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A Framework for Probabilistic Seismic Risk Assessment of NG Distribution Networks

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Lifelines are essential infrastructures for human activities and the economic development of a region. Lifelines vulnerability reduction is an actual question, particularly with reference to NaTech events, like earthquakes. In this regard, worldwide past seismic experiences revealed heavy damages to NG distribution networks. It is therefore essential to perform seismic risk assessment of NG buried pipelines systems with the aim to identify potential criticalities and avoid significant consequences. For such reasons, this work illustrates the proposal of a probabilistic framework for seismic risk assessment of NG lifelines. The proposed procedure is subsequently applied to a specific case study in Italy to highlight its feasibility.

1. Introduction

The gas distribution network is a critical infrastructure and its failure can cause damage to structures and injury to people. Despite the low number of accidents that occurred in the transportation of natural gas (Center for Chemical Process Safety, 1995; TNO, 1999), some serious incidents have confirmed that the transportation of hazardous materials has the potential to pose a high risk to the population.
Two particularly relevant pipeline incidents occurred in 2004: the explosion of a major underground high pressure natural gas pipeline in Ghislenghien industrial park, near Ath, about 50 km (30 miles) south-west of Brussels, Belgium (HInt Dossier, 2005) and a pipeline rupture (ammonia) near Kingman, Kansas (http://www.ntsb.gov/investigations/fulltext/PAB0702.htm).
The development of tools both for the risk assessment and the performance evaluation of preventive and protective measures in the transportation of hazardous materials is thus an issue of primary concern (Vianello and Maschio 2014).
The safety aspects of pipelines conveying dangerous substances are not covered in specific EU regulations.
It must be highlighted that the Seveso III Directive (DIRECTIVE 2012/18/EU) aims to prevent major accidents at industrial facilities, whereas transport by pipeline is not included.
In fact, the same kind of accidental scenarios, in terms of frequency and severity, may occur both in fixed plants and in transportation systems. Additionally transport accidents may occur close to, and sometimes within, densely populated areas (Fabiano et al. 2002).
Several of such studies pointed out that the risk related to transportation activities is comparable or even more critical than the risk due to fixed installations.
A natural gas pipeline is designed to allow gas transport from locations situated at large distances. The characteristic size of a gas transmission pipeline can range up to several hundred centimeters in diameter and several thousand kilometers in length. The pipeline may cross both rural and heavily population areas. Failure of the pipeline can lead to various outcomes, some of which can pose a significant threat to people and buildings in the immediate proximity of the failure location.
Natural hazards in addition can seriously affect functionality of pipelines, causing local failures. In particular in areas prone to seismic risk, buried pipelines can be subject to permanent ground motions or transitory strong ground shakings which can lead to damages and consequent release of transportated substances. Probabilistic seismic risk analyses need to be performed for evaluating effects of earthquake scenarios

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occurrence on a pipeline system, taking into account seismological and geotechnical characteristics of the environment in which the system is located and structural behavior of each pipeline segment. Seismic response is usually defined through fragility functions, which represent exceedance probabilities of having a series of possible damage states conditional to a specific intensity measure value. In this work, a proposal of a probabilistic framework for seismic risk assessment of buried pipelines systems located in areas prone to seismic hazard is briefly described.

2. Seismic hazard modeling

In a classical Probabilistic Seismic Hazard Analysis (PSHA) (Cornell 1968) it is important to take into account an appropriate seismogenic model. Different types of seismogenic sources can be adopted: in the last decades, seismic hazard was mainly assessed through the use of area source models (Giardini 1999). Seismogenic zones are designed with the assumption that seismicity occurs anywhere within each zone. The definition of the boundaries of seismogenic zones was based on seismological, tectonical and geological issues. The estimation of seismic activity rates was based on the construction and subsequent statistical analysis of historical earthquake catalogues. Usually the distribution of events adopted is the classical Gutenberg-Richter (G-R):

$$\log_{10} \lambda(\mathrm{M}) = \mathrm{a} - \mathrm{b} \cdot \mathrm{M} \tag{1}$$

where *M* is the earthquake magnitude, λ is the annual rate of earthquakes of a given magnitude *M* and *a*, *b* are coefficients derived from statistical regression analysis on historical catalogue data.
Once defined a set of potential earthquake scenarios, ground motion is modeled with Ground Motion Prediction Equations (*GMPEs*), that provide a probabilistic distribution of a given intensity measure conditional to earthquake intensity, point-to-source distance and other parameters related to specific geological features. *GMPEs* are usually calibrated through regression analyses on data recorded in past events. The general expression of a *GMPE* relationship is:

$$\log_{10} \mathrm{IM}_{ij} = f(\mathrm{M}_i, \mathrm{R}_{ij}, \theta_{ij}) + \sigma_B \nu_i + \sigma_W \varepsilon_{ij} \tag{2}$$

where IM_{ij} is the intensity measure of interest for a site *j* far R_{ij} from the source i during an event of magnitude M_i, θ_{ij} encloses geological conditions, $\sigma_B \nu_i$ represents the residual inter-event variability whereas $\sigma_W \varepsilon_{ij}$ is the intra-event residual. The ν_i and ε_{ij} terms are random variables normally distributed with mean value μ = 0 and standard deviation σ = 1, whereas σ_B and σ_W are respectively the inter- and intra-event standard deviation values. Spatial correlation models of intra-event residuals available in literature have been mostly estimated using single non-European earthquakes, for which many records were available from dense seismic networks (see Boore et al. 2003; Goda and Hong 2008). It has been observed how the coefficient of correlation ρ_{jk} between intra-event residuals calculated in *j* and *k* sites separated by a distance h_{jk} decreases with increasing mutual distance values. The correlation coefficient is therefore usually a function of the inter-site distance h_{jk}, as follows:

$$\rho_{jk}(h_{jk}) = e^{-3h_{jk}/b} \tag{3}$$

where b represents the inter-site distance at which the spatial correlation is practically lost. In the European strong motion datasets, no dense observations of single earthquakes are available from which reliable estimates of spatial correlation of intensity measures can be obtained. Therefore, strong motion records from multiple events and regions collected in the European Strong-motion Database and the Italian Accelerometric Archive were merged aiming to derive a unique correlation model (Esposito and Iervolino 2011). The use of a correlation function rjk(hjk) exclusively dependent on the inter-site distance hjk for the simulation of the spatial correlation, requires the following assumptions:
- intra-event residuals for a set of spatially distributed sites must follow a multivariate Gaussian distribution;
- Gaussian random field must be second-order stationary;
- GRF must be isotropic.

Under these assumptions, a decomposition approach can be adopted for the simulation of spatially correlated ground motion fields. A random field of residuals *Y* following a multivariate Gaussian distribution, can be defined by a set of y_1, y_2, … y_N residual values for *N* sites, generated as follows:

$$\mathrm{Y} = \mu + \mathrm{LZ} \tag{4}$$

where Z is a vector of z_1, z_2, … z_N values following a Gaussian standardized distribution, μ is a vector representing the mean value of the residuals (herein assumed $\mu = 0$) and L is a lower triangular matrix obtained by the Cholesky factorization, such that $LL^T = C$, where C is the correlation matrix defined positive as follows:

$$C = \begin{bmatrix} 1 & \rho(h_{12}) & \cdots & \rho(h_{1N}) \\ \rho(h_{21}) & 1 & \cdots & \rho(h_{2N}) \\ \vdots & \vdots & \ddots & \vdots \\ \rho(h_{N1}) & \rho(h_{N2}) & \cdots & 1 \end{bmatrix} \quad (5)$$

and $r_{jk}(h_{jk})$ is the correlation coefficient between residual values obtained in pair of sites with a inter-site distance equal to h_{jk}.

3. Seismic fragility and consequence modeling

Pipelines systems can be subject to failures if located in areas prone to seismic hazard. In such cases, release is a direct consequence of structural failure pipes and other elements drift- or acceleration- sensitive.
Seismic vulnerability of gas pipes is defined through fragility curves that represent exceedance probability values for a set of possible damage states as a function of the intensity measure value to which an element is subject during an earthquake. Focusing on the loss of hazardous material, structural damage states are converted in terms of release states (RS). For pipelines three different RSs are taken into account according to Lanzano et al. (2003) namely:

- *RS0* (no damage), in which damage do not cause any loss of containment;
- *RS1* (release from hole), where structural damage involves few loss of containment or a time-distributed;
- *RS2* (catastrophic rupture), representing a structural collapse that leads to the release of large amounts of fluids in a short time-window.

So given an intensity value at a pipe segment it is possible to calculate through the use of loss of containment fragility curves the related *RS* probabilities. A specific event tree is adopted for pipelines components for the assessment of release consequences as shown in Figure 1.

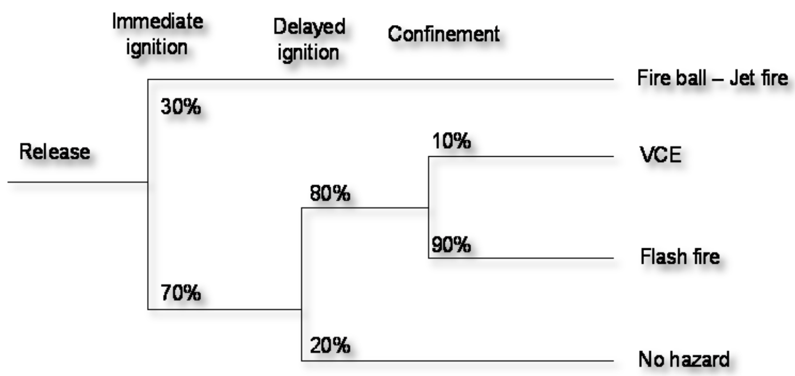

Figure 1: Event tree scheme adopted for pipelines components.

For each specific consequence event it is possible to define a mean consequence radius which identifies the area affected in case of pipe failure. The consequence radius values estimated as function of the fluid contained in the pipe and its geometrical characteristics can be aggregated in a consequence indicator represented by the weighted sum of each value multiplied by its respective final probability of occurrence. In such way, it is possible to highlight which parts of a pipeline system located in an area prone to seismic hazard are more exposed to potential ruptures caused by quake occurrence.

4. Case study

A probabilistic seismic risk analysis is performed on a pipe belonging to the Italian National gas pipeline system with the aim to identify the most exposed segments of the pipe in case of occurrence of a specific earthquake scenario, stocastically simulated via a set of ground motion fields.
The analysis is focused on the pipe #048, located in the North-Eastern Italy, in the Friuli Venezia Giulia region. The area is highly prone to seismic hazard and was recently subject to the Mw 6.4 1976 Friuli earthquake. The aim of this study is to assess consequences of the potential recurrence of the 1976 earthquake on the pipe #048 from Malborghetto to Flaibano, one of the most important pipes, close to the national import point located in the municipality of Tarvisio.

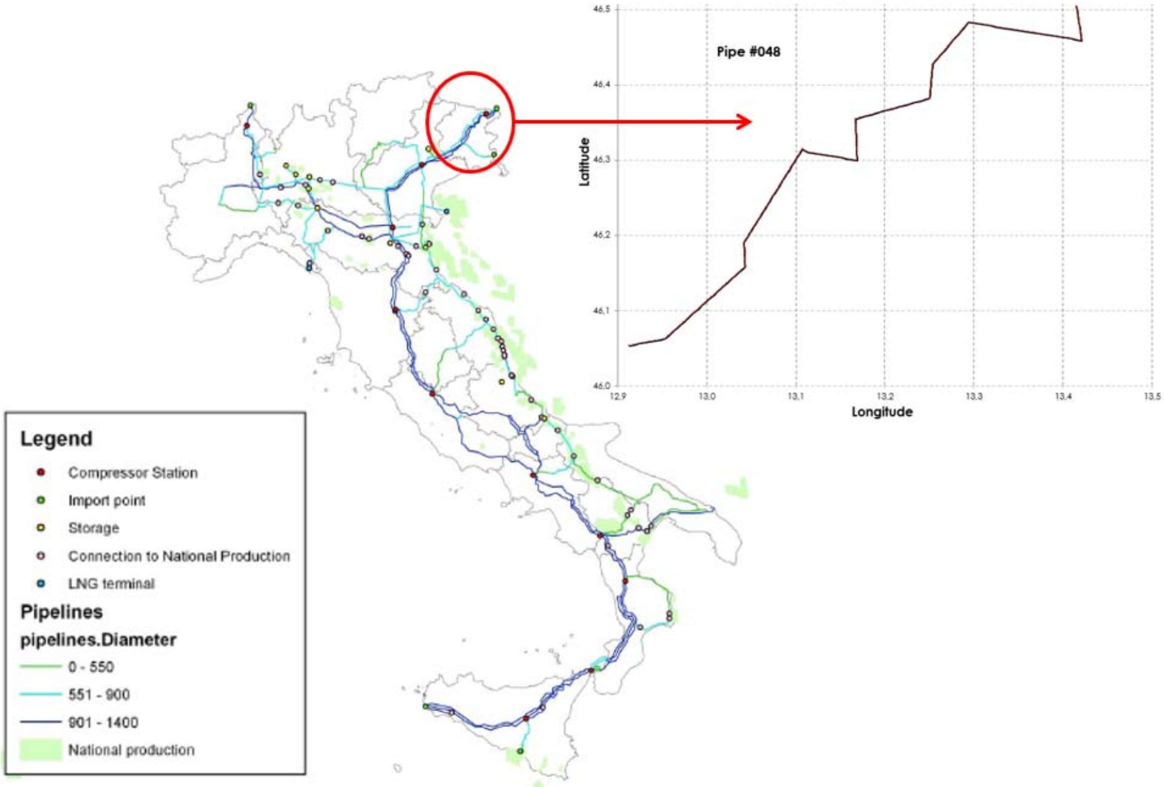

Figure 2: The Italian national gas pipeline network and the analysed Malborghetto-Flaibano pipe #048.

Table 1 lists main input data needed for defining consequence radius values calculated and reported in Table 2, in relation to possible consequences as illustrated in the event-tree diagram of Figure 1.

Table 1: Main input data considered in the analysed case study.

Parameter	Input field	Value
Material	Discharge material	Methane
Process conditions	Temperature	20°C
	Pressure	70 bar
	Diameter	1200 mm
	Flow	294 kg/s
Location	Elevation	-1.5 m

A set of 100 spatially correlated ground motion fields were generated as described above for the stochastic simulation of peak ground velocity (PGV) spatial distribution generated by the M_w 6.4 1976 Friuli earthquake. The *GMPE* of Bindi et al. (2011) was adopted for the characterization of the fields: Figure 3 shows, as example, ground motion field #12.

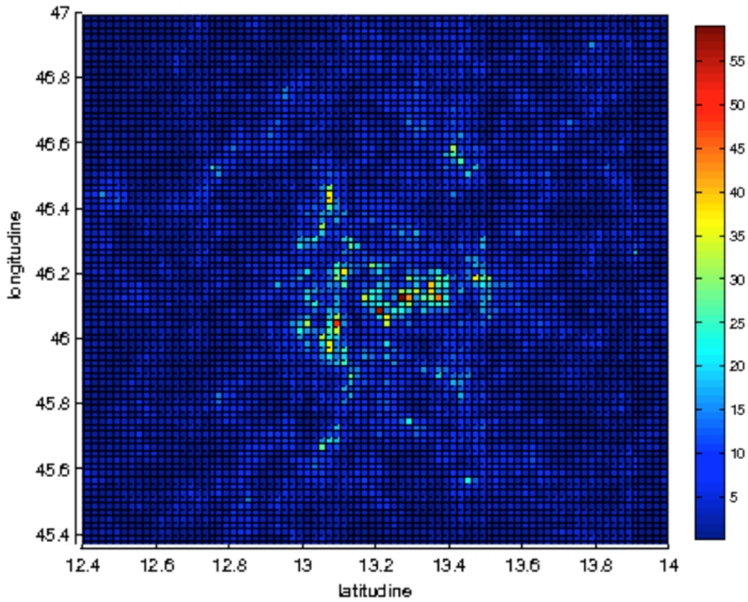

Figure 3: Representation of the M_w 6.4 1976 Friuli earthquake peak ground velocity field #12.

For each *PGV* field structural damages to the different parts of the pipe #048 have been assessed through fragility curves of Lanzano et al. (2013) in terms of release states and associated probability values. Consequence radius listed in Table 2 were subsequently weighed with probability values derived from fragility curves and the event tree diagram illustrated in Figure 1 leading to define an average consequence radius adopted as indicator criterion for the identification of the pipe segments mostly affected in case of Friuli earthquake scenario recurrence. Figure 4 shows the 95th percentile envelope result, representing in green average consequence radius values lower than 200m, in yellow values in the range 200 – 400 m and in red the ones higher than 400m.

Table 2: Consequence radius associated to different possible types of release.

Type of release	Jet fire (37.5 KW/m^2)	VCE (Explosion 0.3 bar)	Flash fire (LFL)
*RS*1 - Release from hole	137	341	1383
*RS*2 - Catastrophic rupture	65	341	1572

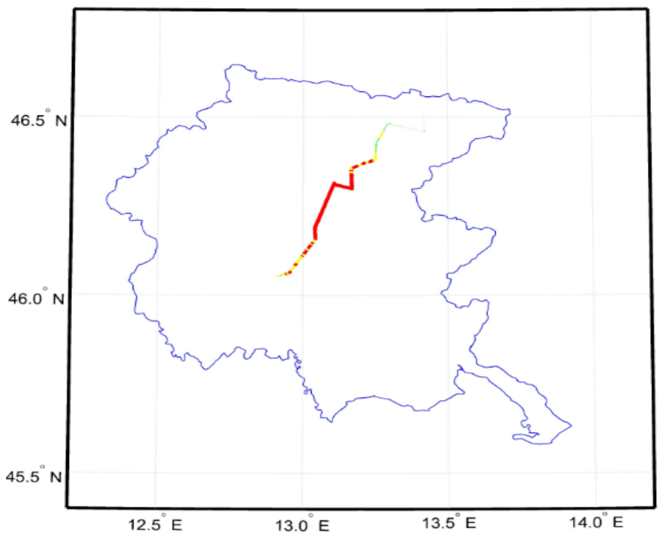

Figure 4: 95th percentile average consequence radius for the pipe #048.

5. Conclusions

In this work, the proposal of a probabilistic framework for seismic risk assessment of buried pipeline systems located in areas prone to seismic hazard was proposed. Seismic hazard modeling coupled with a description of pipelines seismic vulnerability in terms of release states lead to estimate potential consequences in terms of network release scenarios in case of quake occurrence. In particular, for each pipe segment release probabilities were assessed through fragility functions, according to the specific level of shaking induced by the quake, thus leading to different values along the same pipes. Then, event tree analysis allowed to quantify probabilities of occurrence of the different possible consequences of pipe structural failure. The proposed approach was tested through the simulation of the effects on a pipe belonging to the Italian National gas distribution system located in northeast Italy. Once defined a probable earthquake scenario on the basis of the recent seismicity of the area, a set of 100 spatially correlated PGV fields were simulated and for each of them consequences were assessed. Results allowed to identify segments of the pipe mostly affected in case of scenario occurrence.

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