properties considered in parametric analyses

Soil Type	E, kPa	ν	ρ , kN/m ³	V_s , m/s	PI	c_u , kPa
S1	300000	0.3	2000	240	20	450
S2	150000	0.3	1900	174	20	200
S3	75000	0.3	1800	127	20	100

E: Young’s modulus, ν : Poisson’s ratio of soil system, ρ : Density, V_s : Shear wave velocity, PI: Plasticity index, c_u : cohesion

Table 3. Properties of earthquakes considered in parametric analyses [26]

ID	RSN	Earthquake name	M_w	Component	V_{s30}	PGA (g)	PGV (m/s)	PGA/PGV (g/m/s)	R_{jb} (km)	Scale (-)
H	1051	Northridge	6.69	PUL104	2016.30	1.58	0.55	2.87	4.92	0.32
L	1161	Kocaeli	7.51	GBZ000	792.00	0.26	0.45	0.58	7.57	1.92

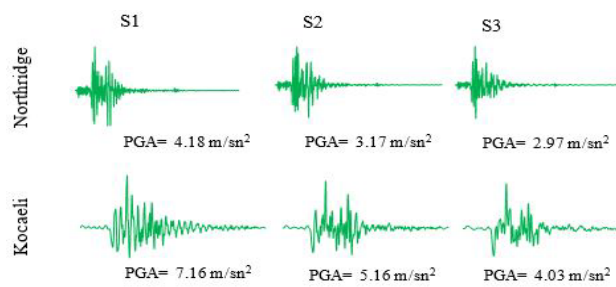


Figure 3. Acceleration-time histories of earthquakes considered at 1 m depth from surface

Table 4. Properties of earthquake obtained at 1 m depth from surface

Soil type	ID	Earthquake name	M_w	Component	PGA (m/sn ²)	PGV (m/s)	PGA/PGV (g/m/s)
S1	I-1	Northridge	6.69	PUL104	4.18	0.41	1.04
	L-1	Kocaeli	7.51	GBZ000	7.16	1.20	0.61
S2	H-2	Northridge	6.69	PUL104	3.17	0.26	1.24
	L-2	Kocaeli	7.51	GBZ000	5.16	1.00	0.53
S3	H-3	Northridge	6.69	PUL104	2.97	0.21	1.44
	L-3	Kocaeli	7.51	GBZ000	4.03	1.02	0.40

5. Result and Discussions

The dynamic peak displacement and von Mises stress values obtained from full-transient analyses are shown in Table 5. As can be seen

interaction and frequency content. Detailed discussions are carried out in the following subsections.

Table 5. Dynamic responses obtained from pipe system in soil systems considered under different earthquake loadings

Earthquake	Response	Soil types		
		S1	S2	S3
		Value	Value	Value
Northridge	$ U_t $ (m)	0.037	0.045	0.036
	Von_s (Pa)	619.920	387.230	390.600
Kocaeli	$ U_t $ (m)	0.882	0.905	0.988
	Von_s (Pa)	1093.900	707.210	530.800

$|U_t|$: Peak absolute displacement of pipe system, Von_s : Peak von-mises stress of pipe system

5.1. Soil-pipe interaction effect on dynamic behavior of pipe system

The dynamic behavior of the pipe system can change significantly depending on the soil-structure interaction. The analyses performed have shown that the dynamic peak responses obtained can be significantly increased due to soil-pipe interaction. As it is well known, von

Mises stresses are quite important when examining the behavior of steel structural systems in finite element models. In this context, von Mises stresses for the steel pipe system have been examined through selected nodes on the outer surface of the pipe system. Von Mises stress variations on outer surface of pipe system have been shown in Figure 4.

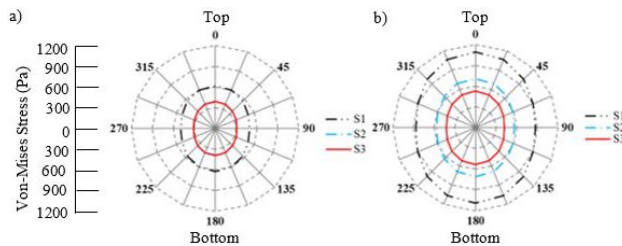


Figure 4. Von Mises stresses obtained from the pipe system for a) Northridge and b) Kocaeli earthquakes in different soil system

It is understood that dynamic von Mises stresses due to earthquake loading develop symmetrically on the outer surface to a significant extent within the framework of the modeling approach, boundary conditions and loading conditions considered. When Figure 4a is investigated, it is understood that under the loading conditions considered, the decrease in soil stiffness generally causes a decrease in von Mises stresses. An example of this situation can be investigated in Figure 4a. For example, under Northridge loading, while the peak von Mises

stress value in the S3 soil system is 390.60 Pa, the same response is obtained about 619.92 Pa, increasing 58.71% for the S1 soil system. It is also worth noting here that due to the complex interaction relationship between the pipe, soil and earthquake loading, no significant change is observed in the von Mises stress values in the S2 and S3 soil systems, as can be seen in Figure 4a.

On the other hand, the decrease in von Mises stresses due to the decrease in soil stiffness is significantly evident from the S1 soil system to

the S3 soil system under the Kocaeli earthquake loading and can be easily seen in Figure 4b. When Figure 4b is investigated, it is seen that while the peak stress response is 530 Pa for S3, the same response is obtained as 1093.9 Pa and 707.21 Pa in S1 and S2 soil systems, increasing by 105.92% and 33.23%, respectively.

It is also possible to examine the changes in dynamic responses using the peak displacements of the pipe system. When such an examination is made based on Table 5 and Figure 5, it is understood that the soil-structure interaction mechanism generally causes an increase in the peak displacement responses of the pipe system

depending on the decrease in soil stiffness. For example, when Figure 5 is examined, it is seen that while the peak dynamic displacement obtained from the pipe system under Northridge loading is 0.037 m, the same response is obtained in the S2 soil system with an increase of 21.62%, about 0.045 m. It is also possible to see similar changes under the Kocaeli earthquake (Table 5 and Figure 5). For example, when Figure 5 is examined, it is seen that while the peak dynamic displacement of the pipe system in the S1 soil system under the Kocaeli earthquake loading is 0.882 m, the same response is obtained as 0.905 m and 0.988 m in the S2 and S3 soil systems, increasing by 2.61% and 12.02%, respectively.

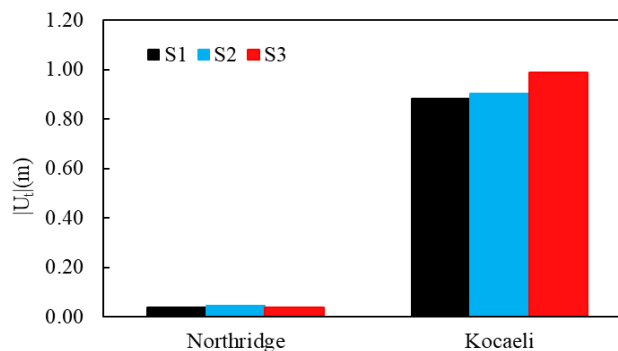


Figure 5. Variations of pipe displacement obtained in different soil system under earthquake loadings considered

5.2. Frequency content effect on dynamic behavior of pipe system

Another issue that may have a critical importance on the dynamic behavior of pipe systems is the earthquake frequency content. While evaluating this issue, it is important to consider that the earthquake waves radiating from the bedrock may have different frequency contents depending on the different soil systems at the central level of the pipe system. In this context, it is again important note that Northridge and Kocaeli earthquakes have been classified separately for each soil system depending on the frequency content ratio and dynamic responses have been investigated in this way (see Figure 6 and Figure 7).

Depending on the frequency content, the von Mises stresses taken from the outer wall of the pipe system can vary significantly. It is possible to say that the tendency of this change is an increase in the von Mises stresses from high frequency content to low frequency content. This

situation can be clearly seen for different soil systems in Figure 6. For example, when Figure 6a is examined, it is understood that while the peak von Mises stress for I-1 loading in the S1 soil system is 619.92 Pa, the same response is obtained as 1093.9 Pa with an increase of 76.45% under L-1 loading. In order to observe similar trends, Figure 6b and Figure 6c can be considered. For example, when Figure 6b is examined, it is seen that the peak von Mises stress obtained under H-2 loading in the S2 soil system is 387.23 Pa, while the same response increases by 82.63% under L-2 loading and reaches 707.21 Pa. When examined in Figure 6c, a similar increasing trend in the peak von Mises stress is observed under L-3 loading compared to H-3 loading in the S3 soil system and this change is obtained as 35.89%.

Figure 7 shows comparisons of peak pipe displacements obtained from loadings with different frequency content in different soil systems. In this context, as can be easily seen from Figure 7, the peak displacement of the pipe

system can increase significantly from high frequency to low frequency. For example, the peak displacement of pipe system under I-1 loading in S1 soil system 0.037 m, the same dynamic response of pipe system under L-1 loading is obtained as 0.882 m, increasing 2283.78%. When a similar increasing trend is evaluated for the S2 soil system, it is understood that the peak response obtained from L-2 loading increased by 1911.11% compared to H-2 loading. It is also worth emphasizing here that a similar increase trend is obtained as 2644.44% for the S3 soil system.

6. Conclusion

Pipe systems may be exposed to significant damages due to earthquakes. In this context, an equivalent spring-dashpot model within the scope of this study is proposed to investigate the effects of soil-structure interaction and earthquake frequency content on dynamic responses of pipe system. For this purpose, two different earthquakes and three different soil systems have been taken into account in parametric analyses. Results obtained are listed below.

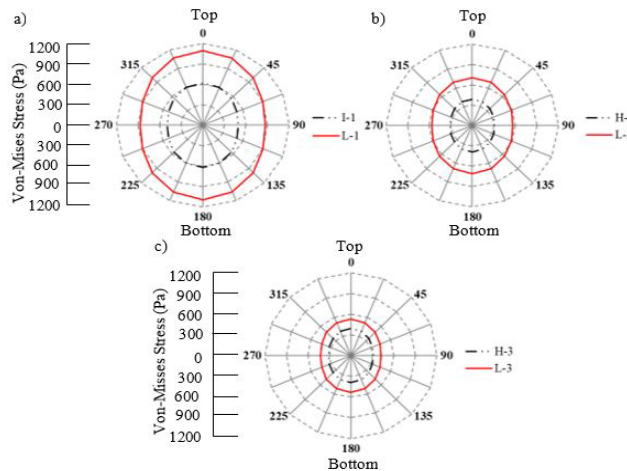


Figure 6. Von-mises stresses obtained from pipe system in a) S1, b) S2 and c) S3 soil system depending on variations of frequency content

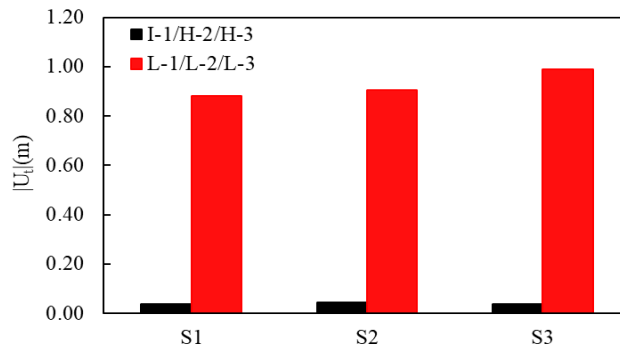


Figure 7. Pipe displacements obtained from pipe system in a) S1, b) S2 and c) S3 soil system depending on variations of frequency content

- Soil-structure interaction can be important role on the dynamic responses of pipe system depending on soil stiffness. The results of the parametric analyses performed indicate that the peak von Mises stresses obtained on the outer surface of the pipe generally decrease from S1 to S3 due to the decrease in the soil stiffness for the considered earthquake.
- Considering the boundary conditions and loading type, it is noteworthy that the von Mises

stress distributions have been obtained as symmetrical on the outer surface of pipe system.

- Soil-structure interaction can change the displacement of pipe system. The displacements of pipe system point out that the soil-structure interaction generally increases these responses of the pipe system from S1 to S3 due to decrease of soil stiffness under considered earthquakes.

- Earthquake frequency content can affect the peak von Mises stresses of the pipe system. The results obtained from the analyses show that the peak von Mises stress of pipe system can generally increase from high frequency content to low frequency content.
- Depending on the earthquake frequency content, the pipe displacement can change significantly. The results show that the dynamic displacements can significantly increase from high frequency content to low frequency content.

It is useful to remind here that the results obtained within the scope of the study and the change trends of the responses are valid for the adopted distance from the pipe center to the ground surface, wall thickness, pipe diameter, boundary conditions, material properties, material models and earthquake loadings. In order to generalize the trends, more parametric studies should be carried out by taking the mentioned effects into consideration.

Article Information Form

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

Artificial Intelligence Statement

No artificial intelligence tools were used while writing this article.

Copyright Statement

The author owns the copyright of their work published in the journal and their work is published under the CC BY-NC 4.0 license.

References

- [1] E. O. Unal, S. Kocaman, C. Gokceoglu, "Impact assessment of geohazards triggered by 6 February 2023 Kahramanmaraş Earthquakes (Mw 7.7 and Mw 7.6) on the natural gas pipelines," *Engineering Geology*, vol. 334, p. 107508, 2024.
- [2] T. K. Datta, *Seismic analysis of structures*. Chichester, UK: John Wiley & Sons, 2010.
- [3] A. Hindy, M. Novak, "Earthquake response of underground pipelines," *Earthquake Engineering & Structural Dynamics*, vol. 7, no. 5, pp. 451–476, 1979.
- [4] A. Hindy, M. Novak, "Pipeline Response to Random Ground Motion," *Journal of the Engineering Mechanics Division*, vol. 106, no. 2, pp. 339–360, 1980.
- [5] T. K. Datta, E. A. Mashaly, "Pipeline response to random ground motion by discrete model," *Earthquake Engineering & Structural Dynamics*, vol. 14, no. 4, pp. 559–572, 1986
- [6] X. Liu, H. Zhang, O. Ndubuaku, M. Xia, J. J. Roger Cheng, Y. Li, S. Adeeb, "Effects of stress–strain characteristics on local buckling of X80 pipe subjected to strike-slip fault movement," *Journal of Pressure Vessel Technology*, vol. 140, no. 4, 2018.
- [7] D. K. Karamitros, G. D. Bouckovalas, G. P. Kouretzis, V. Gkesouli, "An analytical method for strength verification of buried steel pipelines at normal fault crossings," *Soil Dynamics and Earthquake Engineering*, vol. 31, no. 11, pp. 1452–1464, 2011.
- [8] X. Liu, H. Zhang, K. Wu, M. Xia, Q. Zheng, Y. Li, O. Ndubuaku, S. Adeeb, "A refined analytical strain analysis method for offshore pipeline under strike-slip fault movement considering strain hardening effect of steel," *Ships and Offshore Structures*, vol. 15, no. 2, pp. 215–226, 2020.
- [9] L. Xu, X. Cheng, R. Huang, W. Chen, W. Hu, "Local buckling behavior of buried pipeline under seismic oblique-reverse fault displacement," *Scientific Reports*, vol. 12, no. 1, pp. 1–17, 2022.

- [10] K. F. Ozturk, "Investigation of the effects of mainshock-aftershock sequences on the dynamic responses of pipeline considering soil-pipeline interaction," *Tunnelling and Underground Space Technology*, vol. 155, no. P2, p. 106231, 2025.
- [11] H. Pan, H.-N. Li, C. Li, "Seismic behaviors of free-spanning submarine pipelines subjected to multi-support earthquake motions within offshore sites," *Ocean Engineering*, vol. 237, no. August, p. 109606, 2021.
- [12] I. Anastasopoulos, N. Gerolymos, V. Drosos, T. Georgarakos, R. Kourkoulis, G. Gazetas, "Behaviour of deep immersed tunnel under combined normal fault rupture deformation and subsequent seismic shaking," *Bulletin of Earthquake Engineering*, vol. 6, no. 2, pp. 213–239, 2008.
- [13] I. Anastasopoulos, N. Gerolymos, V. Drosos, R. Kourkoulis, T. Georgarakos, G. Gazetas, "Nonlinear response of deep immersed tunnel to strong seismic shaking," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 9, pp. 1067–1090, 2007.
- [14] M. R. Kianoush, A. R. Ghaemmaghani, "The effect of earthquake frequency content on the seismic behavior of concrete rectangular liquid tanks using the finite element method incorporating soil-structure interaction," *Engineering Structures*, vol. 33, no. 7, pp. 2186–2200, 2011.
- [15] T. Cakir, "Evaluation of the effect of earthquake frequency content on seismic behavior of cantilever retaining wall including soil-structure interaction," *Soil Dynamics and Earthquake Engineering*, vol. 45, pp. 96–111, 2013.
- [16] D. Van Nguyen, D. Kim, D. Duy Nguyen, "Nonlinear seismic soil-structure interaction analysis of nuclear reactor building considering the effect of earthquake frequency content," *Structures*, vol. 26, no. December 2019, pp. 901–914, 2020.
- [17] O. Araz, T. Cakir, K. F. Ozturk, "Effect of earthquake frequency content on seismic-induced vibration control of structures equipped with tuned mass damper," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 44, no. 12, p. 584, 2022.
- [18] K. F. Ozturk, T. Cakir, O. Araz, "A comparative study to determine seismic response of the box culvert wing wall under influence of soil-structure interaction considering different ground motions," *Soil Dynamics and Earthquake Engineering*, vol. 162, no. August, p. 107452, 2022.
- [19] K. F. Ozturk, T. Cakir, O. Araz, "Influences of wall configurations on earthquake behavior of cantilever retaining walls considering soil-structure interaction effects," *Journal of Earthquake and Tsunami*, vol. 17, no. 01, 2023.
- [20] ANSYS Inc, "ANSYS Mechanical APDL [Computer Software]," 2015, ANSYS Inc., Conansburg.
- [21] H. Pan, H-N. Li, C. Li, L. Tian, "Parametric study on seismic behaviors of a buried pipeline subjected to underground spatially correlated earthquake motions," *Journal of Earthquake Engineering*, vol. 26, no. 12, pp. 6329–6351, Sep. 2022.
- [22] H. Shakib, V. Jahangiri, "Intensity measures for the assessment of the seismic response of buried steel pipelines," *Bulletin of Earthquake Engineering*, vol. 14, no. 4, pp. 1265–1284, Apr. 2016.
- [23] V. Jahangiri, H. Shakib, "Seismic risk assessment of buried steel gas pipelines under seismic wave propagation based on fragility analysis," *Bulletin of Earthquake Engineering*, vol. 16, no. 3, pp. 1571–1605, Mar. 2018.

- [24] V. Jahangiri, H. Shakib, “Reliability-based seismic evaluation of buried pipelines subjected to earthquake-induced transient ground motions,” *Bulletin of Earthquake Engineering*, vol. 18, no. 8, pp. 3603–3627, Jun. 2020.

- [25] C. M. St John, T. F. Zahrah, “Aseismic design of underground structures,” *Tunnelling and Underground Space Technology incorporating Trenchless*, vol. 2, no. 2, pp. 165–197, 1987.

- [26] Pacific Earthquake Engineering Research (PEER) Center (2024). PEER ground motion database [Online]. Available: <https://ngawest2.berkeley.edu>