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Foreword

This document, after an introduction presenting the general framework for the seismic risk assessment of a gas network according to the SYNER-G methodology, describes the case study of L’Aquila (central Italy) gas distribution system. Subsequently, main features regarding the implementation of the application study in the SYNER-G prototype software (OOFISM) are reported, and the process for the seismic performance characterization is summarized. Then, the analysis of the system is described, and results in terms of connectivity-based performance indicators are presented. These are also discussed with respect to possible working assumptions.

This deliverable is strictly related to other SYNER-G products, which the reader should have available for a comprehensive understanding of the application. These are:

- Deliverable 2.1 General methodology for systemic seismic vulnerability assessment;
- Deliverable 2.4 Definition of system components and the formulation of system functions to evaluate the performance of gas and oil pipeline;
- Deliverable 2.13 A Review and Preliminary Application of Methodologies for the Generation of Earthquake Scenarios for Spatially Distributed Systems;
- Deliverable 3.4 Fragility functions for gas and oil systems networks;
- Deliverable 5.3 Systemic vulnerability and loss for gas and oil networks.

Keywords: gas system, connectivity analysis, loss disaggregation.
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# Table of Contents

1 INTRODUCTION ............................................................................................................................... 1

2 SEISMIC RISK ANALYSIS OF A GAS DISTRIBUTION NETWORK ................................................. 2
   2.1 IDENTIFICATION OF THE MAIN TYPOLOGIES FOR GAS DISTRIBUTION NETWORK ELEMENTS .............................................................. 2
   2.2 SEISMIC INPUT ...................................................................................................................... 2
      2.2.1 TGD ................................................................................................................................. 3
      2.2.2 PGD ................................................................................................................................. 3
   2.3 VULNERABILITY ................................................................................................................... 4
      2.3.1 BURIED PIPELINES .............................................................................................. 4
      2.3.2 STATIONS ....................................................................................................................... 5
   2.4 PERFORMANCE AND LOSS ................................................................................................. 5
      2.4.1 Gas network model and analysis ................................................................................ 5

3 THE CASE STUDY: L’AQUILA (ITALY) GAS DISTRIBUTION NETWORK ........................................ 8
   3.1 SYSTEM TOPOLOGY AND CHARACTERISTICS .................................................................. 8

4 SOFTWARE IMPLEMENTATION ...................................................................................................... 11
   4.1 THE GAS CLASS .................................................................................................................. 11
   4.2 THE GASEDGE CLASS AND SUBCLASSES ....................................................................... 15
   4.3 THE GASENODE CLASS AND SUBCLASSES ................................................................... 16

5 APPLICATION AND RESULTS ........................................................................................................ 18
   5.1 CASE STUDY AND DATA REDUCTION .............................................................................. 18
   5.2 METHODOLOGY .................................................................................................................. 19
      5.2.1 Seismic input simulation ............................................................................................. 20
      5.2.2 Seismic vulnerability and performance assessment ................................................. 21
   5.3 RESULTS ............................................................................................................................. 23
      5.3.1 Disaggregation of gas network performance ......................................................... 25
      5.3.2 Influence of grid size for the computation of the primary IM .................................. 33

6 SUMMARY AND CONCLUSIONS ................................................................................................... 36
   6.1 CONTRIBUTION SUMMARY ............................................................................................... 36
      6.1.1 Hazard .......................................................................................................................... 36
      6.1.2 Vulnerability and performance assessment .............................................................. 36
      6.1.3 Results .......................................................................................................................... 37
A LANDSLIDE POTENTIAL AND GEOLOGICAL ASSESSMENT OF L’AQUILA REGION

40
List of Figures

Fig. 3.1 L’Aquila gas distribution network ........................................................................................................... 8
Fig. 3.2 M/R Metering/Pressure reduction stations in Onna (L’Aquila, Italy): a) external view; b) internal view ..................................................................................................................... 9
Fig. 3.3 L’Aquila gas distribution system: system flow chart (top); one of the 300 GR, housed in a metallic kiosk (bottom) ........................................................................................................... 10
Fig. 4.1 Class diagram for the gas distribution network .......................................................................................... 12
Fig. 5.1 Case study .................................................................................................................................................. 18
Fig. 5.2 Case study resulting from the data reduction process .................................................................................. 19
Fig. 5.3 Histograms of performance indicators: CL (top) and SR (bottom) ............................................................... 23
Fig. 5.4 Moving average μ, μ+σ and μ-σ curves for CL (top) and SR (bottom) ............................................................ 24
Fig. 5.5 Ccdf and confidence bounds for CL (top) and SR (bottom) ........................................................................ 25
Fig. 5.6 Histograms of broken pipes in the simulations (top) and scatter plots of PIs with respect to percentage of broken pipes (bottom) ................................................................................ 26
Fig. 5.7 Histograms of damaged M/R stations in the simulations (top) and scatter plots of PIs with respect to percentage of damaged M/R stations (bottom) ...................................................... 27
Fig. 5.8 Histograms of broken pipes vulnerable to PGD in the simulations (top) and scatter plots of PIs with respect to percentage of broken pipes vulnerable to PGD (bottom) ...................................................... 28
Fig. 5.9 Relative frequency of the number of broken pipes conditional to CL (top) and SR (bottom) .......................................................... 30
Fig. 5.10 Relative frequency of the number of damaged M/R stations conditional to CL (top) and SR (bottom) .......................................................... 31
Fig. 5.11 Relative frequency of percentage of pipes vulnerable to PGD conditional to CL (top) and SR (bottom) .......................................................................................................................... 32
Fig. 5.12 Exponential model used for the case study and correlation values characterizing different grid sizes of the primary IM. ........................................................................................................ 33
Fig. 5.13 Moving average for CL (top) and SR (bottom) for the three grid sizes ...................................................... 34
Fig. 5.14 Exceedance curve of CL (top) and SR (bottom) for the three grid sizes ...................................................... 35
Fig. A.1 Classification of geological groups for L’Aquila region according to HAZUS (FEMA, 2004) methodology .......................................................................................................................... 42
Fig. A.2 Critical acceleration map for L’Aquila region according to HAZUS (FEMA, 2004) methodology .......................................................................................................................... 43
List of Tables

Table 2.1 Main components of a GAS distribution network .................................................... 2
Table 5.1 Data input for the seismic hazard characterization ............................................... 21
Table 5.2 Parameters for the fragility characterization .......................................................... 22
Table A.1 Landsliding Susceptibility Classification ............................................................... 41
Table A.2 Geological groups description for L’Aquila region ............................................... 41
Table A.3 Critical accelerations and map area proportions for each landsliding susceptibility category ............................................................................................................. 43
1 INTRODUCTION

Past earthquakes have caused significant amount of damage to gas networks, especially on buried pipelines (O'Rourke and Palmer, 1996, FEMA, 1992). The 1971 San Fernando earthquake caused extensive damage to underground welded-steel transmission pipelines. The 1923 Kanto earthquakes caused over 4000 breaks to gas pipelines in the Tokyo region. Damage on above ground support facilities such as tanks and compressor stations were also observed in past events (FEMA, 1992), especially in the case of inadequate anchorage of equipment that led to rupture of electrical connections.

A gas system as a whole is comprised of: 1) a number of point-like critical facilities (Production and gathering facilities, Treatment plants, Storage facilities, Reduction stations where gas is pressurized/depressurized or simply metered); 2) the pipelines constituting the transmission/distribution network; 3) the supervisory control and data acquisition sub-system, namely SCADA.

The most critical component are pipelines because they 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. Therefore, the causes of physical damages to components of gas systems included large permanent soil deformations produced by fault displacements, landslides, liquefaction of sandy soils and associated lateral spreading and ground settlements, as well as ground strains associated with travelling seismic waves. 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 PGD zone. Evidence reported in literature indicates that underground pipelines perform worse in areas experiencing significant permanent displacements.

After an introduction presenting the general framework for the seismic risk assessment of a gas network, the case study of L’Aquila gas distribution system is described, and the process for the seismic performance characterization is summarized. Subsequently, the analysis of the system is carried out at the connectivity level and results in terms of performance indicators are presented and discussed for the different cases that have been considered.
2 SEISMIC RISK ANALYSIS OF A GAS DISTRIBUTION NETWORK

In the following the general framework for the risk assessment of a gas network is presented according to the SYNER-G methodology. Since the application study refers to a gas distribution system, the general methodology will be referred to the components of this system.

2.1 IDENTIFICATION OF THE MAIN TYPOLOGIES FOR GAS DISTRIBUTION NETWORK ELEMENTS

The elements of a gas distribution network comprise pipelines, reduction stations, valves and demand nodes (i.e., nodes directly connected with customers). In the SYNER-G framework pipelines and reduction stations are considered seismically vulnerable. Table 2.1 reports the main typologies of these elements. More details can be found in the SYNER-G deliverable 2.4.

Table 2.1 Main components of a GAS distribution network

<table>
<thead>
<tr>
<th>Name</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stations</td>
<td>• Metering /Pressure Reduction Stations</td>
</tr>
<tr>
<td></td>
<td>• Regulator Stations</td>
</tr>
<tr>
<td></td>
<td>• Metering Stations</td>
</tr>
<tr>
<td>Pipes</td>
<td>Pipe typology depends on:</td>
</tr>
<tr>
<td></td>
<td>• Location</td>
</tr>
<tr>
<td></td>
<td>• Material type</td>
</tr>
<tr>
<td></td>
<td>• Material strength</td>
</tr>
<tr>
<td></td>
<td>• Diameter</td>
</tr>
<tr>
<td></td>
<td>• Wall thickness</td>
</tr>
<tr>
<td></td>
<td>• Smoothness of coating</td>
</tr>
<tr>
<td></td>
<td>• Type of connection</td>
</tr>
<tr>
<td></td>
<td>• Pressure classification</td>
</tr>
<tr>
<td></td>
<td>• Nominal flow</td>
</tr>
</tbody>
</table>

2.2 SEISMIC INPUT

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

2.2.1 TGD

During an earthquake, wave propagation causes transient vibratory soil deformations over a wide geographic area affecting stations and also buried pipeline systems. Ground motion effects are usually described by peak parameters (e.g., peak ground acceleration, PGA, or peak ground velocity, PGV). 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-site separation distance (e.g., Esposito and Iervolino, 2011, 2012). Correlation models are, generally, characterized 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, may be considered sensitive to peak PGA, while pipelines are often considered to be more sensitive to 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. According to SYNER-G deliverable 2.13, to address this issue, conditional hazard may be 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.

2.2.2 PGD

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 such as landslides, liquefaction-induced lateral spreading, and seismic settlement (O’Rourke and Liu, 1999). Although PGD hazards are usually limited to small regions, their damage potential may be significant as potentially imposing large deformations on pipelines.

The relative impact of the various earthquake-induced effects on a pipeline system depends on the geological conditions in which surface faulting and the other effects occur, and the coincidence of these regions with the buried infrastructure. In fact, where these phenomena intercept the network, relatively high pipeline damage rates are observed in localized areas.

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 described in SYNER-G deliverable 2.13.

2.3 VULNERABILITY

To estimate earthquake damage for a natural gas system, given knowledge of ground shaking (or ground failure), earthquake intensity parameters have to be correlated with damage in terms of fragility functions for system components. In fact, these relations provide the probability of reaching or exceeding a particular damage state (level of damage) given the level of ground shaking (or ground failure). To this aim, the typological classification of each component, damage scale definitions, and the intensity measures, have to be defined.

2.3.1 BURIED PIPELINES

In the case of pipeline components, fragility curves available in literature are usually based on empirical data collected in past earthquakes. The most common 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. A corrective factor $K$ is 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. For example, considering a linear model, fragility function may be expressed as in equation 2.1:

$$R_R = K \cdot a \cdot IM$$

(2.1)

As mentioned, buried pipelines are sensitive to permanent ground deformation (resulting from various ground failures), in addition to transient ground deformation due to seismic wave propagation. Among the various seismic parameters used to correlate the ground motion effects to the damage suffered by buried pipelines, PGV has been identified as the one having a more direct physical interpretation (O'Rourke et al. 1998). Many PGV fragility relations are available in literature; for a discussion see SYNER-G deliverable 3.4.

Regarding ground failure effects, permanent ground deformation (PGD) is used as the demand descriptor.

Empirical fragility functions 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.

According to HAZUS (FEMA, 2004), two damage states may be considered for pipelines: 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.
2.3.2 STATIONS

In a gas distribution system three different types of stations may exists: (1) metering/pressure reduction stations (M/R stations) that contain metering equipments for monitoring and measuring the gas flow, and reduction lines for the compression of the gas pressure before its distribution into the pipe system; (2) regulator stations, where the gas pressure is reduced as required for the gas to arrive to the end-user; and (3) 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:

- Building typology;
- Anchored or unanchored subcomponents;
- Presence of a SCADA system;
- Electrical and mechanical component;
- Existence of backup power;
- Kiosk Solution;
- Buried equipment;
- Equipment inside or near by the buildings-

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 sometimes PGD, if located in liquefiable or landslide zones. (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.

2.4 PERFORMANCE AND LOSS

2.4.1 Gas network model and analysis

Seismic performance of a gas network may be measured generally in two ways:

- **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;

- **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.

Selected references and examples of these two approaches can be found in the SYNER-G deliverable 2.1.
Therefore, starting from the analysis of seismic damage to gas system components a connectivity or flow-based analysis can be carried out in order to evaluate the system performance of the damaged network.

Depending on the purpose of the analysis, different methods and tools can be used for the evaluation of seismic performance. In the following sections the approaches used for the modelling and the analysis of the gas network for the two methods (connectivity and flow-reliability) are briefly presented; for a discussion see SYNER-G deliverable 5.3.

### 2.4.1.1 Connectivity analysis

This level of analysis requires a simple description of the network in terms of a graph and analysis tools are limited to those of basic graph theory.

A graph $G = (X, A)$ is defined as a collection of points or vertices (node) $x_1, x_2, \ldots, x_n$ (denoted by the set $X$) and a collection of lines (edge/branch) $a_1, a_2, \ldots, a_n$ (denoted by the set $A$) joining all or some of these points. Graphs can be divided into directed graph and undirected graph. If the lines (called arcs) in $A$ have direction – which is usually shown by an arrow – the resulting graph is called a directed graph (Christofides, 1975). With reference to directed graphs, two different types of connectivity are involved: strong and weak. Considering a gas piping network, this system is strongly connected if the gas flows in one direction between two generic nodes. The network is weakly connected if the gas flows in both directions between two generic nodes.

For the analysis of the network, different graph theory algorithms and numerical methods exists, each of them solve a different problem. For example the Dijkstra’s algorithm (Christofides, 1975) solves the shortest path problem for a directed graph and it can be used to find the shortest path between two nodes while the Depth First Search algorithm is used to determine which nodes are reachable from a given node. These algorithms are applied on the network after removing the parts of the system that results damaged (i.e. stations and pipelines).

Moreover, in order to compute the connectivity analysis, nodes should be distinguished considering their functionality. For a gas distribution network the nodes are generally stations and end user nodes. Stations represents source nodes while nodes that are connected directly with customers are considered demand nodes. All the nodes that do not belong to either of these two classifications are considered transmission nodes (e.g., joints).

### 2.4.1.2 Flow-based analysis

In a flow-based analysis the network performance is measured evaluating the satisfied customer demand (in terms of flow) after the earthquake event with respect to that before the earthquake. In the case of gas networks, for the purpose of calculating pipe flows and nodal pressure before and after the seismic event, it is necessary to select a flow equation and a method to solve the gas network analysis problem. (The application of a flow equation is required for the calculation of the pressure drop along the network.) Steady state flow
equations are commonly used in network analysis. A network is in a steady state when the values of the quantities characterizing the flow of gas in the system are independent of time and the system is described by a set of nonlinear algebraic equations. Newton Nodal and Loops methods are commonly used for this purpose. In steady state analysis, the pressure of the nodes and the flow rate in the pipes must satisfy the flow equations and the value of load node and source node must fulfill the two Kirchhoff’s laws (Osiadacţ, 1987). The selection of the flow equation to use depends on type of piping characterizing the network especially in terms of pressure level. Note that also in this case the analysis should be performed on the network after removing the parts of the system that results damaged (i.e., stations and pipelines).

### 2.4.1.3 Performance indicators

Depending on the goal of the analysis (connectivity or flow) 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 PI 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 equation 2.2,

\[
SR = \frac{\sum_{i=1}^{n} w_i \cdot X_i}{\sum_{i=1}^{n} w_i}
\]  

(2.2)

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 modelled 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.

The second index, originally defined by Poljanšek et al. (2011), was adapted for the purpose of this study and it is expressed in equation 2.3. CL measures the average reduction in the ability of demand nodes to receive flow from sources counting the number of the demand nodes connected to the \( i \)-th source in the original (undamaged) network \( N_{demand,orig}^i \) and then in the damaged network \( N_{demand,dam}^i \) where \( \langle \rangle \) denotes averaging over all sources nodes.

Further details can be found in the SYNER-G deliverable 2.4.

\[
CL = 1 - \left\langle \frac{N_{demand,dam}^i}{N_{demand,orig}^i} \right\rangle
\]  

(2.3)
3 THE CASE STUDY: L’AQUILA (ITALY) GAS DISTRIBUTION NETWORK

3.1 SYSTEM TOPOLOGY AND CHARACTERISTICS

In Italy the gas supply transmission and distribution systems include the following principal components: (1) high-pressure transmission lines (national scale); (2) M/R stations; (3) medium-pressure distribution networks (regional scale); (4) Reduction Groups; (5) low-pressure distribution networks (local scale); (6) demand nodes; (7) gas meters.

In L’Aquila region the connection of the distribution medium-pressure network (Fig. 3.1) to the national high-pressure transmission lines is operated via three metering/pressure regulator stations (Re.Mi. “stazioni di Regolazione e Misura”, in Italian).
The three M/R stations of the L’Aquila distribution system are cased in one-story reinforced concrete structures with steel roofs (Fig. 3.2), hosting internal regulators and mechanical equipment (heat exchangers, boilers and bowls) where the gas undergoes the following processes: (1) gas preheating; (2) gas-pressure reduction and regulation; (3) gas odorizing; (5) gas-pressure measurement.

![Fig. 3.2 M/R Metering/Pressure reduction stations in Onna (L’Aquila, Italy): a) external view; b) internal view](image)

In particular the gas is distributed via a 621 km pipeline network: 234 km of which operating at medium pressure (2.5 – 3 bar), and the remaining 387 km with gas flowing at low pressure (0.025 bar – 0.035 bar). The pipelines of the medium and low pressure distribution networks are either made of steel or High Density Polyethylene (HDPE). HDPE pipes have nominal diameters ranging from 32 to 400 mm, whereas diameter of steel pipes is usually between 25 and 300 mm. Steel pipes use gas welded joints, while HDPE pipes use fusion joints.

The transformation of the medium distribution pressure into the low distribution pressure is operated via 300 reduction groups (RGs) that are either buried, sheltered in a metallic kiosk or housed within/close to a building (Fig. 3.3).
Several demand nodes (IDU, “Impianto di Derivazione Utenza” in Italian), consisting of buried and not buried pipes and accessory elements, allow the supply of natural gas to utilities, from low pressure network. For large users (e.g., industrial facilities) the demand node IDU is located along the medium-pressure distribution network (Fig. 3.3).

Depending on the amount of gas and level of service pressure required by the final user, and depending on whether or not an IDU is included in the system, three types of RG can be distinguished: (a) reduction and Measure Groups, GRM, located along MP network and directly connected to large users (e.g., industrial facilities); (b) Reduction Groups, GRU, smaller than GRM for medium pressure users connected to a medium pressure IDU system; (c) Final Reduction Group GRF, connected to low pressure network (Fig. 3.3a).

It is worth noting that all the components contained in both the L’Aquila M/R stations and RGs are unrestrained and therefore vulnerable to seismic (inertia) forces, as it usually happens for non-structural elements not properly seismically designed.
4 SOFTWARE IMPLEMENTATION

For the modelling of physical behaviour of the network with respect to the general methodology presented in the SYNER-G deliverable D2.1 the object-oriented paradigm (OOP) was adopted. Within such a paradigm the problem is described as a set of objects, “software containers” grouping together related procedures and data. Data elements are called attributes of an object. Procedures which operate on data specific for an object are called methods. Objects are instances (concrete realizations) of classes (abstract models) that are used to model the system.

The SYNER-G prototype software includes an object-oriented representation of some systems, among which gas distribution networks. The following sections report the properties and methods of the GAS class and its subclasses.

4.1 THE GAS CLASS

For the purpose of the application study the program was equipped with the GAS class, focusing on the components of a gas distribution system, in order to evaluate seismic performance of the case study (L'Aquila gas distribution network).

The gas distribution system class is modelled as an undirected graph and it is considered a subclass of the Undirected abstract class. As shown by the class diagram\(^1\) in Fig. 4.1, the network is comprised of nodes and link/edges. As consequences it is the composition of GASedge and GASnode abstract classes, of which the first is the generalization of PipeGAS class, while the second is the generalization of GASdemand, GASsource and Joint classes.

The Joint class represents all nodes used to reproduce the geometry of the system, the GASsource class is represented by M/R stations that are used to connect the distribution medium-pressure network to the high-pressure transmission lines and the GASdemand is the generalization of IDU class and Station class. The IDU class represents the node directly connected with customers in the low-pressure network while the Station class is represented by RGs that are considered final nodes when the only medium-pressure network is analyzed.

Each class is characterized by attributes and methods. Attributes refer to properties that describe the whole system and each component. For example, for the gas distribution system class, possible attributes may be related to the number of links and nodes presented in the system, the list of sites where vulnerable elements are located, and the corresponding intensity measures, or the connectivity and adjacency matrix used for the evaluation state by state of connectivity-based performance measures. Possible attributes for link and nodes, instead, may be related to geographical coordinates, site class, material and other data necessary as input to compute fragility and component performance measures. Methods refer to functions used to evaluate the state of the network or of each component of the

\(^1\) Note that with respect to the example given in the deliverable 5.4 for the modelling of the gas distribution example, some changes have been adopted in the scheme of the class diagram.
system. For example, possible methods are functions to evaluate the flow in pipes and nodes, or accessibility of demand nodes, or the damage state of links and nodes (if they are considered vulnerable).

![Class diagram for the gas distribution network](image)

**Fig. 4.1 Class diagram for the gas distribution network**

The following lists the main properties of the GAS class.

**List of pointers**

- **parent**: this is a pointer to the parent object which, in this case, is the Infrastructure (the object from the Infrastructure class);
- **pipe**: pointers to all the pipes in the system, objects from the PipeGAS class;
- **joint**: pointers to all the joints in the system, objects from the Joint class;
- **source**: pointers to all the source stations in the system, objects from the GASsource class;
- **demand**: pointers to all the demand nodes in the system, objects from the GASdemand class;
- **station**: pointers to all stations, objects from the Station class;
Software implementation

- **GR**: pointers to all reduction groups, objects from the StationGR class;
- **GRM**: pointers to all reduction and measure groups, objects from the StationGRM class;
- **idu**: pointers to all final demand, objects from the IDU class.

**Gas network global properties**

- **nEdges**: number of links or edges in the GAS;
- **nNodes**: number of nodes in the GAS;
- **edges**: connectivity matrix of the GAS listing the start and end nodes of each link;
- **edgeDiameterNumber**: number of diameter sizes present in the GAS;
- **gasEquipment**: gas daily equipment of the region of interest;
- **endUserDemand**: gas flows at demand nodes;
- **vulnSites**: list of vulnerable sites of the GAS, containing their location and IMs;
- **adjacencyMatrix**.

**Link and node characteristics**

- **edgeIsVulnerable**: flag indicating if the generic link is considered vulnerable or not;
- **edgeType**: typology of edges
- **edgeIMType**: intensity measures used for the damage assessment of the link;
- **edgeCentroidPosition**: coordinates of the edge centroid;
- **edgeLength**;
- **edgeDiameter**;
- **edgeDepth**;
- **edgeMaterial**;
- **edgeVs30**: Vs30 value at the links centroid;
- **edgeSiteClass**: site class at the edge centroid site according to the amplification method to be used;
- **edgeDepth2GW**: depth of the groundwater at the edge centroid site;
- **edgeLiqSusClass**: liquefaction susceptibility of the edge centroid site;
- **edgeLandSusClass**: landsliding susceptibility of the edge centroid site;
- **edgeYieldAcc**: yielding or critical acceleration for landsliding at the edge centroid site;
- **nodePosition**: coordinates of the node;
- **nodeAnchored**: flag indicating if the source node is considered seismic anchored or not;
- **nodeBuilding**: building typology (e.g. reinforce concrete);
o **nodeType**: typology of nodes;

o **nodeIsVulnerable**: flag indicating if the generic node is considered vulnerable or not;

o **nodeIMType**: intensity measures used for the damage assessment of the node;

o **nodeVs30**: Vs30 value at the node site;

o **nodeSiteClass**: site class at the node site according to the amplification method to be used;

o **nodeDepth2GW**: depth of the groundwater at the node site;

o **nodeLiqSusClass**: liquefaction susceptibility of the node site;

o **nodeLandSusClass**: landsliding susceptibility of the node site;

o **nodeYieldAcc**: yielding or critical acceleration for landsliding at the node site.

*Properties that record the state of the GAS for each event*

o **states**: $n_e \times 1$ collection of properties that describe the current state for each of the $n_e$ events;

  o **CLoss**: Connectivity Loss, first system-level performance indicator;

  o **SR**: Serviceability Ratio, second system-level performance indicator;

  o **mean_CL**: moving average of CLoss, i.e. the unweighted average value associated with the subset of data computed from the first to the current run of the simulation;

  o **mean_SR**: moving average of SR, i.e. the unweighted average value associated with the subset of data computed from the first to the current run of the simulation;

  o **std_CL**: moving standard deviation of CLoss; i.e., the standard deviation associated with the subset of data computed from the first to the current run of the simulation;

  o **std_SR**: moving standard deviation of SR; i.e., the standard deviation associated with the subset of data computed from the first to the current run of the simulation;

  o **covCL**: coefficient of variation of Closs;

  o **covSR**: coefficient of variation of SR.

*Properties that assess the global performance of the GAS at the end of simulation*

o **MAF**: Mean Annual Frequency of exceedance values for the considered system-level PI's.

The following lists the main methods of the GAS class (some of these are briefly explained):

o **computeCovMean**;
Software implementation

- updateConnectivity;
- computePerformanceIndicator;
- discretizeEdges
- retrieveLandSusEdges;
- retrieveLiqSusEdges;
- retrieveSiteClassEdges;
- retrieveYieldAccEdges;
- retrieveSiteClassNodes;
- retrieveVs30edges;
- retrieveVs30nodes;
- retrieveLandSusNodes;
- retrieveLiqSusNodes;
- retrieveYieldAccNodes.

Within the discretizeEdges method, all the links with a length larger than a threshold are subdivided into smaller segments; this is to allow a more refined computation ground intensity measure(s) along the link and, consequently, damage.

The updateConnectivity method, based on the network damage for the generic event, sets to 0 the elements in the adjacency matrix corresponding to broken edges and nodes.

### 4.2 THE GASEDGE CLASS AND SUBCLASSES

The following lists the properties of the GASedge abstract class that are common to the subclass PipeGAS.

- **parent**: this is a pointer to the parent object which is in this case the gas network (the object from the GAS class);
- **connectivity**: start and end node of the edge;
- **centroid**: edge centroid location;
- **Material**: edge material, defining the pipe fragility functions;
- **L**: link length;
- **D**: link diameter;
- **Vs30**: Vs30 at link centroid;
- **isVulnerable**;
- **IMType**;
- **siteClass**;
Software implementation

- depth2GW;
- liqSusClass;
- landSusClass;
- yieldAcc;

- **states:** \( n_E \times 1 \) collection of properties that describe the current state for each of the \( n_E \) events
  - broken: flag indicating if the edge is broken;
  - primaryIM: primary intensity measure at link centroid, as interpolated from the regular grid points;
  - localIMs: secondary or local intensity measures, correlated to the primary IM;
  - distance: source to site distance (km), referred to edge centroid;

The only method implemented for the GASedge class and its subclass is *isBreak*. The *isBreak* method computes the “break” pipe’s damage state according to a fragility function.

### 4.3 THE GASENODE CLASS AND SUBCLASSES

The following lists the properties of the GASNode abstract class. These properties are common to all subclasses of this class.

- **parent:** this is a pointer to the parent object which is in this case the gas network (the object from the GAS class);
- **position:** node location;
- **type**;
- **Vs30:** Vs30 at node;
- **isVulnerable**;
- **IMType**;
- **siteClass**;
- **depth2GW**;
- **liqSusClass**;
- **landSusClass**;
- **yieldAcc**;
- **states:** \( n_E \times 1 \) collection of properties that describe the current state for each of the \( n_E \) events (only for GASsource subclass);
  - broken: flag indicating if the source is broken;
  - primaryIM: primary intensity measure at node;
  - localIMs: secondary or local intensity measures, correlated to the primary IM;
o **distance**: source to site distance (km), referred to the node;

The subclass Regulator has two further properties, i.e. Anchored and Building.

The only method implemented for the Regulator class (subclass of GASsource) is **isDamaged**. The **isDamaged** method computes regulator’s damage state. If such damage state is the most severe (i.e. collapse), then the component is set to broken and successively deleted from the network.
5 APPLICATION AND RESULTS

5.1 CASE STUDY AND DATA REDUCTION

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. 5.1) is characterized by 3 M/R stations, 209 RGs, and pipelines at medium pressure, either made of steel or HDPE.

Fig. 5.1 Case study
For the implementation of the network into the prototype software, it was decided to reduce the amount of data, without compromising the nature of the study; i.e. application to a real case. In fact, in order to completely respect the geometry of the network, more than one thousands of joint nodes should were added and implemented into the input file. This would have resulted in large computational demand, rendering hardly feasible to run the analysis with the SYNER-G software.

Therefore a data reduction process was employed considering:

- Removal of all final links; i.e., pipes that are not carrying gas to regulators;
- Simplification of the geometry merging pipes with the same geometrical and material properties;

The resulting network (shown in Fig. 5.2) is comprised of 602 nodes (3 sources, 209 RGs and 390 joints) and 608 links. All data necessary for the evaluation of seismic vulnerability were imported in the simulation software.

![Fig. 5.2 Case study resulting from the data reduction process](image)

### 5.2 METHODOLOGY

A connectivity analysis was performed within this study. Considering that the function of a gas network at medium pressure is to deliver gas to reduction stations/groups, the network’s performance was assessed evaluating the aggregate availability of end nodes (RGs) composing the L’Aquila gas system.

Both TGD and PGD hazards were evaluated in particular focusing on the effects induced by landslide. Pipes and M/R stations were considered the only sites vulnerable elements within the network, and risk assessment was performed in terms of two connectivity-based performance indicators for the system.

In the following a detailed description of the application of the SYNER-G methodology to the case study is provided, and results of the analysis are discussed.
5.2.1 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 (PGA) 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 $= 1/750$ (Pace et al., 2006). Data on geometric source model used herein can be found in Chioccarelli and Iervolino (2010).

The strong ground motion for the primary IM was evaluated using a GMPE on a regular grid covering the gas network. The regular grid that covers the region of interest was 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). In this case a grid size of 1 km was chosen. As described in the SYNER-G deliverable 2.13, 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 was identified 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 was modeled using correlation models provided by Esposito and Iervolino (2011).

For each site of the grid the averages of primary IM from the specified GMPE were 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 elements' sites) was then obtained interpolating the grid values. The resulting ground motions correspond to rock sites. Then for each site the secondary IM (PGV) was determined by sampling a vector of Gaussian variables described by the conditional mean and variance depending on the primary IM (Iervolino et al., 2010).

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 Akkar and Bommer (2010) GMPE, starting from geology classification derived from 1:50,000 scale ISPRA geological maps (http://www.isprambiente.gov.it) (for more details see Appendix A).

Regarding geotechnical hazards (i.e., PGD), the landslide potential of L'Aquila region, according to the HAZUS (FEMA, 2004) procedure was performed (more details can be found in Appendix A). Therefore, a susceptibility map of L'Aquila region, based on the lithological group, slope angle, and ground-water condition was obtained, and starting from the susceptibility categories a critical acceleration map was derived. In particular, a critical acceleration, $K_c$, value ranging from 0.05g (most susceptible) to 0.6 g (less susceptible) was
associated to each landsliding-susceptible category. The probability of landsliding was 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

In Table. 5.1 all data input for the seismic hazard characterization of the case study are
summarized.

Table 5.1 Data input for the seismic hazard characterization

<table>
<thead>
<tr>
<th>Input</th>
<th>Primary IM</th>
<th>Secondary IM</th>
<th>Landslide</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM</td>
<td>PGA</td>
<td>PGV</td>
<td>PGD</td>
</tr>
<tr>
<td>GMPE</td>
<td>Akkar and Bommer (2010)</td>
<td>Akkar and Bommer (2010)</td>
<td>-</td>
</tr>
<tr>
<td>Spatial correlation model</td>
<td>Esposito and Iervolino (2011)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>-</td>
<td>0.754^2</td>
<td>-</td>
</tr>
<tr>
<td>Site amplification</td>
<td>GMPE</td>
<td>GMPE</td>
<td>-</td>
</tr>
<tr>
<td>Critical acceleration map</td>
<td>-</td>
<td>-</td>
<td>Hazus (FEMA, 2004)</td>
</tr>
<tr>
<td>Displacement model</td>
<td>-</td>
<td>-</td>
<td>Saygili and Rathje (2008)</td>
</tr>
</tbody>
</table>

5.2.2 Seismic vulnerability and performance assessment

To estimate earthquake-induced damage, IMs were related to system component damage
via fragility models. For buried pipelines ALA (2001) Poisson repair rate 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^3 are expressed in equation. 5.1 and 5.2 where K_1 and K_2 represent the
modification factors according to pipe material and diameter.

\[ R_R = K_1 \cdot 0.002416 \cdot PGV \] (5.1)

\[ R_R = K_2 \cdot 11.223 \cdot PGD^{0.319} \] (5.2)

^2 The correlation coefficient has been estimated starting from the dataset used for the Akkar and Bommer (2010)
GMPE.

^3 Note that R_R is expressed in 1/km and PGV and PGD are given in cm/s and m respectively.
Regulator groups were not considered seismically vulnerable, mainly because no quantitative fragility curves are available in literature. For the M/R stations, instead, a lognormal fragility curve for un-anchored compressor stations (FEMA, 2004) was adopted. The fragility functions of M/R station and pipelines (steel and HDPE) are summarized in Table 5.3 where log(µ) and β are the mean and the standard deviation of the normal distribution function used for the fragility assessment of the M/R station.

<table>
<thead>
<tr>
<th>Component</th>
<th>Author</th>
<th>Damage state</th>
<th>Fragility relation parameter</th>
<th>Ground shaking</th>
<th>Ground Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel pipelines (small diameter)</td>
<td>ALA (2001)</td>
<td>Break</td>
<td>K₁ = 0.6</td>
<td></td>
<td>K₂ = 0.7</td>
</tr>
<tr>
<td>HDPE pipelines (small diameter)</td>
<td>ALA (2001)</td>
<td>Break</td>
<td>K₁ = 0.5</td>
<td></td>
<td>K₂ = 0.8</td>
</tr>
<tr>
<td>M/R station (Un-anchored)</td>
<td>HAZUS (FEMA, 2004)</td>
<td>Extensive</td>
<td>µ(g) = 0.77, β = 0.65, µ(inch) = 10, β = 0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 (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.

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 Serviceability Ratio (SR), expressed in equation 2.2 and the Connectivity Loss (CL) expressed in equation 2.3 were considered. In particular for the SR performance indicator the weighting factor considered is represented by the nominal flow (m³/h) of the demand node; i.e., RG.
5.3 RESULTS

A Monte Carlo Simulation (MCS) was carried out in order to evaluate the probability of exceeding a predefined level $u$ of performance, given the occurrence of an earthquake on the fault. This probability was computed empirically using the MCS approach as follows:

$$
\hat{P}(PI > u) = \frac{1}{n} \sum_{j=1}^{n} I(pi_j > u)
$$

(5.3)

where $pi_j$ is the performance indicator level corresponding to the simulation $j$, $n$ is the total number of simulations and $I(pi_j > u)$ is an indicator function which equals 1 if $pi_j > u$ and 0 otherwise.

The number of runs of the simulation was defined in order to yield stable estimates of the probability of exceeding the considered PIs. In particular considering ten levels $u$ of the performance indicators ranging from 0 to 1, the simulation was stopped when the number of occurrences, for each class of CL, was equal at least to ten, as shown in Fig. 5.3.

Fig. 5.3 Histograms of performance indicators: CL (top) and SR (bottom)
Application and results

To stop the simulation as a function of CL was based on the fact that the probability to enumerate high levels of SR (more than 0.9) was too low, implying a large number of run needed. This may be due to the fact that high levels of serviceability are possible only when the most part of components are undamaged. Being the network characterized, as shown in Fig. 5.1, by several tree-type pipeline systems (see SYNER-G deliverable 5.3 for details), the system is not very redundant, and 100% serviceability seems to be not easily feasible. Moreover, the SR performance indicator accounts also for a weighting factor assigned to each distribution node (i.e., the nominal flow of the distribution node), with respect to CL, where all nodes are characterized by the same weight.

Figure 5.4 shows the moving average, $\mu$, curves as well as the $\mu+\sigma$ and $\mu-\sigma$ (moving average plus/minus moving standard deviation) curves for the two performance indicators. Results indicate that the expected value of connectivity loss given the occurrence of an earthquake is 0.65, i.e. it is expected that the average reduction in the ability of demand nodes to be connected to M/R stations is of 65%. While for the SR indicator, it is expected that the 68% of demand nodes receive gas accounting for the importance level related to the nominal flow of the demand nodes. Figure 5.5 shows instead the probability of exceedance (complementary cumulative distribution function, ccdf) of the two PIs expressed in equation 5.3.

![Fig. 5.4 Moving average $\mu$, $\mu+\sigma$ and $\mu-\sigma$ curves for CL (top) and SR (bottom)](image-url)
5.3.1 Disaggregation of gas network performance

In order to evaluate the contribution of some components of the risk on the performance of the network, some variables computed during each run of the simulation were stored and analyzed. In particular regarding hazard, the percentage of sites vulnerable to PGD (i.e., the ratio between the number of pipes where a PGD major to 0 was occurred and the number of pipes located on sites potentially subjected to landslide) were saved, while to study the effects of the performance state of the components of the network, the number of broken pipes\(^4\) and damaged M/R stations were analyzed.

In the following figures histograms and scatter plots of these variables with respect to the two performance indicators are shown.

\(^4\) Note that pipes do not share the same length.
Fig. 5.6 Histograms of broken pipes in the simulations (top) and scatter plots of PIs with respect to percentage of broken pipes (bottom).
Fig. 5.7 Histograms of damaged M/R stations in the simulations (top) and scatter plots of PIs with respect to percentage of damaged M/R stations (bottom).
Correlation coefficients between these variables and performance indicators were also computed in order to evaluate possible linear dependences. As shown in the previous figures it seems that the number of damaged M/R stations is better correlated with the two PIs.

An efficient procedure to investigate the values of variables that contribute most to given values of the network’s performance is *disaggregation*. Disaggregation of seismic performance, in fact, allows identifying the values of some variables providing the largest causative contribution to the risk given exceedance or occurrence of specified values of the performance indicator.

The aim is to evaluate the probability of a variable (X), that is supposed to have an influence on the final performance, conditional to the occurrence of the performance indicator as expressed below:

\[
P[X | u_1 < PI \leq u_2] = \frac{P[X, u_1 < PI \leq u_2]}{P[u_1 < PI \leq u_2]} \tag{5.4}
\]
Therefore, the distribution of the number of broken pipes, damaged M/R stations and the percentage of pipes vulnerable to PGD conditional to the occurrence of the two PI s to ten intervals (equally spaced and ranging from 0 to 1) were computed as in Equation (5.4) and shown in the figures 5.9, 5.10 and 5.11.

Moreover, for each interval of the two PI s, the bars on the right side of the conditional distribution of the damaged M/R stations taper differently than the bars on the left side; i.e. the conditional distributions are asymmetric. In particular, the distribution of damaged M/R stations conditional to large losses (high values of CL and low values of SR) results skewed to the left, i.e., the mode is in correspondence of an high number of damaged M/R stations while the distribution of damaged sources conditional to high level of serviceability (low values of connectivity loss) results skewed to the right and the mode is in correspondence of a number of damaged M/R stations equal to zero.

Regarding other variables, the distributions of number of broken pipes, and percentage of pipes vulnerable to PGD, conditional to the performance of the network are somewhat flat (Figures 5.9 and 5.11).
Fig. 5.9 Relative frequency of the number of broken pipes conditional to CL (top) and SR (bottom)
Fig. 5.10 Relative frequency of the number of damaged M/R stations conditional to CL (top) and SR (bottom)
Fig. 5.11 Relative frequency of percentage of pipes vulnerable to PGD conditional to CL (top) and SR (bottom)
5.3.2 Influence of grid size for the computation of the primary IM

In order to study the effects of regular grid size for the computation of the primary IM, different analyses were set up. The regular grid, as described in the deliverable D2.1, should be based on the correlation structure of the primary IM, i.e. a grid adequately denser than the IM correlation length (i.e. the range). In fact, for all points belonging to a cell, an unique value of the primary IM is associated; i.e., the primary IM evaluated at the centroid of the cell. Therefore, all points belongings to the cell are assumed perfectly correlated in terms of IM. Then, considering that two points that are separated by a distance greater than the range are assumed to be independent (in terms of residuals of the primary IM), the regular grid size should be smaller than the correlation length.

In this case three grid sizes were employed: 1 km, 2 km and 5 km. For each grid size an intra-event residual correlation value for PGA, was calculated starting from correlation models estimated by Esposito and Iervolino (2011), i.e. 0.80, 0.64 and 0.33 respectively, as shown in Fig. 5.12. These values characterize the correlation of PGA at points located at the extremity of each cell that are assumed instead perfectly correlated. Therefore, larger is the size of the grid, larger is the approximation.

Fig. 5.12 Exponential model used for the case study and correlation values characterizing different grid sizes of the primary IM.

Results for the three grid sizes are presented in the following figures. In particular Fig. 5.13 and 5.14 shows the moving average $\mu$ curves and the probability of exceedance for the two performance indicators.
Fig. 5.13 Moving average for CL (top) and SR (bottom) for the three grid sizes

Although it seems that higher grid sizes tend to underestimate the risk, differences are not so pronounced.
Fig. 5.14 Exceedance curve of CL (top) and SR (bottom) for the three grid sizes.
6 SUMMARY AND CONCLUSIONS

6.1 CONTRIBUTION SUMMARY

This study focused on applying, as a validation, the SYNER-G framework on a real case study: L’Aquila (Italy) gas distribution network. The process makes use of probabilistic seismic hazard analysis, empirical relations to estimate pipeline response, fragility curves for the evaluation of facilities' vulnerability, connectivity performance indicators to characterize the functionality of the network.

The study, in fact, has achieved this goal with special emphasis on the medium-pressure part of the L’Aquila gas system for which detailed information were retrieved. In particular, the selected network was characterized by 3 M/R stations, 209 RGs, and pipelines either made of steel or HDPE. Moreover, for the implementation of the network into the SYNER-G prototype software, it was decided to reduce the amount of data, without compromising the nature of the study. In particular a data reduction process was employed considering: 1) removal of all final links; i.e., pipes that are not carrying gas to regulators; 2) simplification of the geometry merging pipes with the same geometrical and material properties. The resulting network was comprised of 602 nodes (3 sources, 209 RGs and 390 joints) and 608 links.

6.1.1 Hazard

In order to characterize the ground shaking hazard of the L’Aquila region, probabilistic scenarios earthquakes were generated using as source the Paganica fault computed for a characteristic earthquake of moment magnitude Mw 6.3. Strong ground motions for the primary IM were evaluated though an European GMPE and an European spatial correlation model on a regular grid covering the gas network. The grid was defined based on the correlation structure of the primary IM; i.e., a grid adequately denser than the IM correlation length. A grid size of 1 km was chosen. PGA was identified 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 value of the primary IM at each site of the network was obtained interpolating the grid values. The resulting ground motions correspond to rock sites. For each site the secondary IM was determined via conditional hazard.

To account for local site conditions GMPE-based amplification factors were considered. Regarding geotechnical hazards (i.e., PGD), the landslide potential of L’Aquila region, according to the HAZUS procedure was performed. Thanks to a process jointly developed with specialists, the landslide potential in the L’Aquila region was evaluated.

6.1.2 Vulnerability and performance assessment

To estimate earthquake-induced damage, IMs were related to component damage via fragility models. For buried pipelines repair rate functions of PGV and PGD were selected for each pipe typology and diameter. Regulator groups were not considered seismically vulnerable, mainly because no quantitative fragility curves are available in literature. 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 (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 was 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.

The adaptation of two connectivity performance indicators (Serviceability Ratio and Connectivity Loss) were considered to include damage of stations and distributing elements into the risk assessment for the system.

6.1.3 Results

A Monte Carlo Simulation was carried out in order to evaluate the probability of exceeding predefined levels of performance, given the occurrence of a characteristic earthquake on the fault.

Results indicate that the expected value of connectivity loss given the occurrence of an earthquake is 0.65. For the SR indicator, it is expected that the 68% of demand nodes receive gas accounting for the importance level related to the nominal flow of the demand nodes.

In order to evaluate the conditional contribution of some components of the risk on the performance of the network, disaggregation of performance was performed. The latter refers to: percentage of sites vulnerable to PGD, number of broken pipes, and damaged M/R stations.

Finally, in order to investigate the effect of grid size for the computation of the primary IM, different analyses were set up. In particular three grid sizes were assumed: 1 km, 2 km and 5 km. These were chosen via specific values of correlation of intra-event residuals for the primary IM. The larger is the size of the grid, larger is the approximation. Results shows that coarser discretizations tend, as expected, to (slightly) underestimate the risk.
REFERENCES


Appendix A

LANDSLIDE POTENTIAL AND GEOLOGICAL ASSESSMENT OF L’AQUILA REGION

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

In order to apply the Hazus methodology the Quaternary deposits and the Meso-Cenozoic formations beneath were grouped into three main subsoil classes (i.e. A,B,C showed in Table A.1) considering both lithological and mechanical properties of the formations.

Class A was mainly constituted by calcareous and flysch deposits, meso-cenozoic in age, forming the ancient and well lithified bedrock. Quaternary cemented breccias were also included into the same class. Terrains grouped into class A are all characterised by effective cohesion $c'$ not lower than 15 kPa and by friction angle $\phi'$ higher than 35 degree. In class B the quaternary clastic deposits that fill the tectonic depression of the Aterno river valley were grouped; in particular: conglomerates, gravels, slope debris, sands and locally clay ad silt. The cohesion of these terrains is low or very low and friction angle is rather high. Finally in class C all the terrains (late Pleistocene-Holocene in age) which represent the more shallow layers (10-15m deep) of the central part of the Aterno river valley were included. They are mainly made up of silts and clays, but sometimes they can contain thin layers of sands and peats. The characteristics of resistance are surely worse respect to “A” and “B” groups so these terrains were characterized with zero value of cohesion and friction angles not exceeding 20°. The classification is synthesized in Table A.2, with the description of each class and the associated values of strength parameters, as suggested by HAZUS and the resulting geological map is shown in Fig. A.1.

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. In particular starting from a topographic map 1:25000 (IGM, http://www.igmi.org/prodotti/cartografia/carte_topografiche) a digital elevation model (DEM) of the studied area was obtained with a grid resolution of 40x40m and a height resolution of 7m. The DEM in turn, allowed to obtain the slope angle map, showing that in the city center the gas network is mainly located in flat areas, whereas in the surrounding small villages the network crosses very steep slopes. Extreme groundwater conditions were assumed, by considering either dry (groundwater below the depth of the sliding surface) or wet conditions (groundwater level at ground surface). Since very limited information were available about groundwater table, a
dry state was attributed to the outcropping rock while wet conditions were assigned to B and C soil classes.

### Table A.1 Landsliding Susceptibility Classification

<table>
<thead>
<tr>
<th>Geologic Group</th>
<th>Slope Angle (Degrees)</th>
<th>0 – 10</th>
<th>10 – 15</th>
<th>15 – 20</th>
<th>20 – 30</th>
<th>30 – 40</th>
<th>&gt; 40</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DRY (groundwater below level of sliding)</strong></td>
<td>Strongly Cemented Rocks (Crystalline rocks and well-cemented sandstone)</td>
<td>None</td>
<td>None</td>
<td>I</td>
<td>II</td>
<td>IV</td>
<td>VI</td>
</tr>
<tr>
<td></td>
<td>Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone)</td>
<td>None</td>
<td>III</td>
<td>IV</td>
<td>V</td>
<td>VI</td>
<td>VII</td>
</tr>
<tr>
<td></td>
<td>Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fill)</td>
<td>V</td>
<td>VI</td>
<td>VII</td>
<td>IX</td>
<td>IX</td>
<td>IX</td>
</tr>
<tr>
<td><strong>WET (groundwater above level of sliding)</strong></td>
<td>Strongly Cemented Rocks (Crystalline rocks and well-cemented sandstone)</td>
<td>None</td>
<td>III</td>
<td>VI</td>
<td>VII</td>
<td>VIII</td>
<td>VIII</td>
</tr>
<tr>
<td></td>
<td>Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone)</td>
<td>V</td>
<td>VIII</td>
<td>IX</td>
<td>IX</td>
<td>IX</td>
<td>IX</td>
</tr>
<tr>
<td></td>
<td>Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fill)</td>
<td>VII</td>
<td>IX</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

### Table A.2 Geological groups description for L'Aquila region

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Strength parameters</th>
<th>Local Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Rock</td>
<td>$c' = 15 \text{ kPa}$ $\phi' = 35^\circ$</td>
<td>Limestones - Flysch-Debris</td>
</tr>
<tr>
<td>B</td>
<td>Soft Rock</td>
<td>$c' = 0$ $\phi' = 35^\circ$</td>
<td>Pleistocene gravels and sands</td>
</tr>
</tbody>
</table>
Fig. A.1 Classification of geological groups for L'Aquila region according to HAZUS (FEMA, 2004) methodology
Table A.3 Critical accelerations and map area proportions for each landsliding susceptibility category

<table>
<thead>
<tr>
<th>Susceptibility Category</th>
<th>None</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Acceleration (g)</td>
<td>None</td>
<td>0.60</td>
<td>0.50</td>
<td>0.40</td>
<td>0.35</td>
<td>0.30</td>
<td>0.25</td>
<td>0.20</td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>Map Area</td>
<td>0</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.08</td>
<td>0.10</td>
<td>0.15</td>
<td>0.20</td>
<td>0.25</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Fig. A.2 Critical acceleration map for L’Aquila region according to HAZUS (FEMA, 2004) methodology