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Effect of Soil Parameters Uncertainty on Seismic Response of Buried Segmented Pipeline

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ABSTRACT: Pipelines are important lifeline facilities spread over a large area and they generally encounter a range of seismic hazards and different soil conditions. The seismic response of a buried segmented pipe depends on various parameters such as the type of buried pipe material and joints, end-restraint conditions, soil characteristics, burial depths, and earthquake ground motion, etc. This study highlights the effect of the variation of geotechnical properties of the surrounding soil on seismic response of a buried pipeline. The variations of the properties of the surrounding soil along the pipe are described by sampling them from predefined probability distribution. The soil-pipe interaction model is developed in OpenSEES. Nonlinear earthquake time-history analysis is performed to study the effect of soil parameters variability on the response of pipeline. Based on the results, it is found that uncertainty in soil parameters may result in significant response variability of the pipeline.

Keywords: Buried pipe, soil-pipe interaction, soil parameters, uncertainty, seismic response

1. INTRODUCTION

Buried segmented pipelines are commonly used in many lifeline systems, such as water distribution and gas supply systems, etc. There are several publication and reports that discuss the severe damage to civil life cause by the failure of buried pipelines during or after the high-intensity earthquake [1], [2]. After the Hyogo-Ken Nanbu earthquake of 1995 in Japan, it was reported that gas leakage from buried pipelines occurred at 234 different places; subsequently, fires started primarily due to gas release and electricity sparks. Fires occurred at 531 different places and burnt areas were over 1 km^2 [3]. Another example, the Chi-Chi earthquake of 1999 in Taiwan also caused serious damage to natural gas supply systems. More than 100,000 industrial and residential customers in the disaster area were cutoff from the natural gas supply after the earthquake, and the estimated economic loss of five major natural gas companies was approximately US$ 25 million [4].

During the 1994 Northridge earthquake, several pipelines and aqueducts were broken due to large permanent ground deformation; and during the 1995 Kobe earthquake, around 2000 repairs had to be done in the water distribution system due to significant ground shaking, ground distortion, and liquefaction in the artificial fills constructed near the bay [5].

Due to the serious consequences of lifeline system failure under earthquakes, their seismic performance has been the subject of many research studies. The performance of a pipeline under seismic load depends on type of buried pipe material and joint, end-restraint conditions, soil characteristics, earthquake ground motion, and burial depths etc. In this paper, the effect of soil parameters uncertainty in seismic response of pipeline in longitudinal direction is investigated. The dynamic soil-pipe interaction is developed using Winkler-based approach with nonlinear discrete soil springs in longitudinal and vertical directions. The effect of soil variability in seismic response is modeled using probabilistic approach.

2. PIPELINE CONSIDERATION

A cast iron pipeline of 120 m long with lead caulked pipe joint buried in sandy soil with fixed end condition is considered in this study. The length of pipe segment (l_s), yield strength (f_y), outer diameter (D) and burial depth (H) are 6 m, 250 MPa, 150 mm and 800 mm, respectively. The friction coefficient (δ), depending on the outer-surface characteristics and hardness of the pipe, is taken as 0.8. It is assumed that the pipeline is placed well above the ground water level; therefore, the soil liquefaction is not considered. The change in internal pressure in the pipeline and the live load over the ground surface are neglected.

3. FINITE ELEMENT MODELING OF PIPELINE

Finite element analysis of the pipe-soil system is performed using OpenSEES finite element analysis package [6]. Pipe segment is modeled with elastic beam element and the joint is modeled using zero-length element with nonlinear material model. Also, the soil response in vertical and axial direction is modeled with zero-length element and nonlinear material model. The schematic diagram of pipe-soil system is shown in Fig.1.

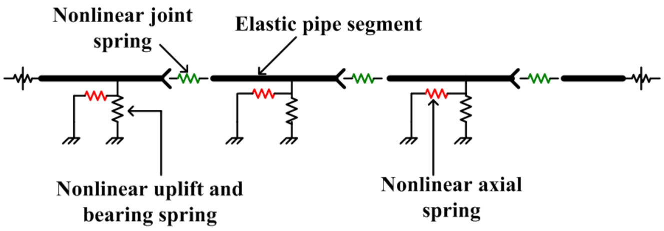


Fig.1. Schematic diagram of pipe-soil system

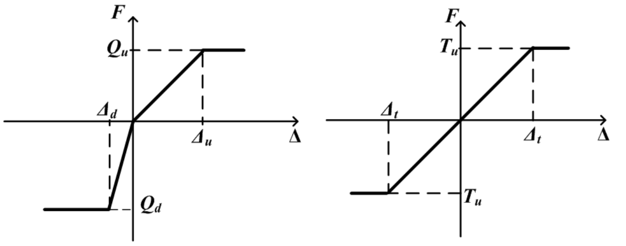
3.1 Behavioral model for soil spring

The force-displacement behavior of axial soil springs are based upon recommendations in the 1984 ASCE Guideline for Gas and Liquid Fuel Pipelines [7] for non-cohesive backfill. The nonlinear behavior of axial spring is shown in Fig. 2 (right).

A symmetric bilinear-type curve (elastic-perfectly plastic) is employed with a peak force per unit length at the soil-pipe interface, T_u:

$$T_u = \frac{\pi}{2} DH\gamma(1+K_0)\tan(\delta\phi) \tag{1}$$

where γ is the effective unit weight of the soil, ϕ is the angle of internal friction of the sand and K_o is the coefficient of lateral soil pressure at rest. The equivalent “yield” displacement (Δ_t) for the soil spring is typically about 2 mm.



Force -displacement response of vertical spring

Force -displacement response of axial spring

Fig.2. Nonlinear force-displacement behavior of soil springs: vertical spring (left); axial spring (right)

The nonlinear behavior of vertical soil springs is shown in Fig. 2 (left). The upward soil resistance per unit length (Q_u) of the pipe in sandy soil can be determined as:

$$Q_u = N_{qv}\gamma HD \tag{2}$$

$$N_{qv} = \frac{\phi H}{44D} \le N_q \tag{3}$$

$$N_q = \exp(\pi\tan\phi)\tan^2\left(45^0 + \frac{\phi}{2}\right) \tag{4}$$

The corresponding displacement, Δ_u at Q_u can be taken as 0.01H for the dense sand.

The vertical bearing soil spring force per unit length (Q_d) can be calculated by:

$$Q_d = N_q\gamma HD + N_\gamma\gamma\frac{D^2}{2} \tag{5}$$

$$N_\gamma = \exp(0.18\phi - 2.5) \tag{6}$$

The displacement, Δ_d , at Q_d is 0.1D for granular soil. A more detailed description of (1) to (6) is provided in the American Lifeline Alliance, ASCE [8].

3.2 Behavioral model for pipe joint

The axial force-deformation relationship considered for the lead caulked pipe joint is based on the study reported in [9]. The force-displacement response is represented by bi-linear relationship as shown in Fig. 3.

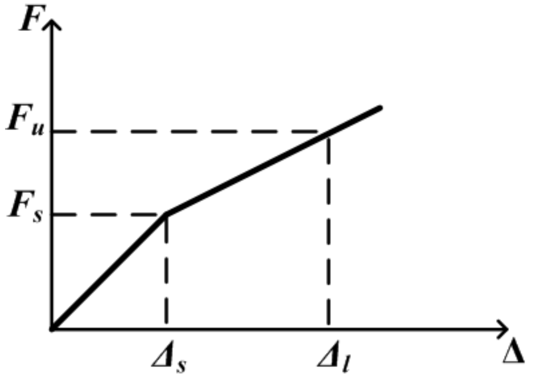


Fig.3. Axial force-displacement behavior of joint spring

There is an initial elastic region until slippage at a relative joint displacement of Δ_s, followed by a linear post-slippage region until leakage at a relative joint displacement of Δ_l. The axial force at slippage, F_s, is based upon a model proposed in [10].

$$F_s = C_a\pi Dd_1 \tag{7}$$

where C_a is the adhesive strength at the pipe/lead interface and d_1 is the depth of lead caulking. The average value of C_a is around 1.7 MPa, and d_1 for a 150 mm diameter pipe is 55 mm. The initial stiffness of the joint and the joint force at leakage also reported in [9]. For 150 mm diameter pipe the initial stiffness is quite large, resulting in a typical slippage displacement of only about 3.3 μm. The joint force at leakage is equal to twice the slippage force. The slippage displacement at leakages (Δ_l) is taken as 16.5 mm.

4. EARTHQUAKE GROUND MOTION

In order to perform nonlinear time-history analyses, the acceleration time history recorded at El-Centro during Imperial Valley California (1940) is considered. The characteristics of the record are: the magnitude (M_w) is 6.6, source-to-site distances (r) range is 8 km and soil condition is stiff. The maximum acceleration to velocity ratio (A/V) is 1.04, where A is in 'g' and V is in m/s. Fig.4 shows the acceleration time history and acceleration response spectra with 5% damping of El-Centro record.

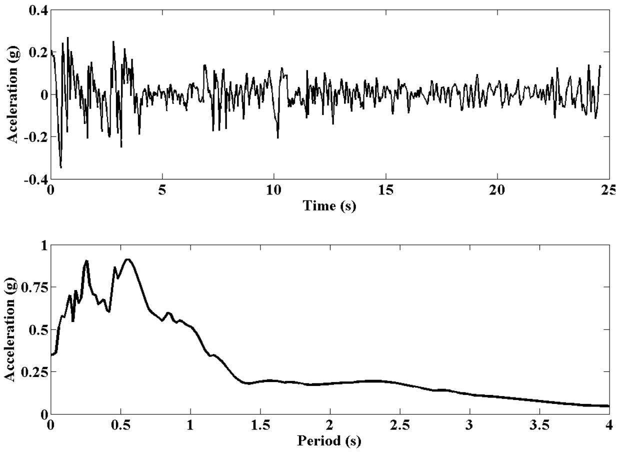


Fig.4. El-Centro acceleration time history (top) and response spectrum (bottom)

5. VARIABILITY IN SOIL PROPERTIES AND THEIR MODELING

It is evidence from section 3.1, that the soil proprieties are one of the performance controlling parameter of pipe-soil system. The force-displacement behavior of soil spring is controlled by the soil parameters. Thus, it is essential to investigate the effect of soil parameters uncertainty in seismic response of buried pipelines. In this study, the soil properties such as internal friction angle and unit weight of soil are considered as uncertain variable. Those variables are assumed be described by lognormal distribution, since they are necessarily positive values. Table 1 shows the list and respective mean values and corresponding 10% coefficient of variation (CV) of the input parameters. Although some studies have reported that a larger variation of the in situ CV, the 10% CV for different soil types including, sand, clay and silt seems to be reasonable [11]. No correlation between internal fraction angle and unit weight is considered.

Table.1 Statistical property of soil parameters

Parameter	Mean	CV (%)	Distribution
Friction angle	35^0	10	Lognormal
Unit weight	16 (kN/m^3)	10	Lognormal

6. TREATMENT OF UNCERTANITY IN SEISMIC RESPONSE ANALYSIS

Seismic response analysis of the pipeline which incorporates the source of uncertainty considered above can be carried out using random sampling Monte Carlo simulation coupled with the finite element pipeline model. Fig. 5 shows histogram of 500 values of random sampled fraction angle and unit weight of soil.

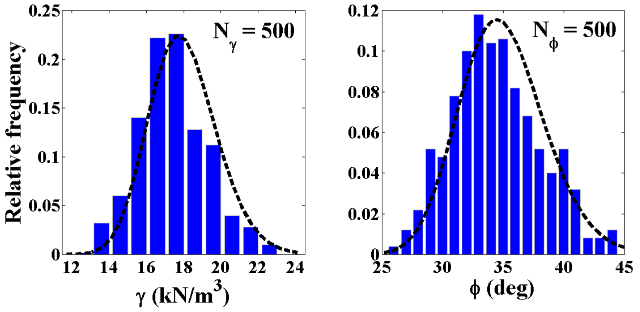


Fig.5. Histogram of sampled soil unit weight (left) and fraction angle (right)

Each randomly generated (γ,φ) pair is input into the finite element model and time history analysis is performed to predict the response. The natural period of the pipeline with mean value of soil property is 0.27 s.

7. RESULTS AND DISCUSSION

Fig.6 shows the axial displacement of pipeline, which has the mean values of the soil properties, at different time in the time history analysis. The displacement is concentrated at the joints and the maximum displacement is occurred at the middle section of the pipeline. The maximum pipe displacement observed at the middle of the pipeline is approximately 24 mm.

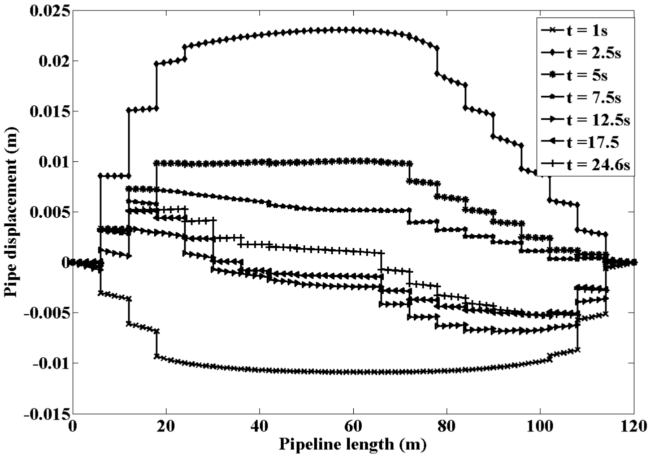


Fig.6. Axial displacement of pipeline at different time in the time history analysis

The maximum relative displacement is observed at the joints which are close to the supports. Fig.7 shows the maximum relative displacement at each joint along the pipeline. The maximum relative displacement at the joints is close to 9 mm which is less than the slippage displacement at leakages. The joint at the middle of the pipeline shows no relative displacement for the mean valued model. The maximum relative displacement is high at the joints close to support and decreases towards the middle of the pipeline.

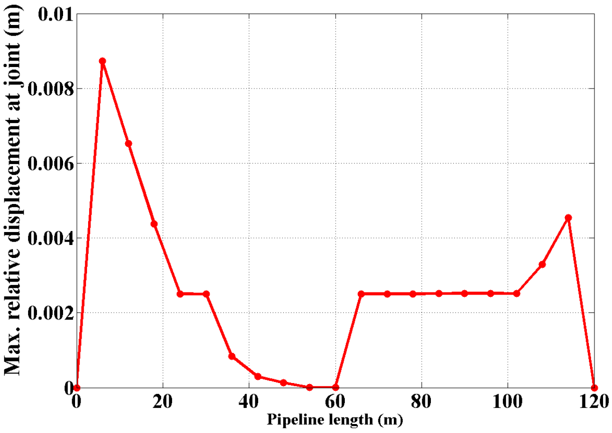


Fig.7. Maximum relative displacement at the joint during time history analysis

To study the effect of single soil parameter on the response, the lower and the upper value among the sampled values of each parameter is selected, while keeping the other one in its mean. Fig. 8 shows the effect of unit weight of soil on the response. For the upper value of the unit weight, the maximum relative joint displacement response is increased in general compare to the mean valued model response and decrease for lower value of the unit weight. It may be due to the fact that the mass of the system is increased with increasing unit weight and consequently the system subjected to higher inertia force, which causes larger displacement in the system. In the case of lower value of unit weight of soil, a few joints at the middle part of the pipeline show no relative displacement.

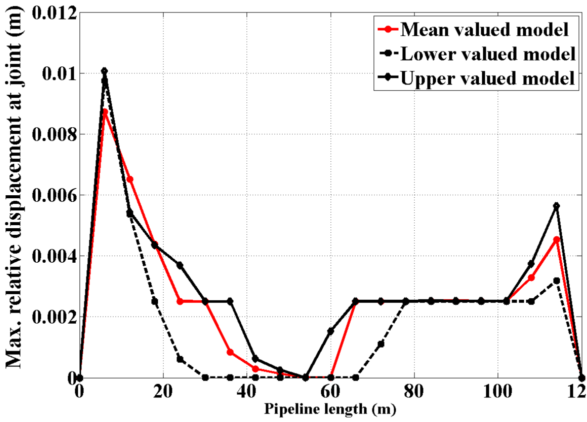


Fig.8. Effect of unit weight on the maximum relative displacement at the joint

Fig.9 shows the effect of internal fraction angle of soil on the maximum relative joint displacement response. For the lower value of the soil fraction angle, the joint displacement is increased and for the upper value of the fraction angel the joint displacement is decreased significantly from the mean valued model. Due to large axial soil fractional forces in the pipe segment, a few joints at each side from the middle section of the pipeline show no relative displacement for upper value of fraction angle. Contrary, the pipeline shows significant increase in relative joint displacement for lower value of frication angle from the mean valued model. Further, the effect of fraction angle on the response of the system is much significant compare to the unit weight of the soil.

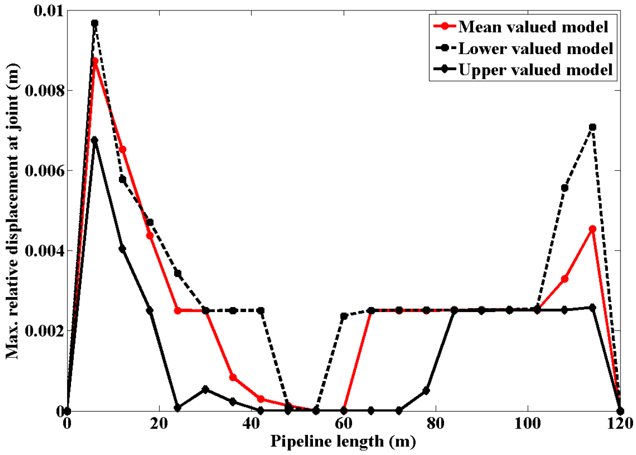


Fig.9. Effect of friction angle on the maximum relative displacement at the joint

Fig. 10 shows the 95% confidence bound and median of the maximum relative joint displacement response from the random sampled model together with the mean-valued model response. The median and mean-valued model responses are essentially the same. But the variability in the response due the uncertainty in the soil properties is significantly high.

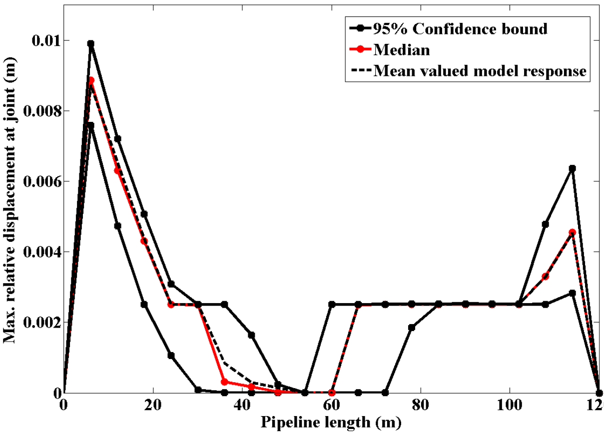


Fig.10. Mean-valued pipeline model response and 95% confidence bound and median of random sampling model response

8. CONCLUSION

The influence of soil parameters uncertainty on the seismic response of buried segmented pipeline is investigated in this paper. A 120 m long pipeline in sandy soil is molded using nonlinear Winkler approach to represent the soil behavior. Random sampling method is used to randomize the soil parameters. The effect of different types of soil is not considered. Within this limitation, the analysis results show that the uncertainty in soil property has significant influence on the displacement response of pipeline. The influence of internal fraction angle is significant compare to unit weight of the soil. The coefficient of variation of joint response is more than 100% in some location. Finally, it is important to consider the variability in soil properties in seismic risk assessment of pipeline.

9. REFERENCES

[1] Ayala G and O'Rourke MJ, "Effects of the 1985 Michoacan earthquake on water systems and other buried lifelines in Mexico", Report No. NCEER-89-0009, National Center for Earthquake Engineering Research, State University of New York at Buffalo, 1989.

[2] Wang L, Shao-ping S and Shijie S, "Seismic damage behavior of buried lifeline systems during recent severe earthquakes in U.S., China and other countries", Technical Report No. ODU Lee-02, Old Dominion University Research Foundation, 1985.

[3] Scawthorn C and Yanev PI, "Preliminary report on Hyogo-ken Nambu, Japanese earthquake" Eng Struct, Vol. 17(3), 1995, pp.146-57.

[4] Chen WW, Shih BJ, Wu CW, "Chen YC. Natural gas pipeline system damages in the Ji-Ji earthquake (The City of Nantou)", In: Proc of the 6th international conf on seismic zonation, 2000, pp ..

[5] Eidinger JM. and Avila EA, Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities. Monograph # 15. Technical Council on Lifeline Earthquake Engineering, American Society of Civil Engineers, 1999.

[6] McKenna F, Fenves GL, Jeremic B and Scott MH,Open System for Earthquake Engineering Simulation, http://opensees.berkely.edu, 2007.

[7] American Society of Civil Engineers, Guidelines for the Seismic Design of Oil and Gas Pipeline Systems Reston, VA, 1984, pp. 473..

[8] American lifelines alliance, Guidelines for the design of buried steel pipe. ASCE, 2001.

[9] Hmadi EI and O'Rourke, MJ, Seismic Wave Effects on Straight Jointed Buried Pipeline. Technical Report NCEER-89-0022, Multidisciplinary Center for Earthquake Engineering Research, New York,1989

[10] O'Rourke TD and Trautmann CH, Analytical Modeling of Buried Pipeline response to Permanent Earthquake Displacements, Report No 08-4, School of Civil Engineering and Environmental Engineering, Cornell University, Ithaca, New York, 1980.

[11] Jones AL Kramer SL and Arduino P, Estimation of uncertainty in geotechnical properties for performance-based earthquake engineering. Technical Report 2002/16, Pacific Earthquake Engineering Research Center, PEER, 2002.