Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 5345-5353

ECCOMAS
Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

SEISMIC RISK ANALISYS OF DISTRIBUTION LINEAR INFRASTRUCTURES

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Abstract

Natural Gas distribution networks are fundamental elements for the socio-economical development of region and of an entire country. Their vulnerability with respect to the so-called NaTech events can imply significant consequences both in terms of physical damage in the area surrounding the infrastructure and in terms of service interruption, as documented in past earthquakes occurred worldwide. Therefore, perform the seismic risk analysis of this type of infrastructure is essential and matter of interest for identify the most relevant critical issues and avoid dangerous consequences. In particular, this paper will focus on Natural Gas buried pipelines, aiming to propose a framework for the seismic risk assessment of such infrastructural system. Finally, the procedure is applied to a case study in Italy for highlighting its value and feasibility.

Keywords: Seismic risk analysis, natural gas pipelines, na-tech events, linear infrastructures, pipelines vulnerability.

Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10805.21409

1 INTRODUCTION

The natural gas (NG) distribution network is a key element for the socio-economic development of each country, representing a primary need for both citizens and industrial facilities. Commonly, a NG pipeline is designed for transporting gas among localities situated at large kilometers, with pipes diameters that can reach several hundred centimeters and length that can reach several thousand kilometers. In their spatial development, pipelines can cross different environments, as highly populated and/or industrialized areas, areas exposed to natural hazards as landslides, earthquakes etc. For these characteristics, their possible failure can cause a series of significant consequence, mainly related to two aspects. The first one is mainly related to the physical damage that an explosion following the structural damage of the pipeline may cause in the surrounding area, while the second one is related to the economic effects that the interruption of the NG supply may induce at different levels. Despite the limited number of accidents occurred so far ([1], [2]), some significant events showed the terrible effects on the population and on the surrounding environment. In 2004, in Ghislenghien industrial park (in Ath, close to Brussels, Belgium), there was the explosion of an underground high pressure NG pipelines [3], while another rupture occurred in Kingman (Kansas, USA [4]). Thus, the development of procedures for a quantitative risk assessment for such kind of critical infrastructure is a key step for investigating the potential impact of such events and developing suitable risk reduction programs, as showed by [5].

In some circumstances, pipelines failures can be triggered by natural hazards: in seismic risk prone area, buried pipelines can be subject to permanent ground motions or transitory strong ground shakings which can lead to damages and consequent release of transported substances, causing abrupt service stop or explosions as in the of the 1994 Northridge [6], 1995 Kobe [7] and 1999 Kocaeli [8] earthquakes. Less recently, the 1971 San Fernando earthquake moment magnitude M_w = 6.7 damaged the underground pipelines, while the 1923 Kanto earthquake (M_w = 7.9) caused several breaks in the gas pipelines in the region of Tokio.

In general, pipelines can be subdivided in aboveground and underground pipelines. In the former case suitable supports are adopted for supporting the pipe, while in the latter case pipelines are commonly buried in a range of 1-2 m; less frequently, as for pipelines with very large diameter, pipelines are buried deeper. The advantage of the buried one than respect to the others, is firstly the fact that the landfill protects the pipelines from the above ground damage sources, and secondly the fact that the lateral confinement provided by the surrounding soil reduces possible earthquake-induced damages. As a consequence, pipelines tends to follow the soil deformation and the structural response is strictly related to the geotechnical effects only. According to [9], geotechnical issues for pipelines can be subdivided in two main groups: the first one is related to strong ground shaking, that can cause the deformation of the soil surrounding the pipelines, while the second one is related to the ground failure, e.g., induced by fault movement, landslide liquefaction etc. Of course, this latter case, is strongly dependent on the site where the pipelines is located.

In particular, this work will analyses the risk of seismic-induced explosion of a buried NG pipelines located in North-eastern Italy. First a Probabilistic Seismic Hazard Analysis (PSHA) is performed in order to compute the seismic hazard of the area where the pipeline is located, then a detailed consequences analysis is provided in order to investigate all the possible consequences that the failure of such infrastructures may cause, together with the likely of each possible outcome.

2 RISK ANALYSIS

2.1 Seismic hazard

The proposed work adopts the classical Probabilistic Seismic Hazard Analysis developed by [10] and [11] for computing the so-called hazard curve, that associates to each level of ground motion intensity measure im the corresponding annual exceedance rate λ_{im} at the site of interest. The PSHA integral is given by:

$$\lambda_{im} = \sum_{i=1}^{n_{SZ}} \nu_{m_{\min,i}} \int_{m_{\min,i}}^{m_{\max,i}} \int_{r_{\min,i}}^{r_{\max,i}} P\left[IM > im \mid m, r\right] f_{M_i}\left(m\right) f_{R_i}\left(r\right) dm dr \tag{1}$$

where $\nu_{m_{\min,i}}$ is the rate of occurrence of earthquakes greater than a suitable minimum magnitude $m_{\min,i}$ of the i^{th} seismogenic zone (SZ), $f_{M_i}\left(m\right)$ and $f_{R_i}\left(r\right)$ represent respectively the earthquake magnitude distribution and the source-to-site distance for the i^{th} SZ. Finally $P\left[IM > im \mid m, r\right]$ commonly computed via a Ground Motion Prediction Equation (GMPE), provide the exceedance probability of a given im value conditioned on a seismic event with a specific magnitude m and occurring at a distance r. In this specific work, the PSHA is performed on a pipe belonging to the Italian National gas pipeline system [12], focusing 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 in the recent past (1976) subject to the M_w 6.4 Friuli earthquake. For the aim of the paper, the pipe has been subdivided in 81 independent sections 1 km spaced (Figure 1).

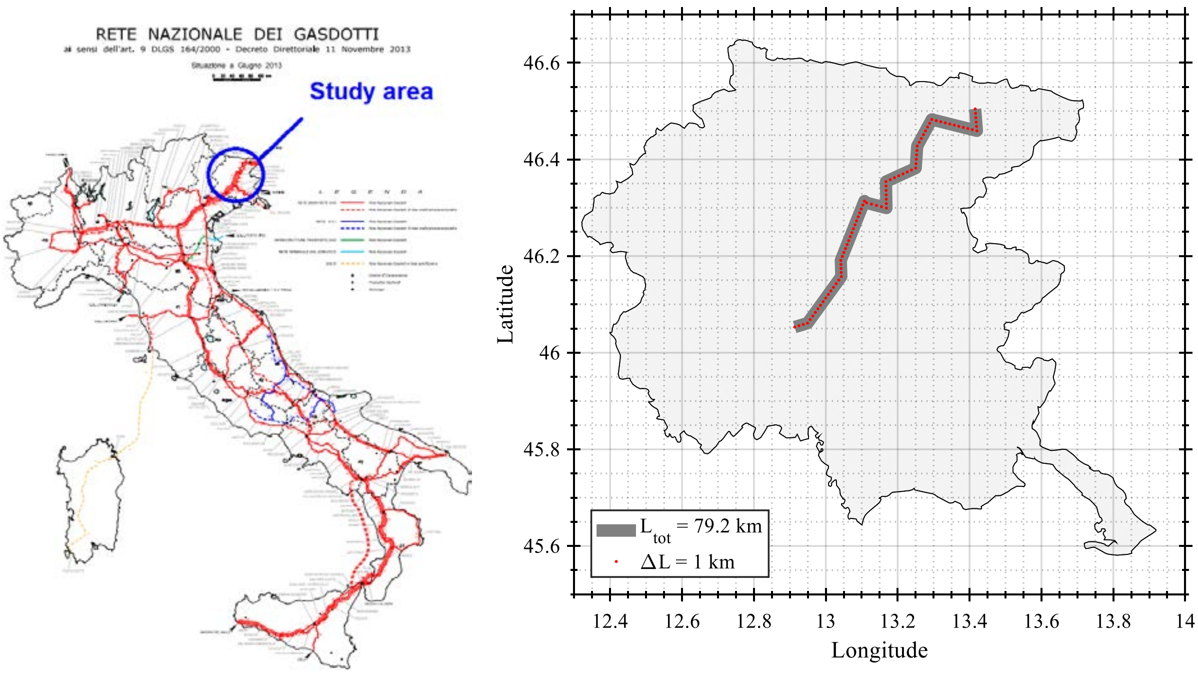


Figure 1: Italian national gas pipeline network (left) and the analyzed Malborghetto-Flaibano pipe #48 (right).

For performing the PSHA, the seismogenic source zone model ZS9 detailed in [13] has been adopted, using Gutenberg-Richter (G-R) recurrence laws for each of the 7 SZs contributing to the seismic hazard (i.e. SZs # 903, # 904, # 905, # 906, # 907, # 912, # 917) within a radius of 200 km from the site of interest (Figure 2). Parameters of the G-R) recurrence laws for each i^{th} SZ, were retrieved from [14], while the GMPE of [15] were selected as suitable attenuation law. The Peak Ground Velocity (PGV) was adopted as reference intensity measure, mainly for its predictivity than respect to the pipelines damage susceptibility [16]. The soil class of each point is determined from the soil map realized by [17] and it is showed in Figure 3a. Finally, Figure 3b shows the output of the PSHA, in particular the PGV values with an exceedance rate of 0.0021 (return period of 475 years).

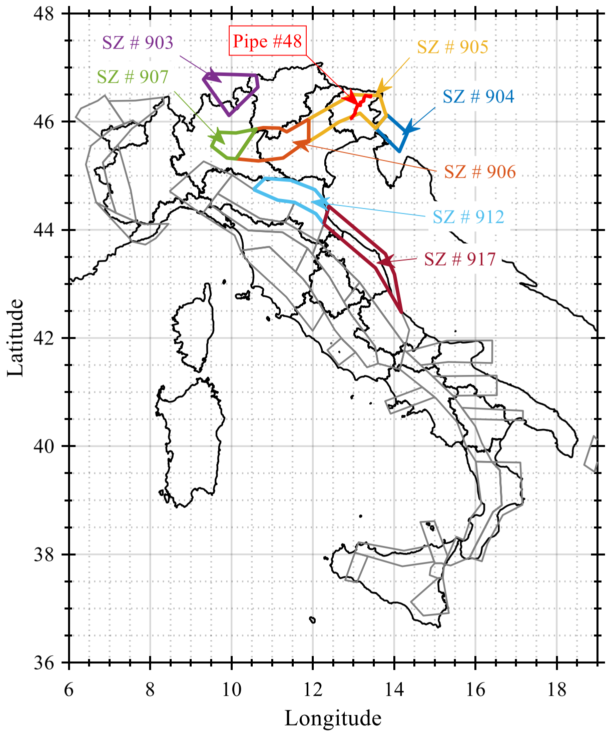


Figure 2: Pipe #48 and adopted seismogenetic source model.

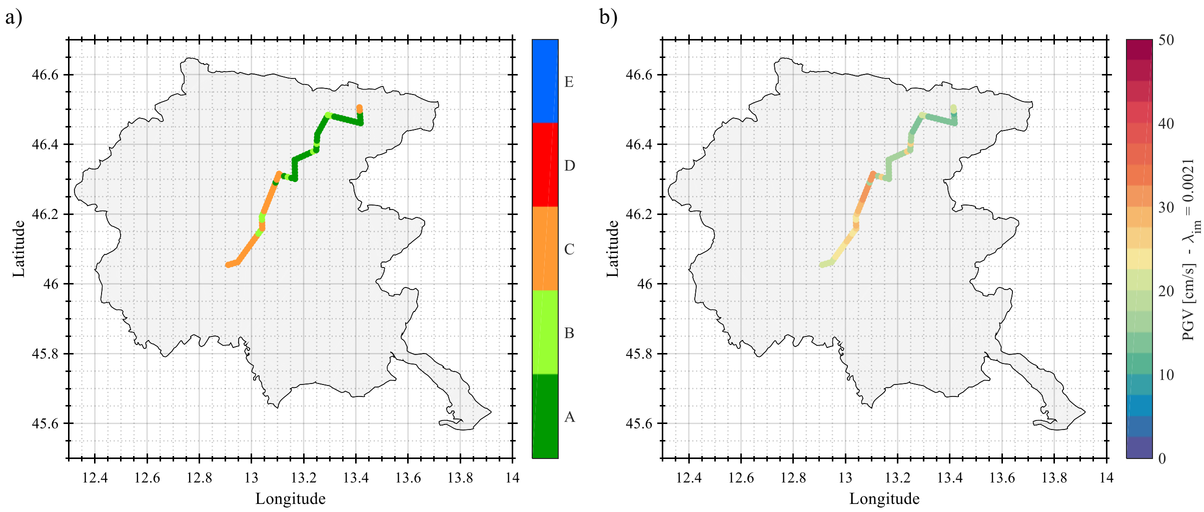


Figure 3: Soil category for each point of Pipe #48 (a) and PGV values for λ_{im} = 0.0021 (b)

2.2 Seismic fragility

The structural fragility of NG pipelines is defined through fragility curves, that represent the exceedance probability of a set of specific damage thresholds, conditioned on a given value of im. Focusing on the loss of hazardous material, structural damage states are converted in terms of release states (*RS*). For pipelines three different RSs are considered according to [16] namely:

- *No damage* (*RS0*), in which the pipe damage does not cause any content loss;
- *Release from hole* (*RS1*), where structural damage causes few content loss, or a time-distributed loss.
- *Catastrophic rupture (RS2),* where the structural collapse leads to the release of large amounts of fluids in a short time-window.

The characteristics of the analyzed pipeline are listed in Table 1, together with the median values μ and the shape parameter β of the fragility curves retrieved from [16].

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

Risk State RS	μ (cm/s)	β
RS1	45.22	0.39
RS2	71.16	0.20

Table 1: Main characteristics of Pipe #48 and fragility curves parameters.

2.3 Consequences modelling

The last step of the risk assessment procedure deals with the computation of the possible consequences. Given an intensity value at a pipe segment it is possible to calculate using the 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 4: each branch of the event tree represents a separate accident sequence, each with the corresponding occurrence probability [5]. In 30% of cases, an immediate ignition can occur, then resulting in a jet fire or fireball. In the remaining 70 % there are no consequences only in the 20% of cases. When there is a delayed ignition, i.e. when released gas finds an ignition source after being dispersed in the atmosphere for several minutes, in 90% of cases it is expected to produce a flash fire (i.e., short-duration fire that spreads by means of a flame front rapidly without the production of damaging pressure) since methane is lighter than air; only in the 10% of cases a vapor cloud explosion (VCE, i.e. the explosion of flammable substance diffused in the surrounding environment) may occur.

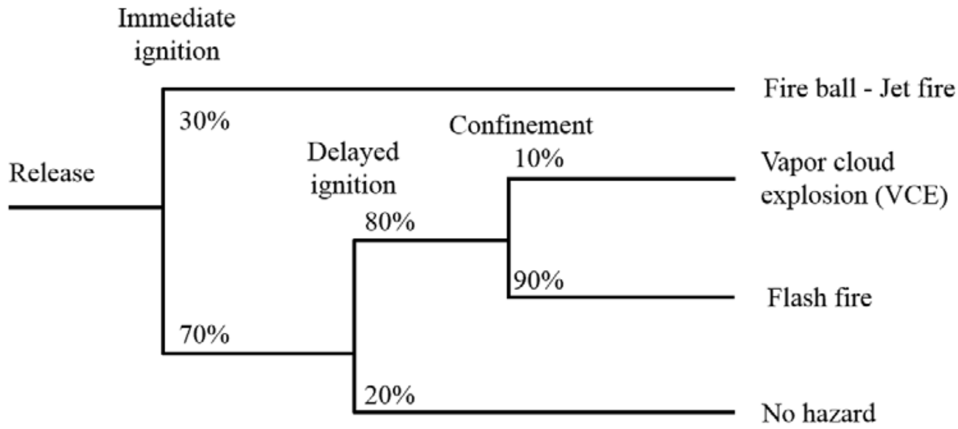


Figure 4: Pipe #48 and adopted seismogenetic source model.

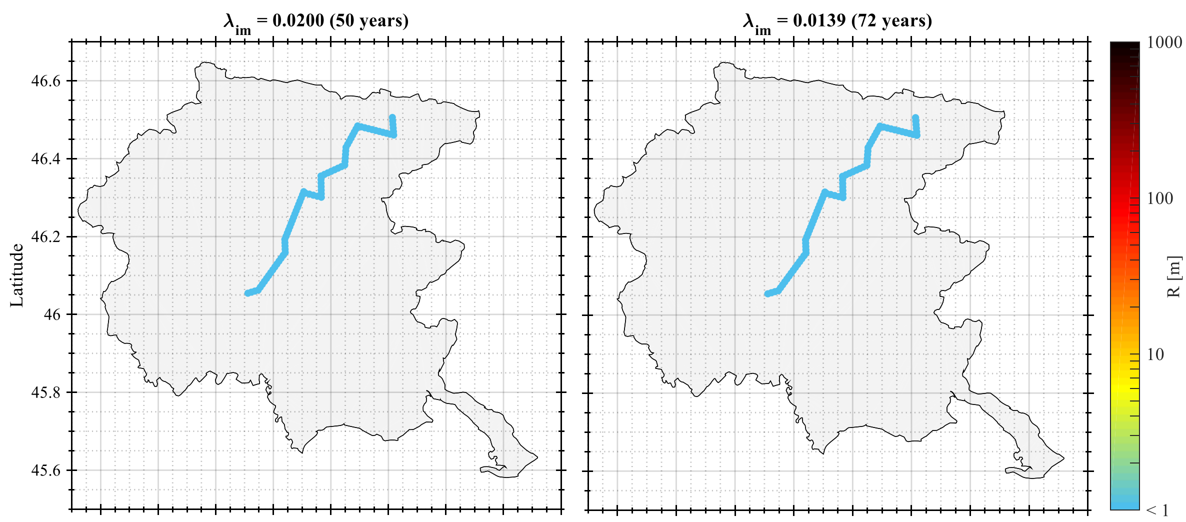
For each specific consequence of Figure 4, it is possible to define a consequence radius which identifies the area affected by each considered outcome, where, for example, consequences can be evaluated in terms of damaged buildings, injured people etc. The consequence radius values are estimated as function of the fluid contained in the pipe and its geometrical characteristics and are reported in Table 2 for each possible damage state.

Type of release	Jet fire (37.5 KW/m^2)	VCE (explosion 0.3 bar)	Flash fire
RS1 - Release from hole	137 m	341 m	1383 m
RS2 - Catastrophic rupture	65 m	341 m	1572 m

Table 2: Consequence radius associated to different possible consequences.

3 RESULTS

The consequence radius values of Table 2 were subsequently weighed with probability values retrieved from fragility curves for a specific PGV, and the event tree diagram illustrated in Figure 4 leading to define an average consequence radius adopted as final indicator. In particular, the consequence radius corresponding to PGV values with 8 specific exceedance rates were computed and reported in Figure 5. The reference PGV exceedance rate are: 0.02 (50 years), 0.0139 (72 years), 0.0099 (101 years), 0.0071 (140 years), 0.0050 (201 years), 0.0021 (475 years), 0.0010 (975 years) and 0.0004 (2475 years).



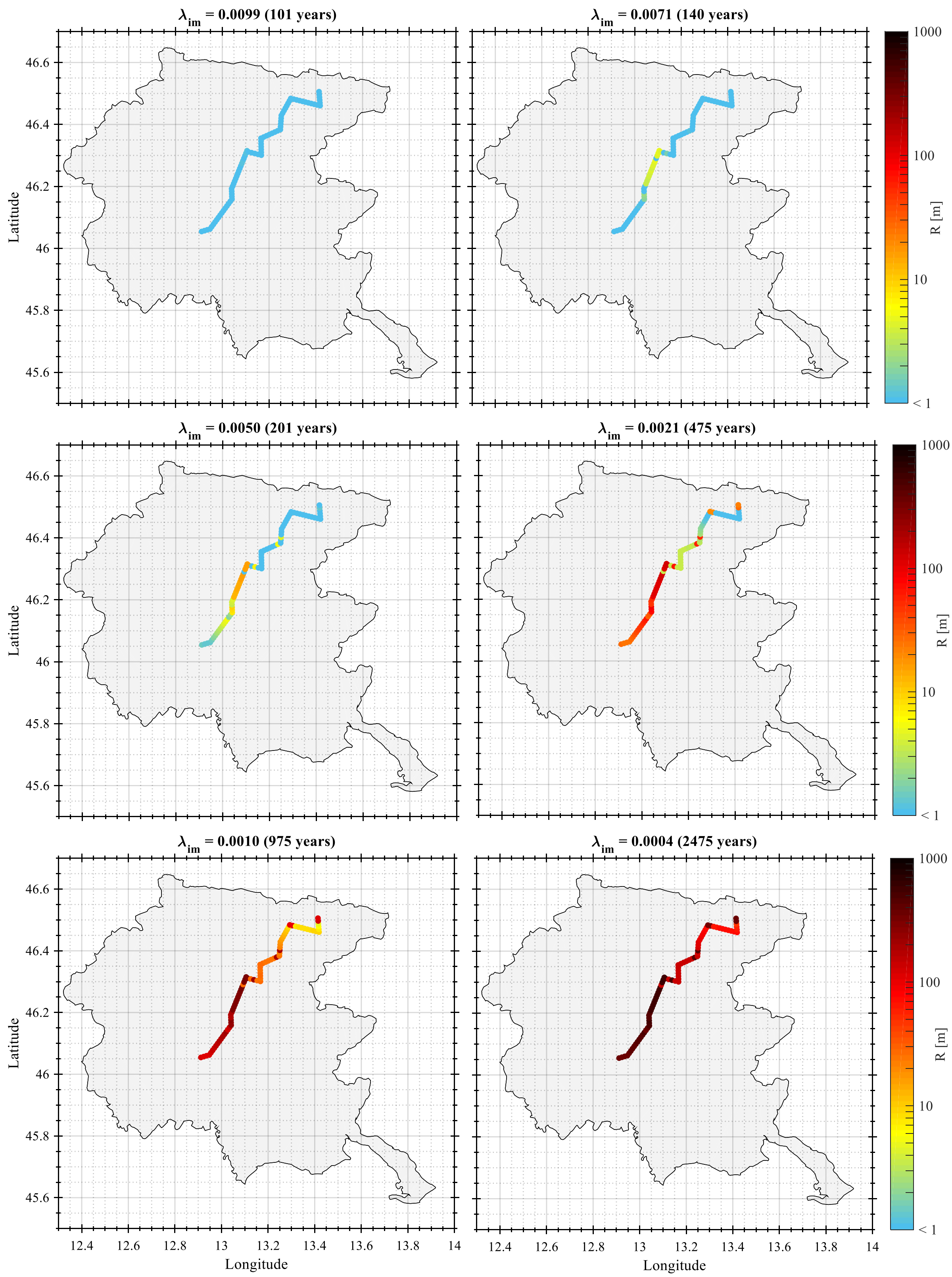


Figure 5: Consequence radius for different PGV exceedance rate.

Results show that for PGV exceedance rate lower than 0.0050 (201 years), i.e. for frequent events of low shaking values, the expected radius is limited for the entire pipe #48, with values lower than 100 m from the pipeline axis. For more rare events, the maximum expected consequence radius significantly increases, still reaching values around 1 km, corresponding to a potential affected area of 3.14 km^2.

4 CONCLUSIONS

This works presents a framework for computing the possible effects of seismic-induced damage on NG pipelines. Seismic hazard modelling coupled with a quantitative description of pipelines seismic vulnerability in terms of release states lead to estimate potential consequences in terms of expected consequence radius. For each pipe segment release probabilities were assessed through fragility functions, according to a specific level of shaking induced by the quake and corresponding to a given exceedance rate. The proposed framework allows, by using an event tree analysis, to quantify probabilities of occurrence of the different possible consequences of pipe structural failure and then to compute the resultant expected radius. 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, showing that for the rarest events, e.g., those characterized by a return period higher than 475 years, the consequence radius can reach values almost close to 1 km, corresponding to a potential affected area of 3.14 km^2. Furthermore, the proposed framework can be a useful tool for estimating the area potentially involved in a seismic-induced explosion.

ACKNOWLEDGEMENT

This work was funded by the European Commission, Project 2014 – 2020 Interreg V-A | Italy – Croatia CBC Programme: FIRESPILL - Fostering Improved Reaction of crossborder Emergency Services and Prevention Increasing safety Level.

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