Esposito S. et al. (2012) Seismic Risk Analysis of Lifelines: Preliminary Results for the Case-Study of L'Aquila ENEL Rete Gas. Proc of. 15WCEE, Lisboa, PT. Paper No. 2998

Seismic Risk Analysis of Lifelines: Preliminary Results for the Case-Study of L'Aquila ENEL Rete Gas.

S. Esposito, I. Iervolino, F. Silvestri, A. d'Onofrio & A. Santo
Università degli Studi di Napoli Federico II, Italy

F. Cavalieri & P. Franchin
Università degli Studi di Roma la Sapienza, Italy

SUMMARY:
This paper presents the seismic risk assessment of L'Aquila gas distribution network in a performance-based earthquake engineering framework. The study was structured in three basic activities: (1) seismic hazard characterization both in terms of ground motion and permanent ground deformation; (2) characterization of system's vulnerability via fragility curves available in literature; (3) performance evaluation in terms of connectivity. In the paper all issues involved in seismic risk analysis of this kind of systems are discussed with respect to a selected part of the whole network. In particular, the importance of modelling spatial correlation of ground motion and geotechnical hazard on risk assessment was investigated. Results indicate that the system performance may be underestimated when spatial correlation and ground failure are ignored. Moreover, the implications of using fragility curves for compressor stations for the reduction cabins, as suggested in literature, were also addressed, and the necessity of developing specific fragilities was pointed out.

Keywords: gas network, spatial correlation, permanent ground deformation, connectivity.

1. INTRODUCTION

Lifelines are commonly used to transport water, oil, electricity, and natural gas. Their disruption due to earthquakes can have an important impact on communities. Therefore, it is important to assess and mitigate the related seismic risk.

This paper focuses on the seismic performance evaluation of gas distribution networks. A gas distribution system is essentially comprised of: pipelines, reduction stations, valves, and demand nodes. These components except for reduction stations are buried, and consequently subjected to transient ground deformation (TGD), due to seismic wave propagation, and permanent ground deformation (PGD), due to soil instability phenomena such as liquefaction and landslides.

This study was aimed at evaluating, in a complete performance-based earthquake engineering framework, the seismic risk of L'Aquila gas distribution network (i.e., Esposito 2011). The work includes the analysis of seismic input, the evaluation of vulnerability of network's components, the analysis of system vulnerability in terms of performance measures, and finally the probabilistic simulations for risk assessment.

The paper is divided in three parts, the first of which describes all the steps needed to evaluate the seismic performance of the network. In particular, detailed information on characterization of TGD and PGD hazards are presented, pointing out the aspects that are peculiar in seismic risk analysis of this kind of systems. The second part describes the case study and summarizes the process for the seismic performance evaluation. Finally results of some preliminary analyses set-up for a relatively small portion of the case-study network are presented and discussed for the different cases that have been considered.

2. GENERAL FRAMEWORK

2.1. Seismic input

This section describes the general process to characterize seismic input (in terms of TGD and PGD) to the components of a gas network. In particular, the principal differences from site-specific seismic input characterization are pointed out for both phenomena.

2.1.1. Transient Ground Deformation

During an earthquake, wave propagation causes transient vibratory soil deformations over a wide geographic area and also affects buried pipeline systems. Ground motion effects are usually described by peak parameters. Since a gas system generally covers a large area, the first aspect to consider in the seismic input characterization is that it is comprised of large vectors of ground motion-intensities (for all sites that describe the region where the system is located) that may be spatially correlated. This is a peculiar feature differing from the seismic risk analysis of individual facilities. In fact, if probabilistic assessment of ground motion at two or more sites at the same time is of concern, the joint probability density function (PDF) of intensity measures (IMs) at all locations has to be modelled by a multivariate distribution characterized by a spatial correlation function that models statistical dependencies between IMs as function of inter-separation distance (e.g., Esposito and Iervolino, 2011). Correlation models are characterized essentially by one parameter, the *range* that represents the inter-site distance at which the spatial correlation is practically lost.

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 regulator stations (to follow), are sensitive to peak ground acceleration (PGA) while pipelines are sensitive to peak ground velocity (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 (Loth and Baker, 2011), in order to model the joint distribution of different *random fields*. Herein, to address this issue, conditional hazard is considered (Iervolino et al., 2010; Chioccarelli et al., 2012). It consists of obtaining the conditional distribution of a secondary IM (e.g., PGV) given the occurrence of a primary IM (e.g., PGA) for which a spatial correlation model is available. Conditional hazard evaluation is possible if correlation coefficients between IMs are known and if the joint normality of the logarithms of the primary and secondary IMs is verified.

2.1.2. Permanent Ground Deformation

The second important aspect to consider in seismic input characterization for systemic risk analysis is that the presence of buried components (i.e., pipelines) implies the consideration of permanent ground deformation hazards (PGD) such as landslide, liquefaction induced lateral spreading, and seismic settlement (O'Rourke and Liu, 1999). While transient effects are felt over a wide geographical area and associated pipeline damage rates (in terms of breaks per unit length of pipe) are low, PGD damage typically occurs in localized areas with high damage rates.

There are many models available that have the intent to relate the PGD, and the probability of occurrence of each geotechnical hazard, to the strength of ground motion (typically measured in terms of PGA), but the main limiting factor of several of these models is the requirement of very detailed data, which may impair actual applicability for lifelines' analysis. Therefore, it may be preferable to consider simpler models, as the approach implemented in HAZUS (FEMA, 2004), and briefly described in the following.

2.2 Vulnerability functions

Earthquake intensity measures have to be correlated with system components' damage via fragility functions. To this aim, the typological classification of each component, damage scale definition, and the vulnerability measures have to be defined.

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. The usual practice is to evaluate the repair rate, R_R, as the number of pipeline repairs in an area divided by the length of the pipelines in the same area, with respect to a parameter representative of ground shaking or ground failure. Corrective factors are usually added to the fragility model in order to account different factors that affect the vulnerability of pipelines such as pipe material, pipe diameter or pipe connections.These relations are mostly based on the recorded number of repairs collected from field crews of gas/oil companies (ALA, 2001). As a result, all fragility relations for pipelines are given in terms of the repair rate per unit length of pipe. Then, using a Poisson probability distribution and the repair rate R_R as its parameter, one can assess the probability of having n pipe breaks/leaks in a pipe segment of length L given the local intensity (e.g. in terms of PGV). According to HAZUS (FEMA, 2004), two damage states may be considered: leaks and breaks, and the type of damage depends 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 0.8 and 0.2, respectively; whereas for ground shaking, leaks and breaks relative proportions are 0.2 and 0.8, respectively.

2.2.2. Stations

In a gas distribution system two different types of stations may exists: (1) metering/pressure reduction stations (M/R stations) that are used for monitoring and managing the natural gas in their pipes, including the reduction of the gas pressure before its distribution into the pipe system; and (2) regulator stations, where the gas pressure is reduced as required for the gas to arrive to the end-user. Although in literature no fragility curves are available for these components, some authors (e.g., Chang and Song, 2007; Song and Ok, 2009) assume that these facilities (especially metering/pressure reduction stations) can be characterized with the same fragility features of compressor stations. Damage states and fragility curves for compressor stations are usually defined and associated with PGA (FEMA, 2004). Moreover, since these facilities may include many subcomponents, fragility curves are usually obtained aggregating the fragility of each subcomponent through the use of a fault tree analysis.

2.3 Performance indicators

Seismic performance of a gas network (and of lifeline networks in general sense) may be measured generally in two ways: (1) *connectivity* between node pairs (where the main goal is related to determine the probability of the existence of a path connecting the source and the demand node when the links and the nodes are subjected to random failure events), that allows assessment of *serviceability* in terms of the aggregate functionality of facilities (nodes) composing the system; i.e. the number of distribution nodes which remain accessible from at least one supply node after the earthquake; (2) *flow-performance*, that includes consideration of the network's capacity; e.g., maintaining minimum head pressure related to leakages from two particular points of the network or related to a demand node. Depending on the goal of the analysis (connectivity or flow-reliability) different performance indicators (PIs) may be evaluated. Performance indicators can be used in order to evaluate both the interaction between components' response to earthquake and the overall lifeline performance. For a gas network two possible PIs are the Serviceability Ratio (SR) and the Connectivity Loss (CL) (Esposito, 2011). The first index, employed in this paper and 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 Eqn. (2.1), where SR ranges in the [0,1] interval, w_i is a weighting factor assigned to the distribution node i (e.g., customers related to the demand node or nominal flow of the distribution node), and X_i represents the functionality of facility i, which is modeled as the outcome of a Bernoulli trial ($X_i = 1$ if facility is accessible from at least one supply facility and zero otherwise), and n is the number of distribution nodes.

$$SR = \frac{\sum_{i=1}^{n}\left(w_i \cdot X_i\right)}{\sum_{i=1}^{n} w_i} \tag{2.1}$$

3. SEISMIC RISK ANALYSIS OF L'AQUILA GAS DISTRIBUTION NETWORK

The evaluation of seismic performance of gas networks was applied to a selected (relatively small) part of L'Aquila gas distribution system, and consisted of five principal steps: (1) seismic input assessment considering as source the Paganica fault on which L'Aquila (central Italy) 2009 earthquake was originated; (2) evaluation of the PGD hazard, in particular focusing on the effects induced by landslides; (3) seismic demand evaluation for each component within the network to obtain the failure probability through the use of appropriate fragility models; (4) system's performance analysis via a connectivity algorithm to integrate the damage of stations and distributing elements to evaluate the damage to the system; (5) probabilistic risk assessment of the case study network in terms of annual rate of exceeance curves using Monte Carlo simulation.

The analysis was performed via the implementation of the case study in the OOFIMS (Object Oriented Framework for Infrastructure Modelling and Simulation) software consistent with the OBJECT-ORIENTED Paradigm (OOP). Details on the object-oriented modeling and software development may be found in Franchin et al. (2011).

3.1 Case study network

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 (0.025-0.035 bar). The medium-pressure distribution network is connected to the high-pressure transmission network through three M/R stations referred to as Re.Mi stations ("REgolazione e MIsura" meaning "Regulation and Measurement" in Italian) providing gas to about 42300 customers in L'Aquila and five municipalities (*Lucoli, Tornimparte, Ocre, Rocca di Cambio, Rocca di Mezzo*). The three M/R stations are housed in one-story reinforced concrete structures with steel roofs hosting internal regulators and mechanical equipment (heat exchangers, boilers and bowls), where the gas undergoes the following processes: (1) gas pre-heating; (2) gas pressure reduction and regulation; (3) gas odorizing; (4) gas-pressure measurement. The pipelines of the medium and low-pressure distribution networks are either made of steel or HDPE (*High Density Polyethylene*) according to the pressure level. HDPE pipes have nominal diameters ranging from 32 to 400 mm, whereas diameter of steel pipes is usually between 25 and 300 mm. The transformation of the medium distribution pressure into the low distribution pressure (LP) is operated via 300 Reduction Groups (RGs). Generally along the low-pressure network (in some cases also along medium distribution pressure network), there are several demand nodes (IDU, "Impianto di Derivazione Utenza" in Italian) consisting of buried and non-buried pipes and accessory elements to supply natural gas to utilities. Moreover, depending on the type of end-user and on whether there is an IDU system, there are three types of RG: (a) GRM, Reduction Groups and Measure along medium distribution pressure (MP) network and direct connection to large users (e.g., industrial facilities); (b) GRU, Reduction Groups smaller than GRM for medium pressure users connected to a medium pressure IDU system; (c) GRF, Final Reduction Group connected to low-pressure network. It is worth noting that all the components contained in both the L'Aquila M/R stations and reduction groups are unrestrained, and therefore especially vulnerable to ground shaking. The 300 reduction groups, that in the L'Aquila gas distribution allow for the transformation of the medium distribution pressure into the low distribution pressure are buried, sheltered in a metallic kiosk or housed within/close to a building.

Close collaboration with the network operator (ENEL Rete Gas s.p.a) has allowed the characterization of the system, necessary for the evaluation of gas system seismic performance. A geographic information system (GIS) database was jointly developed containing data on system physical and operational characteristics.

For the evaluation of seismic performance within this study, a relatively small portion of the L'Aquila gas system has been preliminarily selected. In particular, the network of interest (shown in Figure 3.1) is characterized by one of the three M/R station, 12 regulator stations, and pipelines at medium pressure, either made of steel or HDPE. The function of a gas network at medium pressure is to deliver gas to end-users which, considering in this case only the MP network, are represented by the regulator stations. 39 nodes (1 source, 12 RG stations and 26 joints[1]) and 38 links have been identified and all data necessary for the evaluation of seismic vulnerability have been imported in the simulation software. Nodes and links represent the vulnerable sites for which the seismic demand has to be computed.

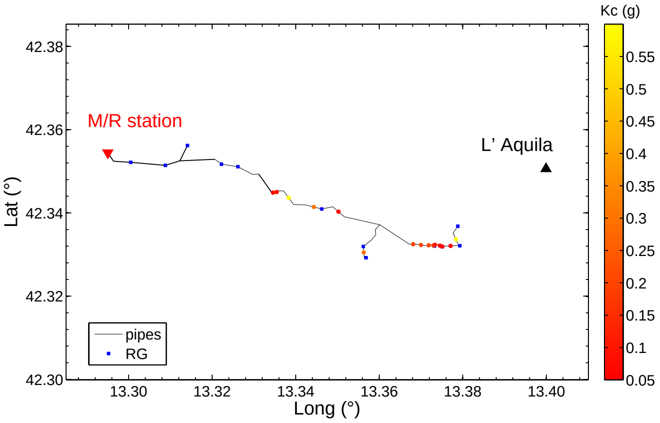

Figure 3.1 Case-study network portion (in the figure also critical accelerations for landslide are shown, see section 3.2)

3.2 Seismic input simulation

Probabilistic hazard scenarios were simulated for the region covering the case-study network. The process is essentially divided into five separate stages:

1. Simulation of the event on the source;
2. Simulation of the random field of the primary IM on rock;
3. Amplification due to local site conditions;
4. Conditional simulation of the cross-correlated ground motion for secondary IMs;
5. PGD estimation.

The Paganica fault (normal fault type) was used as source for the generation of characteristic earthquakes of moment magnitude M_w 6.3 and occurrence rate $\lambda = 1/750$ (Pace et al., 2006). Data on geometric source model used herein can be found in Chioccarelli and Iervolino (2010).

The epicenter of the source is sampled as a point within the source model, with every location assumed equally probable. More details on the approach used for the generation of rupture events can be found in Weatherill et al. (2011).

The strong ground motion for the primary IM is evaluated using a ground motion prediction equation (GMPE) on a regular grid covering the gas network. The regular grid that covers the region of interest is identified based on the correlation structure of the primary IM; i.e., a grid adequately denser than the IM correlation length (i.e. the *range*). As described in section 2, the primary IM is chosen as an intensity measure for which a spatial correlation model is available, and it is used to generate a Gaussian Random Field (GRF) and to obtain the secondary IM for each site of interest through the conditional approach. For this case study PGA has been chosen as primary IM and, since gas network components (pipelines and stations) are also sensitive to PGV (i.e. some of the employed fragility models are expressed in terms of this parameter), the latter was selected as a secondary IM. The GMPE used for the evaluation of strong motion is that by Akkar and Bommer (2010) and spatial variability has been modeled using correlation models provided by Esposito and Iervolino (2011).

For each site of the grid the means of primary IM from the specified GMPE are calculated, and the residual sampled from a random filed of spatially correlated Gaussian variables according to the spatial correlation model. The value of the primary IM at each site of the network (i.e. the vulnerable

---

[1] Joints are nodes used to reproduce the geometry of the system but characterized by a demand equal to zero.

sites) is then obtained interpolating the grid values. The resulting ground motions correspond to a rock site. Then for each site the secondary IM (PGV) is determined by sampling a vector of Gaussian variables described by the conditional mean and variance depending on the primary IM.

To account for local site condition in the simulations, an amplification factor needs to be applied. For the analyses, site condition effects were accounted for according to the GMPE-based amplification factors. To this aim each site of the network was characterized according to the site classification scheme adopted by the Akkar and Bommer (2010) GMPE, starting from geology classification derived from 1:50,000 scale ISPRA geological maps (http://www.isprambiente.gov.it).

Regarding PGD hazards, in order to estimate the seismic demand due to landslides for each site of the network, the methodology presented in HAZUS (FEMA, 2004) was considered. Therefore, a susceptibility map of L'Aquila region, based on the lithological group, slope angle, and ground-water condition was obtained. Geology has been derived from the same ISPRA maps just mentioned. Each terrain type was classified into three geologic groups (A, B and C) using the HAZUS method. Slope angle was generated from topographic data, and was grouped into six slope classes: 3-10, 10-15, 15-20, 20-30, 30-40, >40 degrees. Ground-water conditions have been considered as wet for geologic groups B and C. A spatial overlay of these data layers (geologic group and slope angle) was performed using Arc/GIS software (see Esposito, 2011, Mastrangelo et al, 2012). The resulting polygons were then attributed with the corresponding susceptibility category (I to X) using relationship proposed by Wilson and Keefer (1985). Starting from the susceptibility categories, the critical acceleration map was obtained. In particular, a critical acceleration, K_c, value ranging from 0.05g (most susceptible) to 0.6g (less susceptible) was associated to landsliding susceptible category. The probability of landsliding is then determined for each site using the susceptibility class and the PGA on free field. If simulated surface (amplified) PGA exceeds the determined value of critical acceleration, then displacement occurs at the site. In this case, PGD is calculated via the Saygili and Rathje (2008) empirical model.

3.3 Seismic vulnerability and performance assessment

To estimate earthquake induced damage, IMs were correlated with system component damage in terms of fragility models. For buried pipelines ALA (2001) Poisson repair rate R_R function of PGV and PGD , were selected for each pipe typology (steel and HDPE) and diameter, according to analysis of damage occurred on the gas network following the 6th April 2009 L'Aquila earthquake (Esposito et al., 2011).

These relations[2] are expressed in Eqn. 3.1 and 3.2 where K_1 and K_2 represent the modification factor according to pipe material and diameter.

$$R_R = K_1 \cdot 0.002416 \cdot PGV \tag{3.1}$$

$$R_R = K_2 \cdot 11.223 \cdot PGD^{0.319} \tag{3.2}$$

Regulator stations were not considered seismically vulnerable because no quantitative fragility curves are available in literature. For the M/R station, instead, a lognormal fragility curve for un-anchored compressor stations (FEMA, 2004) was adopted. As a reminder, the three fragility functions of M/R station and pipelines (steel and HDPE) are summarized in Table 3.1 where $\log(\mu)$ and β are the mean and the standard deviation of the normal distribution function used for the fragility assessment of the M/R station. Damage states considered for the evaluation of seismic vulnerability are strictly related to the objective of the analysis. In this case a connectivity analysis has been performed; i.e., the system is considered functional if demand nodes (regulator groups) continue to provide gas and then if they remain accessible from at least one supply node (M/R station). To this aim it is assumed that a pipe segment cannot deliver gas when the segment has at least one break, while for the supply node it is assumed that it loses its connectivity when it is in extensive damage state.

---

[2] Note that R_R is expressed in *1/km* and PGV and PGD are given in *cm/s* and *m* respectively.

As mentioned in section 2, the quantitative measure of the functionality of the gas network is given by performance indicators that are able to quantify the degree to which the system is able to meet established specifications and/or customer requirements following an earthquake event. Herein the adaptation of the Serviceability (SR), expressed in Eqn. 2.1, is considered. In this case the weighting factor is related to the nominal flow (m^3/h) of the demand node (RG). Results in terms of CL may be found in Esposito (2011).

The goal of the analysis is to evaluate the mean annual exceedance rate, ν, of PI for each of its possible value.

Table 3.1 Parameters for the fragility characterization

Component	**Reference**	**Damage state**	**Fragility relation parameter**			
			TGD		**PGD**	
Steel pipelines	ALA (2001)	Break	$K_1 = 0.6$		$K_2 = 0.7$	
HDPE pipelines	ALA (2001)	Break	$K_1 = 0.5$		$K_2 = 0.8$	
M/R station	HAZUS (FEMA, 2004)	Extensive	**μ(g)**	**β**	**μ(inch)**	**β**
			0.77	0.65	N/A[3]	N/A

.

4. ANALYSES AND RESULTS

In order to study the effects of some of the issues involved in seismic risk analysis of gas networks, five types of (preliminary) analyses were carried out (Table 4.1). In the first two cases only the ground shaking effect is considered (i.e., TGD), including or neglecting spatial correlation between intra-event residuals of the primary intensity measure. The third case is an attempt to verify the influence of PGD. Finally the last two analyses aim at evaluating the implications of neglecting the vulnerability of the M/R in the seismic system's performance.

Table 4.1 Case definitions for risk assessment

Case	**Definition**
1	TGD with spatial correlations ignored
2	TGD with spatial correlations considered
3	Both TGD and PGD are considered
4	As case 2 with M/R station non-vulnerable
5	As case 3 with M/R station non-vulnerable

4.1. Spatial correlation

In order to evaluate the influence of accounting spatial correlation between intra-event residuals of primary IM (PGA) the risk assessment was performed assuming in the first case a correlation coefficient equal to zero; i.e., intra-event residuals are considered independent, while in the second case the correlation length is set equal to 13.5 km (Esposito and Iervolino, 2011).

From the results it appears that spatial correlation has relatively mild impact on risk evaluation. In fact, the mean of SR results equal to 0.85 in the first case and 0.81 in the second case; i.e. the 85% of

---

[3] Note that the M/R station is not vulnerable to PGD because the site where the station is located is not susceptible to landslide according to geotechnical analysis.

demand nodes (81% when correlation is included) receive gas after earthquakes accounting for the importance level related to the nominal flow of the RGs. The influence of spatial correlation is also shown in Figure 4.1 where exceedance curves are plotted. Although past research shows that risk may be substantially underestimated when spatial correlation is ignored (Crowley and Bommer, 2006; Esposito and Iervolino, 2011), in this case differences between two cases are not large; likely because of the size of the case study (about 20 km of pipelines) and its topological features (essentially a single long pipeline rather than a meshed network) for which the serviceability is more controlled by the behavior of the M/R that may impair the service of the whole network with respect to pipelines for which spatial correlation has an influence.

4.2. Permanent ground deformation

In order to evaluate the contribution of PGD on system's performance, the latter was evaluated considering the combined effect of TGD and PGD due to landslides. In this case the mean of SR is equal to 0.45; i.e., it is expected that only the 45% of demand nodes receive gas after earthquakes accounting for the importance level related to the nominal flow of the RGs.

Figure 4.1 shows the annual exceedance curve of serviceability ratio considering only the TGD effects and the combined effects of TGD and PGD. It appears that the combined effect of TGD and PGD has an important impact on the probability of exceedance of high values of SR. This may be explained considering that low values of serviceability are strongly influenced by the behavior of the M/R station and pipelines connected to the source node, while high values of SR are controlled by pipes from which few RGs depend. In fact if the source node is damaged all reduction groups result not connected and if pipelines that are more close to the source are damaged, a large number of RGs cannot receive gas. As shown in Figure 3.1 where critical accelerations values are reported, only pipes from which few RGs depend are located in sites that are susceptible to landslide (i.e. corresponding to $K_c<0.6g$).

There is also another important factor that should be considered to explain these results. Due to the conservative nature of the Wilson and Keefer (1985) relationship, the probability of a landslide occurring should be modified by a term to determine the percentage of the map area having a landslide susceptible deposit. Based on Wieczoreck et al. (1985), these percentages were estimated for the San Mateo County (California) as a function of the susceptibility categories. Since these values were not validated for L'Aquila region, the probability of a landslide occurring has not been modified. Therefore, the contribution of PGD on results is affected by this choice on the conservative side.

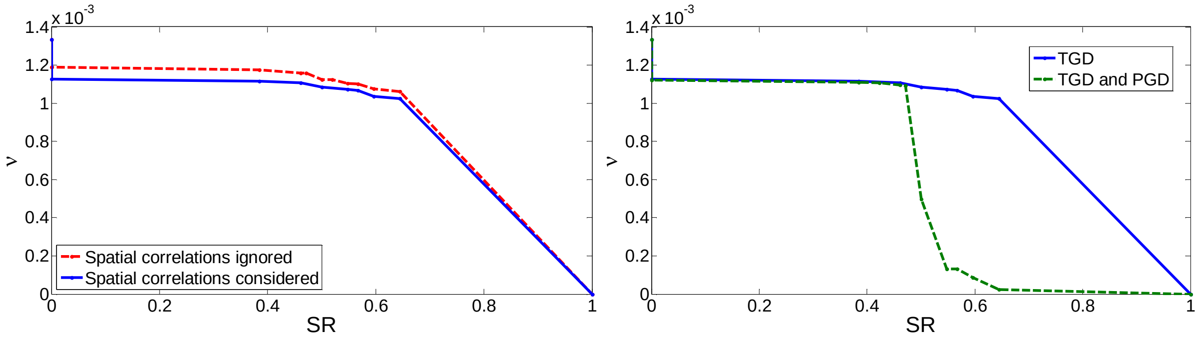

Figure 4.1 Annual exceedance curve of serviceability ratio considering: uncorrelated residuals and correlated residuals (left) and only the TGD effect and the combined effect of TGD and PGD (right).

4.3. Vulnerability of M/R stations

Fragility curves of compressor stations have been adopted in order to evaluate the implications of this assumption in terms of seismic performance. The evaluation has been performed considering also TGD effects and the combined effects of TDG and PGD. Results show that the risk is substantially influenced by the vulnerability of M/R station. In fact, in the case M/R is considered non-vulnerable, and accounting for only the TGD effects, the mean of SR is equal to 0.95. This means that the seismic behaviour of the M/R station is one of the most important factors that influence the seismic performance of the case study. In the second case, where the M/R is not considered vulnerable, and accounting for the combined effects of TGD and PGD effects, the mean of the PI does not change significantly (0.53 with respect to 0.45). This may be explained considering that the M/R station is not vulnerable to PGD and then the seismic behaviour of the M/R station influences only the estimation of damage induced by TGD. The probability of exceedance of the performance indicators is strongly influenced by the seismic behavior of the M/R station when the TGD effects are considered, as shown in Figure 4.2. Comparing the trend of the exceedance curves in case of combined effects of TGD and PGD, the influence of the seismic behavior of the M/R station is stronger for low values of SR. This may be explained considering that sites susceptible to landslide for the case study network are in correspondence of pipelines from which few RGs depend. Therefore, the probability of execedance of low values of SR is more affected by the behavior or M/R station (source) compared to PGD effects.

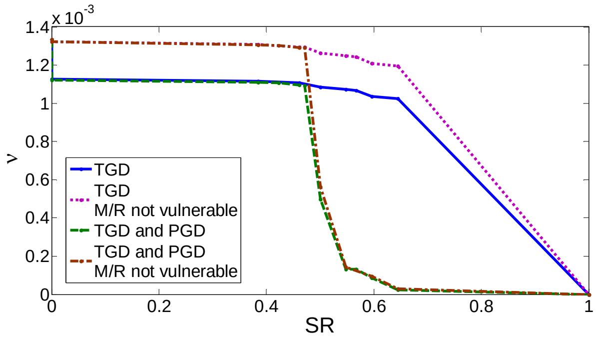

Figure 4.2 Annual exceedance curve of serviceability ratio considering the influence of the M/R station behavior for the TGD case and for TGD and PGD combination case.

5. CONCLUSIONS

The presented study is part of the effort aimed at evaluating the seismic risk of L'Aquila gas distribution network. The process employed probabilistic seismic input analysis, fragility models for the evaluation of gas system components and performance indicators to characterize the serviceability of the network in terms of connectivity. A relatively small portion of the case-study network was preliminarily selected and implemented in a specifically developed software. Probabilistic risk assessment was performed using Monte Carlo simulation. In order to study the effects of different issues on risk assessment, different analyses were set up. In particular, the importance of modeling spatial correlations of ground motion and PGD hazard was investigated. Preliminary results indicate that spatial correlation has a relatively small impact on risk evaluation. It appears that the risk may be substantially underestimated when PGD effects are ignored. However, it is important to consider that the methodology suggested in HAZUS was used without correcting it for the percentage of the area having a landslide-susceptible deposit. Therefore, the contribution of PGD is expected to be conservatively magnified. Regarding the vulnerability of M/R stations, results indicate that neglecting it may have significant influence on the risk assessment. However, because fragilities for compressor stations were employed, results may be revised when M/R-specific fragilities will be developed.

ACKNOWLEDGEMENTS

This study was supported by AMRA scarl (http://www.amracenter.com) in the frame of SYNER-G (7th framework programme of the European Community for research, technological development and demonstration activities; project contract no. 244061. Authors want to acknowledge the network operator for kindly providing data for the characterization of the case study.

REFERENCES

Adachi, T., and Ellingwood, B.R. (2008). Serviceability of earthquake-damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability. *Reliability Engineering and System Safety* **93:1**, 78-88.

Akkar, S., and Bommer, J.J. (2010). Empirical Equations for the Prediction of PGA, PGV and Spectral Accelerations in Europe, the Mediterranean Region and the Middle East. *Seismological Research Letters* **81:2**, 195 – 206.

ALA (2001). Seismic fragility formulations for water systems Part 1 Guidelines. *American Lifeline Alliance,* ASCE.

Chang, L., and Song, J. (2007). Matrix-based system reliability analysis of urban infrastructure networks: a case study of MLGW natural gas network. *5th China-Japan-US Trilateral Symposium on Lifeline Earthquake Engineering*, November 26-28, Haikou, China.

Chioccarelli, E. and Iervolino, I. (2010). Near-Source Seismic Demand and Pulse-Like Records: a Discussion for L'Aquila Earthquake. *Earthquake Engineering and Structural Dynamics*. **39:9**,1039–1062.

Chioccarelli, E. Esposito, S., and Iervolino, I. (2012) Implementing Conditional Hazard for Earthquake Engineering Practice: the Italian Example, *15th World Conference on Earthquake Engineerign,* September, Lisbon, Portugal.

Crowley, H., and Bommer, J. (2006). Modelling seismic hazard in earthquake loss models with spatially distributed exposure, *Bulletin of Earthquake Engineering* **4:3**, 249-273.

Esposito, S. (2011). Systemic seismic risk analysis of gas distribution networks. PhD Thesis, University of Naples Federico II, Naples, Italy. Advisor: I. Iervolino. Available at: wpage.unina.it/iuniervo

Esposito S., and Iervolino, I. (2011) PGA and PGV spatial correlation models based on European muti-event datasets. *Bulletin of the Seismological Society of America* **101:5**, 2532–2541.

Esposito, S., Elefante, L. Iervolino, I., and Giovinazzi. S. (2011). Addressing ground-shaking-induced damage of the gas distribution network in the 2009 L'Aquila earthquake, *XIV Convegno Nazionale "L'Ingegneria Sismica in Italia"*, September, Bari, Italy.

Federal Emergency Management Agency (FEMA) (2004). Multi-hazard Loss Estimation Methodology-Earthquake Model: HAZUS MR4 Technical Manual,Washington, D.C.

Franchin, P. Cavalieri, F., Pinto P.E., Lupoi, A., Vanzi, I., Gehl, P., Kazai, B., Weatherill, G., Esposito, S., and Kakderi, K. (2011). General methodology for systemic seismic vulnerability assessment. Deliverable 2.1 Syner-G Project, http://www.vce.at/SYNER-G/

Iervolino, I., Giorgio, M., Galasso, C., and Manfredi, G. (2010). Conditional Hazard Maps for Secondary Intensity Measures. *Bulletin of the Seismological Society of America* **100:6**, 3312-3319.

Loth, C. and Baker, J. (2011) Spatial cross-correlation of spectral accelerations at multiple periods: model development and risk assessment considering secondary earthquake effects. Project report, USGS award G10AP00046.

Mastrangelo, A., d'Onofrio, A., Penna, A., Santo, A., and Silvestri , F. (2012) Seismic risk analysis of buried pipelines: the case of l'Aquila gas network. *Second int. conf. on Performance-based Design in Earthquake Geotechnical Engineering* May, Taormina, Italy.

O'Rourke, M.J., and Liu, X. (1999). Response of Buried Pipelines Subjected to Earthquake Effects. MCEER Monograph No. 3.

Pace B., Perruzza L., La Vecchia G., and Boncio, P. (2006). Layered Seismogenic Source Model and Probabilistic Seismic-Hazard Analyses in Central Italy. *Bulletin of the Seismological Society of America* **96:1**, 107-132.

Saygili, G., and Rathje, E. M. (2008). Empirical Predictive Models for Earthquake-Induced Sliding Displacements of Slopes. *Journal of Geotechnical and Geoenvironmental Engineering* **134:6**, 790 - 803

Song, J., and Ok, S.-Y. (2009). Multi scale system reliability analysis of lifeline networks under earthquake hazards. *Earthquake Engineering & structural Dynamics* **39:3**, 259-279.

Weatherill, G., Crowley, H., Pinho, R., Franchin, P., Cavalieri, F., Esposito, S., and Iervolino, I. (2011). A Review and Preliminary Application of Methodologies for the Generation of Earthquake Scenarios for Spatially Distributed Systems. Deliverable 2.13 Syner-G Project, http://www.vce.at/SYNER-G/

Wieczorek, G. F., Wilson, R. C. and Harp, E. L. (1985) Map of Slope Stability During Earthquakes in San Mateo County, California. *U.S. Geological Survey Miscellaneous Investigations*. Map I-1257-E, scale 1:62,500.

Wilson, R. C., and Keefer D. K. (1985). Predicting Areal Limits of Earthquake Induced Landsliding, Evaluating Earthquake Hazards in the Los Angeles Region, *U.S.Geological Survey Professional Paper*, Ziony, J. I., Editor, pp. 317-493.