

Earthquake damage estimation of gas continuous buried pipelines

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Abstract. The semi-empirical and semi-theoretical method is adopted to simulate the response of gas continuous buried pipelines subjected to seismic wave propagation. Using the peak ground velocity (PGV) as the intensity measure, the maximum axial responses (strain or stress) of pipelines are calculated. The seismic safety factor is employed as earthquake damage index of a pipeline and the relation between earthquake damage index and earthquake damage level is presented to determine the earthquake damage level with respect to seismic intensity. The weighted statistical average method is introduced to estimate the earthquake damage indexes and earthquake damage states of pipeline network under different seismic intensities. According to the results of numerical example, it is concluded that the improved method is effective and practical.

Introduction

The earthquake damages of historical earthquake show that the lifeline systems, such as water, gas, transportation, electricity and communication, etc., are highly vulnerable, particularly the buried pipeline networks are often severely damaged when subjected to strong ground motion [1-6]. The gas leakage, caused by earthquake-induced damage to pipeline, may lead to serious secondary disasters, such as fire, explosion. They are the serious threats to the safety of resident's life and property, the social order of normal production and life, and the normal usage function of other lifeline systems and buildings and structures, and they greatly increase the difficulties of rehabilitation, post-earthquake relief and reconstruction. Therefore, it is of great necessary to evaluate the seismic performance or earthquake damage levels of gas pipeline network with respect to different seismic intensities.

The study on methods of earthquake damage estimation for buried pipeline network, which can be applied to pre-earthquake prediction and post-earthquake estimation of earthquake damage, are always among the research focuses of lifeline aseismic engineering [7-16]. Since the late 1960s when Newmark [10] and Sakurai and Takahashi [11] presented their simplified analytical methods for evaluating the response of a pipeline surrounded by an infinite elastic media, many estimation methods for the earthquake damage levels of buried pipelines, such as theoretical analysis methods, empirical statistics methods and hybrid methods combining theoretical analysis with empirical statistics based on earthquake damages [17], are proposed and extended by lots of researchers during the last five decades.

The purpose of this study is to investigate the damage levels for gas continuous buried pipelines with different seismic intensities subject to seismic wave propagation. The semi-empirical and semi-theoretical method is used for calculating the maximum axial strain or stress of a pipeline. And the seismic safety factor is employed as earthquake damage index of a pipeline. The weighted statistical average method is introduced to give the earthquake index and then determine the damage states of the pipeline network.

Semi-Empirical and Semi-Theoretical Method

The stress of a buried pipeline due to seismic wave propagation is mainly induced by the relative displacement of the surrounding soil, and the effect of inertia force could be neglected. To the strain response of pipeline, the axial strain is bigger than others [13]. By ignoring the sliding at soil-pipe interface, the simplified analysis method to wave propagation assumes that the strain of pipeline is equal to the free field strain.

If the seismic wave is keeping the shear wave in the propagation process, the displacement of free field is

$$u = f(x + c_s t) \sin \theta, \quad (1)$$

where u represents the displacement of free field in the axial direction of pipeline; x is the distance of wave propagation in the propagation direction; c_s is the shear wave velocity; t is the time of wave propagation; $f(\cdot)$ is the displacement function; θ is the intersection angle between the axial direction of pipeline and the propagation direction of seismic wave.

The free field strain in the axial direction of pipeline is derived as

$$\varepsilon(t) = \frac{V(t)}{2c_s} \sin(2\theta), \quad (2)$$

where $\varepsilon(t)$ is the axial strain of pipeline; $V(t)$ is the velocity of free field. If $\theta = 45^\circ$, the maximum strain of free field in the axial direction of pipeline is

$$\varepsilon_{\max} = \frac{V_{\max}}{2c_s}, \quad (3)$$

where ε_{\max} is the maximum strain of free field in the axial direction of pipeline; V_{\max} is the maximum velocity of free field, or peak ground velocity (PGV).

Actually, there is a certain slip at soil-pipe interface due to stiffness' remarkable difference between pipeline and soil. A conversion factor should be defined so as to account for the relation between the maximum strain of pipeline and soil in the axial direction of pipeline. The maximum axial strain of pipeline is expressed as

$$\varepsilon_{p \max} = \zeta \varepsilon_{\max}, \quad (4)$$

where $\varepsilon_{p \max}$ is the maximum axial strain of pipeline; ζ is the conversion factor obtained from empirical statistics method, and has the following expression,

$$\zeta = \frac{1}{1 + \left(\frac{2p}{L}\right)^2 \frac{EA}{K_1}}, \quad (5)$$

$$A = p(D + t)t, \quad (6)$$

$$L = c_s T_g, \quad (7)$$

$$K_1 = p(D + 2t)k_1, \quad (8)$$

where E is the elastic modulus of pipeline material, $\text{MPa} = \text{N}/\text{mm}^2$; A is the cross-sectional area of pipeline, mm^2 ; D is its inner diameter, mm ; t is its wall thickness, mm ; L is the shear wave length, mm ; c_s is the shear wave velocity at the depth of pipeline, mm/s ; T_g is the characteristic period of the site of buried pipeline, s ; K_1 is the soil resistance per unit length in axial direction, N/mm^2 ; k_1 is the soil resistance per unit area in axial direction, and obtained from experiment or assigned to 0.06 without experimental data, N/mm^3 .

For the safety requirement of gas supply system, the elastic constitutive relation is adopted for the continuous steel pipeline. So the maximum axial stress of pipeline is

$$\sigma_{p \max} = E \varepsilon_{p \max}, \quad (9)$$

where $\sigma_{p \max}$ is the maximum axial stress of pipeline.

In this paper, the seismic safety factor is employed as earthquake damage index of a pipeline. So the earthquake damage index has the following expression,

$$DI = d \frac{R}{kS}, \quad (10)$$

where DI is the earthquake damage index of a pipeline; R is the allowable stress or strain of pipeline material, k is its safety factor and $k = 1.0-1.5$; S is the maximum stress or strain of the pipeline, d is the reduction factor for the current status of the service pipeline and $d = 0.5-1.0$.

In order to evaluate the qualitative damage states of a relatively independent pipeline network, the weighted statistical average method is introduced to give a quantitative index, the earthquake index of the pipeline network with the following formula,

$$DN = \frac{\sum_{i=1}^n L_i DI_i}{\sum_{i=1}^n L_i}, \quad (11)$$

where DN is the earthquake damage index of pipeline network; DI_i is the earthquake damage index of the i th pipeline; L_i is the length of the i th pipeline; n is the total number of pipelines. The relation between earthquake damage index and earthquake damage level is denoted in Table 1.

Table 1 Relation between earthquake damage index and earthquake damage level

EDI	$DNI \geq 1$	$0.9 \leq DNI < 1$	$0.7 \leq DNI < 0.9$	$0.5 \leq DNI < 0.7$	$DNI < 0.5$
EDL	Intact	Slight damage	Moderate damage	Severe damage	Destroy

Note: DNI represents DN or DI . EDI and EDL represents earthquake damage index and level.

Numerical Example

The relatively independent zone of gas pipeline network for this study is selected from a western city of China. All thirty-two main pipelines are continuous buried steel pipes, and their properties and engineering data were obtained, as summarized in Table 2. The yield stress of steel material is used as its ultimate stress. According to the seismic microzoning report, the site type is type II, the average value of measured shear velocity c_s in 3 m depth of surface soil is about 200 m/s and the characteristic period T_g of the site of buried pipeline is 0.45 s, as detailed in Table 3. The safety factor k , the reduction factor for the current status of the service pipeline d and the soil resistance per unit area in axial direction k_1 are shown in Table 3. For evaluating the earthquake damage level, PGV in respect of seismic intensity are denoted in Table 4.

Table 2 Properties and engineering data of gas pipeline

No.	Material	Material type	Elastic modulus E [MPa]	Yield stress σ_s [MPa]	Outer diameter D [mm]	Wall thickness τ [mm]	Length L [m]
1	Steel	L290	210000.00	290.00	355.00	8.00	6614.00
2	Steel	20#	210000.00	245.00	219.00	6.00	4580.00
3	Steel	20#	210000.00	245.00	219.00	6.00	962.00
4	Steel	20#	210000.00	245.00	219.00	6.00	2187.00
5	Steel	20#	210000.00	245.00	219.00	6.00	1320.00
6	Steel	20#	210000.00	245.00	114.00	3.50	334.00
7	Steel	20#	210000.00	245.00	89.00	3.00	1242.00
8	Steel	20#	210000.00	245.00	89.00	3.00	848.00
9	Steel	20#	210000.00	245.00	250.00	6.00	2005.00
10	Steel	20#	210000.00	245.00	89.00	3.00	568.00
11	Steel	20#	210000.00	245.00	250.00	6.00	960.00
12	Steel	20#	210000.00	245.00	114.00	3.50	31.00
13	Steel	20#	210000.00	245.00	114.00	3.50	1051.00

14	Steel	20#	210000.00	245.00	114.00	3.50	886.00
15	Steel	20#	210000.00	245.00	114.00	3.50	502.00
16	Steel	20#	210000.00	245.00	114.00	3.50	526.00
17	Steel	20#	210000.00	245.00	114.00	3.50	824.00
18	Steel	20#	210000.00	245.00	114.00	3.50	635.00
19	Steel	20#	210000.00	245.00	219.00	6.00	4280.00
20	Steel	20#	210000.00	245.00	114.00	3.50	4538.00
21	Steel	20#	210000.00	245.00	114.00	3.50	1736.00
22	Steel	20#	210000.00	245.00	114.00	3.50	1574.00
23	Steel	20#	210000.00	245.00	114.00	3.50	570.00
24	Steel	20#	210000.00	245.00	114.00	3.50	950.00
25	Steel	20#	210000.00	245.00	114.00	3.50	556.00
26	Steel	20#	210000.00	245.00	114.00	3.50	789.00
27	Steel	20#	210000.00	245.00	114.00	3.50	1190.00
28	Steel	20#	210000.00	245.00	219.00	6.00	2125.00
29	Steel	20#	210000.00	245.00	114.00	3.50	2580.00
30	Steel	20#	210000.00	245.00	114.00	3.50	1974.00
31	Steel	20#	210000.00	245.00	114.00	3.50	1843.00
32	Steel	20#	210000.00	245.00	114.00	3.50	1385.00

Table 3 Parameters used in this study

Site type	c_s [m/s]	T_g [s]	k_1 [N/mm ³]	k	δ
II	200	0.45	0.06	1.4	0.6

Table 4 PGV with respect to seismic intensity

Seismic intensity	VI	VII	VIII	IX	X		
PGA [g]	0.05	0.10	0.15	0.20	0.30	0.40	0.80
PGV [mm/s]	60	130	195	250	375	500	1000

The maximum stress and corresponding earthquake damage index of each pipeline are calculated using Eq. 9 and Eq. 10, and the values of earthquake damage index are shown in Table 5. And the earthquake damage index values of gas pipeline network are calculated using Eq. 11, as denoted in Table 6.

Table 5 Earthquake damage index of each gas pipeline (*DI*)

No.	Seismic intensity						
	VI(0.05g)	VII(0.10g)	VII(0.15g)	VIII(0.20g)	VIII(0.30g)	IX(0.40g)	X(0.80g)
1	4.51	2.08	1.39	1.08	0.72	0.54	0.27
2	3.69	1.71	1.14	0.89	0.59	0.44	0.22
3	3.69	1.71	1.14	0.89	0.59	0.44	0.22
4	3.69	1.71	1.14	0.89	0.59	0.44	0.22
5	3.69	1.71	1.14	0.89	0.59	0.44	0.22
6	3.55	1.64	1.09	0.85	0.57	0.43	0.21
7	3.53	1.63	1.09	0.85	0.56	0.42	0.21
8	3.53	1.63	1.09	0.85	0.56	0.42	0.21
9	3.70	1.71	1.14	0.89	0.59	0.44	0.22
10	3.53	1.63	1.09	0.85	0.56	0.42	0.21
11	3.70	1.71	1.14	0.89	0.59	0.44	0.22
12	3.55	1.64	1.09	0.85	0.57	0.43	0.21
13	3.55	1.64	1.09	0.85	0.57	0.43	0.21

14	3.55	1.64	1.09	0.85	0.57	0.43	0.21
15	3.55	1.64	1.09	0.85	0.57	0.43	0.21
16	3.55	1.64	1.09	0.85	0.57	0.43	0.21
17	3.55	1.64	1.09	0.85	0.57	0.43	0.21
18	3.55	1.64	1.09	0.85	0.57	0.43	0.21
19	3.69	1.71	1.14	0.89	0.59	0.44	0.22
20	3.55	1.64	1.09	0.85	0.57	0.43	0.21
21	3.55	1.64	1.09	0.85	0.57	0.43	0.21
22	3.55	1.64	1.09	0.85	0.57	0.43	0.21
23	3.55	1.64	1.09	0.85	0.57	0.43	0.21
24	3.55	1.64	1.09	0.85	0.57	0.43	0.21
25	3.55	1.64	1.09	0.85	0.57	0.43	0.21
26	3.55	1.64	1.09	0.85	0.57	0.43	0.21
27	3.55	1.64	1.09	0.85	0.57	0.43	0.21
28	3.69	1.71	1.14	0.89	0.59	0.44	0.22
29	3.55	1.64	1.09	0.85	0.57	0.43	0.21
30	3.55	1.64	1.09	0.85	0.57	0.43	0.21
31	3.55	1.64	1.09	0.85	0.57	0.43	0.21
32	3.55	1.64	1.09	0.85	0.57	0.43	0.21

Table 6 Earthquake damage index of gas pipeline network (*DN*)

SI	VI(0.05g)	VII(0.10g)	VII(0.15g)	VIII(0.20g)	VIII(0.30g)	IX(0.40g)	X(0.80g)
<i>DN</i>	3.72	1.72	1.15	0.89	0.60	0.45	0.22

Note: SI-seismic intensity; DN-earthquake damage index.

Results and Discussion

According to Table 1, Table 5 and Table 6, the seismic damage levels of each gas pipeline and pipeline network are presented under different seismic intensities, as denoted in Table 7 and Table 8, respectively.

Table 7 Estimated results of each gas pipeline

No.	Seismic intensity						
	VI(0.05g)	VII(0.10g)	VII(0.15g)	VIII(0.20g)	VIII(0.30g)	IX(0.40g)	X(0.80g)
1	Intact	Intact	Intact	Intact	Moderate	Severe	Destroy
2	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
3	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
4	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
5	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
6	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
7	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
8	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
9	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
10	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
11	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
12	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
13	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
14	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
15	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
16	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
17	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy

18	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
19	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
20	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
21	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
22	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
23	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
24	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
25	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
26	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
27	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
28	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
29	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
30	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
31	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy
32	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy

Table 8 Estimated results of gas pipeline network

SI	VI(0.05g)	VII(0.10g)	VII(0.15g)	VIII(0.20g)	VIII(0.30g)	IX(0.40g)	X(0.80g)
EDL	Intact	Intact	Intact	Moderate	Severe	Destroy	Destroy

Note: EDL-earthquake damage level.

Individual Pipeline. It can be seen from Table 7, the seismic damage levels of all of the individual pipelines are intact with respect to seismic intensity in grade VI and VII, ones of virtually all of the pipelines other than pipeline 1 are moderate damage, severe damage and destroy under seismic intensity in grade VIII (PGA=0.20g), VIII (PGA=0.30g) and IX respectively, and ones of all of the pipelines are destroy to seismic intensity in grade X. The estimated results show that pipeline 1 has better seismic performance and the seismic design of the pipelines meets the demands of the city with fortification intensity in grade VII. The results can be useful for gas engineers.

Pipeline Network. From Table 8, it can be seen that the seismic damage levels of the pipeline network are intact, intact, intact, moderate damage, severe damage, destroy and destroy in respect of seismic intensity in grade VI, VII (PGA=0.10g), VII (PGA=0.15g), VIII (PGA=0.20g), VIII (PGA=0.30g), IX and X. The results show a very good agreement with the conclusions of the earthquake site investigation of pipeline network in higher seismic intensity (VIII, IX and X). The results will provide the reference information for the government decision makers and the public.

Conclusions

To improve the earthquake damage estimation method of gas continuous buried pipelines, the semi-empirical and semi-theoretical method subjected to seismic wave propagation is used, and the weighted statistical average method is introduced to calculate the earthquake damage index of pipeline network from the estimated results of all of the individual pipelines. And the relationship between earthquake damage index and earthquake damage level is presented in this study. The results of numerical example show that the improved method for earthquake damage estimation of gas buried pipelines and pipeline network is effective and practical.

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