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Time-dependent Seismic Fragility Analysis of Buried Steel Pipes in Alkaline and Near-Neutral Soil Environments

Time-dependent Seismic Fragility Analysis of Buried Steel Pipes in Alkaline and Near-Neutral Soil Environments

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Abstract. In alkaline and near-neutral soil environments, the mechanical and seismic performance of buried steel pipes degrades with deepening corrosion over time. To study the seismic fragility of buried steel pipes of different service ages in these environments, an incremental dynamic time history analysis of typical pipes was carried out with the time-varying constitutive model of steel. A probabilistic seismic demand model for buried steel pipes of different service ages in alkaline and near-neutral soil environments was then established, which can characterize the probability relationship between the ground motion intensity and structural response. Furthermore, on the basis of the tristate criteria, the limits of each ultimate failure state were determined. Time-varying seismic analytical fragility models of the pipes, including pipe units in two different soil environments and four service ages, were then established, which can characterize the probability of different failure states of structures under different earthquakes. The corresponding seismic fragility curves were then drawn. Seismic fragility curves were also obtained under three different diameter ranges based on seismic damage statistics. Results showed that, under the same ground motion, with increasing service time and decreasing pipe diameter, the probabilities of three failure states, namely, basically intact, moderately damaged, and severely damaged, all increased.

1. Introduction

Buried steel pipes are important components of lifeline systems. The history statistics of strong earthquakes at home and abroad show that earthquakes may make buried steel pipe networks fail, which will further cause huge economic losses and social problems [1]. In recent years, the frequency and intensity of earthquakes are increasing in China. However, most buried pipe networks have been in service for decades, pipeline aging and seismic performance degradation is a serious problem due to soil corrosion, so the networks are venerable to earthquakes. Seismic fragility is a key factor in earthquake risk analysis, it represents the seismic performance of structures from a probability perspective and describes the relation between ground motion intensity and structural damage degree from a macro perspective. By analyzing the seismic fragility of buried steel pipes, we can obtain the probabilities of damage degree of them under the influence of different magnitudes of earthquakes, which are important bases for their seismic performance evaluation and post-earthquake repair and reinforcement.

There have been many studies on seismic fragility analysis of buried pipelines currently. Wang Ligong [2] and Lanzano et al. [3] have made analysis on seismic fragility based on history earthquake damage data, but the factors analyzed in their research are not systematic and there are some limitations. Liu Zhi et al. [4] and Yoon et al. [5] have made theoretical analysis on seismic vulnerability based on pipeline materials, diameters, burial depths, soil and other parameters, but the impact of service age on the seismic vulnerability of buried pipelines is not considered. Yu Shurong et al. found the accumulative effect of pipeline failure increases as the increase of the pipe's service age, and its impact on failure probability also increases. Therefore, it is of great significance to make time-dependent seismic fragility analysis on buried steel pipes.

Based on related researches, this paper set up a finite element model of buried steel pipes, used 24 qualified earthquake ground motion records to perform incremental dynamic time history analysis (IDA) on buried pipelines of different service ages, established a seismic fragility model of buried steel pipelines of different service ages in alkaline and near neutral soils, and drew earthquake fragility curves correspondingly. This paper further composed earthquake vulnerability curves of buried steel pipelines of different service ages according to earthquake damage data and pattens.

2. Corrosion model of buried steel pipes

Corrosion in buried steel pipes occurs randomly. Liu Wei et al. applied Markov process to stimulate the random corrosion process in steel pipelines. Assuming probability of transition from uncorroded state to corroded state, that is state transition rate, to be q, the probability that the steel pipe corrosion occurs at the time t to be P(t), that is, the steel pipe is in an uncorroded state at time t and changes to corroded state at the time dt, then:

$$P(t) = \mathrm{e}^{-qt} q \, \mathrm{d} t \tag{1}$$

The soil environments studied in this paper is near neutral environment (6.5<pH<7.5) and alkaline environment (7.5<pH<8.5). In such environments, corrosion of steel pipes occurs relatively slowly, pipes are corroded to a lesser extent, and the corrosion generally concentrated in certain areas, so it is assumed that it is local corrosion in steel pipes. Based on related researches, assuming that it is multiple pitting corrosion, which develops independently in four directions along the pipe section. Among them, the corrosion profile along the depth direction is parabolic, then the cross-sectional corrosion rate γ of buried steel pipes and its mean value E(γ) are:

$$\gamma = \frac{A_t}{A_0} = \frac{8 v_{\mathrm{d}} v_{\mathrm{b}} (T-t)^2}{3\pi dh} \tag{2}$$

$$E(\gamma) = E(\gamma(t)) = \int_0^T \gamma(t) e^{-qt} q dt = \int_0^T \frac{8 v_d v_b (T-t)^2}{3\pi dh} e^{-qt} \cdot q dt = \frac{v_b v_d \cdot (16 - 16 e^{-qT} + 8 q^2 T^2 - 16 qT)}{3\pi dh q^2} \tag{3}$$

Where: At is the corrosion area of pipe section, mm2; A_0 is the area of the pipe section before corrosion, mm^2; T is the service age, a; t is the time when corrosion occurs, a; d is pipe diameter, mm; h is the wall thickness of the pipe, mm; v_{d} and v_{b} are the corrosion rates in the depth and radial width directions of the pipe respectively, mm/a, all values are taken according to reference.

Assuming the corrosion rate of different sections within the pipeline is the same, and that the steel density and pipeline length do not change due to corrosion, then the weight loss rate D_{w} is

$$D_{\mathrm{w}} = \frac{\rho_t A_t L_t}{\rho_0 A_0 L_0} = \frac{A_t}{A_0} \tag{4}$$

Where: ρ_0 and ρ_t are steel densities before and after corrosion; L_0 and L_t are lengths of the pipeline before and after corrosion.

From formulas (2) to (4), the relationship between weight loss rate and service age in alkaline and near neutral soils is as follows:

$$D_{\mathrm{W}} = E(\gamma) = \int_0^T \gamma(t) \mathrm{e}^{-qt} q \, \mathrm{d} t = \frac{v_{\mathrm{b}} v_{\mathrm{d}} \cdot (16 - 16 \mathrm{e}^{-qT} + 8 q^2 T^2 - 16 qT)}{3\pi dh q^2} \tag{5}$$

In addition, the degradation model of the mechanical properties of steel with the increase of weight loss rate through tensile test of corroded steel in reference is as follows:

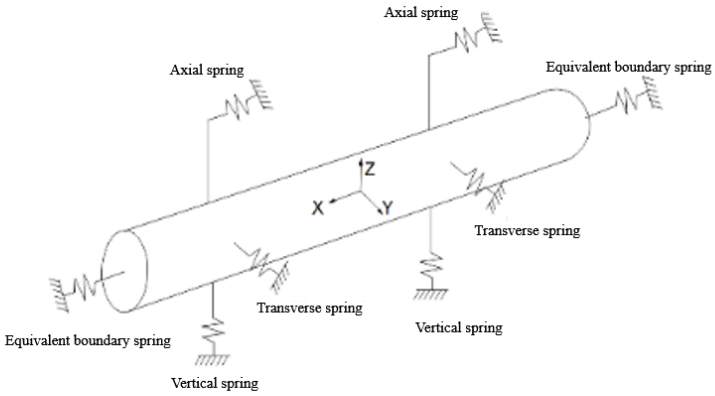
$$\begin{cases} f_{\mathrm{y}}'/f_{\mathrm{y}} = 1 - 0.983\,3D_{\mathrm{w}} \\ f_{\mathrm{u}}'/f_{\mathrm{u}} = 1 - 0.879\,1D_{\mathrm{w}} \\ \delta'/\delta = 1 - 1.778\,0D_{\mathrm{w}} \\ E'/E = 1 - 0.931\,2D_{\mathrm{w}} \end{cases} \tag{6}$$

Where: f_y, f_u, δ and E are the yield strength, ultimate strength, elongation and elastic modulus of the steel before corrosion; $f_{y'}$, $f_{u'}$, δ' and E' are the yield strength, ultimate strength, elongation and elastic modulus of the steel after corrosion.

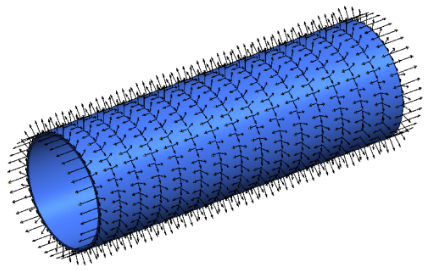
From formulas (5) and (6), a time-dependent constitutive model of corroded steel is obtained, which is applied to the seismic fragility analysis of buried steel pipelines in this paper.

3. Numerical model of buried steel pipes

Based on ANSYS finite element platform, this paper uses a evenly-distributed shell spring model to analyze the seismic response of buried steel pipes, and applies equivalent spring boundary proposed in references 8 and 9 at the ends of the shell element analysis model in a non-leaner spring form, so as to take the influence of the pipe section outside the model into consideration, shorten the selected length from the shell element, and improve calculation efficiency. The pipe-soil spring model is shown in Figure 1.



(a) Pipe-soil spring model



(b)Infinite element model

Figure 1 Pipe-soil spring model

The calculated length of the steel pipe is 15 m, the pipe diameter is 500 mm, and the wall thickness is 20 mm. Q235 steel is used, the state transition rate q = 0.2; and soil type II is used in this paper. In this paper, a 4-node shell63 element is used to simulate the pipeline, a combine39 element is used to simulate the spring, the spring elements connected in 3 directions at each node are used to simulate the interaction between the pipe and the soil, and a set of parallel springs connected axially on the nodes at both ends of the model are used as the boundary in the pipeline model analysis. The constitutive models of equivalent soil spring and equivalent spring boundary are selected according to reference 15. The constitutive model ofsteel pipes adopts the trifold-line model specified in SY/T0450-2004 "Codes for Seismic Design of Oil (Gas) Steel Pipelines". This paper only considers the degradation of the mechanical properties of buried steel pipes in service in the finite element model, that it, a time-varying constitutive model of corroded steel is adopted, and the size of the model is unchanged.

24 ground motion records recommended by the ATC-63 report were selected from the PEER ground motion database. In this paper, the IDA method is used to analyze the seismic demand of the structure. In order to take into account of the efficiency and accuracy of IDA, the unequal step amplitude modulation method is used to amplitude modulate the 24 ground motion records, and the PGA is uniformly adjusted to 0.1g, 0.2g, 0.4 g, 0.6g, 0.8g, 0.9g, 1.0g. In order to truly reflect the actual earthquake damage suffered by the buried pipelines, three-way seismic waves are input in IDA analysis, and the horizontal maximum component of ground motion is input laterally along the pipeline.

4. Seismic fragility analysis

4.1 Probabilistic seismic demand analysis

Probabilistic seismic demand analysis (PSDA) embodies the transfer process of uncertainty from ground motion to structures, and can reveal and characterize the probabilistic relationship between ground motion intensity and the response of structures. The relation between the structural seismic demand median $m_{D|\mathrm{IM}}$ and the ground motion intensity IM is as follows:

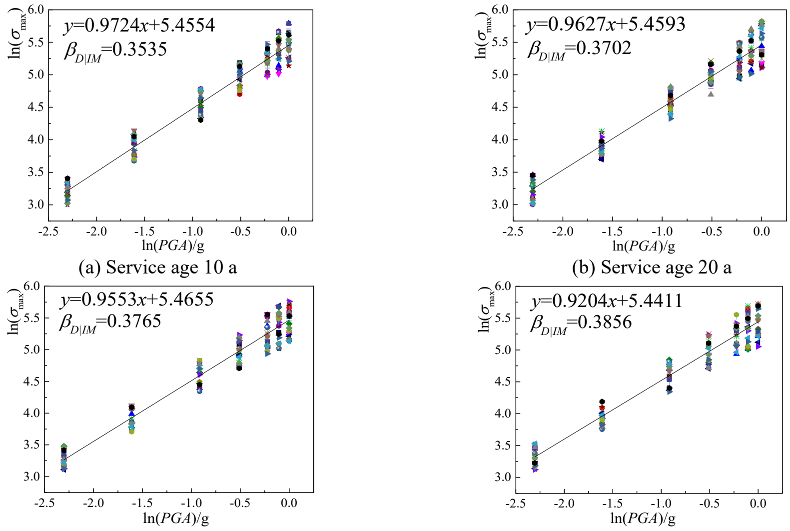
$$\ln m_{D|\mathrm{IM}} = \alpha + \beta \ln(\mathrm{IM}) \tag{7}$$

Parameters α and β are obtained from the logarithmic linear fitting of the results of the structural incremental dynamic time history analysis D_i, and the logarithmic standard deviation $\beta_{D|\mathrm{IM}}$ of the structural seismic demand D is:

$$\beta_{D|\mathrm{IM}} = \sqrt{\frac{1}{N-2}\sum_{i=1}^{N}(\ln D_i - \ln m_{D|\mathrm{IM}})^2} \tag{8}$$

Where: N is the number of data points in regression analysis.

Considering the influence of different service ages (10 a, 20 a, 30 a, 40 a), IDA analysis is performed on buried steel pipes in alkaline (7.5<pH<8.5) and near neutral (6.5<pH<7.5) soils, and the logarithmic linear regression results of the probability seismic demand model with PGA as the ground motion intensity index are obtained, as shown in Figure 2 and Figure 3.



(a) Service age 10 a (b) Service age 20 a

(c) Service age 30 a (d) Service age 40 a

Figure 2 Probabilistic seismic demand results of buried steel pipes of different service ages in alkaline soil

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Table 1 Judging standard of failure state of pipes of different service ages in alkaline soil

Service age/a	Stress threshold value (MPa)		Damage transition		
	σ_r	σ_b	Basically intact	Moderate failure	Severe failure
10	186.94	298.15	[0, 186.94)	[186.94, 298.15)	[298.15, +∞)
20	181.90	289.31	[0, 181.90)	[181.90, 289.31)	[289.31, +∞)
30	172.08	272.12	[0, 172.08)	[172.08, 272.12)	[272.12, +∞)
40	157.39	246.37	[0, 157.39)	[157.39, 246.37)	[246.37, +∞)

Table 2 Judging standard of failure state of pipes of different service ages in near-neutral soil

Service age /a	Stress threshold value/MPa		Damage transition		
	σ_r	σ_b	Basically intact	Moderate failure	Severe failure
10	187.80	299.65	[0, 187.80)	[187.80, 299.65)	[299.65, +∞)
20	186.85	297.99	[0, 186.85)	[186.85, 297.99)	[297.99, +∞)
30	185.01	294.76	[0, 185.01)	[185.01, 294.76)	[294.76, +∞)
40	182.24	289.92	[0, 182.24)	[182.24, 289.92)	[289.92, +∞)

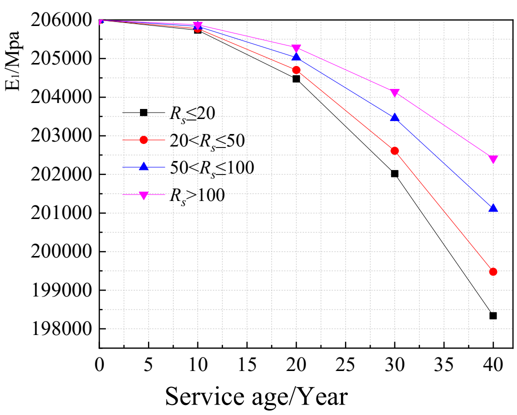


Figure 3 Relationship between elastic modulus and service age

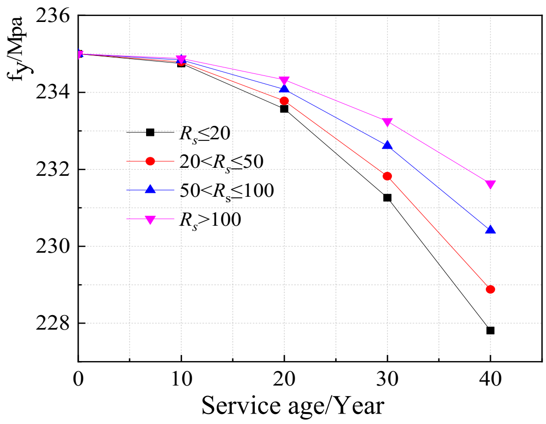


Figure 4 Relationship between yield strength and age

4.2 Analytical model of seismic fragility

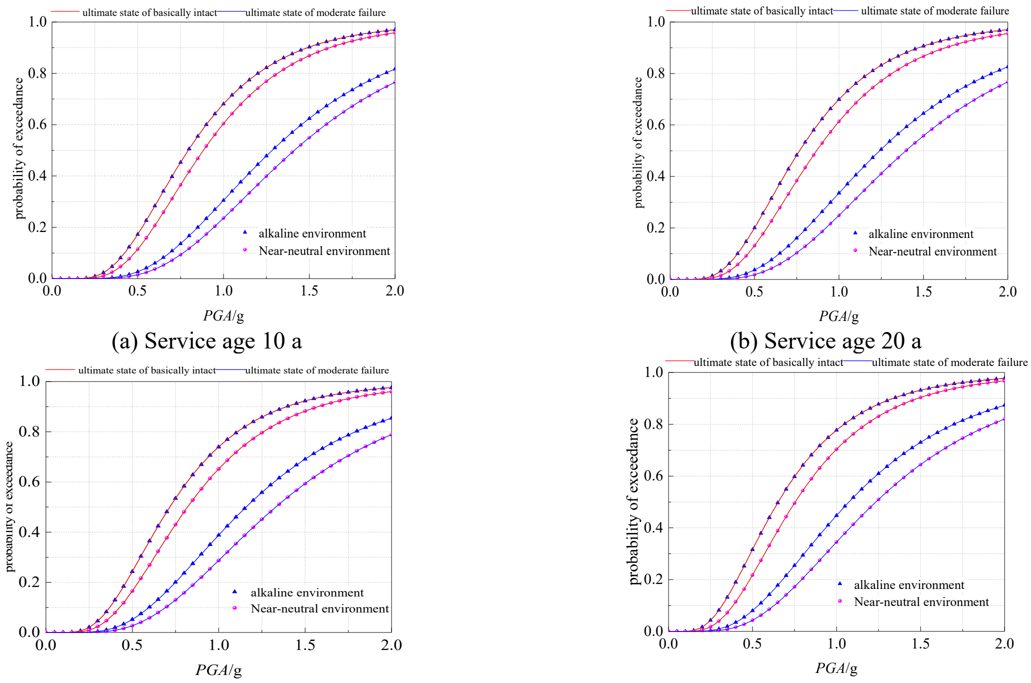
The analytical model of seismic fragility is:

$$F_R(x) = \Phi\left[\frac{\ln(m_{D|\mathrm{IM}}) - \ln(m_C)}{\sqrt{\beta_{D|\mathrm{IM}}^2 + \beta_C^2 + \beta_M^2}}\right] \tag{9}$$

Where: $F_R(x)$ is seismic fragility function; $m_{D|\mathrm{IM}}$ is the median value of the seismic demand D of the structure under a certain seismic intensity level; m_C is the average value of the seismic capacity of the structure in different limit states C, and the values are taken based on Table 1 and Table 2; $\beta_{D|\mathrm{IM}}$ is the uncertainty of the seismic demand, which is derived from formula (8); β_C is the uncertainty of the seismic capacity of the structure, taking $\beta_C = 0.25$; β_M is the modeled uncertainty, taking $\beta_M = 0.2$.

4.2.1 Seismic fragility of buried steel pipes of different ages in different soils

Substituting the probabilistic seismic demand analysis results of buried steel pipes of different service ages in alkaline and near-neutral soil environments, the standard value of the failure state of the structure and the quantitative results of uncertainty into equation (9), the time-varying seismic fragility curves of buried steel pipes of different service ages in the alkaline and near-neutral soil corrosion environment of 500 mm in the soil type II are shown in Figure 5.



(a) Service age 10 a (b) Service age 20 a

(c) Service age 30 a (d) Service age 40 a

Figure 5 Seismic fragility curves of buried steel pipes of different ages in alkaline and near-neutral soils

Comparing the seismic fragility curves of buried steel pipes with different service ages (10 a, 20 a, 30 a, 40 a) in alkaline and near-neutral soil corrosion environments in Figure 5, it can be found that under the same seismic intensity, there are significant differences in the probability of different damage states occurring in different soil environments, and the probability of steel damage increases as the service age increases.

5. Conclusions

(1) Based on random corrosion process, setting up a local corrosion model of buried steel pipes in alkaline and near-neutral soil environments; obtaining a time-varying constitutive model of corroded steel based on the relation between the weight loss rate and mechanical property degradation of steels; based on numerical simulation, performing IDA on buried steel pipes and setting up a probabilistic seismic demand model of pipes with different service ages in alkaline and near-neutral soil environments.

(2) Taking the equivalent stress as the engineering requirement parameter and based on the three-state failure criterion of the pipeline, the limits of each ultimate failure state of the steel pipes of different service ages in alkaline and near-neutral soil environments are determined.

(3) Combining the results of probabilistic seismic demand analysis and the quantitative results of judging standard for the failure states of steel pipes, establishing a time-varying seismic fragility model of buried steel pipes with different service ages in different soil environments, and composing the time-varying seismic fragility curves correspondingly. Combing the empirical statistics of seismic damage, composing the time-varying seismic fragility curves of buried steel pipes with different diameters.

(4) Comparing the seismic fragility curves, it can be found that in alkaline and near-neutral soil environments, the exceeding probabilities of buried steel pipes in ultimate damage states under the same ground motion increase as the service age increases and the diameter decreases.

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References
[1] Guo Endong, Yu Shizhou, Wu Wei.(2006) Seismic damage analysis of buried pipeline engineering. Earthquake Engineering and Engineering Vibration, 26(3): 180-183.
[2] Wang Ligong. (1985) Principal pipeline vulnerability analysis and prediction of earthquake hazards for water supply system in Xuzhou urban districts. North China Earthquake Sciences, 3(1): 38-46 .
[3] Lanzano G, Salzano E, Santucci de Magistris F, et al. (2014) Seismic vulnerability of gas and liquid buried pipelines. Journal of Loss Prevention in the Process Industries, 28: 72-78.
[4] Liu Zhi, Guo Endong, Hu Shaoqing, et al. (2013) Seismic vulnerability analysis of heat supply pipeline. Engineering Mechanics, 30(7): 187-192.
[5] Yoon Sungsik, Lee Do Hyung, Jung Hyung Jo. (2019) Seismic fragility analysis of a buried pipeline structure considering uncertainty of soil parameters. International Journal of Pressure Vessels and Piping, 175: 103932.