16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

DETERMINATION AND DEVELOPMENT OF FRAGILITY CURVES FOR BURIED PIPELINES REGARDING PIPE-SOIL INTERACTION EFFECTS

Mahsa SHAMSAEI[1]*, Mohammad Iman KHODAKARAMI[2], Mohammad Reza MANSHOORI[3]

ABSTRACT

Buried pipelines are known as lifelines in today's societies. These types of structures have complex behavior during earthquakes; therefore, the design criteria and seismic considerations in order to have a safe pipeline which have acceptable performance respect to seismic excitations is very important. In this paper, the fragility curves of buried pipelines under the low-frequency in-plane seismic waves are determined considering the effects of soil-steel pipe interaction, and soil conditions. The simulation of soil-pipe systems is conducted using two-dimensional direct approach by finite element method. Results show that the probability of failure of buried pipelines due to maximum longitudinal strain increases in soft soils and the failure will happen at the lower earthquake acceleration.

Keywords: Lifeline; Pipeline; Fragility Curve; Interaction Soil-Pipe; Wave Propagation

1. INTRODUCTION

The reports of the past earthquakes such as 1995 Kobe, 1999 Chi Chi, 1999 Dozese and 2004 Niigata earthquakes show that underground structures experienced extensive damage during seismic vibrations (Eidinger 2001 and Ferritto 1997). Also, it is mentioned that the damages in buried pipelines due to seismic surface waves are more extensive rather than seismic body waves (Ayala and O'Rourke 1989). (see Figure 1).

In general, seismic hazards related to buried pipelines can be divided into two general categories as (i) wave propagation which is known as dynamic effects and (ii) permanent ground displacement which is known as static effects (Liu and O'Rourke 1997 and O'Rourke and Liu 2011); which is explained for continuously buried pipelines where corrosion has not occurred, the major failure modes are axial stretching, local buckling due to axial pressure and flexural failure.

The seismic performance gas pipeline systems during the past earthquakes, seismic hazards (Golara 2014) and their quantitative assessment (Golara and Esmaeily 2017), the design criteria of pipelines, maintenance considerations is presented in Veletsos (1984) and Ferritto (1997). Audibert and Nyman (1977) presented an analytical method for determining the load-displacement curve for buried pipes with different parameters. The effect of soil-pipe-interaction subject to lateral displacement of the earth is investigated by Trautmann and O'Rourke (1985). Investigation of the effects pipe diameter on the seismic behavior of pipelines are studied in O'Rourke and Ayala (1993). Evolution over the past

[1] M.sc student of earthquake engineering, Faculty of civil engineering, Semnan university, Semnan, Iran, M.Shamsaei@semnan.ac.ir
[2] Assistant Professor of earthquake engineering, Faculty of civil engineering, Semnan university, Semnan, Iran, Khodakarami@semnan.ac.ir
[3] M.sc earthquake engineering, Deputy of Technical and Administrative System and Project Assessment, Tehran, Iran, R.Manshoori@gmail.com

three decades of seismic damage estimation for buried pipelines and identifies some challenges for future research studies on the subject (Pineda-Porras and Najafi 2010), Theoretically, pipe orientation plays a very important role in pipe- line damage caused by seismic wave propagation. For instance, if a straight pipeline is oriented in the same direction as the propa- gation direction of a group of Rayleigh waves, the damage is maximum. But if the same straight pipeline is perpendicular to the propagation direction of the same group of Rayleigh waves, the damage is zero. Evaluation issues concerning the seismic risk assessment of underground structures under transient ground deformations (Paolucci and Pitilakis 2007) presents the capabilities of Build-X, a recently developed knowledge-based system tailored to the prediction of the seismic response of 3D buildings.

(a) (b)

Figure 1. Failure of pipelines in Mexico City earthquake (1985): (a) fracture steel pipe and (b) concrete pipeline connection Failure (Berrones and Liu 2003)

The fragility curve is one of the most effective methods in order to assessing seismic performance of the structures, in which, we investigate the probability of failure of the structure due to earthquake instead of examining the seismic behavior of a structure. It means, in order to quantitatively explain the vulnerability of different structural components in terms of the magnitude of the earthquake risk, probability of occurrence or exceeded a certain amount of damage in terms of a quake-specific feature such as PGA, PGV and PGD. Many researches obtained the fragility curves for structural frames such as Frankie, Gencturk et al. (2012), Abo-El-Ezz, Nollet et al. (2013) and Shinozuka, Feng et al. (2000), but there is no evidence for developing the fragility curves for buried pipelines.

It is mentioned that damage due to seismic wave propagation are occurred in the wider length of pipelines and the assessment of the intensity of damages it is required to evaluated using fragility curves.

In this paper, the fragility curves of buried steel pipelines are developed based on the maximum acceptable longitudinal strain under low-frequency excitations. To this end, a buried steel pipeline is simulated in three soil types using OpenSEES software and is subjected to four earthquake ground motions and then incremental dynamic analysis (IDA) is employed in order to analyzing the models regarding earthquakes.

2. PROBLEM STATEMENT

The schematic simulation of the problems which are studied in this paper is shown in Figure 2. A series of 2D soil-pipe systems with a 200*100 m soil block are modeled using finite element software OpenSEES. The effect of soil type on the behavior of buried pipelines of earthquake excitations has been investigated.

As the pipeline is known as low-frequency structures, in this study 4 different earthquake records with low frequency content are used in order to evaluate the seismic behavior of soil-pipe system in the critical situation due to resonance conditions, and the PGA of these earthquakes has been scaled from 0.1g to 1.5g and the horizontal earthquake excitation are imposed to the bedrock and the fragility curves is developed accordingly. The details of these selected ground motions are presented in Table 1 and the related response spectrum are plotted in Figure 3.

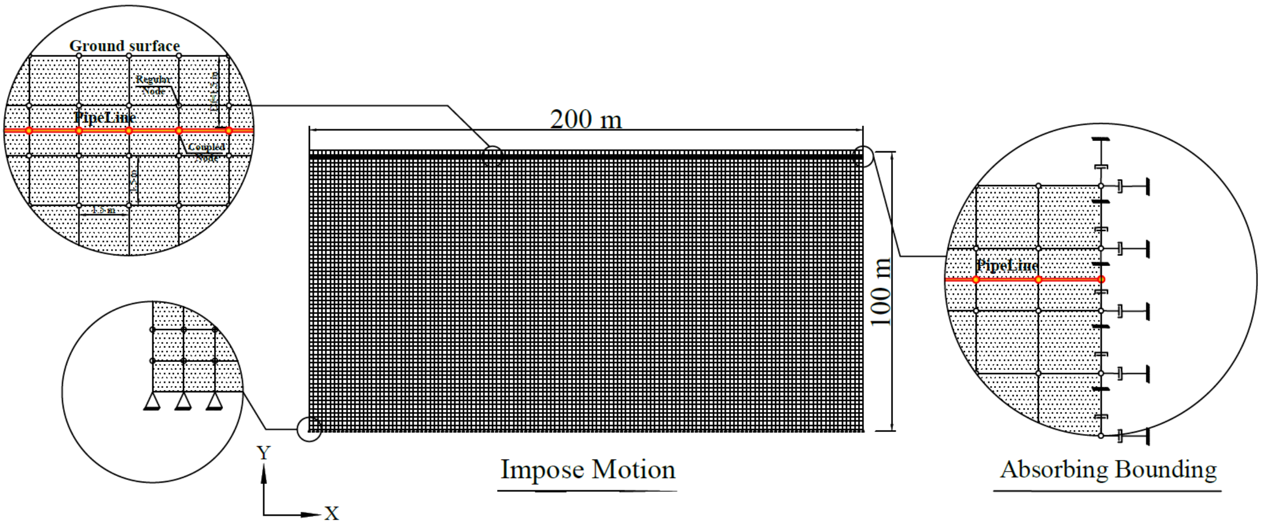

Figure 2. Geometry of the model, boundary conditions, mesh dimension and model dimension

Table 1. Details of the selected low-frequency ground motions.

Code	**Name**	**PGA (g)**	**Station**	**Effective Duration**	**Predominant Period (s)**	$\frac{\mathbf{PGA}}{\mathbf{PGV}}$ **(s)**
R1	Lomaperieta	0.433	Los gatos-lexington dam	4.09	1.02	0.5
R2	Imperial Valley	0.439	Elcentro Array #6	8.48	0.24	0.4
R3	Tabas	0.852	Tabas	16.12	0.2	0.7
R4	Kobe	0.616	Takatori	9.93	0.18	0.5

The material and geometrical properties of the grade X42 steel pipe is selected according to Dash and Jain (2007) and are presented in Tables 2. Also the mechanical properties of the three soil types which are implemented in this study are presented in Table 3.

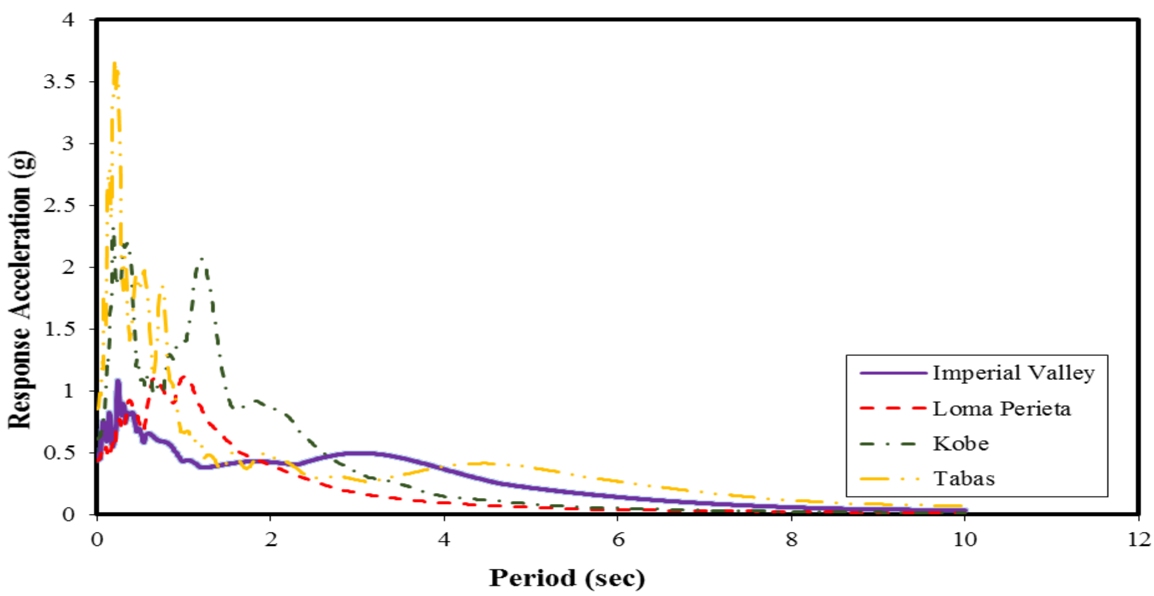

Figure 3. Response spectrum of the selected earthquakes

Table 2. Mechanical and geometrical properties of the pipe.

Normal pipe Size (inches)	Normal pipe Size (mm)	Outside Diameter (mm)	Grade	Yield strength (kPa)	Wall thickness (mm)	kg/m
8	200	219.1	X42	290000	12.7	64.64

Table 3. Properties of soil types.

Soil Type	ρ (kN/m^3)	Shear modulus (kpa)	Poisson ratio	Void ratio	Friction Angle	Vs (m/s)
S2	1.7	595472	0.33	0.55	37	600
S3	1.5	211022	0.33	0.7	33	375
S4	1.3	37130	0.33	0.85	29	170

3. NUMERICAL MODELING

The soil block with 200 *m* length and 100 *m* depth is modeled in OpenSees software. In this simulation, the PressureDependMultiYeild material has been used for soil. Other parameters required for soil modeling have been extracted from the soil mechanics specifications. The geometry of the soil is simulated using 1.5×1.5 *m* four-nodes quadratic element; the size of the elements are used based on the concept of shear wave propagation at a certain frequency, with the assurance of the existence of a number of suitable elements in a wave length (λ), on the other hand, the size of the geometry of the elements should be less than $\frac{\lambda}{8}$ and also in order to stability of the solution, Courant's condition should be satisfied.

The absorbing boundaries must be modeled so that earthquake waves do not reflect from the boundaries. For this purpose, viscous damper along x and y direction is used to model the absorbing boundaries (Wolf and Motosaka 1989);

$$C_x = a\rho V_s \tag{1}$$

$$C_y = a\rho V_p \tag{2}$$

Where, ρ is the soil density and V_s and V_p are shear and longitudinal wave velocity in the soil, respectively, and a is a constant coefficient.

The material properties of the steel pipe line are simulated using Steel02 material in OpenSEES which can satisfy the nonlinear behavior of pipe and the pipeline are modeled using two-nodes nonlinearBeamColumn element and the pipeline element size are compatible by the soil element size. The pipe and soil nodes are tied and there is an interaction force and hardness between them.

4. FRAGILITY CURVE

A fragility curve is a conditional math relation for an element or system that represents the passage from a pre-defined damage state which is evaluated based on seismic hazard parameters such as seismic intensity and structural responses; in which, the fragility curves varies depend of seismic region and construction conditions.

In most of these functions, the specified failure in the structure is expressed as a probability of passing through a specified failure level. The general form of these functions can express as (Colangelo 2008),

$$P_{ij} = P\left(D \geq C_i \middle| C = g_j\right) \tag{3}$$

where, Pij is the probability of occurrence of a given failure state (ds), D is seismic demand, Ci is capacity of the member, gj is the seismic intensity scale that is also shown with IM; herein, the failure state of pipeline is selected equal to the allowable strain criteria (ds=0.03) according to (Veletsos 1984).

5. RESULTS AND DISCUSSION

A series of 240 models are simulated according the modeling technique which is explained above are analyzed by imposing 80 earthquakes and results of incremental dynamic analysis (IDA) are prepared considering maximum axial strain (see Figure 4).

This figure shows the maximum axial strain of pipe in all condition exceeded from the allowable criteria when the PGA of the imposed excitation at the bedrock is greater 0.2~0.5g. In this figure, the gradient of maximum strain respect to PGA in the soft soil (S4) is faster than the similar conditions in soil type S2 and S3; it means that as the soft soil has longer vibration time period and the pipe is low frequency as well as the imposed earth, so extensive damages are shown for the soil that are located in the softer soils.

Figure 5 shows the fragility curves of buried pipelines in the various soil types which are subjected to the earthquake with low frequency content; from this figure it is clear that the probability of failure of the pipelines which are located in softer soils are greater than the similar pipelines which are placed in stiffer soils.

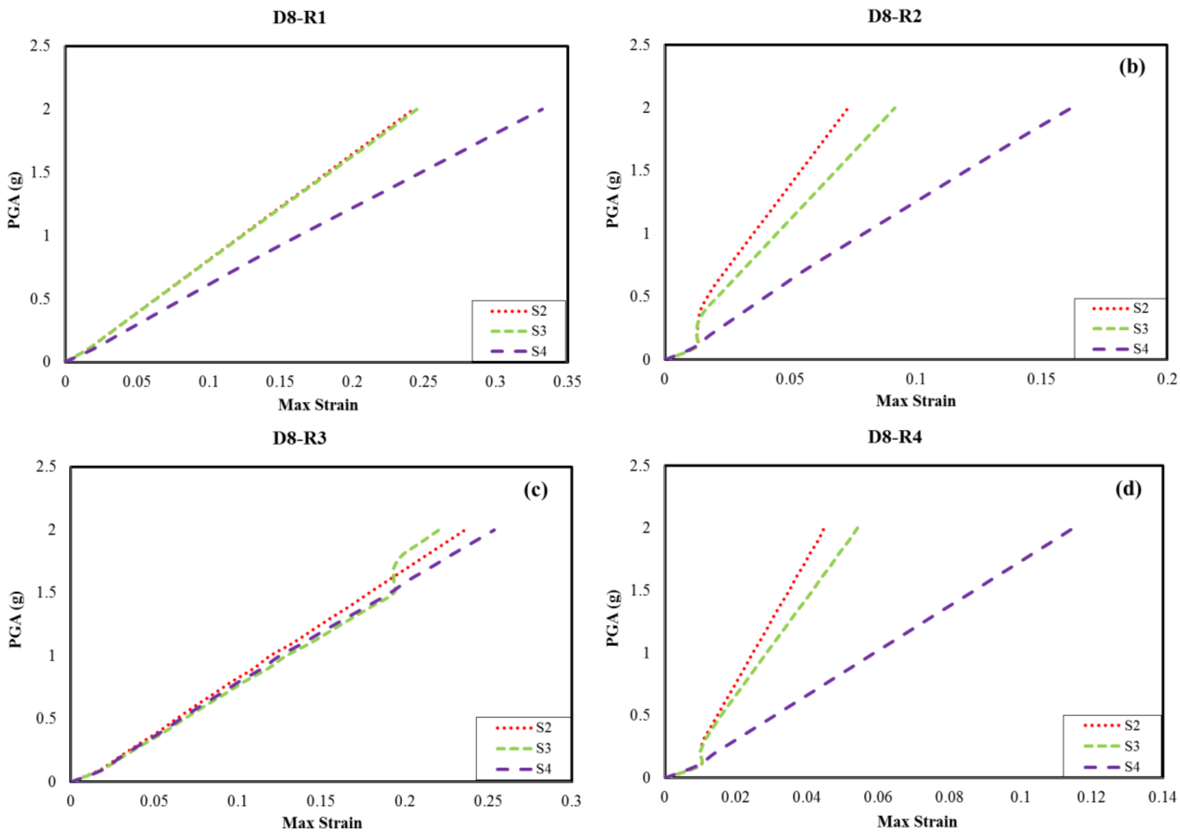

Figure 4. Results of IDA analysis due to each earthquake excitation; (a) Lomaperieta earthquake (R1), (b) Imperial Valley earthquake (R2), (c) Tabas earthquake (R3), (d) Kobe earthquake (R4)

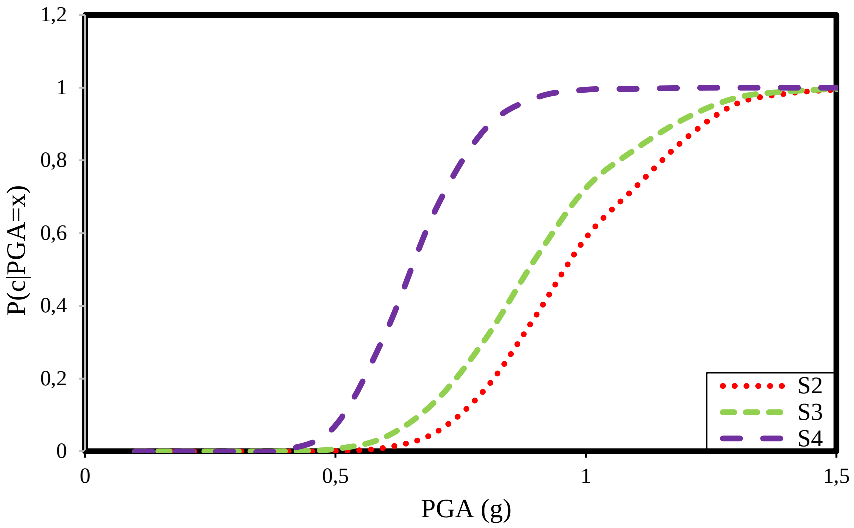

Figure 5. Fragility Curve of buried pipeline

6. CONCLUSION

In this paper, the two-dimensional soil-pipe-systems are studied using direct approach simulation by OpenSEES software under four low-frequency earthquake excitations. The diameter of the considered pipeline is 8 inches and three soil types are considered. IDA is conducted and fragility curves are obtained; the results show that the maximum axial strain of the pipeline in soft soil occurs at a smaller PGA of the imposed earthquake at the bedrock. On the other hand, the maximum axial strain in the pipeline exceeded the allowable strain criteria at the smaller PGA when the surrounding soil is soft.

7. ACKNOWLEDGMENTS

The authors of this paper would like to acknowledge of the National Iranian Gas Company (NIGC) because of providing financial support of this project.

8. REFERENCES

Abo-El-Ezz, A., M.-J. Nollet and M. Nastev (2013). Seismic fragility assessment of low-rise stone masonry buildings. *Earthquake Engineering and Engineering Vibration*, 12(1): 87-97.

Audibert, J. M. and K. J. Nyman (1977). Soil restraint against horizontal motion of pipes. *Journal of the Geotechnical Engineering Division*, 103(10): 1119-1142.

Ayala, A. G. and M. J. O'Rourke (1989). Effects of the 1985 Michoacan earthquake on water systems and other buried lifelines in Mexico, *National Center for earthquake engineering research.*

Berrones, R. F. and X. L. Liu (2003). Seismic vulnerability of buried pipelines. *Geofisica Internacional*, 42(2): 237-246.

Colangelo, F. (2008). On the computation of seismic fragility curves. *The 14th World Conference on Earthquake Engineering*, Beijing, China.

Dash, S. and S. Jain (2007). IITK-GSDMA Guidelines for seismic design of buried pipelines: provisions with commentary and explanatory examples. *National Information Center of Earthquake Engineering*, Kanpur, India.

Eidinger, J. (2001). Seismic fragility formulations for water systems. *sponsored by the American Lifelines Alliance, G&E Engineering Systems Inc*., web site.< http://homepage. mac. com/eidinger.

Ferritto, J. M. (1997). Seismic design criteria for lifelines, *Naval facilities engineering service center port* *hueneme ca.*

Frankie, T. M., B. Gencturk and A. S. Elnashai (2012). Simulation-based fragility relationships for unreinforced masonry buildings. *Journal of Structural Engineering,* 139(3): 400-410.

Golara A, Esmaeily A (2017). Quantification and Enhancement of the Resilience of Infrastructure Networks. *Journal of Pipeline Systems Engineering and Practice*, *8*(1). DOI: 10.1061/(ASCE)PS.1949-1204.0000250

Golara A (2014). Probabilistic seismic hazard analysis of interconnected infrastructure: a case of Iranian high-pressure gas supply system. *Natural hazards*, 73(2), 567-577

Liu, X. and M. J. O'Rourke (1997). Behaviour of continuous pipeline subject to transverse PGD. *Earthquake engineering & structural dynamics,* 26(10): 989-1003.

O'Rourke, M. and G. Ayala (1993). Pipeline damage due to wave propagation. *Journal of Geotechnical Engineering,* 119(9): 1490-1498.

O'Rourke, M. and X. Liu (2011). Seismic Design of Buried and Offshore Pipelines, MCEER Monograph No. X, University at Buffalo, NY.

Paolucci, R. and K. Pitilakis (2007). Seismic risk assessment of underground structures under transient ground deformations. *Earthquake Geotechnical Engineering,* Springer: 433-459.

Pineda-Porras, O. and M. Najafi (2010). Seismic damage estimation for buried pipelines: challenges after three decades of progress. *Journal of Pipeline Systems Engineering and Practice,* 1(1): 19-24.

Shinozuka, M., M. Q. Feng, J. Lee and T. Naganuma (2000). Statistical analysis of fragility curves. *Journal of engineering mechanics,* 126(12): 1224-1231.

Trautmann, C. H. and T. D. O'Rourke (1985). Lateral force-displacement response of buried pipe. *Journal of Geotechnical Engineering,* 111(9): 1077-1092.

Veletsos, A. (1984). Guidelines for the seismic design of oil and gas pipeline systems ASCE. New York: Technical council on lifeline earthquake engineering ASCE: 255-370.

Wolf, J. P. and M. Motosaka (1989). Recursive evaluation of interaction forces of unbounded soil in the time domain from dynamic-stiffness coefficients in the frequency domain. *Earthquake engineering & structural dynamics,* 18(3): 365-376.