Chapter 9
Application to L'Aquila Gas Network

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Abstract This chapter, after an introduction presenting the general framework for the seismic risk assessment of a gas network according to the SYNER-G methodology (Chap. 2), describes the case study of L'Aquila (central Italy) gas distribution system, a 621 km pipeline network managed by Enel Rete Gas s.p.a. and operating at medium- and low-pressure. Subsequently, the main features regarding the implementation of the application study within the SYNER-G framework are reported, and the process for the seismic performance characterization is summarized. Then, the risk analysis of the system is described, and results in terms of connectivity-based performance indicators are presented.

9.1 Introduction

This study presents the probabilistic seismic risk assessment of a gas distribution system. A gas distribution system comprises two main categories of components: (i) a number of point-like facilities (reduction stations and groups where gas is reduced or simply measured); (ii) pipelines constituting the distribution network.

The causes of earthquake damage to components of gas distribution systems include large permanent soil deformations produced by fault displacements, landslides and liquefaction (O'Rourke and Liu 1999), as well as ground shaking associated with traveling seismic waves. The latter case is often referred to as transient ground deformation (TGD), while the former is generally referred to as permanent ground deformation (PGD); i.e., the *geotechnical hazard*.

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Ground shaking usually affects wide geographical areas and can produce well-dispersed damage. Damage induced by permanent ground deformation typically occurs in isolated and localized areas and results in high damage and consequent repair rates, varying in relation to the amount, geometry, and spatial extent of the zone subjected to PGD.

This application study was aimed at evaluating, in a complete performance-based earthquake engineering framework, the seismic risk of a gas distribution network. The work includes the probabilistic characterization of seismic input, the evaluation of the vulnerability of network's components, the analysis of the system's performance measures, and finally the probabilistic simulation for risk assessment.

As an illustrative, yet real, application, the mid-pressure part of the L'Aquila (central Italy) gas distribution system is considered. In particular, the selected network is characterized by three reduction stations connecting the network to the high-pressure nationwide network, more than 200 km of pipelines, either made of steel or high density polyethylene (HDPE) pipes, and about 200 reduction groups.

In fact, detailed information about the system was available for this network, including performance in the 2009 M_w 6.3 earthquake (Esposito et al. 2013a), due to a dedicated partnership with the network's operator (*Enel Rete Gas s.p.a.*). For the purposes of seismic risk assessment, a single earthquake source is considered, the Paganica fault (Pace et al. 2006); it is beneath the region served by the network and it is believed to have generated the 2009 L'Aquila earthquake.

Seismic performance is expressed in terms of probability of exceedance of service disruption levels, measured by connectivity-based indicators, given the occurrence of an earthquake on the considered source.

The chapter is structured such that Sect. 9.2 presents the general framework for the seismic risk assessment of a gas network according to the SYNER-G methodology. Section 9.3 describes the case study and provides details on the implementation in the prototype SYNER-G software. Subsequently, the analysis of the system is carried out at the connectivity level, and results in terms of performance indicators are, finally, presented in Sect. 9.4.

9.2 Methodology

In this section the SYNER-G framework for the risk assessment of spatially distributed systems is recalled focusing on gas distribution system and its components (namely pipelines and stations). In particular, a concise summary of: the methodology with respect to seismic hazard analysis (Chap. 3), fragility functions of the vulnerable elements (Gehl et al. 2014), and performance analysis (Chap. 5), is provided in order to facilitate the understanding of the application study.

9.2.1 Seismic Hazard Analysis

The analysis of seismic hazard (in terms of both TGD and PGD) for spatially distributed systems, presents different challenges with respect to those addressed by consolidated tools adopted for hazard characterization of point-like structures.

First, because this kind of systems is extended in space, a key difference is that the seismic hazard has to be evaluated jointly for all the locations of the system components. Large vectors of ground motion intensity measures (*IMs*), usually expressed in terms of peak parameters (e.g., peak ground acceleration, PGA, or peak ground velocity, PGV) should be estimated through ground motion prediction equations (GMPEs), but also accounting for spatial correlation. In fact, if probabilistic assessment of ground motion intensity at two or more sites, at the same time, is of concern, then a spatial correlation model accounting for the statistical dependencies between intra-event residuals of *IMs* as a function, for example, of inter-site separation distance, is needed. This serves to model the joint probability density function of *IMs* at all locations. This means that seismic hazard has to be represented in terms of random fields (e.g., Esposito and Iervolino 2011, 2012).

Furthermore, the performance of spatially distributed systems may be conditional upon the failure of many components each of which is sensitive to different *IMs*. In particular, some elements of a gas system, such as reduction stations, have fragility curves typically expressed in terms of PGA, while fragility of pipelines may be a function of PGV. Each *IM* is spatially correlated, but the seismic input assessment has to take into account the possibility of the existence of a cross-correlation between *IMs*, in order to model the joint distribution of different random fields. To address this issue, the *conditional hazard* approach may be considered (Iervolino et al. 2010).[1] It consists of obtaining the conditional distribution of a secondary intensity measure, IM_2, at a site (e.g., PGV), given the occurrence of a primary intensity measure, IM_1, at the same site (e.g., PGA) for which a spatial correlation model is available (see Chap. 3 for more details).

Finally, geotechnical hazards associated with earthquakes (i.e., liquefaction, landslide and co-seismic rupture) may have a significant impact on lifelines, particularly those with buried elements. An assessment of seismic risk of spatially distributed elements must, therefore, incorporate PGD hazard in a manner that is also consistent with the TGD hazard. There are many models available that have the intent to relate PGD, and the probability of occurrence of each geotechnical hazard, to the intensity of ground motion (typically expressed in terms of PGA). In this context, the need of practical implementation of PGD for large areas is addressed following the HAZUS (FEMA 2004) approach that requires limited information about the geotechnical characterization of the region. In fact, the HAZUS approach has been slightly refined within SYNER-G, considering recent semi-empirical

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[1]The simplest application of conditional hazard requires site-specific correlation coefficients between *IMs* and acceptability of the hypothesis of joint normality of the logarithms of the primary and secondary *IMs*.

models for the computation of the permanent ground deformation, and including the probabilistic distribution of model residuals (again, details are given in Chap. 3).

9.2.2 Fragility Functions

To estimate earthquake damage for a natural gas distribution system, given ground shaking (or ground failure), earthquake intensity parameters have to be related to the seismic impact on the system's components via fragility functions. In particular, for point-like components (i.e., stations) these relations typically provide the probability of reaching or exceeding some *damage state* given the intensity. This applies to the aboveground components of a gas distribution network, while for pipelines the fragility models usually consist of a seismic-intensity-dependent rate, providing the number of damages (e.g., *leaks* or *breaks*) per unit length.

9.2.2.1 Buried Pipelines

In the case of pipeline components, fragility curves available in literature are usually based on empirical data collected in past earthquakes. Empirical fragility functions are mostly based on the recorded number of repairs collected from field crews (e.g., ALA 2001). As a result, all fragility relations for pipelines are given in terms of the repair rate, R_R, per unit length of pipe. Further factors affecting the vulnerability of pipelines, usually accounted for in the formulation of the repair rate, are material, diameter, or connection type. Then, using a Poisson probability distribution and R_R as its parameter, one can assess the probability of having any number of damages in a pipe segment, given the local intensity.

As mentioned above, buried pipelines are sensitive to permanent ground deformation, in addition to TGD due to seismic wave propagation. Among the various seismic parameters used to correlate the ground shaking effects to the damage suffered by buried pipelines, PGV is often preferred (O'Rourke et al. 1998). Regarding ground failure effects, permanent ground deformation (PGD), a measure of displacement, is used as the demand descriptor.

According to HAZUS, two damage states may be considered for pipelines: leaks and breaks, with the type of damage depending on the type of hazard. In particular, when a pipe is damaged due to ground failure, it is assumed that the proportions of leaks and breaks are 0.2 and 0.8, respectively; whereas for ground shaking, leaks and breaks relative proportions are 0.8 and 0.2, respectively.

9.2.2.2 Stations

In a gas distribution system, three different types of stations may exists: (i) metering/pressure reduction stations (M/R stations) that contain metering

equipments for monitoring and measuring the gas flow, and reduction lines for the reduction of the gas pressure (from high to medium) before its distribution into the pipe system; (ii) reduction groups, where the gas pressure is reduced (from medium to low) as required for the gas to arrive to the end-user; and (iii) metering stations that are only flow measurement points.

Considering that stations comprise the shelter and the equipment inside, they may be classified with respect to different features such as building typology and/or presence of anchored or unanchored subcomponents. Although in literature no fragility curves are available for, at least, (i), some authors (e.g., Chang and Song 2007; Song and Ok 2009) assume that they can be characterized by the same fragility functions of compressor stations. Damage states and fragility curves for compressor stations are usually defined as a function of PGA (FEMA 2004).

9.2.3 Vulnerability of the System and Performance Indicators

9.2.3.1 Gas Network Model and Analysis

As mentioned in Chap. 5, the seismic performance of a gas network (and of lifeline networks in a general sense) may be measured according to two categories of indices: (1) those based on connectivity analysis that allows assessment of serviceability in terms of the aggregate functionality of facilities (nodes) composing the system; e.g., the number of distribution nodes which remain accessible from at least one supply node after the earthquake; (2) those based on capacitive analysis that include consideration of flow equations used to compute flows from sources to sinks (i.e., distribution nodes), based on the damages sustained by the network components.

Connectivity analysis requires a simple description of the network, defined as a collection of nodes (i.e., stations) and lines (i.e., pipes) joining all or some of these points. Connectivity analysis tools are limited to those of graph theory (e.g., Ching and Hsu 2007). These algorithms are applied on the network after removing the parts of the system that failed in the seismic event.

In flow-based analysis, the network's performance is measured by evaluating the actual flow delivered to end users, as a function of pressure at demand nodes. For the purpose of calculating pipe flow and nodal pressure, before and after the seismic event, it is necessary to consider flow equations (the application of flow equations is required for the calculation of the pressure drop along the network) and a method to solve the network analysis problem (see Osiadacz 1987, for a discussion).

9.2.3.2 Performance Indicators

Depending on the goal of the analysis (connectivity- or flow-based) different performance indicators (PIs) may be evaluated. PIs are able to quantify the degree

to which the system is able to meet established specifications and/or customer requirements following an earthquake event. For a gas distribution network two possible system-level PIs that may be used for a connectivity analysis are: the Serviceability Ratio (SR) and the Connectivity Loss (CL).

The first index, originally defined by Adachi and Ellingwood (2008) for water supply systems, is directly related to the number of distribution nodes in the utility network, which remain accessible from at least one supply facility following the earthquake. It is computed as in Eq. 9.1, where w_i is a weighting factor assigned to the distribution node i (i.e., customers related to the demand node or nominal flow of the distribution node), X_i represents the functionality of i-th demand node, which is modeled as the outcome of a Bernoulli trial ($X_i = 1$ if the facility is accessible from at least one supply facility and zero otherwise), and n is the number of distribution nodes.

$$SR = \sum_{i=1}^{n} (w_i \cdot X_i) \Big/ \sum_{i=1}^{n} w_i \tag{9.1}$$

The second index, originally defined by Poljanšek et al. (2012), was adapted for the purpose of this study and it is expressed in Eq. 9.2. In particular, it is related to the number of the demand nodes connected to the i-th source in the original (undamaged) network and then in the damaged network, $N^i_{demand,dam}$. In Eq. 9.2, $\langle\rangle$ denotes averaging over all source nodes.

$$CL = 1 - \left\langle \frac{N^i_{demand,dam}}{N^i_{demand,orig}} \right\rangle_i \tag{9.2}$$

For a more extended discussion on other possible PIs see Chap. 5 and Esposito (2011).

9.3 Application to L'Aquila Gas Network

9.3.1 The Case Study

In the L'Aquila region (central Italy) the gas is distributed via a 621 km pipeline network, 234 km of which with gas flowing at medium pressure (2.5–3 bar), and the remaining 387 km with gas flowing at low-pressure (LP) (0.025–0.035 bar).

The medium-pressure (MP) distribution network is connected to the high-pressure transmission network through three M/R stations [referred to as Re.Mi stations ("*stazioni di Regolazione e Misura*" in Italian)]. The three M/R stations are cased in one-story reinforced concrete structures with steel roofs (Fig. 9.1) hosting internal regulators and mechanical equipment (heat exchangers, boilers and bowls), where the gas undergoes the following processes: (1) gas pre-heating; (2)
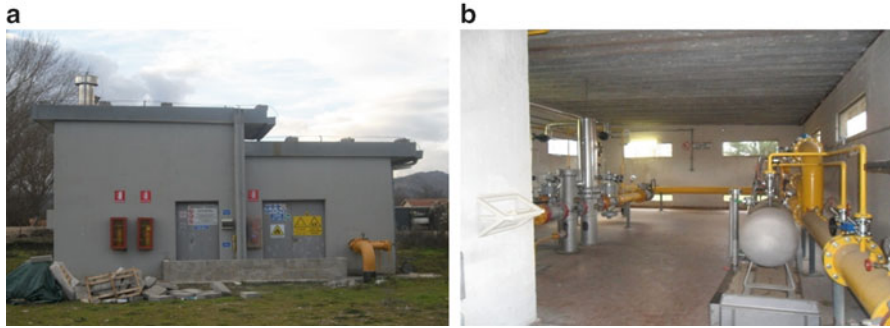
Fig. 9.1 M/R reduction stations in Onna (L'Aquila, Italy): (**a**) external view; (**b**) internal view (Esposito et al. 2013a)
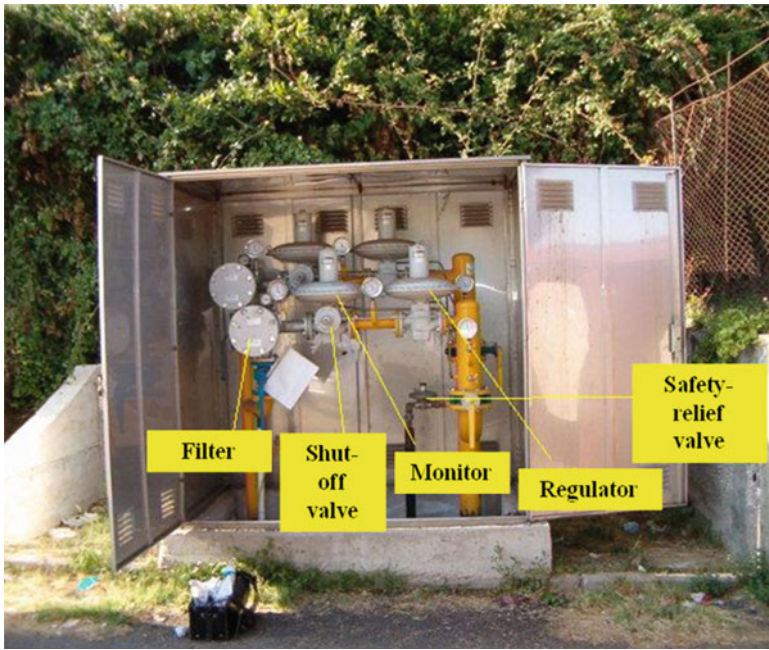

Fig. 9.2 One of the 300 RGs housed in a metallic kiosk (Esposito et al. 2013a)

gas pressure reduction; (3) gas odorizing; (4) gas pressure measurement. Pipelines of medium and low-pressure distribution network are either made of steel or HDPE according to the pressure level.

The transformation of the MP into the LP is operated via 300 Reduction Groups (RGs) that are buried, sheltered in a metallic kiosk or housed within/close to a building (Fig. 9.2).

Several demand nodes (referred to as IDU, *Impianto di Derivazione Utenza* in Italian), consisting of buried and above-ground pipes and accessory elements, allow the supply of natural gas to utilities from LP network. For users such as industrial facilities, the demand node IDU is located along the MP network.

Close collaboration with the network operator has allowed the characterization of the system, necessary for the evaluation of gas system seismic performance. A geographic information system (database) was jointly developed and contains data on system physical and operational characteristics.

For the evaluation of seismic performance within this study, the medium-pressure portion of the L'Aquila gas system was selected. In particular, the selected part (shown in Fig. 9.3) is characterized by 3 M/R stations, 209 RGs, and pipelines either made of steel or HDPE.

9.3.2 Implementation of the Gas Distribution System Within the SYNER-G Framework

This section provides additional details regarding the software implementation of the case study with respect to the general description reported in Chap. 5 for gas systems. For the purposes of the application study, the SYNER-G computational framework (i.e., the SYNER-G prototype software) was equipped with the *GAS* class. The gas distribution system is modeled as an undirected graph, hence, the *GAS* class is considered a subclass of the *Undirected* abstract class. As shown by the class diagram in Fig. 9.4, the network is composed of nodes and link/edges. As a consequence, the *GAS* class is the composition of the *GASedge* and *GASnode* abstract classes, the first of which is the generalization of the *PipeGAS* class, while the second is the generalization of the *GASdemand*, *GASsource* and *Joint* classes. The *Joint* class represents all nodes used to reproduce the geometry of the system, the *GASsource* class represents M/R stations that are used to connect the distribution mid-pressure network to the high-pressure transmission lines, and the *GASdemand* is the generalization of *IDU* class and *RG* class. The *IDU* class represents the nodes directly connected with customers in the low-pressure network, while the *RG* class represents reduction groups that are considered as final nodes when only the mid-pressure network is analyzed. The definition of these edge typologies, together with associated fragility models are given in Gehl et al. (2014).

All the attributes and methods of the *GAS* class and its subclasses (listed in Esposito and Iervolino 2013) were defined in order to evaluate the state of the network and of each component of the gas system. Attributes refer to properties that describe the whole system and each component. They can be listed as:

1. *List of pointers (e.g., all the connections between objects);*
2. *Gas network global properties (e.g., the number of nodes, or edges);*
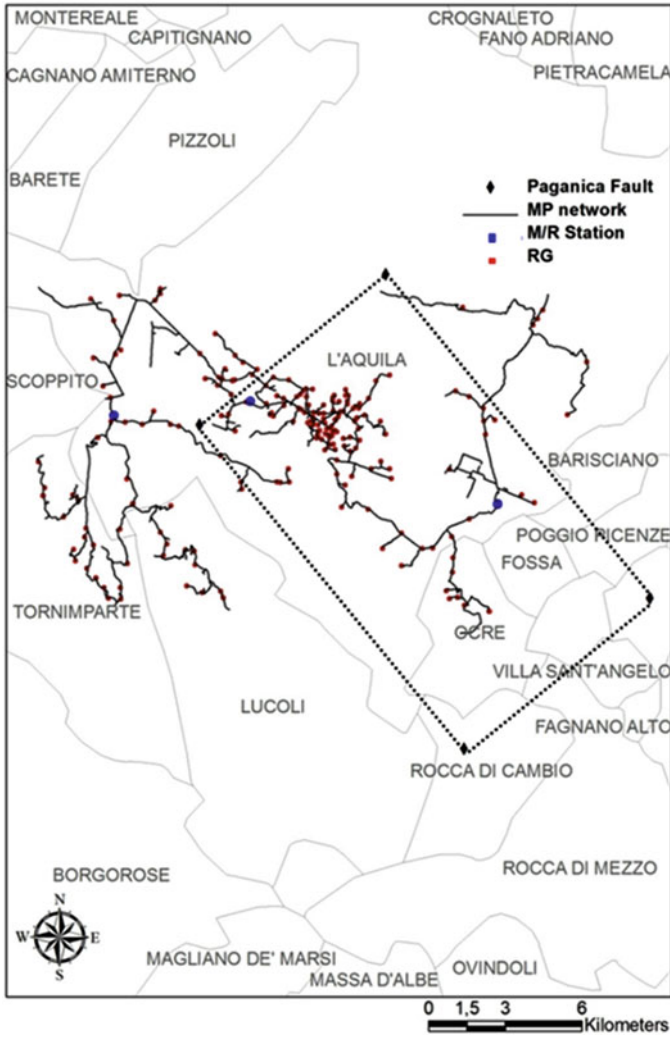
Fig. 9.3 Application network (L'Aquila, central Italy)

3. *Edge and node properties (e.g., the length of the edge or the position of a node, or the corresponding landslide susceptibility);*
4. *Properties that record the state of the GAS for each event;*
5. *Properties that store the global performance of the GAS at the end of simulation.*

Methods refer to functions used to evaluate the state of the network or of each component of the system. For example, methods include functions to evaluate the
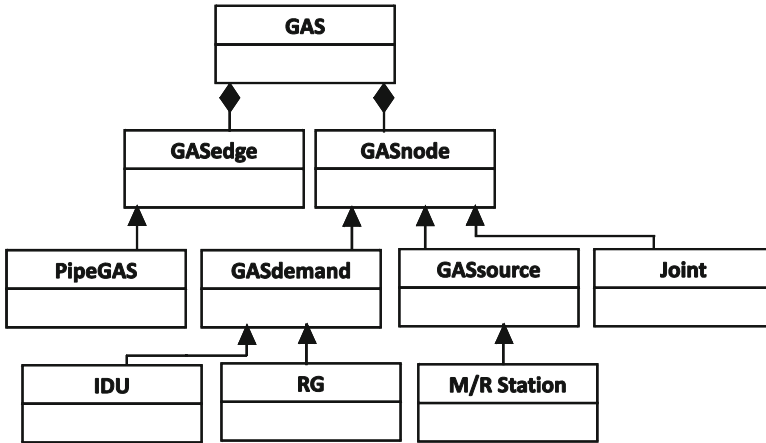
Fig. 9.4 Class diagram for the gas distribution network

accessibility of demand nodes, based on the network damage for the generic event, or the damage state of links and nodes (if they are considered vulnerable) according to a fragility function selected for these elements.

In order to cope with the limitations of the prototype MATHWORKS-MATLAB$^{®}$ implementation of the SYNER-G framework, it was decided to simplify the analysis reducing the amount of data, without compromising the nature of the study; i.e., the application to a real case. Therefore, a data reduction process was performed by means of: (i) removal of all *dead ends* (i.e., pipes that are not carrying gas to stations or end users); (ii) simplification of the geometry merging adjacent pipes with the same geometrical and material properties. The resulting network is composed of 602 nodes (3 sources, 209 RGs and 390 joints) and 608 links.

9.4 Analysis and Results

As mentioned, a simulation-based connectivity analysis was the subject of this chapter. Considering that the mission of a gas network at mid-pressure is to deliver gas to reduction groups, the network's performance was assessed evaluating the availability of end nodes (RGs) of the L'Aquila system.

Both TGD and PGD hazards were addressed. Pipelines and M/R stations were considered as the only vulnerable elements within the network, and the risk assessment was performed in terms of two performance indicators (SR and CL).

In the following sub-sections a detailed description of the methodology and tools adopted is provided.

9.4.1 Procedure

The process to compute the seismic performance, in terms of CL and SR is essentially divided into eight separate stages:

1. Simulation of the event on the considered seismic source.

The Paganica fault (normal fault type) was used as source for the generation of characteristic earthquakes of moment magnitude M_w 6.3 and return period equal to 750 years (Pace et al. 2006). Data on geometric source model used herein can be found in Chioccarelli and Iervolino (2010).

2. Simulation of random field of the primary *IM* at bedrock (PGA$_r$).

The strong ground motion for the primary *IM* was evaluated using a GMPE computed on a regular grid of points discretizing the region covered by the gas network. The regular grid that discretizes the region occupied by the network was identified based on the correlation structure of the primary *IM* intra-event residual; i.e., a grid able to represent correlation of *IMs* in one earthquake. In this case, 1 km grid spacing was selected.

3. Conditional simulation of the cross-correlated ground motion for secondary *IM* at bedrock (PGV$_r$).

As mentioned in Sect. 9.2 and discussed in Chap. 3, the primary *IM* is chosen as an intensity measure for which a spatial correlation model is available, and it is used to generate the realization of a random field in each event, and to obtain the secondary *IM* for each site of interest via the *conditional simulation* approach.

For this case study, PGA was identified as primary *IM*, which is needed in the fragility function for stations. On the other hand, since pipelines are sensitive to PGV (i.e., their fragility models are expressed in terms of this parameter), the latter was selected as the secondary *IM*.

The GMPE used for the evaluation of strong motion is that by Akkar and Bommer (2010) and spatial variability was modeled using correlation models provided by Esposito and Iervolino (2011).

For each event the primary *IM* was calculated for each site of the grid and then interpolated at vulnerable sites by a distance-based interpolation. The resulting ground motion intensities correspond to rock sites (PGA$_r$). Then, at each site, the realization of the logarithm of PGV at bed-rock (PGV$_r$) was obtained sampling a Gaussian variable whose parameters are conditional on PGA$_r$.[2]

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[2]To this aim, assuming the joint normality between the two *IMs*, the correlation coefficient between PGA$_r$ and PGV$_r$ was specifically estimated starting from the dataset used for the Akkar and Bommer (2010) GMPE.

4. Amplification due to local site conditions to get PGA_s and PGV_s that are the *IMs* at the surface.

To account for local site conditions GMPE-based amplification factors were considered. To this aim each site of the network was characterized according to the site classification scheme adopted by the employed GMPE, starting from geological analysis of the region described in the next paragraph. This allows to obtain PGA_s and PGV_s (see Esposito et al. 2013b).

5. Simulation of displacement consequential to PGD.

Regarding the PGD hazard, the landslide potential of L'Aquila region, according to the HAZUS (FEMA 2004) procedure was evaluated (no significant liquefaction potential was found in the region, and co-seismic surface ruptures were neglected). A landslide-susceptibility map of L'Aquila region, based on the lithological groups, slope angles, and ground-water conditions, was specifically obtained for the purposes of this study, starting from the methodology formulated by Wilson and Keefer (1985), and described in Chap. 3.

More than 40 different outcropping formations were detected in the region of interest, starting from 1:50,000 scale ISPRA geological maps (http://www.isprambiente.gov.it).

A slope angle map was generated from topographic data and six slope classes were defined: 3–10, 10–15, 15–20, 20–30, 30–40, >40°. In particular, starting from a topographic map 1:25,000 (Istituto Geografico Militare, http://www.igmi.org/prodotti/cartografia/carte_topografiche) a digital elevation model of the studied area was obtained.

Bounding groundwater conditions were assumed, by considering either dry (groundwater below the depth of the sliding surface) or wet conditions (groundwater level at ground surface).

Finally, a critical acceleration (*yield coefficient*) value, k_c, ranging from 0.05 g (most susceptible) to 0.6 g (least susceptible) was associated to each landsliding-susceptible category.

Overlying the slope angle, groundwater and lithology class maps, it was possible to draw a map of the landslide susceptibility, which was finally transformed into the critical acceleration map shown in Fig. 9.5, where the white color corresponds to the non-susceptible areas; i.e., those characterized by a slope angle lower than 5°. The critical acceleration value corresponds to the threshold acceleration above which slope displacement is initiated. In fact, permanent displacements either occur or not in a susceptible deposit, with probability P^* in those cases in which PGA_s exceeds k_c. A different P^* (corresponding to the map area proportions showed in Table 3.3, Chap. 3) is associated to each landsliding-susceptible category. The resulting displacement is finally calculated via the Saygili and Rathje (2008) empirical model.

6. Computation of repair rate, R_R, for pipelines.

As mentioned, to estimate the earthquake-induced damage, *IMs* were related to system component damage via fragility models. For buried pipelines, the Poisson repair rates functions of PGV_s and PGD proposed in ALA (2001), for different pipe

Fig. 9.5 Critical acceleration map for L'Aquila region where the network deploys
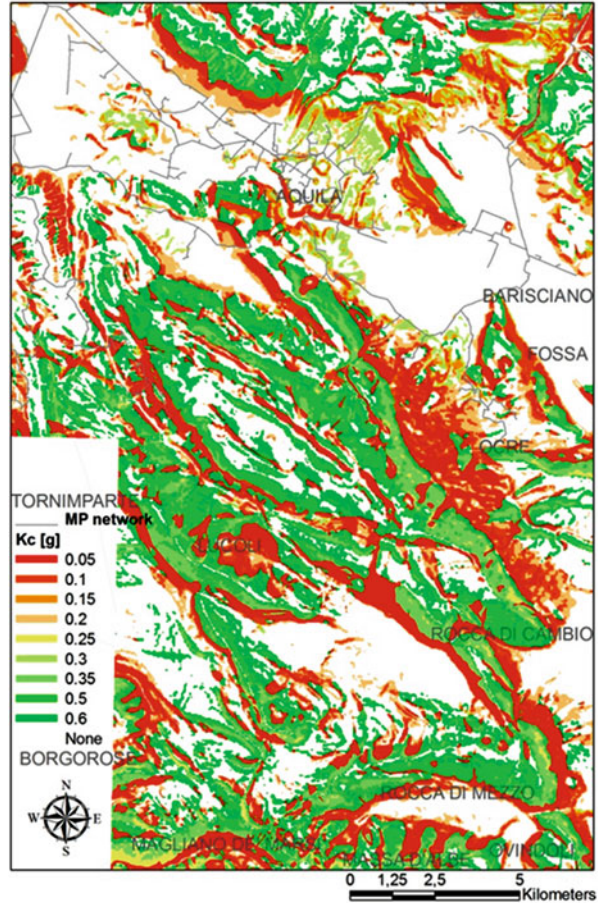
material (steel and HDPE) and diameter, were selected according to the analysis of damage occurred on the gas network following the 6th April 2009 L'Aquila earthquake (Esposito et al. 2013a). These relations are expressed in Eqs. 9.3 and 9.4 where R_R is expressed in 1/km, PGV$_S$ and PGD are given in cm/s and m, respectively; K_1 and K_2 represent the modification factors according to pipe material and diameter.

$$R_R = K_1 \cdot 0.002416 \cdot PGV_s \tag{9.3}$$

$$R_R = K_2 \cdot 11.223 \cdot PGD^{0.319} \tag{9.4}$$

At each location, and in each event (i.e., simulation run), the repair rate is equal to the largest value calculated as a function of PGV$_s$ and PGD, and is then multiplied by 0.2 and 0.8, respectively; since only breaks are considered in the connectivity analysis. In fact, damage states selected for the evaluation of seismic

vulnerability are chosen on the basis of the objective of the analysis; i.e., the performance indicators. In this case, the system is considered functional if demand nodes (reduction groups) continue to provide gas, and then if they remain accessible from at least one supply node (M/R station). To this aim it was assumed that a pipe segment cannot deliver gas when the segment has at least one break.

7. Computation of damage state for M/R stations.

While reduction groups were not considered seismically vulnerable, for the M/R stations, instead, lognormal fragility curves for un-anchored compressor stations (FEMA 2004) were adopted; the median and standard deviation (of the logarithms) are equal to 0.77 g and 0.65, respectively.

Regarding the damage state of interest for the supply node, it was assumed that it loses its connectivity when it is in *extensive* damage state.

8. Computation of connectivity-based performance indicators.

As mentioned, the quantitative measure of the functionality of the gas network is given by performance indicators. Herein the SR and the CL were considered. In particular, for SR, the weighting factor considered is represented by the nominal flow (m^3/h) of the demand node.

9.4.2 Results

A Monte Carlo simulation was carried out in order to evaluate the probability of exceeding predefined levels, *u*, of performance (i.e., the complementary cumulative distribution function, CCDF), given the occurrence of an earthquake on the fault.

The number of runs of the simulation was defined in order to yield stable estimates of the probability of exceeding the considered PI.

Results indicate that the expected value of connectivity loss given the occurrence of an earthquake is 0.66; i.e., it is expected that the average reduction in the ability of demand nodes to be connected to M/R stations is of 66 % when a 6.3 event occurs on the Paganica fault. While for the SR indicator, it is expected that the 68 % of demand nodes receive gas. Figure 9.6 shows the moving average, μ, curves as well as the $\mu + \sigma$ and $\mu - \sigma$ (moving average plus/minus moving standard deviation) curves for the two performance indicators, and the probability of exceedance of the two PIs.

It may be observed from the 'steps' in the curve that the connectivity loss is characterized by a multi-modal distribution. This different behavior may be due to the different definitions of the two performance indicators and the network configuration specific to the application case.

Finally, the influence of modeling of spatial correlation of intra-event residuals on risk assessment was also investigated. In particular, the risk assessment was performed also assuming in the first case a correlation coefficient equal to zero; i.e., considering intra-event residuals uncorrelated. Minor differences with respect
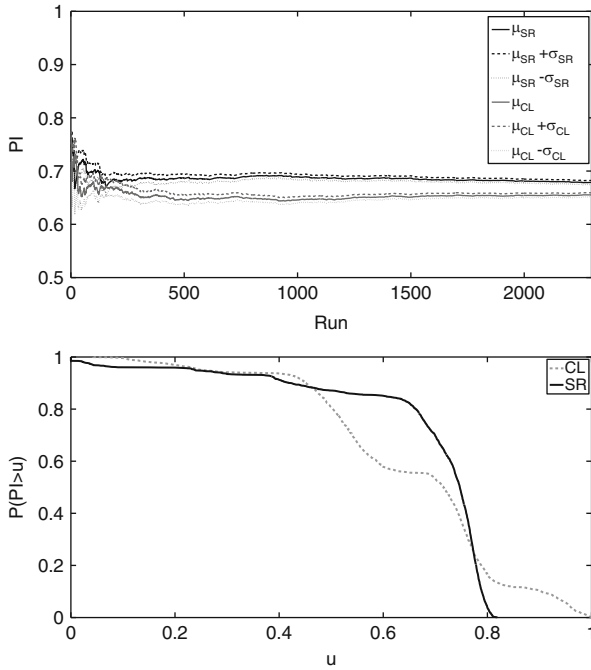
Fig. 9.6   Moving average μ, $\mu + \sigma$ and $\mu - \sigma$ curves (*top*) and CCDF for CL and SR (*bottom*)

to results in Fig. 9.6 indicate that spatial correlation has a relatively small impact on risk evaluation of the selected system and with reference to the considered performance indicators (see Esposito et al. 2013b, for more details).

9.5   Conclusions

This chapter summarized the application of the SYNER-G framework to a real case study: L'Aquila (central Italy) gas distribution network. The study employed probabilistic seismic and geotechnical hazard analysis, empirical relations to estimate pipeline response, fragility curves for the evaluation of vulnerability, and connectivity performance indicators to characterize the functionality of the network.

In fact, special emphasis was put on the medium-pressure part of the L'Aquila gas system for which detailed information was retrieved. In particular, the selected network was characterized by 3 M/R stations, 209 reduction groups, and pipelines either made of steel or HDPE.

The principal result of the risk analysis was the probability of exceeding a set of performance levels, which can be transformed in the annual rate of their exceedance, given the occurrence of a characteristic earthquake on the fault beneath the region where the system deploys.

In particular, earthquakes were generated using as source the Paganica fault and considering characteristic earthquakes of moment magnitude *Mw* 6.3. Strong ground motion intensities for the primary TGD intensity measure were evaluated though an European GMPE and an European spatial correlation model on a regular grid defined based on the correlation structure of PGA; since fragilities of gas pipelines are often expressed in terms of PGV, the latter was selected as the secondary *IM*. For each site, the secondary *IM* was determined, in a probabilistically consistent manner, via the conditional hazard approach. The resulting intensities correspond to rock sites. To account for local site conditions GMPE-based amplification factors were applied.

Regarding geotechnical hazards, often resulting the most effort-demanding issue in this kind of problems, the landslide potential of L'Aquila region according to the HAZUS procedure was performed.

To estimate earthquake-induced damage for buried pipelines, repair rate functions of PGV_s and PGD were selected for each pipe typology and diameter. Reduction groups were not considered seismically vulnerable. For the M/R stations, instead, a lognormal fragility curve for un-anchored compressor stations was adopted. Damage states considered for the evaluation of seismic vulnerability are strictly related to the objective of the analysis. In this case a connectivity analysis was performed; i.e., the system is considered functional if demand nodes (reduction groups) continue to provide gas after the earthquake, and then if they remain accessible from at least one supply node (M/R station). To this aim it was assumed that a pipe segment cannot deliver gas when the segment has at least one break, while for the supply node it was assumed that it loses its connectivity when it is in extensive damage state.

The adaptation of two connectivity performance indicators (serviceability ratio and connectivity loss) was considered to include damage of stations and distributing elements into the risk assessment for the system.

The study finally proves feasibility of simulation-based seismic risk assessment of gas distribution networks in a performance-based earthquake engineering framework.

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