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Discussions

Seismic behavior of buried pipelines constructed by design criteria and construction specifications of both Korea and the US

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Abstract

Lifeline damage induced by earthquake loading not only causes structure damage but also communication problems resulting from the interruption of various energy utilities such as electric power, gas, and water resources. Earthquake loss estimation systems in the US, for example HAZUS (Hazard in US), have been established for the purpose of prevention and efficient response to earthquake hazards. Sufficient damage records obtained from earthquakes are required to establish these systems, however, in Korea, insufficient data sets of damage records are currently available. In this study, according to the design criteria and construction specifications of pipelines in Korea and the US, the behavior of both brittle and ductile pipelines embedded in dense sand overlying various in-situ soils, such as clay, sand, and gravel, were examined and compared with respect to the mechanical characteristics of pipelines under various earthquake loadings.

1 Introduction

Buried pipelines, one example of lifelines, have not been damaged by previous earthquakes in Korea. However vibrations of the ground and buildings were perceived by people living in both Busan and Masan, located in the southern part of Korea, during the 2005 Fukuoka earthquake which occurred in Japan. In recent years, earthquakes have become frequent in Korea and thus the behavior of buried pipelines subjected to seismic loading should be carefully examined.

A simplified quasi-static seismic deformation analysis for buried pipelines subjected to earthquake loadings was carried out to examine the effects of seismic parameters and found that the behavior of buried pipeline was dominantly influenced by the time delay of seismic waves and the non-uniformity of soil resistance (Wang and Cheng, 1979). A three dimensional quasi-static numerical analysis of continuous or jointed pipelines subject to large ground deformations or seismic ground motions has also been developed (Takada and Tanabe, 1987). The wave propagation hazard for a particular site is characterized by the peak ground motion parameters as well as the appropriate propagation velocities. The ground strain and curvature due to wave propagation were analyzed and the influence of various subsurface conditions on ground strain was discussed (O'Rourke and Liu, 1999). Transient ground strains are recognized to govern the response of buried elongated structures, such as pipelines and tunnels, under seismic wave propagation. The shear strain and the longitudinal strain variability with depth were investigated through qualitative examples and comparisons with analytical formulas (Scandella and Paolucci, 2010). In Korea, earthquake time-history analyses were performed for a buried gas pipeline using various parameters such as the type of buried gas pipeline, end restrain conditions, soil characteristics, single and multiple earthquake input ground motions, and burial depths (Lee et al., 2009).

Buried pipeline damage correlations are a critical component of loss estimation procedures applied to lifelines expected to experience future earthquakes. Buried pipelines are damaged by transient ground motions and permanent ground deformation. Pipeline damage induced by wave propagation for relatively flexible pipe materials was found to be somewhat less than damage of relatively brittle material (O'Rourke and Ayala, 1993). Permanent ground deformation and its effect on pipelines has been extensively investigated (O'Rourke et al., 1998), especially in countries of high seismicity. During representative earthquakes, including the Loma Prieta earthquake in 1989, buried pipelines were damaged mostly in landfill areas by means of joint pullout failures and pipeline cracking. In addition to these damage patterns, artificial connections between relatively rigid pipelines and largely deformable plastic pipe experienced damage during the Kobe earthquake in 1995. Trunk pipeline damage and cracks in the axial direction of concrete pipelines were assessed. Pipeline repair rates following the 1994 Northridge earthquake were evaluated and explained (Jeon, 2002; Jeon and O'Rourke, 2005).

Seismic fragility analysis of underground polyvinyl chloride (PVC) pipelines was performed and demonstrated that there was no significant difference between the analyses results and the empirical equation used by HAZUS (Hazard in US), earthquake loss estimation software developed by the Federal Emergency Management Agency (Shih and Chang, 2006). Pipeline damage was estimated for each damage relationship and earthquake scenario. The results show that the variation in ductile pipeline damage estimations by various relationships was higher than the variation in brittle pipeline damage estimations for a particular scenario earthquake (Toprak and Taskin, 2007). A new seismic intensity parameter utilizing peak ground velocity (PGV) and peak ground acceleration (PGA) to estimate damage in buried pipelines due to seismic wave propagation was proposed (Pineda-Porras and Ordaz, 2007).

The probability of system serviceability was estimated as the ratio of the number of networks that were found to be serviceable to the sample size used for simulation. The water transmission network was adopted and analyzed to serve as a numerical example demonstrating how to assess the probabilities of system unserviceability under a set of assumed parameter values deemed reasonable (Tan and Chen, 1987). A decision support system for the management of geotechnical and environmental risks in oil pipelines was developed using GIS (Filho et al., 2010).

Historical data and recorded data sets after 1905 show that Korea is in a zone of low to medium seismicity but it has a high frequency of earthquake occurrences. In this study, pipelines were classified by their mechanical properties followed by a numerical analysis which examined the behavior of the buried pipelines constructed by the design criteria and construction specifications of Korea and the US. The analysis considered seismic parameters including PGA achieved from previous earthquake records, pipeline types, and in-situ ground conditions.

2 Repair rate of pipelines

The damages of water pipelines in HAZUS were assessed by historical data of pipeline repairs from previous earthquakes. As shown in Fig. 1, the algorithm of RR for brittle and ductile pipelines in HAZUS was developed by O'Rourke and Ayala (1993). They developed the empirical relationship of RR with peak ground velocity (PPV) based on the damage reports of the pipelines from previous earthquakes (FEMA, 1999).

Since the mechanical characteristics of pipelines, design criteria, and construction specifications of both Korea and the US are very similar, the pipeline damages induced by seismic loadings in Korea has been predicted by repair rate (pipeline repairs/pipeline length (km)), RR, suggested in HAZUS. As the seismic loading was applied to buried pipelines constructed based on the design criteria and construction specifications in Korea and the US, the mobilized stresses and strain rates of pipelines were examined and compared.

As listed in Table 1, buried utilities in Korea, including water, gas, and communication pipelines, were classified into two categories; ductile and brittle (Ministry of Environment, 2010a, b).

3 Design criteria and construction specifications

The burial depth, the backfill compaction ratio, and the diameter and thickness of pipelines listed on the construction specifications were used in a numerical analysis to examine the dynamic behavior of pipelines as seismic loading was applied.

3.1 Korea

As listed in Table 2, the burial depths, considering traffic loading, should be greater than 1.2 and 1.5 m for the 900- and 1000-mm diameter pipelines, respectively (Ministry of Land, Transport, and Maritime Affairs, 2010). The burial depth for large diameter pipelines should be greater than their diameter but, in the case that a burial depth of 1.2 m is not available due to spatial constraints associated with adjacent underground structures, the burial depth can be reduced to 0.6 m with permission from the officer in charge of roadway management.

3.2 The US

Table 3 lists the specifications for the burial depth of pipelines with respect to construction sites where there are no special conditions (Office of Pipeline Safety Community (OPS), 2010). Pipeline burial depth should be greater than the frozen ground depth or frost line. High quality soil is used as backfill material for buried pipelines. Each layer of backfill should have a thickness less than 0.3 m and a compaction ratio of greater than 90 %. At important construction sites, the water content of backfill materials should be around the optimum water content and at most 0.2-m lifts with high compaction ratios are required. Sands used as trench backfill material should have a high compaction ratio with moisture near the optimum water content and the use of soil lifts is recommended.

Lift thickness of 20 to 50 % of the minimum diameter of a pipeline are required in Korea. A lift thickness corresponding to one-eighth of the minimum diameter of the pipeline or 100 mm is required in the US.

4 Evaluating dynamic behavior of the pipeline using numerical analysis

In this study, a numerical analysis using the commercial finite element software ABAQUS (2006) was carried out to analyze the dynamic behavior of pipelines subjected to seismic loading. The analyses results show the strain rates and stresses of buried pipelines constructed by the design criteria and construction specifications suggested by both Korea and the US. The applied seismic loadings were generated from real PGV time records measured at strong motion stations (SMSs) No. 24436 and CHY080 for the 1994 Northridge and 1999 Chi-Chi earthquakes, respectively. Figures 2 and 3 show the measured PGV time records of Northridge and Chi-Chi earthquakes, respectively (COSMOS, 2010). In addition to these, the virtual values of various PGAs, such as 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 g, at a period of 0.5 s and earthquake duration of 10 s were applied as seismic loadings.

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4.1 Numerical modeling

The numerical analyses for brittle and ductile pipelines greater than 1000-mm diameter and constructed based on the design criteria and construction specifications of both Korea and the US were carried out. Since a compaction ratio of 90 % for backfill materials is required in both countries, dense sand soil properties were used. The analyses were performed considering various in-situ ground conditions such as clay, loose sand, medium dense sand, dense sand, and sand with gravels. In Korea, the diameter and thickness of the brittle and ductile pipelines used in the analyses were 1050 and 75 mm and 1130 and 16 mm, respectively. For the US, these values were 1058 and 75 mm and 1144 and 16 mm, respectively.

Figures 4 and 5 show the configuration and finite difference meshes of numerical analysis associated with pipeline, ground conditions, and boundary conditions. The figure shows an in-situ ground depth of 30.5 m with a width of 120 m. No horizontal displacements are allowed at the left and right sides and no horizontal nor vertical displacements are allowed at the bottom. In Korea and the US, pipeline cover depths (h_{B1}) of 1.5 m and 0.9 m and thickness of bedding beneath pipelines (h_{B2}) of 0.25 m and 0.15 m, respectively, were used in numerical analysis. Tables 4 and 5 list the mechanical properties of the soils and pipelines, respectively.

4.2 Dynamic behavior of the pipeline

4.2.1 Ductile pipeline

Figure 6 shows the maximum mobilized stress for ductile pipeline subjected to various ground conditions. As shown in the figure, the mobilized stress in pipelines linearly increases as PGA increases and ground stiffness decreases. The mobilized stress of pipelines in Korea relative to the US is slightly smaller. Differences mobilized along the pipelines range from 4.7 to 11.3 %, 4.7 to 11.8 %, 4.7 to 10.1 %, 2.6 to 11.7 %, and 3.9

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to 10.7 % for in-situ ground conditions of clay, loose sand, medium dense sand, dense sand, and dense sand with gravels, respectively.

Figure 7 shows the maximum strain mobilized on ductile pipelines for various ground conditions. As shown in the figure, the strain rate mobilized along the pipelines increases as PGA increases and ground stiffness decreases. The strain rate of pipeline in Korea relative to the US is slightly higher. The strain rates differ from 6.4 to 8.9 %, 7.4 to 9.8 %, 4.8 to 9.7 %, 3.5 to 9.1 %, and 4.5 to 8.8 % for in-situ ground conditions of clay, loose sand, medium dense sand, dense sand, and dense sand with gravels, respectively. As the seismic loadings of Northridge and Chi-Chi earthquakes were applied, the mobilized pipeline strains were 1.9 and 4.5 %, respectively.

4.2.2 Brittle pipeline

Figure 8 shows the maximum mobilized stress for brittle pipeline subjected to various ground conditions. As shown in the figure, stresses in pipelines linearly increases as PGA increases and ground stiffness decreases. The mobilized stress of pipelines in Korea, relative to the US, is slightly smaller. Stress differences mobilized along pipelines range from 4.2 to 9.3 %, 4.4 to 9.3 %, 4.7 to 7.8 %, 4.7 to 9.1 %, and 4.9 to 8.2 % for in-situ ground conditions of clay, loose sand, medium dense sand, dense sand, and dense sand with gravels, respectively.

Figure 9 shows the maximum mobilized strain for brittle pipeline subjected to various ground conditions. As shown in the figure, strain rates mobilized along pipeline increases as the PGA increases and ground stiffness decreases. Pipeline strain rate in Korea relative to the US is smaller. Strain differences mobilized along pipelines range from 3.8 to 8.5 %, 3.0 to 9.9 %, 2.8 to 8.9 %, 2.2 to 9.9 %, and 4.5 to 9.8 % for in-situ ground conditions of clay, loose sand, medium dense sand, dense sand, and dense sand with gravels, respectively. As the seismic loadings of Northridge and Chi-Chi earthquakes were applied, the generated strains were 6.5 and 3.8 %, respectively.

Tables 6 and 7 present the differences of the strain and stress, calculated by using Eqs. (1) and (2), respectively.

$$\varepsilon_{diff} = \frac{\varepsilon_k - \varepsilon_u}{\varepsilon_k} \times 100(\%) \quad (1)$$

$$\sigma_{diff} = \frac{\sigma_k - \sigma_u}{\sigma_k} \times 100(\%) \quad (2)$$

where,

ε_{diff} = difference of strain mobilized in Korea and US pipelines,

ε_k = strain mobilized in Korea pipeline,

ε_u = strain mobilized in US pipeline

σ_{diff} = difference of stress mobilized in Korea and US pipelines,

σ_k = stress mobilized in Korea pipeline,

σ_u = stress mobilized in US pipeline.

The results show that differences of stress and strain mobilized along the pipelines in Korea and the US are 6 to 7.4 % and 6 to 8.6 % with standard deviations of 1.08 to 3.69 and of 0.94 to 3.28, respectively. Differences of both stress and strain mobilized along the pipelines in Korea and US are less than 10 %. Based on the analyses results, RR in HAZUS can be used for the earthquake damage estimation of pipelines in Korea with a 90 % confidence level.

5 Conclusions

The objective of this study is to examine the confidence level when RR recommended in HAZUS is directly used for the damage estimation for Korea pipelines due to seismic loading. RR in HAZUS was developed based on historical data of high magnitude

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earthquakes in the US. There is deficient or no historical data available for pipelines damaged by earthquakes in Korea. Therefore, as an approximate earthquake damage estimation of pipelines, RR recommended in HAZUS can be used for the damage estimation. However, since the design criteria and construction specification for buried pipelines in Korea and the US are different, the earthquake pipeline damage of Korea using RR recommended in HAZUS was reevaluated with the degree of confidential level when RR is used without modification for the damage estimation of pipelines in Korea.

The numerical analyses using commercial finite element model, ABAQUS (2006), were carried out to compare stresses and strains mobilized in buried pipelines constructed by the design criteria and construction specifications of both Korea and US. The numerical results show that differences in the stress and strain rates are less than 10 %. This implies that RR in HAZUS can be used for earthquake damage estimation of pipelines with a 90 % confidence level in Korea.

Acknowledgements. This work was supported by the INJE Research and Scholarship Foundation in 2011.

References

ABAQUS Inc.: Analysis User's Manual, version 6.6, Hibbit, Karlsson & Sorensen, Inc., Pawtucket, RI, 2006.

COSMOS: Peak Ground Acceleration Records, available at: http://db.cosmos-eq.org (last access: 10 December 2010), 2011.

FEMA: HAZUS99 Technical Manual, National Institute of Building Science, Washington DC, 1999.

Filho, O. A., Hirai, J. N., Oliveira, A. S., and Liotti, E. S.: GIS applied to geotechnical and environmental risk management in a Brazilian oil pipeline, Bull. Eng. Geol. Environ., 69, 631–641, 2010.

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Jeon, S.-S.: Earthquake performance of pipelines and residential buildings and, rehabilitation with cast-in-place pipe lining systems, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, 2002.

Jeon, S.-S. and O'Rourke, T. D.: Northridge earthquake effects on pipelines and residential buildings, B. Seismol. Soc. Am., 95, 1–25, 2005.

Lee, D. H., Kim, B. H., Lee, H., and Kong, J. S.: Seismic behavior of a buried gas pipeline under earthquake excitations, Eng. Struct., 31, 1011–1023, 2009.

Ministry of Environment: Standard of wastewater facility, Korea Water and Wastewater Works Association, Seoul, Korea, available at: http://www.kwwa.or.kr/reference/devlop02_list.php (last access: 5 Octoeber 2010), 2010a.

Ministry of Environment: Standard of water facility, Korea Water and Wastewater Works Association, Seoul, Korea, available at: http://www.kwwa.or.kr/reference/devlop01_list.php (last access: 5 October 2010), 2010b.

Ministry of Land, Transport, and Maritime Affairs: Road Act, Seoul, Korea, available at: http://mltm.go.kr/USR/ordinance/m_15019/lst.jsp (last access: 5 October 2010), 2010.

Office of Pipeline Safety Community (OPS), Pipeline Safety Act, Washington, DC, available at: http://ops.dot.gov.regulations (last access: 12 September 2010), 2010.

O'Rourke, M. J. and Ayala, G.: Pipeline damage due to wave propagation, J. Geotech. Eng. ASCE, 119, 1490–1498, 1993

O'Rourke, M. J. and Liu, X.: Response of Buried Pipelines Subject to Earthquake Effects, Monograph No. 3, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 33–57, 1999.

O'Rourke, T. D., Toprak, S., and Sano, Y.: Factors affecting water supply damage caused by the Northridge earthquake, in: Proceedings of 6th US National Conference on Earthquake Engineering, Seattle, WA, 1–12, 31 May–4 June, 1998.

Pineda-Porras, O. and Ordaz, M.: A new seismic intensity parameter to estimate damage in buried pipeline due to seismic wave propagation, J. Earthq. Eng., 11, 773–786, 2007.

Saeedzadeh, R. and Hataf, N.: Uplift response of buried pipelines in saturated sand deposit under earthquake loading, Soil Dyn. Earthq. Eng., 31, 1378–1384, 2011.

Scandella, L. and Paolucci, R.: Earthquake induced ground strains in the pressure of strong lateral soil heterogeneities, B. Earthq. Eng., 8, 1527–1546, 2010.

Shih, B.-J. and Chang C.-H.: Damage survey of water supply systems and fragility curve of PVC water pipelines in the Chi-Chi Taiwan earthquake, Nat. Hazards, 37, 71–85, 2006.

Takada, S. and Tanabe, K.: Three-dimensional seismic response analysis of buried continuous or jointed pipelines, J. Press. Vess.-T. ASME, 109, 80–87, 1987.
Tan, R. Y. and Chen, S. M.: The performance of water transmission systems under seismic loadings, Soil Dyn. Earthq. Eng., 6, 149–157, 1987.
Toprak, S. and Taskin F.: Estimation of earthquake damage to buried pipelines caused by ground shaking, Nat. Hazards, 40, 1–24, 2007.
Wang, L. R.-L. and Cheng, K.-M.: Seismic response behavior of buried pipelines, J. Press. Vess.-T. ASME, 101, 21–30, 1979.

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Table 1. Brittle and ductile pipelines classified by pipe materials (Ministry of Environment, 2010a,b).

Types of pipeline	Pipe materials
Ductile	Ductile Iron, Steel, Galvanized Steel, Polyethylene, Stainless Steel, Copper, Polyethylene Sheeting, Fiber Reinforced
Brittle	Steel Reinforced Concrete, Cast Iron, Earthen, Centrifugal Reinforced Concrete, Lime Cast Iron, Steel Reinforced Concrete Box, Hume Concrete

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Table 2. Required minimum embedded depth for buried pipeline as loading is applied to ground surface (Ministry of Land, Transport, and Maritime Affairs, 2010).

Pipeline Diameter (D)	Required minimum embedded depth (mm)
$D \leq 900$ mm	1200 mm
$D \geq 100$ mm	$D \leq$ and ≥ 1500 mm

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Table 3. Minimum embedded depth for buried pipeline (Office of Pipeline Safety Community (OPS), 2010).

Location	Embedded depth for normal excavation (mm)
Industrial and Residential Areas	914
30-m width stream	1219
Public roadway and railway ditch	914
Port areas in deep water	1219
Mexico Bay and water depth (ebb tide) $\leq$ 4.6 m	914
water depth (ebb tide) $\leq$ 3.6 m	914
Other areas	762

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Table 4. Mechanical characteristics of soils used in numerical analysis.

Soil types	γ (kN m^{-3})	E (MPa)	ν	c (kPa)	φ (°)
Clay	15	5	0.35	10	20
Loose sand	19	15	0.3	0	25
Medium dense sand	19	25	0.3	0	28
Dense sand	19	45	0.3	0	30
Dense sand and gravel	20	120	0.25	0	35

Table 5. Mechanical characteristics of pipelines used in numerical analysis.

Types of Pipelines	γ (kN m^{-3})	E (MPa)	ν
Ductile	69.1	160 000	0.28
Brittle	22.5	19 600	0.17

Table 6. Mobilized strain difference (%) of pipeline modeled based on Korea and the US design criteria and construction specification.

Pipe	Soil/PGA (g)	0.2	0.4	0.6	0.8	1.0	1.2	Avg[a]	SD[b]
Ductile Pipe	Clay	8.8	8.6	8.7	8.9	8.3	6.4	8.3	0.94
	Loose sand	9.8	9.8	8.3	8.5	7.8	7.4	8.6	1.02
	Medium dense sand	9.7	8.7	8.6	7.9	4.8	7.7	7.9	1.65
	Dense sand	9.1	6.1	5.0	6.3	6.2	3.5	6.1	1.85
	Dense sand and gravel	8.8	4.8	5.0	4.6	4.6	4.5	5.4	1.69
Brittle Pipe	Clay	8.5	8.5	4.9	4.4	3.8	6.0	6.0	2.09
	Loose sand	8.8	9.9	6.0	3.0	3.1	4.1	5.8	2.97
	Medium dense sand	8.9	7.5	5.2	3.1	3.0	2.8	5.1	2.62
	Dense sand	9.9	9.3	8.0	4.4	2.2	3.3	6.2	3.28
	Dense sand and gravel	9.8	6.7	8.0	4.2	5.3	5.4	6.5	2.06

[a] Avg: Average; [b] SD: Standard Deviation.

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Table 7. Mobilized stress difference (%) of pipeline modeled based on Korea and the US design criteria and construction specification.

Pipeline	Soil/PGA (g)	0.2	0.4	0.6	0.8	1.0	1.2	Avg[a]	SD[b]
Ductile Pipe	Clay	11.3	8.8	5.2	7.2	5.7	4.7	7.2	2.53
	Loose sand	11.8	9.7	7.1	5.9	4.9	4.7	7.3	2.84
	Medium dense sand	10.1	7.9	9.3	5.9	6.3	4.7	7.4	2.10
	Dense sand	11.7	9.2	4.1	5.9	2.9	2.6	6.1	3.69
	Dense sand and gravel	10.7	4.6	5.9	5.4	6.1	3.9	6.1	2.39
Brittle Pipe	Clay	8.0	9.3	7.2	7.5	5.6	4.2	7.0	1.82
	Loose sand	7.2	9.3	6.4	6.6	5.1	4.4	6.5	1.73
	Medium dense sand	7.8	6.1	6.3	6.4	4.8	4.7	6.0	1.15
	Dense sand	7.0	9.1	8.0	6.5	6.8	4.7	7.0	1.49
	Dense sand and gravel	6.9	7.5	8.2	4.9	6.7	7.1	6.9	1.08

[a] Avg: Average; [b] SD: Standard Deviation.

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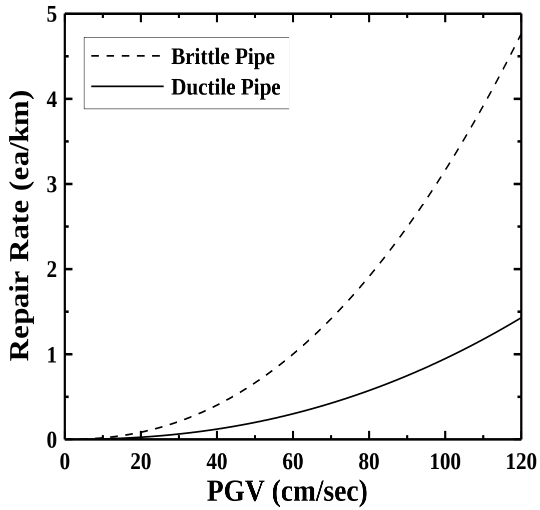

Fig. 1. Fragility curve of buried pipelines provided by HAZUS (FEMA, 1999).

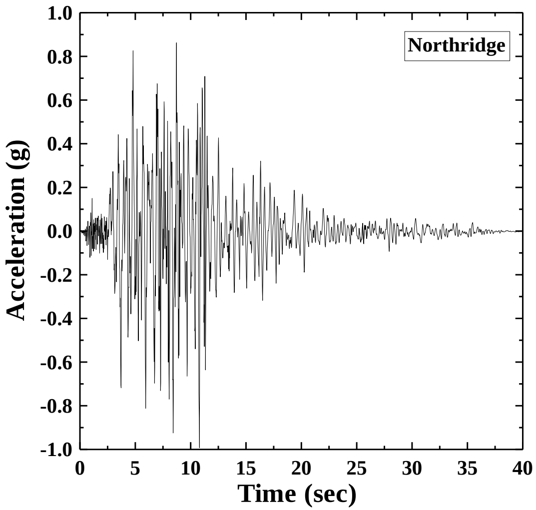

Fig. 2. History of ground acceleration record during Northridge earthquake (COSMOS, 2010).

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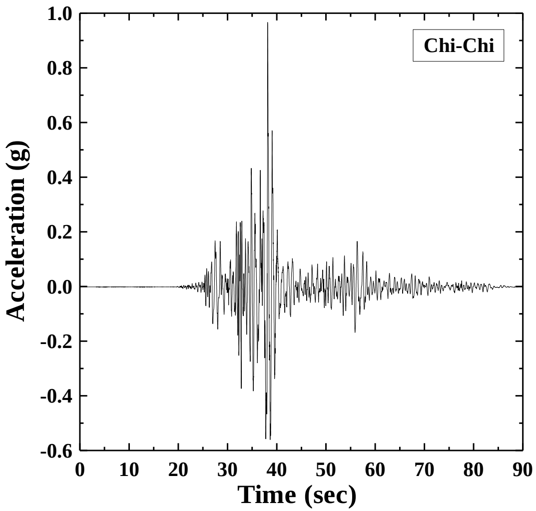

Fig. 3. History of ground acceleration record during Chi-Chi earthquake (COSMOS, 2010).

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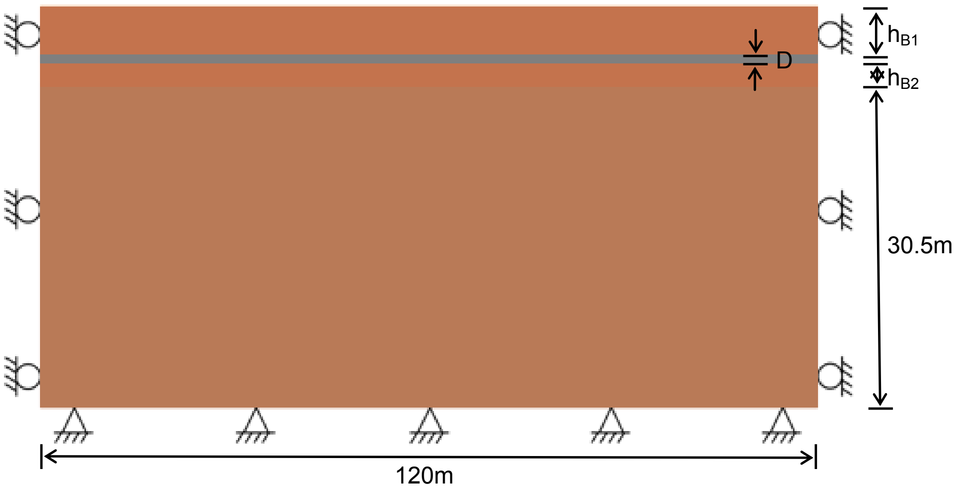

Fig. 4. Configuration of numerical model associated with pipeline and ground conditions.

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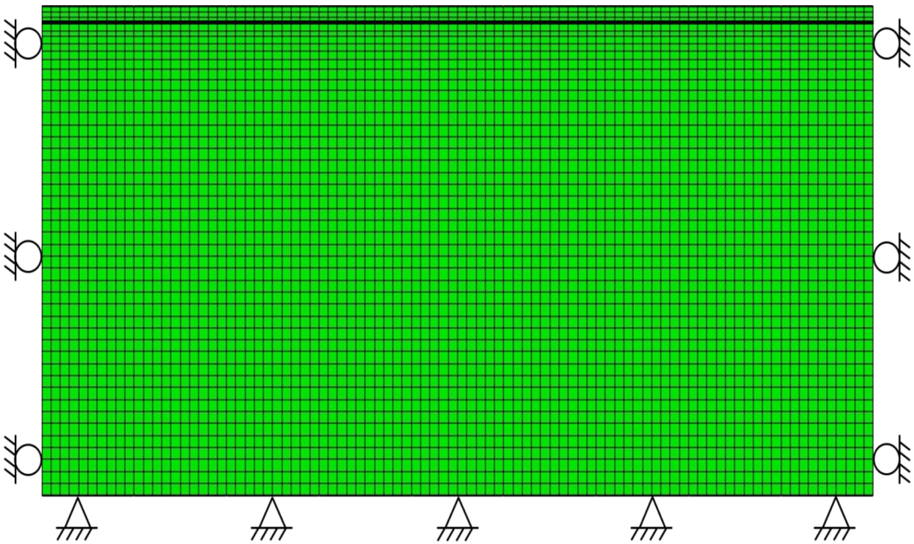

Fig. 5. Finite element mesh configuration and boundary conditions for pipelines.

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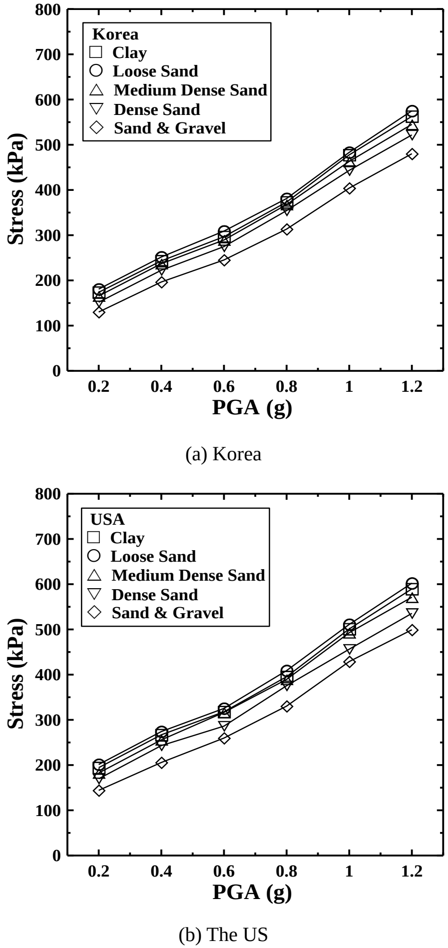

Fig. 6. Stress of ductile pipeline mobilized by earthquake loadings with respect to peak ground acceleration (PGA) in various in-situ ground conditions.

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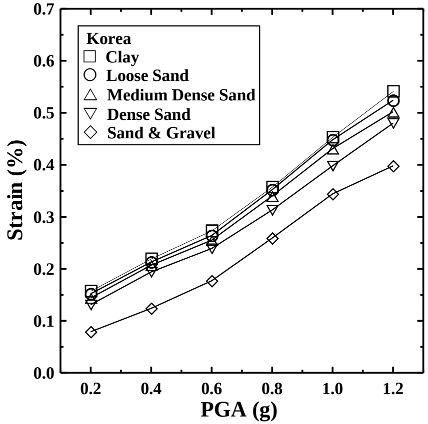
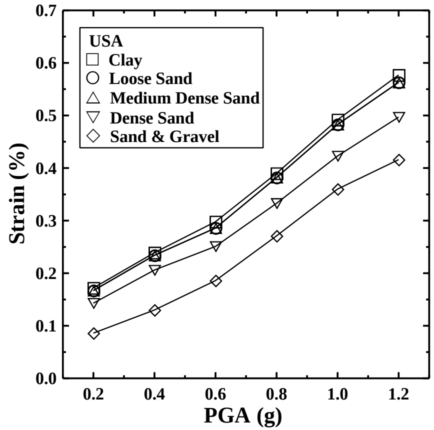
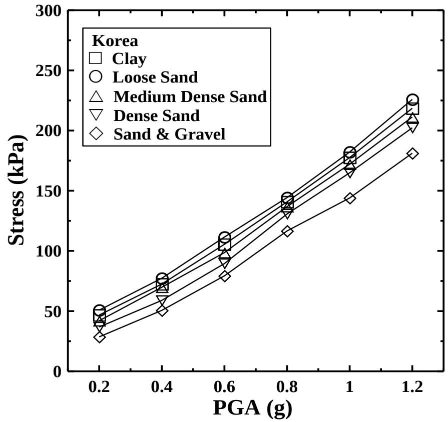


(a) Korea

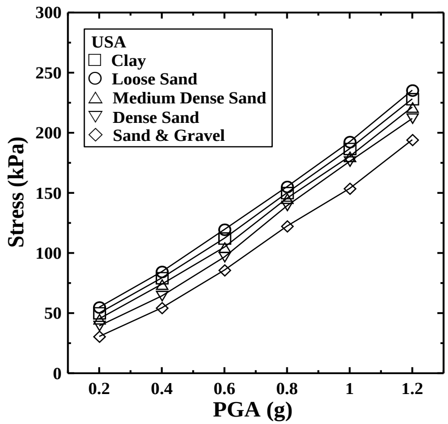


(b) USA

Fig. 7. Strain (%) of ductile pipeline mobilized by earthquake loadings with respect to peak ground acceleration (PGA) in various in-situ ground conditions.



(a) Korea



(b) The US

Fig. 8. Stress of brittle pipeline mobilized by earthquake loadings with respect to peak ground acceleration (PGA) in various in-situ ground conditions.

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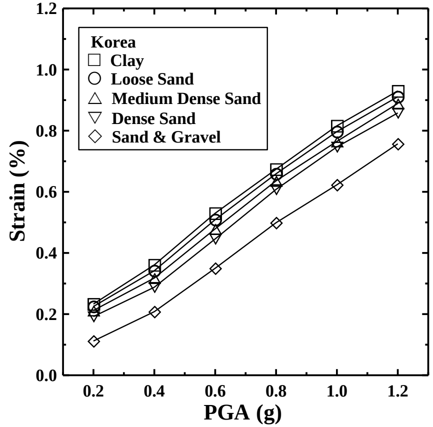
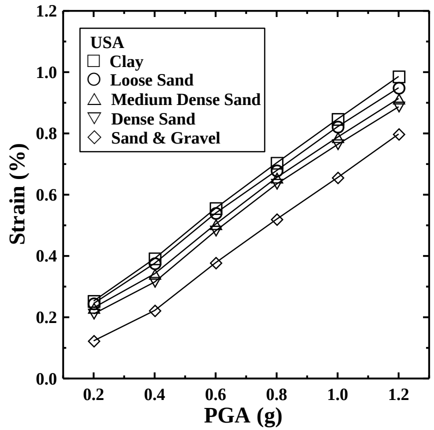


(a) Korea



(b) The US

Fig. 9. Strain (%) of brittle pipeline mobilized by earthquake loadings with respect to peak ground acceleration (PGA) in various in-situ ground conditions.

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