Seismic Reliability Evaluation of City-Level Gas Distribution Networks Using Flow-Based Simulation Modeling

Vindhyawasini Prasad[1]; Kalyan R. Piratla[2]; Bradley Caswell[3]; and Siddharth Banerjee[4]

[1]Graduate Student, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC. E-mail: vindhyp@g.clemson.edu
[2]S. E. Liles, Jr. Distinguished Associate Professor, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC. E-mail: kpiratl@clemson.edu
[3]Undergraduate Student, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC. E-mail: bcaswel@g.clemson.edu
[4]Graduate Student, Dept. of Civil, Construction, and Environmental Engineering, North Carolina State Univ., Raleigh, NC. E-mail: sbaner22@ncsu.edu

ABSTRACT

Natural gas is becoming increasingly popular across the globe due to its growing affordability and lower carbon footprint compared conventional fossil fuels. It is also suitable for distributed power generation using combined heat and power (CHP) units. The continuous functioning of a gas distribution system is therefore crucial. Majority of the studies on reliability assessment of gas networks have studied the networks in the aftermath of the earthquake using connectivity-based metrics, while this paper presents a flow-based quantification method to evaluate the reliability of city-level gas distribution networks. A representative gas distribution network is initially designed for an urban area that is prone to liquefaction. Seismic reliability of the designed network is subsequently investigated for a hazard of magnitude M_w=7. The reliability metric used in this study is the fraction of demand satisfied immediately after the seismic event. Appropriate fragility functions for various components of a gas distribution network have been identified from the literature and used in a Monte-Carlo simulation (MCS) approach for reliability assessment. A computationally efficient, physics-based linear-pressure analog (LPA) model has been developed and used to solve the steady-state flows in the gas distribution networks. The novelty of this work lies in the use of LPA model that will minimize the computational effort associated with the numerous iterations in MCS as it leverages linearized formulations of the physics-based gas network dynamics. This work provides a framework which can be used to advance the reliability assessment of city-level gas distribution networks. The framework presented in this paper can be used to improve restoration and rehabilitation strategies for gas networks in order to enhance their performance during earthquakes.

Keywords: Gas distribution network, seismic reliability, Monte-Carlo simulations, Liquefaction

INTRODUCTION

Gas distribution networks (GDN) form the last leg of gas delivery systems. Thus, the reliability of the distribution system is vital for proper sustenance of communities. Distributed generation in recent years has provided impetus to gas-fired power plants. According to (Owens 2014), 42% of the new additions in electricity generation would be invested in applications related to distributed power by the year 2020. Majority of the distributed generation units serve as a backup which makes reliability analysis of GDN more important during a natural or manmade calamity. Performance of GDN in seismically active regions is one such critical instances that is investigated in this study.

Seismic reliability of natural gas supply networks has been analyzed using various approaches in recent decades. A seismic damage estimation model was proposed by (Cret et al. 1993) to assist the safe supply of gas to different blocks by optimal control of shut-off valves using fuzzy set theory. Their framework was tested on a real-world network for an earthquake of 6.7 magnitude and the results predicted by the model were consistent with the observations from a real-world network in Tokyo city. Miao et al. developed a benchmark buried gas network system which spanned 24m x 24m and experimentally simulated a seismic event by using trinitrotoluene (TNT) explosives. They concluded that the axial strains are larger than bending strains. However, the study analyzed the network for only transient ground deformations (TGD). A comprehensive analysis to evaluate the risks associated with buried natural gas pipelines subject to PGD in the form of landslides was performed by (Yiğit et al. 2017). Landslides, on the other hand, are not a spatially distributed PGD deformations and are considered abrupt cases of PGD with localized impacts (Keefer 1984).

Repeated random sampling which is also known as Monte Carlo method has been used in this study for the reliability assessment. Monte Carlo Simulations (MCS) have been increasingly used to analyze networked infrastructures in recent decades. Nuti et al. developed an MCS-based framework and demonstrated it for water and electricity networks. MCS was used by (Liu et al. 2018; Stern et al. 2017) in conjunction with connectivity-based metrics to evaluate reliability of gas networks. A real-world gas transmission network was analyzed for random component failures using MCS by (Praks et al. 2017). In a recent study by (Ameri and van de Lindt 2019), MCS was used in a comparative evaluation of restoration time of a hypothetical gas distribution network for different pipe materials. The network was analyzed for liquefaction-induced PGD, but it did not consider the flow characteristics of the gas and relied solely on connectivity-based metric.

The studies summarized above have focused on different aspects of gas distribution networks subject to a seismic event, but there remains a lack of integrated model where efficient flow-based analysis has been conducted for a network affected by PGD. Liquefaction has been found to cause majority of the damage to buried pipelines in historical earthquakes (Eidinger and Avila 1999; O'Rourke et al. 2014). But not many studies except (Ameri and van de Lindt 2019) gave due consideration to liquefaction. This study attempts to fill this gap by developing and demonstrating a comprehensive seismic reliability model focused on liquefaction hazards. The model integrates a computationally efficient flow simulation model with component failures arising due to PGD to evaluate a serviceability-based reliability metric.

This paper is organized in four sections. Second section of this work presents the methodology. Network design, flow model and details of the reliability model have been discussed in the methodology section. The methodology has been applied to networks consisting of pipelines of different materials. Third section presents the results from the demonstration of the reliability model on a network hypothesized to be made of different pipe materials. The last section is focused on conclusions of the study. The paper concludes with a brief discussion of the impact of this work and main limitations that should be addressed in the future.

METHODOLOGY

The methodology is summarized in Figure 1. It can be divided into four parts – (i) Network design (ii). Hazard characterization (iii). Fragility model and (iv). Reliability evaluation using gas flow simulation model.

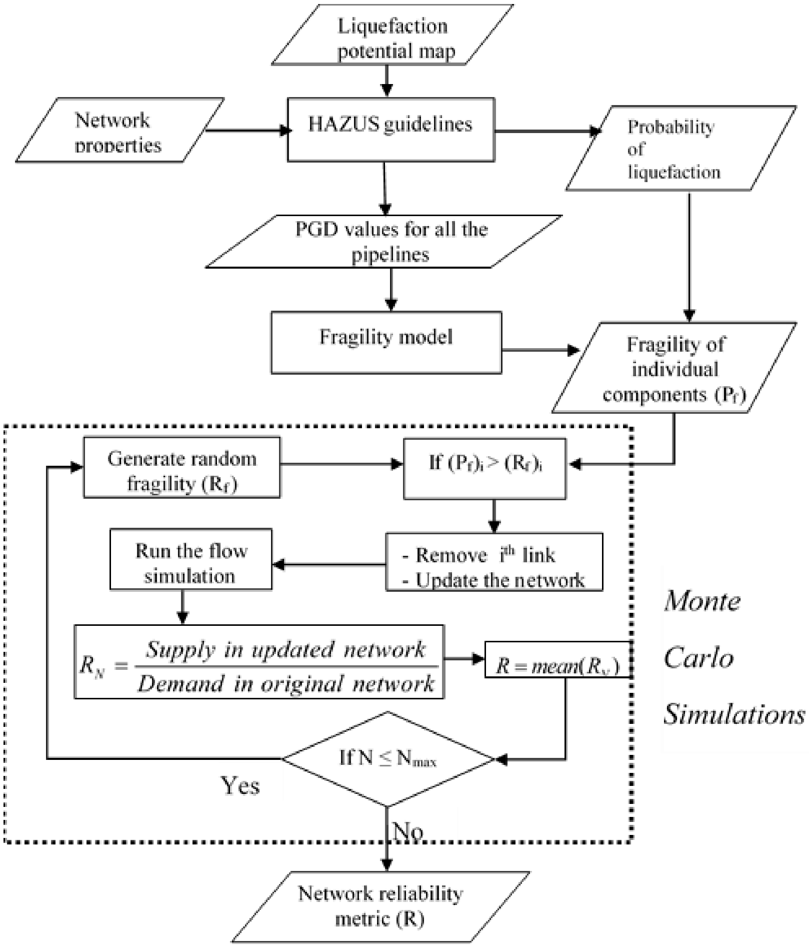

Figure 1. Methodology of the reliability model adapted from Prasad (2019)

Peninsular region of Charleston city has been considered as the study area for this research. Charleston region is prone to permanent ground deformations (PGD) which was evident from the 1886 Charleston earthquake (Hayati and Andrus 2008). The 1886 earthquake is considered one of the deadliest earthquakes to hit the east coast of the U.S. (Farahmandfar et al. 2016). Seismic hazard considered in this study resembles the seismic event of 1886 in terms of key characteristics. A seismic reliability model for gas distribution networks is proposed and demonstrated using the Charleston study area.

Network Design

A hypothetical GDN is designed for the Charleston peninsula study area. The following general gas flow equation (1) needs to be solved to determine the steady-state flow of natural gas in the pipeline network (Osiadacz 1987):

$$Q_n = C\frac{1}{\sqrt{f}}\frac{T_n}{P_n}\frac{D^{2.5}}{\sqrt{SLTZ}}\left((p_1^{\,2} - p_2^{\,2}) - k\frac{p_{av}h}{ZT}\right)^{0.5} \tag{1}$$

Where Q is flow in pipe, C and k are constants, $\frac{1}{\sqrt{f}}$ is friction factor, D is diameter of pipe, S is specific gravity of the gas and $k\frac{p_{av}h}{ZT}$ is elevation factor. When written for a network, the gas-flow equation becomes increasingly cumbersome as the size of the network increases. For a network with 'n' number of nodes, the flow can be simulated by simultaneously solving mass-balance equations at all 'n' nodes as described in the method given by (Osiadacz 1987):

$$f_i(p_1, p_2, p_3.....p_n) = 0,$$

There are various numerical methods to simultaneously solve the gas flow equations, most common of which is the Newton-Raphson method (Ayala H. and Leong 2013). Newton-Raphson method can be used to solve a real-valued function of the form *f(x)=0.*

Linear Pressure Analog (LPA)

The following are some drawbacks associated with the Newton-Raphson method: (i). Initial guess values need to be close to the actual solution (ii). Complicated formulation of the Jacobian matrix (iii). Computationally expensive. Ayala H. and Leong came up with a simplified gas flow equation where the pressure variables in the equation were linearized with the help of an algebraic transformation term. The linearization made the simultaneous solutions significantly easier. The same methodology has been adopted in the flow simulation model used in this study. More details of the LPA method can be found in (Ayala H. and Leong 2013) and (Prasad 2019).

Summary of the network

The pipelines in the network have been designed in two legs – (i). Distribution mains and (ii). Service branches. Maximum allowable operating pressure (MAOP) for distribution mains is 6.89 bar (100 psig) and MAOP for service branches is 3.10 bar (45 psi). The final designed network consists of a total of 23 service branches which are connected to distribution mains through regulator stations at 16 different locations. The network also consists of 3 gas-fired power plants which are directly connected to the mains. Further details of the network design can be found in (Prasad 2019).

Hazard characterization

1886 Charleston earthquake has been considered as the seismic hazard scenario in this study. The epicenter of the earthquake was around 30km to the northeast of the peninsula near the Woodstock fault. Peak ground acceleration value of 0.3g and peak ground velocity of 49 cm/s has been used as the intensity measure (Farahmandfar et al. 2016; Hayati and Andrus 2008). Permanent ground deformations (PGD) can occur during an earthquake in the form of – fault movement, landslide, settlement and liquefaction. Since the study-area does not contain any fault plane, PGD due to fault movements are not considered in this study. On the other hand, liquefaction and settlement were the observed forms of PGD during 1886 Charleston earthquake, some first-hand records of liquefaction are summarized in (Hayati and Andrus 2008). Liquefaction map of the study-area was first developed by (Elton et al. 1990) based on standard penetration tests (SPT). Liquefaction potential index (LPI) is a widely used index to quantify the vulnerability of a region to liquefaction (Iwasaki et al. 1984). A liquefaction potential map for the study-area was developed by (Hayati and Andrus 2008) which is based on cone penetration tests (CPT) conducted at 44 different locations across the peninsula. The map also used the previously available SPT-based liquefaction map, firsthand evidences of liquefaction during the 1886 earthquake and geology of the region. The liquefaction potential map developed by (Hayati and Andrus 2008) has three different zones – (i). <10% probability (ii). 45% probability and (iii). 95% probability of LPI>5. The map along with the network has been shown in Figure 2. PGD for all the components has been calculated using the methodology followed in HAZUS-MH loss assessment model (FEMA 2012). PGD has been evaluated as the vector sum of lateral spread and settlement for the three different zones which have been summarized in Table 1.

Table 1. Summary of PGD in Areas with Different Liquefaction Susceptibility Adapted From (Prasad 2019)

P(LPI>5)	Probability of liquefaction	Lateral Spread (cm)	Settlement (cm)	PGD (cm)
10%	0.009	13.06	2.54	13.31
45%	0.088	30.48	5.08	30.91
95%	0.421	135.46	30.48	138.86

Figure 2. Liquefaction potential map and the hypothetical gas distribution network. Liquefaction map is adopted from (Hayati and Andrus 2008)

Pipes which protrude to more than one liquefaction zone, are discretized at the points of intersection with the zone boundary. PGD values are then weighted for the length lying in the different zones using Eq. 2.

$$PGD = PGD_{10} \cdot w_{10} + PGD_{45} \cdot w_{45} + PGD_{95} \cdot w_{95} \quad (2)$$

Where, PGD is weighted PGD values. PGD_{10}, PGD_{45} and PGD_{95} are the PGD values calculated for the region with 10%, 45% and 95% probabilities of LPI>5 respectively. And w_{10}, w_{45} and w_{95} are the ratios of lengths of pipes lying in these zones.

Fragility model

Empirical fragility functions have been used to evaluate the probability of failure of pipelines. Fragility models for buried pipelines are given by (ALA 2001; Eguchi RT, Legg MR, Taylor CE, Philipson LL 1983; Eidinger and Avila 1999; Heubach W 1995). A brief comparison of these fragility curves has been presented in (Pitilakis et al. 2014). Fragility curve given by (ALA 2001) are derived from the damage records of 18 different earthquakes and is considered the most accurate model among the available fragility models (Pitilakis et al. 2014). Fragility curves are generally written in terms of repair rate, i.e. number of breaks in a pipeline per unit length. (ALA 2001) gives separate fragility curves for TGD and PGD hazards. Fragility of just the pipelines is considered in this study based on the assumption that the metering and regulator stations remain unaffected during earthquakes (Ameri and van de Lindt 2019; Esposito et al. 2013).

$$RR_{TGD} = K_1 \cdot K_t \cdot 0.00187 \cdot PGV \quad (3)$$

$$RR_{PGD} = K_1 \cdot K_t \cdot 1.06 \cdot PGD^{0.319} \quad (4)$$

$$RR = RR_{PGD} \cdot P_{liq} + RR_{TGD} \cdot (1 - P_{liq}) \quad (5)$$

Assuming a Poisson distribution for the pipe breaks, failure of a pipe is considered when at least one break appears on the pipe. Probability of pipe failure is given by:

$$P_{fi} = 1 - e^{-RR_i L_i} \quad (6)$$

Table 2. Coefficients for Different Materials and Sizes of Pipes (ALA 2001)

Pipe material	K_1	K_2
Ductile Iron	0.5	0.5
Steel (welded, diameter ≤ 305 mm)	0.7	0.7
Steel (welded, diameter ≥ 406.4 mm)	0.15	0.7
Cast Iron	1.0	1.0
PVC	0.5	0.8
Asbestos cement	1.0	1.0

Reliability evaluation

Reliability model contains three steps – random probability generation, network modification and flow simulation. The fragility curves discussed in the previous sub-section have been fixed as the probability of failure of each pipeline. Following steps are involved in a single iteration of the MCS – (i). A random number ranging between 0 and 1 is assigned to all pipelines which represent the random probability of failure (ii). The random probability of failure is compared with the fragility of the associated pipeline. (iii). All pipelines for which random probability exceeds the fragility, are removed (i.e., simulating their failure or unavailability) from the network (iv). Flow simulations are performed for the updated network and network reliability is evaluated as the ratio of supply after earthquake and demand in the original network (v). Steps (i) to (iv) are repeated until a maximum number of generations is achieved.

RESULTS

A typical convergence of reliability metric is shown in Figure 3. The methodology is demonstrated for networks consisting of different pipeline materials and at different levels of deterioration. Cast iron, welded steel, and ductile iron pipes are considered for two different states of deterioration: K_t=1 denotes the pipelines which have zero breaks in the past.

K_t=2 is used to denote deteriorated pipelines with at least one and less than four breaks in the past. Reliability of these six networks (combination of three materials and two cases of past break record) is given in Table 3.

Table 3. Reliability of Networks Made of Different Pipelines and Historical Break Records

Pipe material	K_t=1	K_t=2
Cast iron	0.1169	0.0421
Welded steel	0.1788	0.0792
Ductile iron	0.2371	0.1287

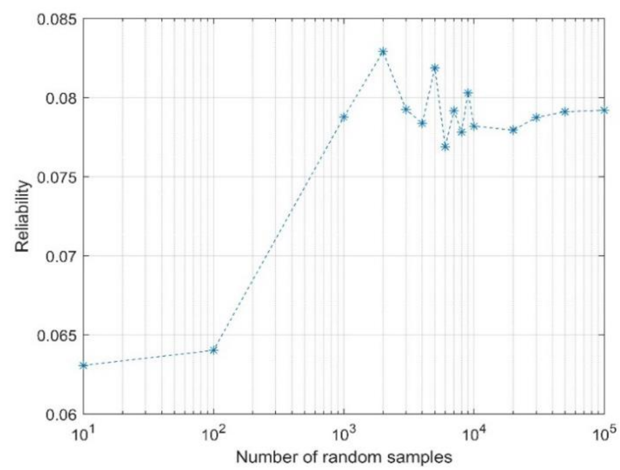

Figure 3. Typical convergence of reliability metric in MCS

CONCLUSIONS, DISCUSSION AND FUTURE WORKS

Ductile iron has been found to offer most reliability, but ductile iron pipes are not commonly used in gas distribution networks. Condition of the pipeline has a significant effect on the reliability of the network, which is evident from the results. The methodology presented in this study attempts to integrate a computationally efficient gas flow simulation model with a liquefaction hazard model to predict the reliability of a gas distribution network during an earthquake in a region highly susceptible to liquefaction. Because of the serviceability-based metric, the model can be a good tool for utilities during design, rehabilitation and restoration planning of a gas distribution network. The flow-simulation model is computationally efficient and more stable than the previously used steady-state flow models which makes it an ideal candidate to advance the design of earthquake-resistant gas networks. A quantitative comparison with efficiency of previous model has been avoided because of completely different components used in this study.

Some of the limitations of this study include the use of a particular seismic event with a return period which is manifold higher than the usual design period of a gas distribution network. Earthquakes of lesser magnitudes which are more frequent would need another liquefaction susceptibility map. Fragilities of the components have been derived using empirical models which have limited applicability. For example, fragility models of HDPE which is the most commonly used material for gas pipelines currently are not available in the literature. Developing analytical fragility models for high-density polyethylene (HDPE) pipes would make the framework more impactful. In a nutshell, the reliability framework consists of different modules, each of which can be improved with a focused approach to advance the knowledge on seismic reliability of gas networks.

ACKNOWLEDGMENTS

This study is supported by National Science Foundation (NSF) under grant number CRISP-1638321. All the views and interpretations presented in the paper are of the authors and do not represent the views of NSF on the topics discussed herein.

REFERENCES

ALA. (2001). "Seismic Fragility Formulations for Water Systems." *American Lifeline Association*

Ameri, M. R., and van de Lindt, J. W. (2019). "Seismic Performance and Recovery Modeling of Natural Gas Networks at the Community Level Using Building Demand." *Journal of Performance of Constructed Facilities*, 33(4), 04019043.

Ayala H., L. F., and Leong, C. Y. (2013). "A robust linear-pressure analog for the analysis of natural gas transportation networks." *Journal of Natural Gas Science and Engineering*, Elsevier B.V, 14, 174–184.

Cret, L., Yamazaki, F., Nagata, S., and Katayama, T. (1993). "Earthquake damage estimation and decision analysis for emergency shut-off of city gas networks using fuzzy set theory." *Structural Safety*, 12(1), 1–19.

Eguchi RT, Legg MR, Taylor CE, Philipson LL, W. J. (1983). *Earthquake performance of water and natural gas supply system*.

Eidinger, J. M., and Avila, E. A. (1999). "Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities." ASCE.

Elton, D. J., Hadj-Hamou, T., and Members, A. (1990). "LIQUEFACTION POTENTIAL MAP FOR CHARLESTON, SOUTH CAROLINA." *Journal of Geotechnical and Geoenvironmental Engineering*, 116(2), 244–265.

Esposito, S., Giovinazzi, S., Elefante, L., and Iervolino, I. (2013). "Performance of the L'Aquila (central Italy) gas distribution network in the 2009 (Mw 6.3) earthquake." *Bulletin of Earthquake Engineering*, 11(6), 2447–2466.

Farahmandfar, Z., Piratla, K. R., and Andrus, R. D. (2016). "Resilience Evaluation of Water Supply Networks against Seismic Hazards." *Journal of Pipeline Systems Engineering and Practice*, 8(1), 04016014.

FEMA, F. E. M. A. (2012). "Multi-Hazard Loss Estimation Methodology, Earthquake Model: Hazus-MH 2.1 User Manual." 863.

Hayati, H., and Andrus, R. D. (2008). "Liquefaction Potential Map of Charleston, South Carolina Based on the 1886 Earthquake." *Journal of Geotechnical and Geoenvironmental Engineering*, 134(6), 815–828.

Heubach W. (1995). "Seismic damage estimation for buried pipeline systems." *Proceedings of the 4th US conference on lifeline earthquake engineering, Monograph No.6*, American Society of Civil Engineers, 813.
Iwasaki, T., Arakawa, T., and Tokida, K.-I. (1984). "Simplified procedures for assessing soil liquefaction during earthquakes." *International Journal of Soil Dynamics and Earthquake Engineering*, 3(1), 49–58.
Keefer, D. K. (1984). "Landslides caused by earthquakes." *Geological Society of America Bulletin,* v. 95, 406–421.
Liu, W., Li, Z., Song, Z., and Li, J. (2018). "Seismic reliability evaluation of gas supply networks based on the probability density evolution method." *Structural Safety*, Elsevier Ltd, 70, 21–34.
Miao, H., Liu, W., Wang, C., and Li, J. (2016). "Artificial earthquake test of gas supply networks." *Soil Dynamics and Earthquake Engineering*, 90(February), 510–520.
Nuti, C., Rasulo, A., and Vanzi, I. (2010). "Seismic safety of network structures and infrastructures." *Structure and Infrastructure Engineering*, 6(1–2), 95–110.
O'Rourke, T. D., Jeon, S. S., Toprak, S., Cubrinovski, M., Hughes, M., Van Ballegooy, S., and Bouziou, D. (2014). "Earthquake response of underground pipeline networks in Christchurch, NZ." *Earthquake Spectra*.
Osiadacz, A. (1987). "Simulation and analysis of gas networks."
Owens. (2014). *The Rise of Distributed Power. A Whitepaper by General Electric*.
Pitilakis, K., Crowley, H., Kaynia, a M., and Facilities, C. (2014). *SYNER-G : Typology Defi nition and Fragility Functions for Physical Elements at Seismic Risk. 11*.
Praks, P., Kopustinskas, V., and Masera, M. (2017). "Monte-Carlo-based reliability and vulnerability assessment of a natural gas transmission system due to random network component failures." *Sustainable and Resilient Infrastructure*, Taylor & Francis, 2(3), 97–107.
Prasad, V. (2019). "Optimal Rehabilitation Plannign of Gas Distribution Networks Considering Seismic Reliability." *All Theses. Clemson University.*
Stern, R. E., Song, J., and Work, D. B. (2017). "Accelerated Monte Carlo system reliability analysis through machine-learning-based surrogate models of network connectivity." *Reliability Engineering & System Safety*, Elsevier, 164, 1–9.
Yiğit, A., Lav, M. A., and Gedikli, A. (2017). "Vulnerability of Natural Gas Pipelines under Earthquake Effects." *Journal of Pipeline Systems Engineering and Practice*, 9(1), 04017036.