PERFORMANCE-BASED SEISMIC RESPONSE OF BURIED STEEL PIPELINSE

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ABSTRACT

Performance-Based Earthquake Engineering (PBEE) has appeared as a basis of modern earthquake engineering as it attempts to improve deciding about seismic risk by methods that are more informative than current approaches. However, little work has been carried out investigating the seismic response of buried steel pipelines within a performance-based framework. In this research the seismic demands of buried steel pipelines are studied in a performance-based context. Several nonlinear dynamic analyses of four buried steel pipe models with different D/t, H/Dratios and different soil properties and different pressures, performed under an ensemble offar-field earthquake ground motion records were scaled to several intensity levels to capture the behavior of buried pipeline from elastic response through to global instability. Several scalar ground motion intensity measures (IMs) are used to investigate their correlation with engineering demand parameter (EDP) which is measured by peak axial compressive strain in critical section of pipe. Using regression analysis it is concluded that, velocity-based IMs are the most appropriate ones in evaluating the buried steel pipelines response efficiently.

INTRODUCTION

Seismic demand estimation is one of the main aspects of Performance-based seismic design (PBSD), or performance-based earthquake engineering (PBEE) as some have selected that name (Moehle and Deierlein, 2004). Uncertainties in the earthquake ground motions as well as uncertainties in the nonlinear behaviour of structures are the major challenges in assessing seismic demands, thus probabilistic seismic demand analysis (PSDA) is utilizedto such a framework (Luco, 2002). PSDA is applied as a tool to evaluate the mean annual frequency of exceeding a particular value of an engineering demand parameter.

Probabilistic evaluation of performance has been applied in the SAC project for steel buildings (FEMA, 2000), but the method may be applied for any type of investigated structures including buried steel pipelines. Incremental Dynamic Analysis (IDA) is an appropriate method for meeting these needs. In this parametric analysis method a structural model is subjected to an ensemble of earthquake records, each scaled to multiple intensity levels, to obtain response of structure from elasticity to final failure (Vamvatsikos and Cornell, 2002). Finally, IDA curves can be generated. The IDA curve is a graph of an Engineering Demand Parameter (EDP) versus an Intensity Measure. Eliminating of the uncertainties in performance-based design framework is performed by using of Intensity Measure. Considerable research has been conducted on specifying IMs which efficiently estimate structural response due to seismic excitation (e.g. Shome and Cornell, 1999; Baker and Cornell, 2005).

In this paper the performance-based response of buried steel pipelines is examined. Nonlinear dynamic analyses of buried steel pipeline structure models with different pipe and soil properties are used to obtain the most suitable EDP and IM for buried steel pipelines. Firstly, a measure of demand (EDP) with ability of appropriate characterizing the seismic response of the pipeline and its related damage, is proposed. Finally, different proposed IMs are investigated andthe most appropriate ones in evaluating the buried steel pipelines response efficiently are obtained.

BURIED STEEL PIPELINE MODEL

To investigate the effects of different geometrical and material properties, three buried pipeline models of API 5L Grade X65, which is typically used in the natural gas and oil industries, with different pipe and soil properties are examined as summarized in Table1 : M1 to M3.(Herein ‘M’ will be used as shorthand notation for ‘model’). In this paper it is assumed that the ground water level is under the buried pipeline; therefore, soil liquefaction is not considered and the dry unit weight of the soil is used in the analyses. The material properties of the selected buried pipeline are summarized in Table 1.

Table 1. Considered models in the analyses

Parameter	Model		
	M1	M2	M3
D(mm)	356	508	610
t(mm)	7.9	7.9	6.4
D/t	45.1	64.3	95.3
H(m)	1.928	1.928	1.5
H/D	5.4	3.8	2.5
P(psi)	750	750	250
Φ(°)	30	30	40
C (Kpa)	0	0	0
ɣ (kg/m^3)	1700	1700	2000

To simulate soil-pipeline interaction effects in axial, transverse and vertical directions the bilinear force displacement curves (elastic-perfectly plastic),as illustrated in Figure 1, representation of soil stiffness are employed based on suggestions of the American Lifeline Alliance (ASCE, 2001) and equivalent dashpots in aforementioned directions were considered as representation of soil damping. The buried pipeline is modeled using PIPE288 element. This element is well-suited for large rotation, and large strain nonlinear applications (ANSYS, 2007). The surrounding soil is modeled using COMBIN39 element for soil springs and COMBIN14 element as dashpots. The COMBIN39 element has large displacement capability (ANSYS, 2007). To simulate the soil-pipeline interaction effects, each node of the model was connected to three spring-dashpots. The constants of the spring and dashpot at the level of the center of the pipe cross-section are calculated and equally distributed among all of nodes.

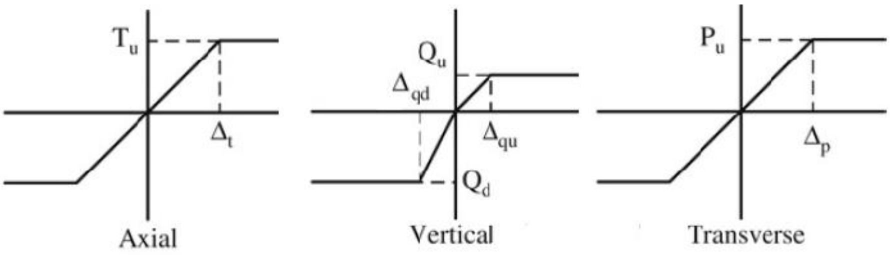


Figure 1. Nonlinear soil springs

The design of buried pipelines is performed according to American Lifeline Alliance (ASCE, 2001).The three designed buried pipelines with different outside diameter to thickness (D/t) and burial depth to diameter (H/D) ratios are used as numerical models (as shown in Table 1) in nonlinear dynamic analysis. Parameters such as the maximum soil spring forces and associated relative displacements that are needed for the definition of the discrete nonlinear springs are computed according to the American Lifeline Alliance (ASCE, 2001)and showed in Table 2.

Table 2. The maximum soil force per unit length of the pipe and corresponding displacement

Model	Initial stiffness per unit length(N/mm2)				Displacement at maximum soil force per unit length of pipe (mm)			
	Axial direction	Transverse direction	vertical direction		Axial direction	Transverse direction	vertical direction	
			Uplift	Bearing			Uplift	Bearing
M1	12.24	107.79	43.09	234.29	5	53.4	35.6	35.6
M2	17.47	136.22	43.09	346.25	5	76.2	38.6	50.8
M3	26.94	130.32	40.91	1583.89	3	72.2	15	61
M4	75.41	167.19	192.80	148.92	10	76.2	101.6	101.6

Figure2 gives the damping coefficients of the equivalent dashpots for transverse and axial vibrations of buried pipelines (Hindy and Novak, 1979).Equations of the damping coefficients are given by

$$c_{sl} = G\overline{S}_u \frac{rl}{V_s}, c_{sa} = G\overline{S}_w \frac{rl}{V_s} \tag{1}$$

Where, l is the length of the element, r is the radius of the pipe cross-section, and h is the buried depth.

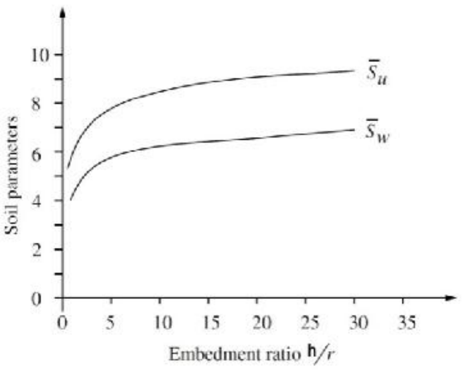


Figure 2. Variation of dimensionless soil damping coefficients with h/r (Hindy and Novak, 1979)

To achieve a correct simulation, the pipeline should be modeled with infinite length. These assumption will produce computational problems and will be time consuming. In order to reduce this problems, the equivalent boundary method (Liu et al., 2004) is used in this study as boundary conditions at the two ends of pipeline.Thus the boundaries can be modeled asnonlinear axial spring element that is applied at two ends. The relationship between axial force F and longitudinal extension ΔL of these springs is given by

$$F(\Delta L) = \begin{cases} \sqrt{\frac{3EAf_s}{2}} U_0^{-\frac{1}{6}} \Delta L^{\frac{2}{3}}, 0 \le \Delta L \le U_0 \\ \sqrt{2EAf_s(\Delta L - \frac{1}{4}U_0)}, U_0 \le \Delta L \le \frac{\pm_y^2 A}{2Ef_s} + \frac{U_0}{4} \end{cases} \tag{2}$$

Where E is the pipe modulus of elasticity, A is the pipe cross section area, σ_y is the yield stress of the pipe material, and f_s is the sliding soil friction per unit length (maximum axial soil force per unit length of the pipe that can be transmitted to the pipe)(Liu et al., 2004).

Before deciding which ground motion IMs efficiently evaluates structural seismic response of buried pipes the first issue is related to the determination of appropriate engineering demand parameter (EDP) for specifying the seismic response of a buried pipes. In this study the peak axial compression strain at the most critical section of pipe (denoted ε_{max} herein) is selected for EDP of buried pipelines, as it directly relates to occurrence of damage.

GROUNDMOTIONS

In this study, An ensemble of seven earthquake records (listed in Table 3) is selected according to closest distance to fault rupture, magnitude and site class. The ground motions magnitudes and distances are in the range of M_w =6.5-7.5 and R =21.4–69.2 km, respectively, and recorded on stiff soils. All of which have no effects of directivity. Each of these records are scaled and used as input motions in the nonlinear dynamic analyses and finally the results are postprocessed.

Table 3. The suite of seven ground motion records

No.	Event	Magnitude	R(km)	PGA(g)	Vs (m/s)
1	Borrego Mtn, 1968 (117 El Centro Array #9)	6.8	46	0.13007	213.4
2	Friuli, 1976 (Codroipo)	6.5	33.4	0.09047	274.5
3	Imperial Valley, 1979 (Delta)	6.53	22	0.35112	274.5
4	Kobe,1995 (OSAJ)	6.9	21.4	0.07867	256
5	Kobe,1995 (Kakogawa)	6.9	22.5	0.34472	312
6	Kocaeli, 1990 (Iznik)	7.51	30.7	0.13616	274.5
7	Landers, 1992 (Amboy)	7.28	69.2	0.14608	271.4

INTENSITYMEASURES

16 different IMs (detailed in Table 4) are considered for determining the best IM for estimation of the buried pipeline response. Meaning of the used IMs is available in (Riddell, 2007).

Table 4. Intensity Measures used in the analyses

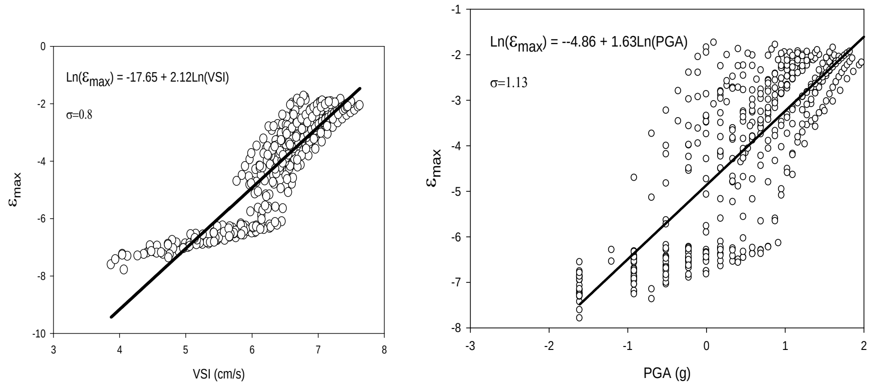
No.	Intensity measure(IM)	No.	Intensity measure(IM)
1	Peak ground acceleration, PGA	9	Cumulative absolute velocity, CAV
2	Peak ground velocity, PGV	10	Acceleration spectrum intensity, ASI
3	Peak ground displacement, PGD	11	Velocity spectrum intensity, VSI
4	PGV^2/PGA	12	Sustained maximum acceleration, SMA
5	RMS acceleration, RMS_a	13	Sustained maximum velocity, SMV
6	RMS velocity, RMS_v	14	Spectral acceleration, Sa (T_1 , 5%)
7	RMS displacement, RMS_d	15	Spectral velocity, Sv (T_1 , 5%)
8	Arias intensity, I_a	16	Spectral displacement, S_d (T_1 , 5%)

CHOSING EFFICENT IM APPROACH

Using efficient IM reduces the number of analyses and earthquake records required to estimate probability of exceeding each value of EDP given the value of IM(Luco and Cornell ,2001). The efficiency is characterized in terms of the dispersion, standard deviation of the logarithm of the residuals (quantified by σ).The residuals represent the error between the Observed value and predicted value (trend line from regression).

RESULTS AND DISCUSSION

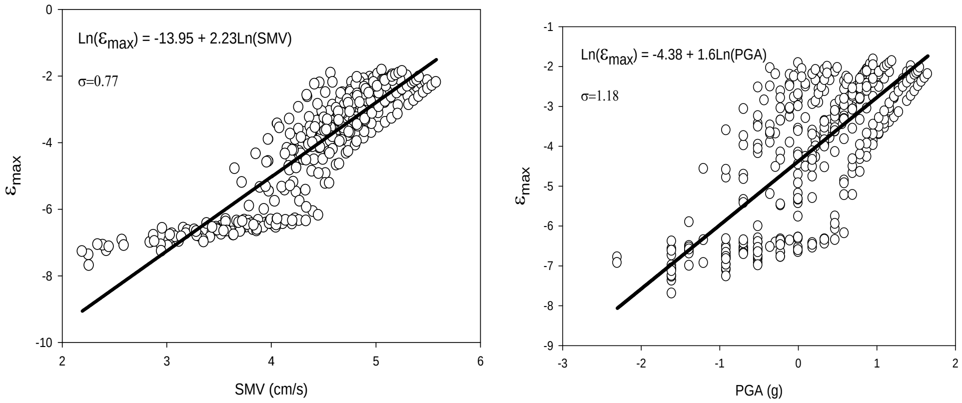
IM comparisons, the regression of ε_{max} on IM, are illustrated in figure 4to figure 7. VSI, SMV and RMSv are compared with PGA for models M1, M2 and M3, respectively. The figures represent the data and the regression fit. Dispersion of data (σ) and trend line equation areshown in the figures.



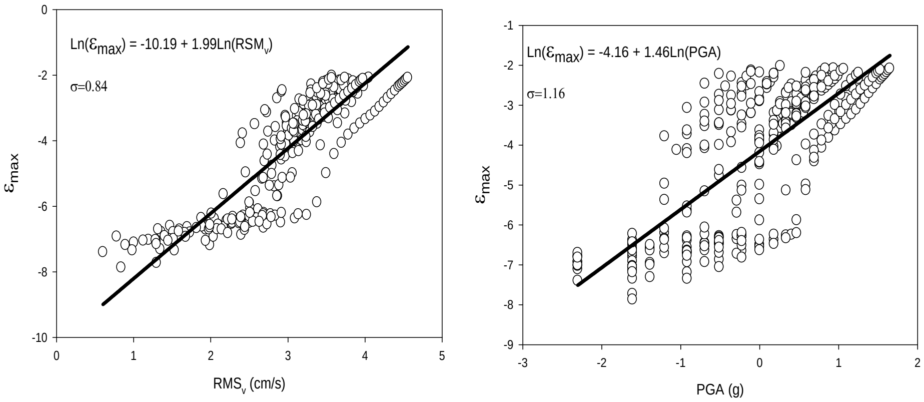
(a) Velocity spectrum intensity (VSI) (b) Peak ground acceleration (PGA)

Figure 4. Comparison of EDP-IM plots for Model1

Figure 4 represents the calculated maximum compressive strain at the critical sections of model M1for VSI and PGA intensity measures. The plot illustrates that scatter in the relationship between ε_{max} and SMV is noticeably smaller than that of ε_{max} and PGA.Values of σ for VSI and PGAis 0.8and 1.13 for Model M1, respectively. Figure 5 indicates that dispersion of SMV on ε_{max} (σ=0.77) is lower than the dispersion of PGA on ε_{max} (σ=1.18) for model M2 and therefore SMV is an efficient IM. According to Figure 6 it can be seen that RMSv with value of 0.84 for σ efficiently predict the response of model M3 as compared to PGA with much higher value of dispersion (σ=1.16).



(a) Sustained maximum velocity (SMV)(b) Peakground acceleration (PGA)
Figure 5. Comparison ofEDP-IMplotsfor Model2



(a) Velocity RMS (RMS$_v$)(b) Peakground acceleration (PGA)
Figure 6. Comparison ofEDP-IMplotsfor Model3

CONCLUSIONS

The objective of this study was to determine the IM that efficiently evaluates the seismic response of buried steel pipelines.Three buried pipeline models with different pipe and soil properties were considered and nonlinear dynamicanalyses were carried out by using far field ground motion records. The peak axial compression strain at the most critical section was employed for EDP of buried pipelines. Efficiency of investigated IMs was determined using regression analyses. For the models investigated in this study it was seen that the velocity-based intensity measures (such as VSI, SMV and RSM_v) efficiently predict the seismic response of buried steel pipelines.

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