

SOIL-PIPE-INTERACTION PHENOMENA ON SLOPES UNDER ASYNCHRONOUS EARTHQUAKE EXCITATION

Athanasios A. MARKOU¹, Amir M. KAYNIA², Anastastios G. SEXTOS³, George D. MANOLIS⁴

ABSTRACT

The present work focuses on the response of pipelines traversing slopes under asynchronous acceleration time histories induced by earthquakes. To this end, nonlinear generalized mechanical models are developed and used in order to describe the soil-pipe interaction phenomena. More specifically, two basic types of models are used: the first one comprises two elastoplastic generalized spring elements connected in parallel with a trilinear elastic spring (labeled as sub-models 1 and 3), while the second model comprises three elastoplastic elements, all connected in parallel (labeled as sub-models 2 and 4). The purpose of the current study is twofold; (a) to introduce nonlinear mechanical models that enable a smooth transition between the elastic and plastic phases while, at the same time, control the damping in the soil-pipe interaction, and (b) to investigate the effect of the soil strength and soil damping on the axial force that develops in pipelines on slopes. Results are presented for the case of a real pipeline subjected to asynchronous accelerations along a submarine slope.

Keywords: soil-pipe interaction; mechanical models; offshore pipeline; nonlinear analysis; asynchronous motion.

1. INTRODUCTION

Water, gas and oil pipelines have become important parts of a lifeline system. In the offshore sector, for example, the recent decades have witnessed a marked development in submarine pipelines associated with the production and distribution of oil and gas as a major energy source for the economic development of numerous countries around the world. Earthquake is considered a major threat to this lifeline in certain regions. The performance of pipelines under earthquake excitations has been studied in the last three decades (ASCE 1984, ASCE 2001). The damage sustained by pipelines subjected to earthquake excitation were attributed to permanent ground deformation in the direction normal to the pipeline route, for example due to landslides, and high soil strains due to seismic wave propagation along the pipeline (O'Rourke and Liu 1999).

Papadopoulos et al. (2017) studied the damages to a natural gas pipeline due to seismic wave propagation. More specifically, the authors examined the effect of asynchronous excitation due to the basin effect on the response of an underground pipeline, and they concluded that the stress distribution along the pipeline is affected by the wave passage effect particularly in inhomogeneous soil media. Kaynia et al. (2014) investigated the response of pipelines on submarine slopes under asynchronous earthquake accelerations along the pipeline. Their study accounted for soil-pipe interaction (SPI) by

¹Postdoctoral Researcher, Norwegian Geotechnical Institute, Oslo, Norway, <u>athanasiosmarkou@gmail.com</u>

²Technical Expert, Vibrations and Earthquake Engineering, Norwegian Geotechnical Institute, Oslo, Norway, <u>amir.m.kaynia@ngi.no</u>

³Reader in Earthquake Engineering, Department of Civil Engineering, University of Bristol, Bristol, UK, <u>a.sextos@bristol.ac.uk</u>

⁴Professor, Department of Civil Engineering, Aristotle University, Thessaloniki, Greece, <u>gdm@civil.auth.gr</u>

means of soil springs, which traditionally are taken linear to the peak shear strength and strainsoftening post-peak strength. The current research aims at extending that study for the case of nonlinear soil-pipe interaction by introducing nonlinear mechanical models that are capable of capturing the smooth transition between elastic and plastic phases of nonlinear response (e.g. Markou and Kaynia 2018; Markou and Manolis 2016a; 2016b) and are able to control soil damping within acceptable limits as observed in cyclic soil tests. Finally, a model of a real offshore pipeline subjected to asynchronous accelerations along a submarine slope (Kaynia et al 2014) is employed to investigate the effect on the axial pipe force during soil-pipeline interaction as a function of soil strength and damping.

2. NUMERICAL SIMULATION OF SOIL-PIPE INTERACTION

In this section, a computational model is developed for the response of a continuous pipeline lying on or embedded in the ground while subjected to asynchronous ground motions along its length. The analysis does not account for the material carried by the pipeline, gravity loads or thermomechanical effects arising from the difference in temperature between the pipeline and the surrounding water. The pipeline itself is modelled as a generalized beam element.

2.1 Computational model for pipeline

An idealization of a pipeline of arbitrary geometry lying on the ground and supported by lateral and axial springs representing the SPI is shown in Figure 1 (Smith and Kaynia 2015). The pipeline is excited under asynchronous earthquake motions in two directions on the X-Z plane. The actual geometry of the pipeline for a real offshore pipeline is shown in Figure 2, along with the nodes used to define its structure. Figure 3 shows an example of the asynchronous ground acceleration time histories used in the present study at nodes 19 and 49 (see Figure 2). The horizontal and vertical motions along the entire set of pipeline nodes were computed from a 2D FE dynamic nonlinear analysis of the soil accounting for soil stratification and surface topography (Kaynia et al., 2014). It should be noted that self-weight of the pipe is applied statically before any earthquake excitation, to take into consideration initial soil conditions. The SPI phenomena are described by means of generalized nonlinear mechanical models, which are discussed in the following section.



Figure 1. Soil-pipe interaction model under asynchronous earthquake excitation



Figure 2. Longitudinal pipeline profile in X-Z plane.



Figure 3. Horizontal acceleration histories at nodes (a) 19 and (b) 49.

2.2 Nonlinear mechanical modeling of SPI

In 2017, Stubbs studied the SPI behavior of buried pipelines in shallow depths by implementing laboratory experiments, see Figure 4 (Stubbs 2017, Crewe, 2018). As it is shown in Figure 5, the SPI curves show a smooth transition from linear phase to the plastic one. Usually in most applications this nonlinear transition is simulated by a linear function. However, in the present study, the form of the

SPI curve is preserved. To this end, two different nonlinear mechanical models are developed and used to account for SPI. The first generalized model, labeled as sub-models 1 and 3, is presented in Figure 6. It consists of three elements connected in parallel, namely two elastoplastic elements (elements 1 and 2) and a trilinear elastic spring (element 3). The second generalized model, denoted as sub-models 2 and 4, comprises three elastoplastic elements connected in parallel, see Figure 7. Both models are able to describe the smooth transition from the linear to plastic phase observed in the aforementioned model tests. Additionally, model 2 is able to control the damping in the soil springs to acceptable limits around 30% for large displacement amplitudes (e.g. Vucetic and Dobry 1991), while model 1 provides a larger damping ratio, of the order of 60% for large displacement amplitudes. It should be noted that the lateral soil springs in Figure 1 are assumed to obey a linear elastic constitutive law.



Figure 4: Photographs of experimental setup, (a) during filling of a preliminary loose experiment (b) the load transfer mechanism with load cell (photos taken by R. C. Stubbs, used with permission).



Figure 5. Force-horizontal displacement curve for loose sand at different depths, where D denotes the diameter of the pipe (Stubbs 2017).



Figure 6. Generalized mechanical models labeled 1 and 3 to account for SPI: (a) mechanical formulation with the force-displacement loops for (b) sub-element 1, (c) sub-element 2 and (d) sub-element 3.



Figure 7. Generalized mechanical models labeled 2 and 4 to account for SPI: (a) mechanical formulation with the force-displacement loops for (b) sub-element 1, (c) sub-element 2 and (d) sub-element 3.

The material parameters of the axial soil springs of sub-models 1 and 3 considered in the present study are given in Table 1. It should be noted that these parameters are presented in values (force and stiffness) per length and that sub-models 2 and 4 dissipate two times the amount of energy compared to sub-models 1 and 3, respectively. In Table 2 the material parameters of the pipeline are summarized.

The force per length against displacement amplitudes for sub-models 1-4 are presented in Figure 8. As it was mentioned previously, the different energy dissipation ability of the models is clearly demonstrated, while the same loading path is provided in all cases. Furthermore, the difference between sub-models 1 and 3, shown in Figures 8(a) and (c), and sub-models 2 and 4, shown in Figures 8(b) and (d), is the reduction of the order of 50% of the damping ratio. The difference between sub-models 3 and 4 and sub-models 1 and 2 is in their shear strength. More specifically, the shear strength in sub-models 3 and 4 are half of those in sub-models 1 and 2.

Sub-model 1		Sub-model 3	
Q ₁ (kN/m)	0.52	Q1(kN/m)	0.28
Q ₂ (kN/m)	1.03	Q ₂ (kN/m)	0.56
$Q_{1s}(kN/m)$	1.55	Q _{1s} (kN/m)	0.84
$k_{01}(kN/m^2)$	199.80	$k_{01}(kN/m^2)$	199.80
$k_{02}(kN/m^2)$	199.80	$k_{02}(kN/m^2)$	199.80
$k_{01s}(kN/m^2)$	166.50	$k_{01s}(kN/m^2)$	89.91

Table 1. Material parameters per unit length of the four models.

Table 2. Material parameters of the pipeline.

EI (kNm ²)	EA (kN)	m (tn/m)
$2.51 \ 10^4$	$4.15 \ 10^6$	0.217



Figure 8. Force per length-displacement loops of (a) sub-model 1, (b) sub-model 2, (c) sub-model 3 and (d) submodel 4 for SPI.

In reference to the above, the differential equation of motion of the model can be described as follows (Equation 1):

$$[M]\{\ddot{U}(t)\} + [F(t)] = -[M]\{\ddot{U}_{g}\}$$
(1)

where [M] is the mass matrix, $\{\ddot{U}(t)\}\$ is the acceleration array, $\{\ddot{U}_g\}\$ is the vector of the earthquakeinduced acceleration array and [F(t)] can be defined as follows (Equation 2):

$$[F(t)] = [K] \{ U(t) \} + \{ F_N(t) \}$$
(2)

where [K] is the stiffness matrix of the system, $\{U(t)\}\$ is the displacement array and $\{F_N(t)\}\$ is the array of the nonlinear forces. The above system was solved by using the Newmark constant acceleration method (e.g. Chopra 2012).

3. NUMERICAL RESULTS

3.1 Maximum axial forces simulated by different SPI models

In this section, the results of maximum axial forces over the length of the pipeline are presented for the four models. The envelope of the maximum axial force is presented for the case of tension, as well for compression, along with the pipeline profile. More specifically, Figure 9(a) presents the axial forces using sub-models 1 and 2. As expected, the largest forces occur at areas of largest changes in the topography such as the escarpment (node 19 in Figure 2). The plots in Figure 9 show identical forces indicating that for the case considered here, and possibly for similar cases, hysteretic damping in the SPI springs has negligible effect on the pipe forces. This observation could imply that the response of the pipeline on the slope is not dominated by the pipe dynamics. Figure 10 plots the axial forces using sub-model 3, while Figure 11 displays the axial force for sub-model 4.



Figure 9. (a) Maximum axial force along the pipeline using models 1 and 2 and (b) longitudinal pipeline profile



Figure 10. Maximum axial force along the pipeline using model 3.



Figure 11. Maximum axial force along the pipeline using model 4.

In all cases, the maximum values of the axial forces in terms of both tension and compression occurs at the edge of the escarpment. In all numerical modeling scenarios, the tension force is larger than the compression force apart from model 4, where the opposite is true.

3.2 Comparison of results for different SPI models

In this subsection, a comparison between the four models in terms of axial forces is presented. More specifically, the results in Figure 12 display that the maximum tension and compression is provided by the models with the highest strength (sub-models 1 and 2). On the other hand, the lowest value of the maximum tension and compression is provided by the model with increased damping ratio and reduced strength. The results show that the maximum earthquake-induced forces are reduced as the shear strength of the soil is reduced. This behavior is expected as reduced soil strength can be viewed as providing a kind of base isolation for the pipeline against earthquake motions along the slope.

Finally, in Figure 13 the reference acceleration records are increased over 30% and the results are compared for the case of sub-model 1. Despite the fact that the increase of the acceleration records is of the order of 30%, the increase of the maximum tension and compression forces is not more than 20%. The results show that the relation between acceleration and axial force is not linearly proportional, due to the nonlinear nature of the problem.



Figure 12. (a) Maximum axial force along the pipeline using models 1, 3, 4 and (b) longitudinal pipeline profile.



Figure 13. (a) Maximum axial force along the pipeline using model 1 under reference and increased over 30% acceleration (b) longitudinal pipeline profile.

4. CONCLUSIONS

A sensitivity analysis on the effect of the soil damping ratio and stiffness of the combined soil-pipeline mechanical system on the maximum axial force that develops in a submarine pipeline under seismically-induced ground motions is presented in here. To this end, two nonlinear generalized models are introduced in order to provide smooth transition between the elastic and plastic phases of response and in order to control the energy dissipation over a cycle of loading. The results indicated that reduction in the soil stiffness and damping ratio of the order of 50% produced a significant variation in the maximum axial force developed under asynchronous earthquake excitation. Both tension and compression forces play a significant role in the design of the pipelines. To this end, the parameters of the SPI system, namely soil strength and damping ratio, should be chosen carefully in order to produce a successful design in terms of safety and performance.

5. ACKNOWLEDGMENTS

This work was supported by the Horizon 2020 MSCA-RISE-2015 project No. 691213 entitled "Experimental Computational Hybrid Assessment of Natural Gas Pipelines Exposed to Seismic Risk (EXCHANGE-RISK)". This support is gratefully acknowledged.

6. REFERENCES

ASCE (1984). Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, Committee on Gas and Liquid Fuel Lifelines, American Society of Civil Engineers Publication, Reston Virginia.

ASCE (2001). Guidelines for the Design of Buried Steel Pipe, American Lifelines Alliance, American Society of Civil Engineers Publication, Reston Virginia.

Chopra AK (2012). Dynamics of Structures, Theory and Applications to Earthquake Engineering, 4th edition, Prentice Hall, Boston.

Crewe, A., Sextos, A., Stubbs, R., Mylonakis, G. (2018). Experimental Identification of Stiffness and Ultimate Resistance Of Buried Soil-Pipe Systems, *16th European Conference in Earthquake Engineering*, Thessaloniki 18-21 June, paper no. 2177.

Kaynia AM, Dimmock P, Senders M (2014). Earthquake Response of Pipelines on Submarine Slopes. *Offshore Technology Conference 2014*, OTC-25186-MS, 5-8 May, Houston USA.

Markou AA, Kaynia AM (2018). Nonlinear soil-pile interaction for wind turbines, *Wind Energy*, accepted for publication.

Markou AA, Manolis GD (2016a). Mechanical models for shear behavior in high damping rubber bearings. *Soil Dynamics Earthquake Enginering*, 90: 221-226.

Markou AA, Manolis GD (2016b). Mechanical formulations for bilinear and trilinear hysteretic models used in base isolators, *Bulletin of Earthquake Engineering*, 14(12): 3591-3611.

O'Rourke MJ, Liu X (1999). Response of Buried Pipelines Subject to Earthquake Effects, Monograph, National Center for Earthquake Engineering Publication, University at Buffalo, The State University of New York.

Papadopulos S, Sextos A, Kwon O, Gerasimidis S, Deodatis G (2017). Impact of spatial variability of earthquake ground motion on seismic demand to natural gas transmission pipelines. *Proceedings of the 16th World Conference on Earthquake Engineering*. 9-13 January, Santiago, Chile.

Smith V, Kaynia AM (2015). Pipe-soil interaction under rapid axial loading. *Frontiers in Offshore Geotechnics III*. ISBN: 978-1-138-02848-7.

Stubbs R (2017). Stiffness and ultimate resistance of buried soil-pipe system. Report, University of Bristol, UK.

Vucetic M, Dobry R (1991). Effect of soil plasticity on cyclic response. ASCE Journal of Geotechnical Engineering, 117: 89-107.