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SEISMIC VULNERABILITY ASSESSMENT OF AN URBAN NATURAL GAS NETWORK

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Abstract

Natural and man-made hazards have shown that modern societies are heavily dependent on critical infrastructures. The natural gas network plays a key role in a community economy, and seismic events might be detrimental for its safety and wellness. This paper proposes a methodology to assess the seismic vulnerability of urban natural gas networks. A physical-based model of the network of a virtual city has been developed. The modeling and calibration have been executed using a Python simulation tool. The model has then been used to evaluate the damage induced by the ground shaking and permanent soil deformation caused by a given seismic scenario. Network damage has been estimated in terms of gas leaks and pipe breaks. The methodology provides an effective tool to measure vulnerability and identify the critical components of the network. The results of the analysis can be used to assess the resilience of the gas infrastructure and to implement strategies for improving the overall community resilience.

Keywords: gas infrastructure, seismic vulnerability assessment, gas leak model, pipe break model, seismic damage simulation.

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1 INTRODUCTION

Natural gas networks are one of the most critical infrastructures at the urban level. Man-made and natural hazardous disasters, such as earthquakes, might disrupt this lifeline, causing significant economic and social losses.

Most of the current methodologies to assess the seismic vulnerability of natural gas networks are based on the Performance-Based method adapted to spatially distributed systems [1]. The seismic hazard characterization involves identifying the Intensity Measure (IM) parameters that quantify the hazard intensity within the urban area, typically, the Peak Ground Velocity (PGV) and Peak Ground Displacement (PGD). The first describes the failure mechanism induced by the transient soil deformation caused by the seismic wave [2]. The latter describes ground failure due to the permanent soil movements caused by liquefaction phenomena and uplifts.

A frequently discussed aspect of buried pipeline systems is the vulnerability assessment through seismic fragility functions. Lanzano, et al. [3] adopted an extensive database to define reliable fragility models of buried pipelines. The HAZUS [4] is one of the most widespread fragility relationships database. It uses fragility functions defined by [5] based on the damage due to wave propagation and ground deformation. Several studies have been done using the HAZUS methodology at different scales [6, 7]. Cavalieri [8] integrated the use of the FEMA methodology with the guidelines published by the American Lifeline Alliance [2]. A review of existing fragility curves for buried natural gas pipelines subjected to seismically-induced transient ground deformations was carried out by Tsinidis, et al. [9], who put particular emphasis on evaluating the efficiency of different IMs. Although these research works have focused on the seismic vulnerability assessment of NG networks using fragility functions as empirical relationships, the effects of the physical damage to the NG network behavior has not been deeply investigated.

In this work the damage occurrence through fragility functions is simulated, reproducing the physical damage effects in the NG network components (e.g., pressure losses), and updating the gas balance to evaluate the out-of-service network branches and unserved users.

The gas network modeling and calibration are performed through Pandapipes, a python-based simulation tool [10]. The mean thermodynamics and geometric characteristics of the gas network are defined according to the Italian design requirements and technical practices [11]. The case study is a virtual city consisting of an area of about 120 km^2 and 900,000 inhabitants [12]. A simplified seismic scenario was defined to test the capabilities of the proposed computational methodology. The results of the simulation are used to evaluate the reduction of pressure and to estimate the vulnerability of the gas network.

2 NETWORK MODEL

In this work, the Italian guidelines were followed to model the natural gas network. The Italian national gas pipeline network is mainly composed of a high-pressure transport network, a regional high-medium pressure network, and a local low-pressure distribution network. The latter consists of small diameter pipes and its role is to supply domestic and commercial utilities. The pipes of the distribution network are classified according to the national code [11] as a function of the Maximum Operating Pressure (MOP), defined as the maximum pressure at which the pipeline can operate under normal conditions (Table 1).

Pressure Class	MOP [bar]
1	MOP>24
2	12<MOP<24

3	5<MOP<12
4	1.5<MOP<5
5	0.5<MOP<1.5
6	0.04<MOP<0.5
7	MOP<0.04

Table 1: Pressure classes according to [11].

Pipelines belonging to classes 1, 2, and 3 are defined as high pressure, those belonging to classes 4, 5, 6 are medium pressure (MP), while class 7 pipelines are low pressure. The medium pressure pipelines are those considered at the urban level.

3 NETWORK VULNERABILITY

3.1 Definition of the seismic hazard

The seismic characterization of a given site requires detailed geotechnical data, knowledge on the geology profile, and properties of the seismic sources. Many earthquake-prone areas lack the data needed for a detailed seismic hazard characterization. Therefore, in this work, a simplified seismic scenario was implemented. The seismic scenario is defined in terms of (*i*) seismic source, (*ii*) soil characteristics, (*iii*) geometry of the fault rupture area, and (*iv*) PGV and PGD at the source. The NGA West attenuation law [13] was then used to estimate the PGV and PGD at any node of the network. The seismic source is described by the expected moment magnitude and location of the epicenter.

3.2 Pipeline fragility model

The assessment of the NG network damage was performed using empirical fragility functions. Current methodologies provide a correlation between the pipeline repair rate (RR), defined as the ratio between number of pipeline repairs and pipeline length, and the seismic IM. The RR per unit of length can be expressed as a function of seismic wave passage or ground failure. The first is usually less damaging for pipes, whereas extensive damage occurs in case of large displacements caused by ground failure phenomena such as liquefaction and landslides uplifting. Seismic wave failure mechanism is typically linked to PGV while ground failure mechanism to PGD. Several PGV-based empirical relationships of the pipe RR can be found in the literature [14, 15].

In this paper, the ALA formulations [2] have been chosen (Equation 1).

$$\begin{aligned} RR &= 0.002416 \cdot PGV \cdot K_1 \\ RR &= K_2 \cdot 1.06 \cdot PGD^{0.319} \end{aligned} \tag{1}$$

The values of the modification factors K_1 , K_2 are provided by [2] for different pipe material, diameter, joint type, soil. For the ground failure mechanism, the proposed PGD relationship is based on post-earthquake data where soil liquefaction was the predominant ground failure mechanism. These formulations are independent from the damage state (DS). Instead, the HAZUS methodology [15] considers leakage and failure of pipelines as possible DSs. In case of ground failure, it is assumed that 80% of the pipes breaks and 20% leaks, while in case of ground shaking it is assumed that 20% of the pipes breaks and 80% leaks [15]. The probability to have a total of n damages and repairs for a pipeline with length l is given by a Poisson distribution (Equation 2).

$$P(DS) = 1 - e^{-RR \cdot l} \tag{2}$$

The expression in Equation 2 can be seen as a binomial term. If the probability value is greater than a predefined percentile, the pipe is considered damaged. The percentile value has been fixed to 50% for both leak and break DSs, which corresponds the median probability of having leak and break on the pipeline. In this research, it was considered that NG components located inside buildings suffering from extensive and complete damage are failed.

4 NETWORK MODEL

4.1 Simulation approach

To model and simulate the effects of earthquakes on the natural gas network, the Pandapipes Python package was used [10]. It provides pressure values in all network nodes and the flow rates in the pipes. The node balance rule is based on the principle behind Kirchhoff's laws (Equation 3).

$$\begin{aligned} &\sum_{b=1}^{N_b} m_b + m_n = \sum_{b=1}^{N_b} v_b A_b \rho_b + m_n = 0 \\ &\sum_{b=1}^{N_b} q_n = \sum_{b=1}^{N_{b,in}} m_b c_p T_b - \sum_{b=1}^{N_{b,out}} m_b c_p T_n = 0 \end{aligned} \tag{3}$$

where m_b is the mass flow of pipe connected to the analyzed node and m_n is the mass flow, incoming or outcoming; q_n refers to the incoming or outcoming heat flow; N_b is the number of connected branches. The temperature is assumed constant in the branch. The mesh rule states that the sum of the pressure or temperature variation is null. The pressure variation along a pipe section can be defined using Equation 4:

$$dp = -\frac{\rho \cdot v^2}{2} \cdot \left(\frac{\lambda}{d} \cdot dl + \zeta \right) + \rho \cdot g \cdot dh \tag{4}$$

where friction is considered through the Darcy factor λ, d is the pipe diameter, ζ is a lumped pressure loss, ρ is the fluid density and v the flow velocity. The second addend is the pressure variation caused by the height difference dh.

In Pandapipes, the previous equations are set up in a nonlinear system and the unknown variables are computed through the Newton–Raphson method.

4.2 Modeling leaks and breaks

A novel methodology is proposed to update the network in case of leaks and breaks. When there is a leak, this generates a lumped loss of pressure (Equation 5).

$$dp = -\frac{\rho \cdot v^2}{2} \cdot \zeta \tag{5}$$

Pressure, velocity, density and temperature can be considered constant at low pressures. The loss coefficient ζ is strictly connected to the leak flow rate. In this paper, the flow rate model through a small hole proposed by Hou, et al. [16] was adopted (Figure 1). In their model the soil column height was fixed to 0.6m and the soil weight to 1500 kg/m^3 which are common for an urban network. The thermodynamics characteristics of methane were taken from Moran, et al. [17] and reported in Table 2.

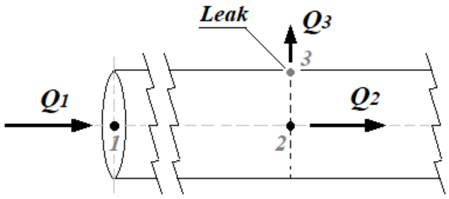

Figure 1: Scheme of the leak model.

Parameter	Value
M [g/mol]	16.044
ρ [kg/m^3]	0.662
k [-]	1.31
Z [-]	1.000
C_D [-]	1.000
R [J/mol °K]	8.314

Table 2: Thermodynamics characteristics of methane.

For minor leaks the main challenge is estimating the ζ coefficient. In the proposed method the flow rate is assessed through iteration and the loss coefficient is estimated using Equation 6:

$$\zeta = 7 \cdot 10^{-6} \cdot \frac{d^4}{T^2 \cdot \left(Q_1 - Q_3\right)^2} \cdot P_2^2 \cdot \left(P_1 - P_2\right) \tag{6}$$

where T is the temperature (assumed to be constant) P1 and P2 are the pressures at sections 1 and 2 as indicated in Figure 1, Q1 is the incoming flow rate, Q3 is the leak flow rate. Finally, the lumped loss of pressure in section 3 is computed and the Pandapipes model balance is updated. This iterative procedure is repeated for each pipe. The inlet flow rate for each pipe depends on the cumulated losses due to leaks or breaks. For the i^{th} pipe, the inlet flow can be expressed as shown in Equation 7:

$$Q_{in,p(i)} = Q_{in,p(i-1)} - \sum_{j=1}^{i-1} Q_{leak,p(j)} \tag{7}$$

Pipe breaks are modeled as out of service pipes in Pandapipes, which means that the entire flow rate leaks in that breakage area.

5 APPLICATION TO IDEAL CITY

The proposed method was applied to the natural gas network of Ideal City (Sebastiano Marasco et al., 2020). This consists of three MP classes of pipelines as summarized in Table 3.

	v_{max} [m/s]	$Q_{min,req}$ [kg/s]	Q_{peak} [kg/s]	d [m]	l [km]	P [bar]
MP 4th class	20 - 25	1.70	2.40	0.32	62.40	2.50
MP 5th class	10 - 15	0.30	0.90	0.20	16.20	1.00
MP 6th class	10	0.10	0.30	0.15	83.70	0.20

Table 3: Design parameters per class of pipelines.

A simplified seismic scenario based on the 6.9 M_w Northridge earthquake was defined. The epicenter was located 6.5 km away from the downtown. Accordingly, a PGV of 26.30 cm/s and a PGD of 12.20 cm were assumed at the epicenter location. The [13] ground motion model was used to estimate the PGV and PGD in all nodes. The building damage was assessed using the HAZUS methodology [18]. As a result, 14% of the buildings suffered extensive damage and 27% were completely damaged. It was assumed that network components inside buildings which suffered extensive and complete damage failed.

The gas network of *Ideal City* consists of 12 metering and reduction (M/R) stations, 775 final reduction groups (FRGs) for standard and 102 for commercial users, and 33 industrial reduction groups (IRGs). Each IRG serves a given number of users based on the population density. The pipelines are made of steel, and a constant temperature of 278 °K was assumed across the network. The pipe roughness was set to 0.04 mm.

Results in terms of node pressures are shown in Figure 2. Compared to the normal conditions (Figure 2a), the applied seismic scenario caused few pipe breaks in the area closer to the epicenter (Figure 2b). In the same area, the pressure of some MP class 4 pipes also decreased due to leaks.

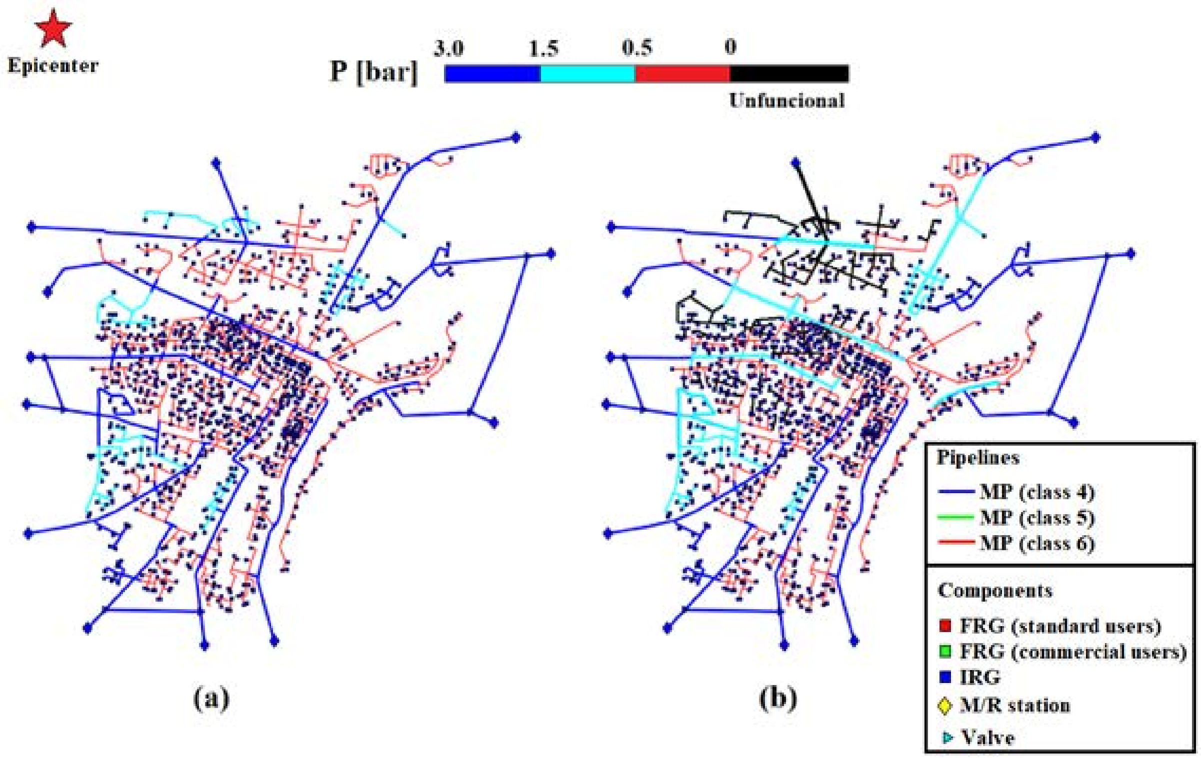

Figure 2: Pipe pressures (a) before and (b) after the seismic event.

A straightforward indicator of the vulnerability of the network R can be defined as the ratio between the number of supplied users (U_{SUPPL}) and the total number of users (U_{TOT}) as described in Equation 8.

$$R = \frac{U_{SUPLL}}{U_{TOT}} \tag{8}$$

It was found that in this application for standard users R = 0.85, while R = 0.92 for commercial users.

6 CONCLUSIONS

This research focused on the evaluation of the seismic vulnerability of natural gas networks at the urban scale. A physical-based methodology was proposed to simulate pipeline damage caused by ground shaking and ground failure. The model and computation were performed using the Pandapipes Python package. The methodology consists of three steps: (i) assessment of leaks and breaks for each pipe; (ii) evaluation of the expected leak and break flow rate through a physical model; (iii) update the network model. The updated Pandapipes model is capable of evaluating the new node balance and flow rate.

The methodology was applied to *Ideal City*, a virtual case study, considering the interdependence between the building damage and the gas network components. This application showed how the physical-based model can simulate the pressure reduction due to leaks and breaks of pipes caused by the seismic input. Finally, a straightforward indicator of the vulnerability of the network was introduced. The presented method could be replicated on different scales, providing an effective tool that can be used to implement strategies aimed at improving the overall community resilience.

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REFERENCES

[1] J. W. Baker, "Issues with applying performance-based engineering to distributed infrastructure systems," in *Eleventh US National Conference on Earthquake Engineering: Integrating Science, Engineering & Policy, Los Angeles, CA, United States*, 2018.

[2] ALA. (2001). *Seismic fragility formulations for water systems*.

[3] G. Lanzano, E. Salzano, F. S. de Magistris, and G. Fabbrocino, "Seismic vulnerability of natural gas pipelines," *Reliability Engineering & System Safety,* vol. 117, pp. 73-80, 2013.

[4] F. NIBS, "Hazus MR4 Multi-Hazard Loss Estimation Methodology," in *Earthquake model*, ed, 2003.

[5] M. J. O'Rourke and X. Liu, *Response of buried pipelines subject to earthquake effects*: Mceer New York, 1999.

[6] P. Vazouras and S. A. Karamanos, "Structural behavior of buried pipe bends and their effect on pipeline response in fault crossing areas," *Bulletin of Earthquake Engineering,* vol. 15, pp. 4999-5024, 2017.

[7] G. C. Sarvanis, S. A. Karamanos, P. Vazouras, E. Mecozzi, A. Lucci, and P. Dakoulas, "Permanent earthquake - induced actions in buried pipelines: Numerical modeling and experimental verification," *Earthquake Engineering & Structural Dynamics,* vol. 47, pp. 966-987, 2018.

[8] F. Cavalieri, "Seismic risk assessment of natural gas networks with steady-state flow computation," *International Journal of Critical Infrastructure Protection,* vol. 28, p. 100339, 2020.

[9] G. Tsinidis, L. Di Sarno, A. Sextos, and P. Furtner, "A critical review on the vulnerability assessment of natural gas pipelines subjected to seismic wave propagation. Part 1: Fragility relations and implemented seismic intensity measures," *Tunnelling and Underground Space Technology,* vol. 86, pp. 279-296, 2019.

[10] D. Lohmeier, D. Cronbach, S. R. Drauz, M. Braun, and T. M. Kneiske, "Pandapipes: An Open-Source Piping Grid Calculation Package for Multi-Energy Grid Simulations," *Sustainability,* vol. 12, p. 9899, 2020.

[11] *Regola tecnica per la progettazione, costruzione, collaudo, esercizio e sorveglianza delle opere e dei sistemi di distribuzione e di linee dirette del gas naturale con densita' non superiore a 0,8,* Decreto interministeriale 16 aprile 2008, 2008.

[12] S. Marasco, A. Cardoni, A. Z. Noori, O. Kammouh, M. Domaneschi, and G. P. Cimellarof, "Integrated platform to assess seismic resilience at the community level," *Sustainable Cities and Society,* p. 102506, 2020.

[13] K. W. Campbell and Y. Bozorgnia, "NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s," *Earthquake Spectra,* vol. 24, pp. 139-171, 2008.

[14] M. O'Rourke and G. Ayala, "Pipeline damage due to wave propagation," *Journal of Geotechnical Engineering,* vol. 119, pp. 1490-1498, 1993.

[15] FEMA, "HAZUS-MH flood loss estimation methodology. I: Overview and flood hazard characterization," in *Natural Hazards Review* vol. 7, ed, 2006, pp. 60-71.

[16] Q. Hou, D. Yang, X. Li, G. Xiao, and S. C. M. Ho, "Modified Leakage Rate Calculation Models of Natural Gas Pipelines," *Mathematical Problems in Engineering,* vol. 2020, 2020.

[17] M. J. Moran, H. N. Shapiro, D. D. Boettner, and M. B. Bailey, *Fundamentals of engineering thermodynamics*: John Wiley & Sons, 2010.

[18] C. A. Kircher, R. V. Whitman, and W. T. Holmes, "HAZUS earthquake loss estimation methods," *Natural Hazards Review,* vol. 7, pp. 45-59, 2006.