Determination of Pipeline Damages during Earthquakes Considering Different Soil Formations

Ali Koçak[1], Mehmet Şükrü Özçoban[1], Ali Coşar[1], Murat Ergenekon Selçuk[1],

[1]*Department of Civil Engineering, Yildiz Technical University, Turkey*

ABSTRACT

It is necessary that infrastructure systems in urban areas remain functional, especially during various disasters. Drinking water should be provided without any disruption and waste water disposed without any adverse environmental and health effects. However in Turkey, infrastructure facilities and pipelines suffer heavy damages at every earthquake. Therefore, the damages that may occur during an earthquake should be taken into consideration when infrastructure pipelines are designed. These damages have been observed especially in recent earthquakes, such as 1992 Erzincan (M_w= 7.9), 1995 Dinar (M_w= 6.0), 1999 Kocaeli (M_w= 7.8), and 2011 Van (M_w= 7.2).

In addition to soil properties, material properties of pipeline, soil-pipeline interactions, connection points and details of pipes play an important role when post-earthquake damages are analyzed.

In this study, the displacements of infrastructure pipelines in areas of high earthquake risk are estimated through a numerical model to assess likely damages. Furthermore, the relationship between damage patterns and displacements of infrastructure systems after an earthquake is examined based on varying soil types and conditions.

Keywords: *Pipelines, Infrastructure Damages, Earthquake, Soil*

INTRODUCTION

Liquids and gases such as drinking water, wastewater and natural gas have to be transported through pipelines, which are commonly buried below grade during construction. It is necessary that these buried pipelines stay operational in the event of disasters, such as earthquakes and floods. However, ability of pipes to remain operational depends on pipe type, soil properties, pipe diameter and filling material, and bearing conditions.

Pipelines move with soil and become deformed as a result of movements arising from earthquakes. It is necessary that such deformations stay within certain limits depending on pipe material, in order to ensure that pipes are not cracked. Thus, earthquake behavior should be examined depending on type of soil and pipe type. The variation and extent of deformations need to be calculated and verified that the limit deformation that a pipe can withstand is not exceeded.

Pipelines are usually integrated and combined systems with long distances. The whole system becomes non-functional if any deformation that exceeds limits occurs at any point on the pipelines. Therefore, no cracks/damages should occur not even on a single point along entire pipelines.

Important information has been obtained about the type, magnitude, location and properties of damages on buried pipelines from past earthquakes, and work has been carried out on measures to prevent such damages. Pipe material has as much effect on earthquake-related damages of buried pipes as soil conditions and placement conditions.

External loads applied on buried pipelines are caused by backfilling of the trenches, self-weight of pipes and its components, and traffic loads. Type of soil and filling, ditch depth, deformation of the pipe and construction method of the pipe are also very important. Therefore amount of deformation depends on filling height, filling material, placement conditions, pipe diameter, pipe type, pipe material and especially, external loads [1, 2, 3, and 4].

Performance of the structure and the soil should be taken into consideration together (soil-structure interaction) in the design of buried structures. Soil on buried pipe exerts pressure on pipe. Pressure accumulates on pipes if they cannot sufficiently deform. However, soil weight on the pipe decreases due to soil resistance if the pipe is compressible. In this case soil arches over the pipe and the pressure on the pipe is decreases as a result of this arching effect. The arching effect depends on soil resistance and pipe-soil interaction [5]. Vertical soil pressure on a rigid pipe is greater than soil weight on the pipe. As a result, negative arching occurs, side fillings settle and an additional pressure is exerted on the pipe. In this case stresses increase around the pipe and decrease on the side fillings.

On the other hand, vertical soil pressure on a flexible pipe is less than soil weight acting on the pipe. Positive arching occurs in this case and part of the pressure on the pipe is transferred to the side fillings. As a result, load on a rigid pipe is greater than load on a flexible one under the same conditions [1, 3]. Damages resulting from earthquakes on buried pipelines and places of such damages have been classified according to soil conditions and type of damage, based on field studies and various other works [6, 7, 8, and 9]. Methods similar to seismic behavior of superstructures are used in works to estimate earthquake behavior of underground structures. However, behavior of buried pipes differs from that of superstructures [6, 7, and 11].

Factors such as soil movement, liquefaction and landslide cause significant damage depending on wave propagation resulting from earthquake. It increases with the ability to resist fault movements and friction forces acting on the pipeline. Flexible pipes show more resistance during fault movements. Displacements resulting from fault movements constitute the main reason for damage of buried pipelines [11]. Eguchi (1982) has evaluated pipeline damages caused by the 1971 San Fernando earthquake (M_w= 6.6) in North San Fernando Valley.

The 1985 Michoacan-Mexico (M_w= 6.5) earthquake is a good example of high rates of pipeline repair due to temporary displacement. This earthquake resulted in high damages in water distribution pipelines. Ayala and O'Rourke (1989) have reported these damages and observed that no liquefaction occurred and damages were essentially a result of earthquake waves [12].

Toprak (1998), O'Rourke et al. (1998) and O'Rourke and Toprak (1997) have presented in their papers a database for the damages inflicted on the pipes in Los Angeles and for characterizing and examining these damages. Repair was necessary at 74 points in the water transmission pipes (pipe diameter ≥ 600 mm) of the Los Angeles Department of Water and Power (LADWP) and Metropolitan Water District of Southern California (MWD) and at 1013 points in the distribution pipelines (pipe diameter < 600 mm) of LADWP [13].

The Hanski region of Japan, together with Kobe and Osaka were subject to intense effects of the 1995 Kobe earthquake. Very high damages have been observed especially in zones with permanent soil deformations. Old pipes and joints had much more damage compared to new and flexible pipes. Kobayashi et al. (2001) and Masuda et al. (2002) have carried out a research project from 1996 to 2000 in order to build "Proposed Applications for Gas Transfer Pipeline Design in Zones Subject to Liquefaction" by examining displacements resulting from liquefaction, soil and pipe interaction, evaluation of deformations in pipelines and pipe deformations that satisfy conditions of no gas leakage [17, 18]. Japanese Water Works Association (JWWA) established a technical committee after the Kobe earthquake. This committee made amendments in the regulations for earthquake resistant structures, based on results of examinations of damages in pipelines [23].

NUMERICAL INVESTIGATIONS

Numerical investigation of dynamic behavior of pipes are investigated by two-dimensional Plaxis 2012 finite element software. Numerical analysis are carried out on a combination of two different soil types and three different pipe materials. Soil is defined as loose sand and dense sand (typical back-fill material) while pipe materials are taken as PVC, concrete and steel. It is assumed that pipe is constructed on a 30 cm height of bedding material in 1m width of trench and bottom of the pipe is placed at 3 m below the surface (Figure 1). Backfill material is taken as same as the bedding material. All of the computations are executed for pipe with a diameter of 300 mm. numerical modelling of soil is achieved by using Hardening Small Strain Model. Dimension of the numerical model is taken as 20mx15m. The material properties used in analyses are given in Table1.

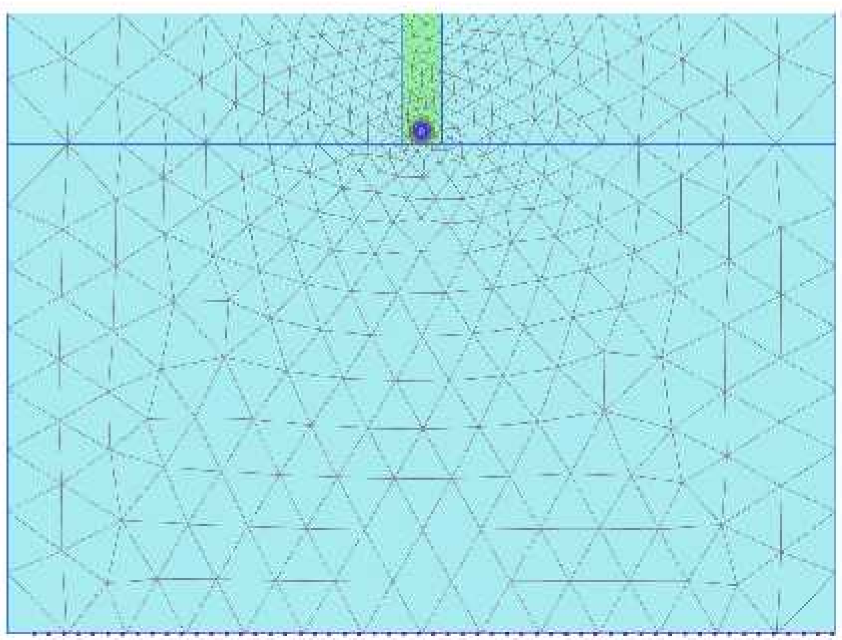

Figure 1. Mesh created for the numerical model

Table 1. Material properties used in numerical analyses

SOIL	E (kPa)	c (kPa)	()	(kN/ m^3)
Loose Sand	10000	1	30	17

Dense Sand	60000	1	38	21
Bedding	30000	1	37	20
PIPE MATERIAL	EA (kN/m)	EI (kNm^2/m)		
PVC	4.5E4	9.38		
Concrete	1E6	208		
Steel	1E7	2080		

40 seconds of the N-S component of 2010 Van Earthquake strong ground motion record, which has a peak ground acceleration of 0.19g is used in dynamic analyses (Figure 2).

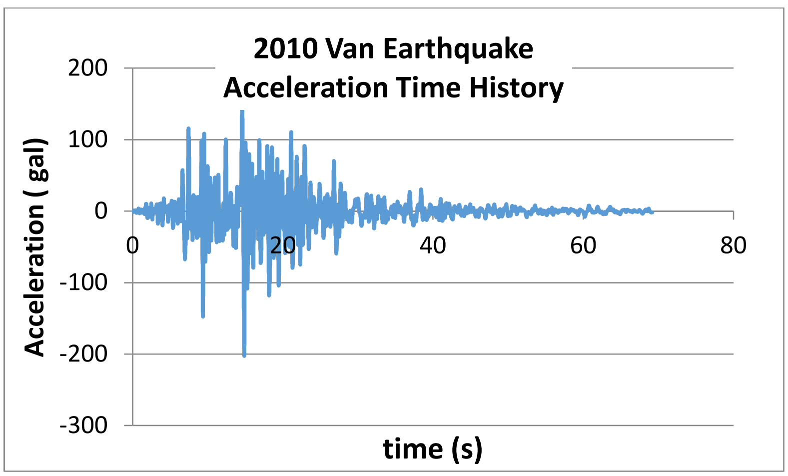

Figure 2. Acceleration time history of 2010 Van Earthquake N-S component

The effect of soil type and material type on the displacement-time history is depicted in Figure 3. Results of the numerical analysis of pipe placed on dense soil show that total displacement of pipe is about 0.115 m, while it is about 0.12m on loose soil. The total displacement does not vary by a large amount. However, displacement rate is faster in loose soils than dense soils.

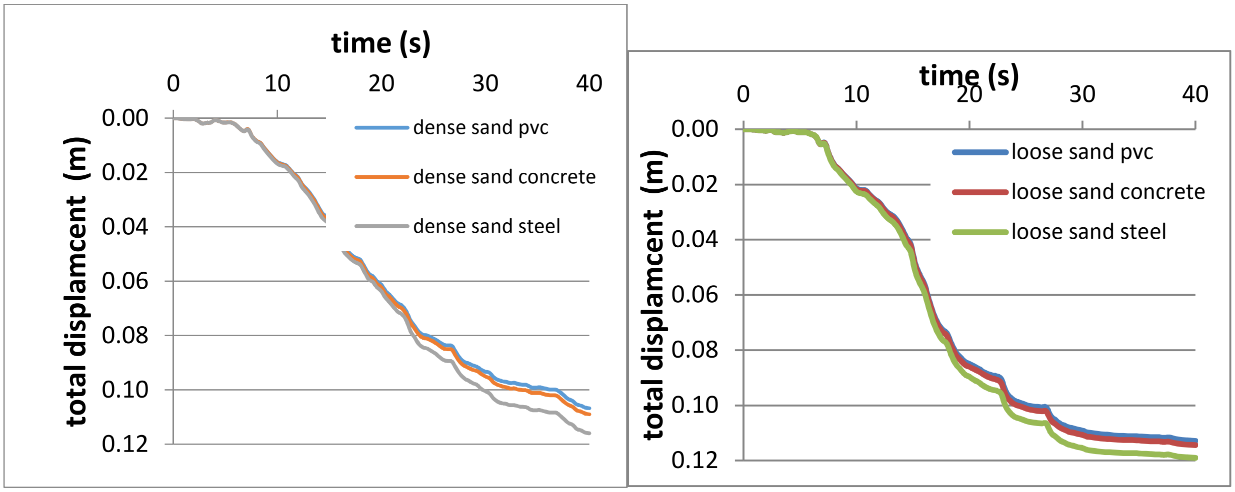

Figure 3. Total displacement of pipes on dense and loose sands

Horizontal displacement of pipe is compared with the base of the model. Relative horizontal displacement time history for different soil type and materials are given in Figure 4. Relative horizontal displacement of pipe is about 0.05m. The horizontal displacement difference between various types of pipe material are not significant. Also effect of soil type on the horizontal displacement of pipe is not clear.

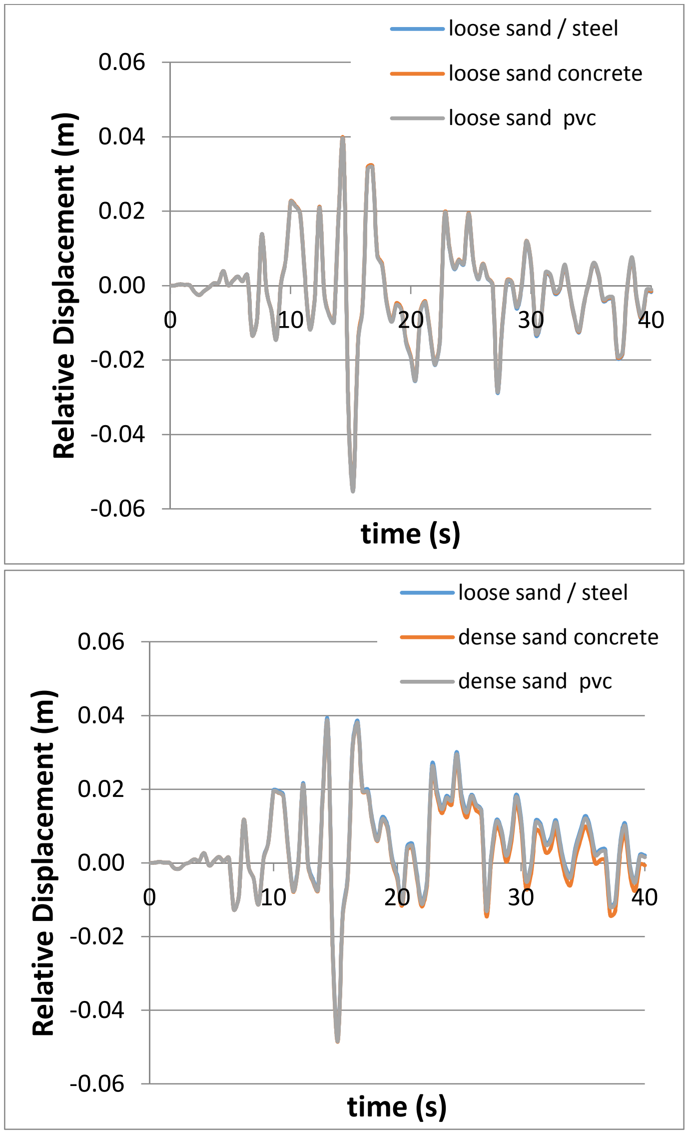

Figure 4. Relative displacement time history of pipe

The changes of the cross-sectional forces acting on pipe from the static condition to after dynamic effects are applied for different soil type and different pipe material in Table 2. It is seen on the table that, soil type effects the cross sectional forces for the three different type of pipes. Forces are much higher than the pipes seated on dense sand. Moment, shear forces acting on concrete pipes seated on loose soil are increased about 4% while it is about 27% in dense soil. Same behavior is seen also on steel and PVC pipes.

Furthermore, the comparison of cross sectional forces shows that PVC pipes are the most affected pipes. Moments acting on PVC pipes placed on loose sand is about 76% while it is about 26 % in steel pipes. The tendency of increment on cross sectional forces are same on pipes built on dense sand.

Table 2. Changes in cross-sectional forces acting on pipes

		LOOSE SAND/ CONCRETE			DENSE SAND/CONCRETE		
		M (kNm/m)	V (kN/m)	N (kN/m)	M (kNm/m)	V (kN/m)	N (kN/m)
Change %	max	42.10%	41.34%	37.09%	26.14%	27.99%	-32.39%
	min	38.53%	40.39%	-2.13%	22.31%	24.47%	-1.55%

		LOOSE SAND/STEEL			DENSE SAND/STEEL		
		M (kNm/m)	V (kN/m)	N (kN/m)	M (kNm/m)	V (kN/m)	N (kN/m)
Change %	max	31.89%	31.95%	-4.04%	30.62%	35.21%	-25.18%
	min	28.99%	30.61%	-0.52%	27.43%	31.94%	0.90%

		LOOSE SAND/PVC			DENSE SAND/PVC		
		M (kNm/m)	V (kN/m)	N (kN/m)	M (kNm/m)	V (kN/m)	N (kN/m)
Change %	max	76.40%	71.06%	-31.17%	57.72%	56.08%	-35.76%
	min	63.98%	70.63%	5.79%	49.01%	54.38%	1.52%

CONCLUSIONS

The effects of pipe material and soil type cannot be observed easily based on the results of numerical analyses. 2D analyses is insufficient to observe displacement behavior of a pipe. Thus, numerical analysis should be carried out on 3D to better understand the displacement behavior of pipe. Moreover, experimental observation should be collected to support numerical findings. The computation results of cross sectional forces acting on pipe show that material properties of pipe and soil type influence the results. PVC pipes are mostly effected pipe type from dynamic forces while steel pipes effected less. Also pipes on loose sand have much more cross sectional forces than pipes built on dense sand medium. To better understanding of dynamic behavior of pipes, effect of bedding material, diameter of pipe and depth of pipe placement should also be studied.

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