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ORIGINAL RESEARCH PAPER

Performance of the L'Aquila (central Italy) gas distribution network in the 2009 (M_w 6.3) earthquake

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Abstract Despite the seismic vulnerability of gas systems and the significance of the direct and indirect consequences that loss functionality might have on large communities, the analysis of the earthquake performance and of post-earthquake management for this kind of distribution networks appears under-represented in the international literature, with respect to other lifeline systems. To contribute on this matter, the study presented comprises an investigation of the impact of L'Aquila 2009 earthquake (M_w 6.3) on the performance of the local medium- and low-pressure gas distribution networks. The assessment of the physical impact of the earthquake to the buried components of network, namely pipes, valves, and demand nodes, was carried out when processing post-earthquake repair activity reports. Repair data, along with geometrical and constructive features, were collected in a geographic information system linked to the digitized maps of the network, and compared with the interpolated map of recorded transient ground motion, measured in terms of peak ground velocity (i.e., a *Shakemap*^{TM}). The impact of permanent ground deformation was also investigated and found to be limited in the study area. The resulting observed repair rates (number of repairs per km), presented for different pipeline materials, were compared with repair ratio fragility functions available in literature, showing relatively agreement especially to those for steel pipes, likely also because of the uncertainties in the estimations. Finally, the management of the L'Aquila gas system in the emergency phase and the resilience (functionality recover versus time) of the system was discussed.

Keywords Lifelines · Repair rate · Pipelines · Resilience · Transient and permanent ground deformations

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1 Introduction

The earthquake safety of gas systems has attracted large attention in recent years. Seismic events have, in fact, highlighted the vulnerability of gas systems and the significance of the direct and indirect consequences that the loss of functionality might have on the served communities. In particular, recent earthquakes have caused significant amount of damage to gas networks, especially on buried pipelines (e.g., O'Rourke and Palmer 1996; FEMA 1992). The 1971 (moment magnitude or M_w 6.7) San Fernando (California) earthquake caused extensive damage to underground welded-steel transmission pipelines; most of the breaks were localized at the welds of pre-1931 lines. The 1923 Kanto (M_w 7.9) Japan earthquake caused over four thousand breaks to gas pipelines in the Tokyo region; most of the damage occurred at the joints of small diameter cast-iron pipe. Generally speaking, the performance of reticulated gas networks following large earthquakes all over the world has been poor (Schiff 1995 and 1998), especially where the use of cast iron and other older transmission and distribution pipe is still common. Conversely following the recent earthquake in Christchurch, New Zealand (2011, M_w 6.2) the performance of the liquefied petroleum gas system was remarkably good. Indeed, no damage was observed both to the 170 km of medium density polyethylene pipelines and their electro-fusion welded joints, despite the gas pipes were located in zones that experienced severe liquefaction and ground deformations (e.g., O'Rourke et al. 2012; Giovinazzi et al. 2011).

Damages to above-ground support facilities for gas system, such as tanks and compressor stations, were also observed in past events, especially in presence of inadequate anchorage of equipment that led to rupture of electrical connections. Experience also indicates that damage to bridges and to other supporting facilities might have significant effect on the performance of gas systems. In the 1976 Tangshan (M_w 7.5) China earthquake a pipeline mounted on a bridge was totally destroyed.

A damaged gas system can also increase the probability of occurrence of cascading hazard such as explosions and fire following earthquake. The explosion subsequent to the 1971 San Fernando earthquake, causing crater-like depressions in residential streets, is probably the most striking example.

The causes of physical damages to components of gas systems in the aforementioned earthquakes included large permanent soil deformations produced by fault displacements, landslides, liquefaction of sandy soils associated lateral spreading, ground settlements, and ground strains associated with travelling seismic waves.

Ground shaking usually affects wide geographical areas and can produce well-dispersed effects. Pipeline damage from travelling ground waves has been observed in natural gas pipelines weakened either by corrosion or by poor quality welds (EERI 1986). Damage induced by permanent ground deformation (PGD due to fault rupture, liquefaction and, most importantly, landsliding) 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.

A significant part of the research on the seismic performance of gas networks has focused on the assessment of the seismic vulnerability of gas pipelines, when subjected to ground motion (O'Rourke and Ayala 1990; Paolucci and Pitilakis 2007), permanent ground deformation (EERI 1986; O'Rourke and Trautmann 1981; O'Rourke 1988), or both (O'Rourke and Palmer 1996). Empirical data on pipeline failures from past earthquakes have been processed to define empirical correlations (ALA 2001a), able to predict the number of repairs per unit length of pipe required with respect to a parameter representative of ground shaking (e.g., peak ground velocity or acceleration, PGV and PGA, respectively) or ground failure (i.e., PGD). Procedures for mitigating seismic risk in existing gas systems are discussed by O'Rourke and Palmer (1994).

The April 6, 2009 L'Aquila (central Italy) earthquake (M_w 6.3) was the first earthquake occurring in Italy, in the modern-era of earthquake engineering, with a densely urbanized region close to the source of a severely damaging seismic sequence. Thanks to the permanent seismic monitoring networks deployed in the L'Aquila area, a relatively large number of near-source records are available allowing for an improved understanding of the seismic features of the event (see Sect. 2). On the other hand, the high industrial and residential urbanization in L'Aquila area allowed to directly observe the seismic performance of a number of different structural typologies and engineering systems.

This paper analyses the impact of L'Aquila earthquake on the performance of the local gas distribution network. The latter, operated by *ENEL Rete Gas spa* and supplying about forty thousand customers, consists of: one medium-pressure and one low-pressure distribution system, made of 621 km steel and high density polyethylene pipes (HDPE); 3 metering/pressure reduction stations and about 300 reduction groups.

In the study it was, as a first step, investigated the earthquake-related repairs to the network's components as a proxy in order to evaluate the seismic damage. To this aim, post-earthquake repair activities reports, referring to a five months period following the earthquake and available from the network's operator, were processed and analyzed.[1] Repair data were collected in a geographic information system (GIS) linked to the digitized maps of the network and compared with an interpolated map of recorded transient ground deformation described in terms of peak ground velocity (i.e., a *Shakemap*™, Wald et al. 2006). Particular focus was given to the analysis of the damage induced by the transient ground deformation (i.e., ground shaking) on the buried pipelines, because: (1) the impact from permanent ground deformation and geotechnical induced hazards was found to be negligible due to the geological/geotechnical features of the region; (2) the impact of the earthquake on other components of the gas systems, namely reduction stations, was minor.

The impact of the L'Aquila earthquake on the gas system functionality, along with the effective reinstatement process were also described and summarised in the paper in terms of functionality recovery (i.e., *resilience*) curve.

The following is structured such that, background information on the L'Aquila earthquake, including the description of geotechnical effects induced by the event, that is landsliding and surface faulting, is provided first. Then, L'Aquila gas network is described, providing information on the components of the network. Subsequently, repair data are analyzed to gain an understanding of the physical performance of different components and to compute observed repair rates; a comparison with repair ratio fragility functions available in literature is also given. Finally, the management of the L'Aquila gas system in the emergency and recovery phase is illustrated and the resilience of the system is discussed.

2 Basic facts of the 2009 L'Aquila earthquake

On April 6, 2009, 03:32:40 UTC, a M_w 6.3 earthquake struck the Abruzzo region, in central Italy. The earthquake occurred at about 10 km depth along a normal fault, namely the Paganica fault, located below the city of L'Aquila (INGV 2009).

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[1] Because the extended database was affected by some incompleteness in the first month period following the earthquake, the analysis was performed for a limited area corresponding to the central areas of L'Aquila region, where all repair data were completely reported.

Considerable damage to structures and infrastructures was detected over a broad area of approximately 600 km^2, including the downtown of L'Aquila and several villages in the Aterno river valley. After the mainshock, three aftershocks with moment magnitude $M_w > 5$ were recorded within a few days.

The sequence was recorded by several digital stations of the Italian strong-motion network, RAN—*Rete Accelerometrica Nazionale* (Zambonelli et al. 2011), owned and maintained by the *Italian Department of Civil Protection*. PGA recorded in the near-source region ranged from 0.33 to 0.65 g, the latter representing one of the highest PGA values measured in Italy (Chioccarelli et al. 2009).

Regarding the geotechnical effects induced by the earthquake, evidence of surface rupture was found along the Paganica fault. In particular in the areas of Tempera and Paganica villages, a set of well aligned ground ruptures was observed (Blumetti et al. 2009; Vittori et al. 2011) that caused damage to infrastructures (Dolce et al. 2009). Minor and negligible coseismic ruptures occurred also along several other faults, including Pettino, Bazzano and Roio faults (Vittori et al. 2011). Secondary effects of ground deformation and failure, mainly related to slope instability, collapse of some underground cavities, and ground settlement induced by liquefaction, were reported soon after the earthquake. Numerous rock falls occurred especially near the village of Fossa and within the Gran Sasso Mountain along the north-east slope of Mt. Bazzano. Cases of liquefaction (ground settlement, sand boils and sand volcanoes developed in free field) were detected in an area, approximately 45 km far from the epicenter (Monaco et al. 2009). However, geotechnical effects on the area interested by the gas network were found minor with respect to reported damages (see Sect. 5).

3 The L'Aquila medium- and low-pressure gas distribution system

In Italy the gas transmission and distribution systems include the following principal components: (1) high-pressure (HP) transmission lines (at a national scale); (2) metering/pressure reduction stations (M/R stations); (3) medium-pressure (MP) distribution networks (at regional scale); (4) reduction groups (RGs); (5) low-pressure (LP) distribution networks (at urban scale); (6) demand nodes; (7) gas meters (at the customer scale).

In L'Aquila region the connection of the MP distribution network to the national HP transmission lines is operated via three M/R Stations (referred to as 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. 1), hosting internal regulators and mechanical equipment (heat exchangers, boilers and bowls) where the gas undergoes the

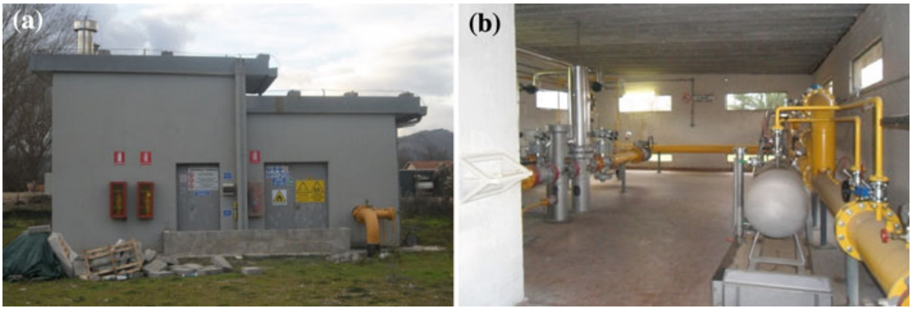

Fig. 1 M/R metering/pressure reduction stations in Onna (L'Aquila, Italy): **a** external view; **b** internal view

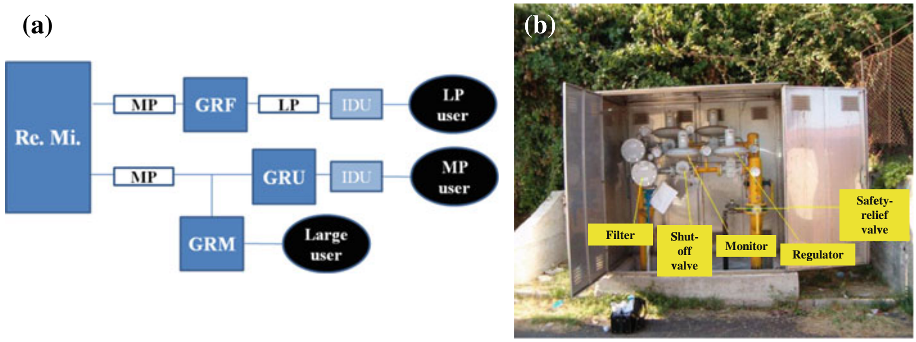

Fig. 2 L'Aquila gas distribution system: **a** system flow chart; **b** one of the 300 RGs, housed in a metallic shelter

following processes: (1) gas preheating; (2) gas–pressure reduction and regulation; (3) gas odorizing; (4) gas–pressure measurement.

The gas is distributed via a 621 km pipeline network: 234 km of which operating at MP (2.5–3 bar), and the remaining 387 km with gas flowing at LP (0.025–0.035 bar). Pipelines of the medium and low pressure distribution networks are either made of steel or HDPE. The latter pipes have nominal diameters ranging from 32 to 400 mm, whereas diameter of steel pipes is usually between 25 and 300 mm. Before 1990 steel pipes were usually characterized by gas welded joints, while since 1990 gas welded joints are used for diameter less than 250 mm and arc welded joints otherwise. HDPE pipes use fusion joints.

Construction years of the analyzed network range from 1968 to 2009 and the burial depth was usually between 0.6 and 0.9 m before 1992, and equal to 1 m after 1992.

Different types of in-line valves may be found along the pipeline network, mainly: *gate* valves; *butterfly* valves; *check* valves; *ball* valves.

The transformation of the MP into the LP is operated via 300 RGs that are buried, sheltered in a metallic kiosk, or housed within/close to a building (Fig. 2b).

Several demand nodes (referred to as IDU, *Impianto di Derivazione Utenza* in Italian), consisting of buried and above-ground pipes and accessory elements, allow the supply of natural gas to utilities, from LP network. For users such as industrial facilities, the demand node IDU is located along the MP network (Fig. 2a).

Depending on the amount of gas and level of service pressure required by the end user, and depending on whether or not an IDU is included in the system, three types of RGs can be identified: (a) reduction and measure groups, GRM, located along MP network and directly connected to large users; (b) reduction groups, GRU, smaller than GRM, for MP users connected to a MP IDU system; (c) final reduction groups GRF, connected to LP network (Fig. 2a).

It is worth noting that all the components contained in both the L'Aquila M/R stations and RGs are unrestrained and therefore sensitive to seismic (inertia) forces.

4 Physical impact of the earthquake on the system

4.1 Processing of repair and reconstruction reports

Aiming to assess the physical damage occurred to the gas network components as a consequence of the 6 April 2009 L'Aquila earthquake, the technical reports describing the repair

Table 1 Macro-categories identified for maintenance/repair operations from *Rei.activities* reports

Pipelines	Valves	Demand nodes, IDU	Other and mixed
Inspection or screening (P_scr)	Excavation for valve inspection (V_exc)	New unburied IDU (I_rea_nb)	Transport/excavation operations (other)
Pipeline repair (P_rep)	Valve insertion (V_ins)	New buried IDU (I_rea_b)	Repairs made to more than one component (mixed)
Pipeline reconnection (P_rec)	Valve removal (V_rem)		

and replacement activities to affected components of the gas network, were processed. In fact, following the earthquake, *ENEL Rete Gas* acted targeting two main objectives: (1) recovery of the gas system efficiency to its state before the earthquake; (2) reconstruction of damaged/affected components to improve the gas network efficiency beyond its original condition. These objectives were pursued by two types of technical activities: (1) *Rei.activities*, that is repair activities aiming at recovering the system efficiency in response to exceptional events; (2) *E1E.activities*, that is reconstruction activities targeting the construction and/or reconstruction of facilities for investments as a result of extraordinary operations.

Reports related to *E1E.activities* were analyzed and processed with respect to a 6-months period; i.e., from June 2009 (when reconstruction activities started to be reported) to November 2009, distinguishing between: (1) replacement of damaged parts, mainly components of cabins, and pipelines; (2) extension of the pipe network in response to different needs, including by-pass of inaccessible zones in cordoned areas of the city center, addition of missing links, connection of temporary or new urbanized areas. The results from the processing of *E1E.activities* reports were organized in a specific GIS database, consisting of 51 records, linked to the digitized maps of the network.[2]

Regarding *Rei.activities*, namely maintenance/repair activities, more than 500 technical reports from *ENEL Rete Gas*, referring to a five-month period (from April 2009 to August 2009), were analyzed. From such a processing, different maintenance/repair operations have been identified and geocoded in a specific GIS database, linked to the digitized maps of the network. For different components of the gas network, maintenance/repair operations were classified into macro-categories (Table 1).

The aim of the *Rei.activities* reports, filled by field crews, was to justify the cost for the repair rather than to describe the damage that the repair activity was addressing. Unfortunately, the extent and description of the damage sustained by the network components were usually insufficiently reported in the technical reports. Furthermore repair records suffered from some inaccuracies, including omitted address indication, vague damage description and multiple repairs at a single site combined into one record. Therefore, from the processing of 513 technical reports, a database of repair/maintenance operations consisting of 431 records has been obtained after excluding incomplete records. Figure 3 illustrates the repair/maintenance operation database with respect to the categories of Table 1.

The level of completeness of the repair/maintenance operation database varies geographically and with time.

From a time point of view, the database can be considered complete starting from June 2009. In the period April–May 2009, indeed, in a situation of full emergency, the technical reports describing the repair activities were not filled. Therefore, only the costs of the

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[2] More than 3 years after the earthquake, the *E1E.activities* activities are still on-going.

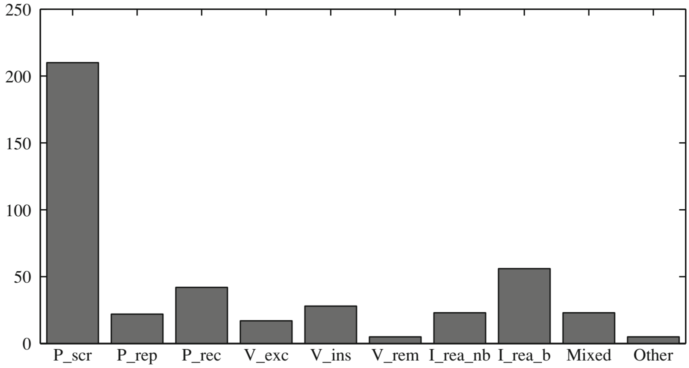

Fig. 3 Number of interventions to the components of L'Aquila gas system for each identified maintenance/repair category, as defined in Table 1

Table 2 Minimum, maximum and mean value of time required and aggregated costs for the identified macro categories of maintenance/repair operations

Macro-categories	Time required [h.min]			Aggregated costs [€]		
	Min	Max	Mean	Min	Max	Mean
P_scr	1.00	12.30	5.00	400	5800	1700
P_rep	2.00	12.00	6.45	1500	2750	1850
P_rec	2.00	15.00	8.00	1550	4900	2550
V_exc	1.00	10.00	4.00	350	1200	800
V_ins	2.00	10.00	5.30	450	2950	1650
V_rem	2.00	11.00	6.30	1550	1550	1550
I_rea_nb	1.00	12.30	4.30	50	600	350
I_rea_b	1.00	14.30	6.00	700	4500	2050
Mixed	1.00	9.30	4.00	400	3650	1250
Other	1.30	9.30	4.30	300	300	300

operations are available. However, activities to repair/restore the gas network were limited in the immediate aftermath of the earthquake, since resources and efforts of the gas system operators were mainly concentrated on emergency management (see Sect. 6).

From a spatial point of view, during the recovery phase, to effectively manage and prioritize the repair activities, four different areas were identified in the region served by the gas network, namely: central area (Zone 1 or Z1); west area (Zone 2 or Z2), east area (Zone 3 or Z3), sud-east area (Zone 4 or Z4). The central area (Zone 1, Z1) is the only one where the maintenance/repair database resulted completed (Fig. 8).

Despite the aforementioned completeness issues, the maintenance/repair operation database, being obtained from the joint processing of technical and addendum economic reports, provides important information, including: (1) inferred earthquake-induced damage to the gas system components; (2) aggregate cost associated with different types of repair operations; (3) the time required for different types of repair operations. Table 2 shows statistics of time required and aggregated costs for the eight macro-categories in Table 1. The interested reader can find further details in Esposito et al. (2011).

Fig. 4 Damage to stations: **a** repairs to the input/output network of Onna M/R and inclusion of stop-system; **b** RG housed in a masonry kiosk closed to building and damaged following the 6 April 2009 earthquake (photos courtesy of *ENEL Rete Gas*)

4.2 Damage to above-ground system components

Damage to above-ground components of the gas system has been inferred from *E1E.activities* reports that address the repair/upgrade of M/R and RG stations. Regarding the three M/R stations, no damage was observed to the one-story reinforced concrete buildings. All the M/R station buildings were classified as *A* (corresponding to a green tag in the US system; i.e., safe building, ATC-20, 1989) according the AeDES forms (*Agibilità e Danno nell'Emergenza Sismica* form in Italian; Baggio et al. 2000) used in Italy for the post-earthquake building safety assessment by the civil protection. The regulator and mechanical equipment for all the M/R stations resulted undamaged. *E1E.activities* addressed the repair and upgrade (inclusion of safe-stop systems, Fig. 4a) of the input/output substation network of two of the three M/R stations (located in Onna, Centi Colella and Sassa), as described in the following.

- M/R station in Onna: gas leak reparations including excavations, welding joints with special pieces like dielectric joints, welding pipes and recovery steel/polyethylene piping connections (Fig. 4a).
- M/R station in Centi Colella: valve replacements and input/output substation network repair.
- M/R station in Sassa: no post-earthquake interventions according to *E1E* reports analysed.

Few RGs in L'Aquila and Onna had to be replaced concurrently with the laying of new pipe. One of the principal causes of earthquake-induced damage to different typologies of RG stations was the collapse of rubble from adjacent buildings (Fig. 4b).

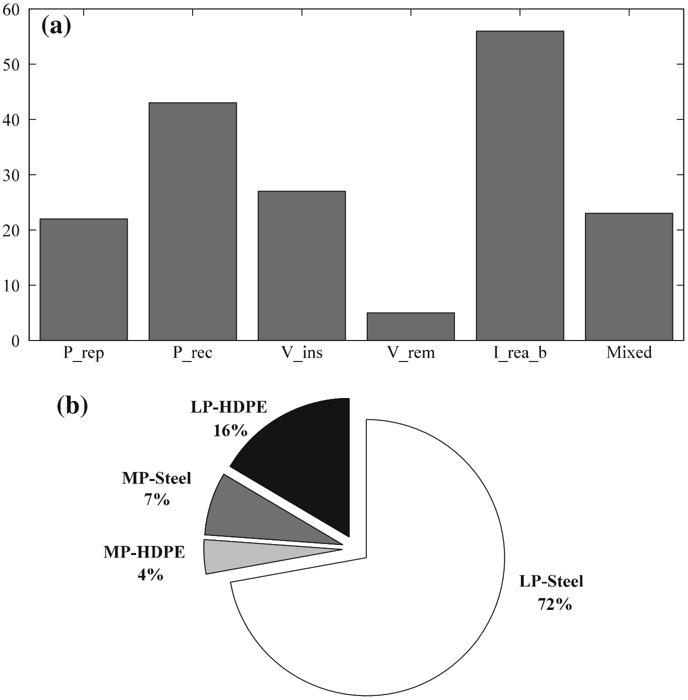

Fig. 5 Repair operations addressing damage to buried components for the entire gas network: **a** number of repairs for the different buried component and intervention category; **b** number of repairs distinguished with respect to pressure level and pipe material

4.3 Damage to buried components

Repair and maintenance operations to buried components, namely pipelines, valves, demand nodes, described in the *Rei.activities*, included: (1) testing operations (disconnecting and reconnecting the network); (2) gas-leak detection and repair; (3) valve replacement; (4) demand node repair. A first understanding of the impact of L'Aquila earthquake on buried components can be obtained from the analysis of the repair/maintenance operation database (discussed and presented in the Sect. 4.1) after excluding: (1) the activities that were addressing repair to above-ground components (e.g., realization of above-ground nodes, I_rea_nb); and (2) activities that were not explicitly addressing repair of damage (first row in Table 1), namely: screening operations (P_scr); valve excavation (V_exc); and interventions indicated as "other", usually referring to transport operations or closure of pre-existing excavations.

Following the screening process, it resulted that 176 repair/maintenance operations addressed the damage to different buried components (Fig. 5a) in the following proportion: pipelines (37 %); valves (18 %); demand nodes (32 %); mixed (13 %), namely repairs made to more than one component (e.g., repair to pipe and unburied node; or repair to valve and unburied node). Figure 5b illustrates the repair/maintenance operations with respect to: pressure level of the distribution network, namely MP and LP; and pipe material, namely steel or HDPE. The largest proportion of repairs (72 %), and therefore of the damage, was localized on the LP distribution network, made of steel pipes (Fig. 6a). The repair and replacement for the steel pipes of LP distribution network were mainly due to breaks or leaks in correspon-

Fig. 6 Damage to gas pipes following the L'Aquila earthquake: **a** gas welded joint of a LP steel pipe pulled apart in Paganica (AQ); **b** gas pipe connected to a damaged bridge in Onna (AQ) replaced with a stand-alone pipe (photos courtesy of *ENEL Rete Gas*)

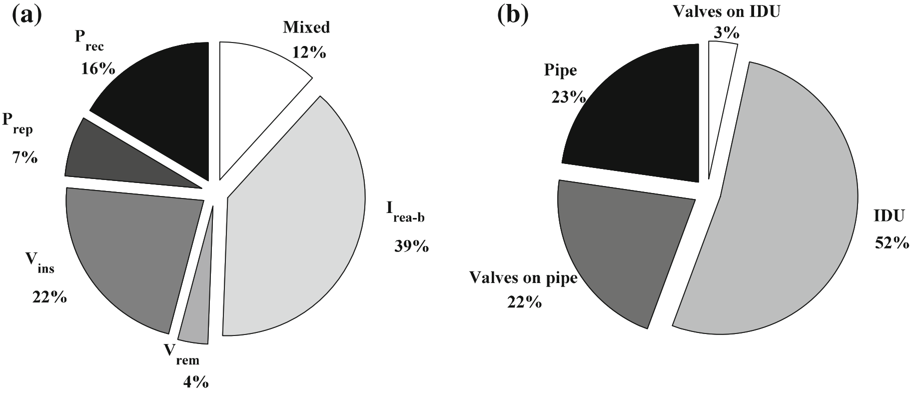

Fig. 7 Repair operations addressing damage to buried components for the portion of the gas network located in Zone 1: **a** number of repairs for six intervention categories; **b** number of repairs for different buried components

dence of the gas welded joints (Fig. 6a). One of the pipe of the MP distribution network, connected to a damaged bridge in Onna, was replaced with a new stand-alone supported on either side of the crossing by two new concrete abutments. The pipe was rigidly connected to the abutment with no flexible connection between the pipe and the bridge foundations (Tang and Crooper 2009). A flexible join for the river crossing pipe would have been preferable solution (Fig. 6b).

It has to be mentioned, however, that the damage distribution to different buried components reported in Fig. 5a might be biased by the mentioned inaccuracy and incompleteness issues affecting the maintenance/repair database. To enhance the understanding of the proportion of damage suffered by different buried components, reference has been made to a reduced database, composed of 85 repair records, corresponding to the Zone 1, the only area where the maintenance/repair database resulted completed and reliable. It is worth noting that any data belonging to the network included in the *crater*, located within the central area, was excluded from the analysis. In fact, the complete replacement of the gas network for this part of L'Aquila downtown was planned by the network operator.

Figure 7a shows the percentages for the six macro categories associated with the repair operations to buried components (Table 1, excluding first row) for the portion of gas network

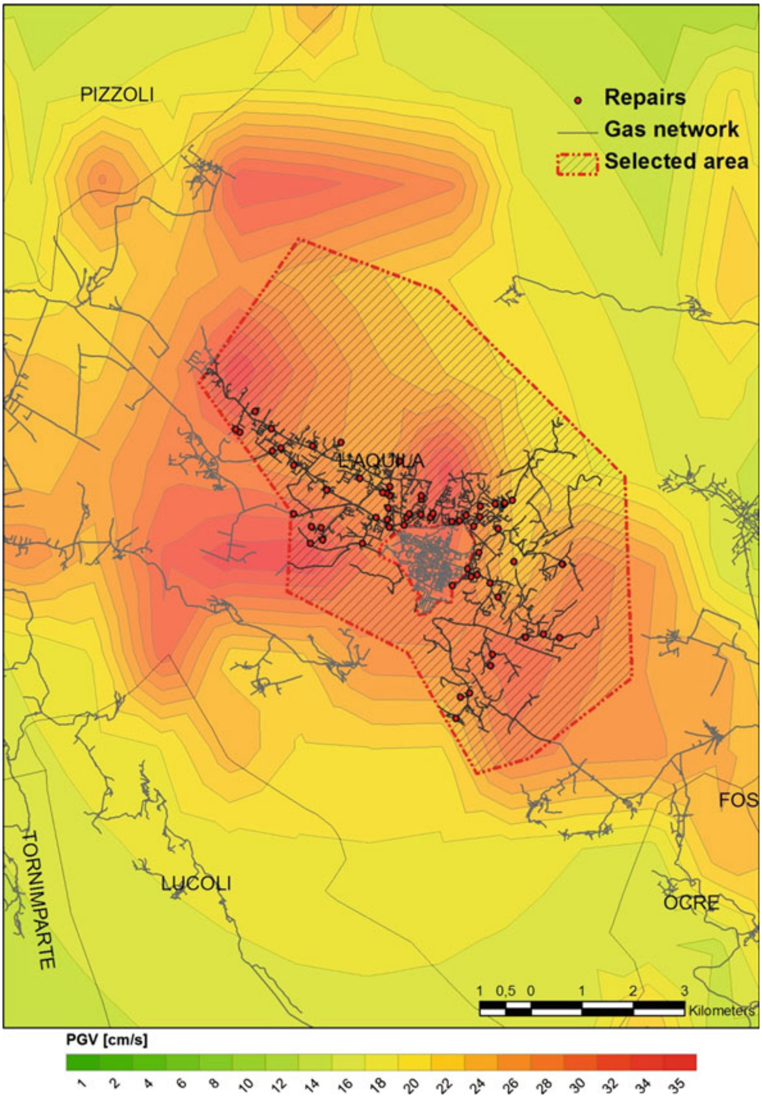

Fig. 8 Map of PGV (cm/s) relative to L'Aquila earthquake (superimposed to the gas network and repair data for the selected area)

located within the selected area (Fig. 8). Figure 7b groups the same percentages for the four buried system components considered in this analysis, namely: pipe; service laterals (IDU system); valves along pipes; and valves along IDU systems.

5 Pipeline repair-rate versus recorded transient ground motion

Earthquake damage to buried pipelines can be attributed to transient ground deformation (TGD), caused by ground shaking, to PGD, or both (Toprak and Taskin 2007).

Wave passage effects cover a wide geographic area and affect pipe in all types of soil. Strains are induced in buried components because of their restraint within the soil mass. Ground failure effects are instead permanent soil movements caused by such phenomena as liquefaction, landslides and localized tectonic uplifts. These tend to be fairly localized in a geographic area and potential zones can be identified a priori by the specific geotechnical conditions. Ground failure can be damaging to pipes because potentially large and localized deformations can develop as soil masses deform and move relative to each other.

The earthquake impact on the pipeline is commonly measured in terms of average repair rate, R_R, evaluated as the number of pipeline repairs in an area divided by the length of the pipelines in the same area. Empirical data on pipeline failures from past earthquakes have been processed to define repair rate empirical estimations, Eq. (1), able to predict number of repairs per unit length as a function of a ground motion measure (or IM), such as PGV, PGA and/or PGD (ALA 2001a).

$$R_R = K \cdot \alpha \cdot \mathrm{IM}^{\beta} \tag{1}$$

In Eq. (1) K is a corrective factor accounting for different characteristics that might affect the seismic vulnerability of pipelines (e.g., pipe material, pipe diameter or pipe connections) while α and β are regression coefficients. Table 5 provides some examples of R_R-PGV pipelines fragility relations, which will be used to benchmark with L'Aquila data. Indeed, this study derives R_R values for a selected area of the gas network, as a function of the transient ground motion of L'Aquila earthquake, expressed in terms of PGV. In fact, among various possible IMs, PGV has been identified as the one having a more direct physical interpretation. It is correlated with the ground strain that can be transferred to the pipeline (O'Rourke et al. 1998).

Observed ground failure deformations (Vittori et al. 2011; Monaco et al. 2009) were also analyzed to understand their possible influence on the repair rate. Comparing earthquake-induced ground failure locations with the repair data points, it was concluded that in the analyzed area, namely Zone 1 (Fig. 8), none of the repairs was interested by ground deformations.

With respect to transient ground deformation, a continuous map of the ground motion, for the whole extension of the analysed gas network, was developed by INGV (*Italian National Institute of Geophysics and Volcanology*) for the mainshock and made available at http://cnt.rm.ingv.it/earthquakes_map.html. The map was derived from the records available from RAN strong-motion network, using *Shakemap*™ software.

To develop the map, the observed ground motions were first converted into rock-site conditions to obtain a rock-site grid and then amplification factors were applied to the rock-site estimates using values of near surface shear velocities, estimated using a simplified geology classification (Michelini et al. 2008). Therefore the accuracy of the PGV values is strictly related to the site correction procedure implemented in the software. Figure 8 shows the resulting PGV map, contoured for the maximum horizontal velocity (cm/s) at each station, with contour intervals of 2 cm/s.

In order to evaluate R_R for the L'Aquila gas network, as a function of the recorded PGV from the mainshock, the digitized map of the network and linked repair database was overlaid and compared with the interpolated map just mentioned.

It is to recall that, only the data belonging to Zone 1 have been considered and processed for deriving the R_R-PGV points, in order to avoid any issue with data incompleteness and any consequent underestimation of the resulting repair rate.

Table 3 Repair rate data evaluated for buried components with or without discontinuities

PGV (cm/s) (contour value)	Length (km)	Repair rate		
		R_R Pipes	R_R In-line valves	R_R Pipes and valves
22	6.42	0.16	0.00	0.16
24	8.97	0.00	0.11	0.11
26	17.04	0.12	0.23	0.35
28	41.09	0.12	0.15	0.27
30	51.18	0.14	0.06	0.20
32	21.71	0.05	0.18	0.23
34	13.17	0.08	0.08	0.15

5.1 Pipeline repair rates

This section focuses on the R_R analysis for in-line components (e.g., pipe and valves), aiming at investigating the relative seismic vulnerability of different pipe materials and diameters. Unfortunately GIS maps for utility-owned service laterals (i.e., pipes and other components connecting the gas mains to the utility costumer meters) were not available to *ENEL Rete Gas*. Therefore, repairs to IDU systems were excluded from the repair rates processing. As a consequence, the final dataset used for the repair rate evaluation of L'Aquila gas system was composed of 36 records, targeting repairs to pipe and valves in the Zone 1 of the network (Fig. 8). Because of the possibility to distinguish among repair to pipe and valves, and to the availability of geometrical and constructive features for these components, it has been possible to analyze R_R with respect to some of these characteristics, in particular: (1) the presence of discontinuities (e.g., in-line valves) on the pipes; (2) joint type and pipe material.

First, R_R was evaluated distinguishing buried components with or without the presence of discontinuities. The presence of in-line valves, service connections, appurtenances has been identified, in fact, as one of the factors increasing earthquake-induced damage for buried pipe, by promoting the creation of anchor points for stress concentration (ALA 2001a). Table 3 shows repair rates evaluated, respectively for pipes, valves, and the two combined. Discontinuities and appurtenances counted for a significant proportion in R_R for the pipe, almost for all the PGV values.

Second, repair rates were evaluated with respect to geometrical and constructive features of the pipes. In fact, material, joint type and pipe diameter are considered the most important factors that may influence the seismic vulnerability of buried pipeline (Tromans 2004).

Network data and repairs were processed distinguishing between: steel pipes with gas welded joints (GWJ)[3] and HDPE pipes with fusion joints (FJ). It is worth to note that the diameter ranges for all the pipes in L'Aquila gas network fall in the *small diameter* category (i.e., from 10 to 30 cm) as defined by ALA (2001a). Therefore, repair rates were not put as a function of diameter.

For each PGV class identified in the ground motion map, the number of repairs was divided by pipe length located in the given PGV class. The obtained repairs rates are shown in Table 4.

Regarding HDPE, no repair points occurred in the selected area. This seems to be in-line with the recognized good properties (e.g., ruggedness) of HDPE material and its earthquake performance observed after the Canterbury earthquake sequence (O'Rourke et al. 2012).

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[3] According to diameter and construction year characterizing pipelines in the study area.

Table 4 Repair rate data evaluated for steel pipes with GWJ and HDPE pipes with FJ

PGV (cm/s) (contour value)	Length (km)		Repair rate	
	Steel-GWJ	HDPE-FJ	Steel-GWJ	HDPE-FJ
22	5.49	0.94	0.18	0.00
24	8.58	0.39	0.12	0.00
26	15.27	1.77	0.39	0.00
28	38.26	2.82	0.29	0.00
30	46.71	4.47	0.21	0.00
32	17.89	3.82	0.28	0.00
34	11.24	1.94	0.18	0.00

5.2 Benchmark with international studies and data from past earthquakes

A concise summary of empirical fragility curves for buried pipes as a function of ground shaking can be found in Tromans (2004) including the dataset used to derive and or validate them and including the range of applicability (in terms of pipe, joint typologies and range of ground shaking) for each relation. In Figs. 9 and 10 the resulting R_R-PGV points (Tables 3 and 4) are compared with buried pipeline fragility relations considered suitable (in terms of pipe material and diameter) for the L'Aquila gas network, reported in Table 5.[4]

In this analysis PGV values have been identified as the maximum horizontal velocity (cm/s); although some fragility curves consider the geometrical mean horizontal component for PGV, no conversion has been applied (see Beyer and Bommer 2006).

Figure 9 shows that the repair rates trend estimated for L'Aquila seems somewhat underestimated by existing fragility curves; however, it must be highlighted that the considered fragilities relations have been obtained combining data from different kinds of pipes (e.g., ALA 2001b). Moreover, the different sources of uncertainties related to PGV values and repairs may have influenced the results obtained. The estimates of repair rates were in fact based on *Shakemap*$^{\text{TM}}$ to retrieve local ground motion intensity; these are large-scale emergency management tools affected by large uncertainty. Finally, repair reports analyzed for the damage assessment are not post-earthquake standardized forms, and the processing could be affected by missing data or inaccuracy of the maintenance technicians.

Regarding the comparison as a function of pipe material, Fig. 10, the repair rate trend observed in L'Aquila is larger with respect to existing fragility curves. A reason may be that selected fragility relationships were derived for arc-welded joints steel pipes. L'Aquila network, in the selected area, is instead characterized by gas welded steel pipes (for which fragilities are unavailable in literature) that, according to Ballantyne (1995), are more vulnerable to earthquakes with respect to arc-welded joint. Moreover, also in this case, the different sources of uncertainties related to PGV values and repairs may have influenced the results obtained.

6 Impact of the earthquake on the gas network performance

6.1 Emergency management of the gas network

The priority identified for the management of the gas network, in the first hours following the earthquake, was the securing of the network in order to avoid explosions, gas leaks and

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[4] Fragility relations reported in Table 4 were converted from Tromans (2004): in km (R_R) and cm/s (PGV).

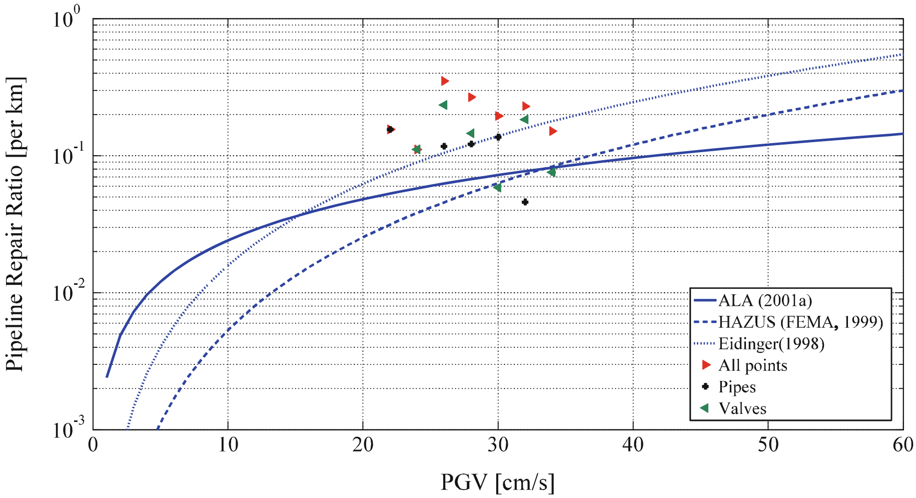

Fig. 9 R_R-PGV points compared with some existing fragility curves

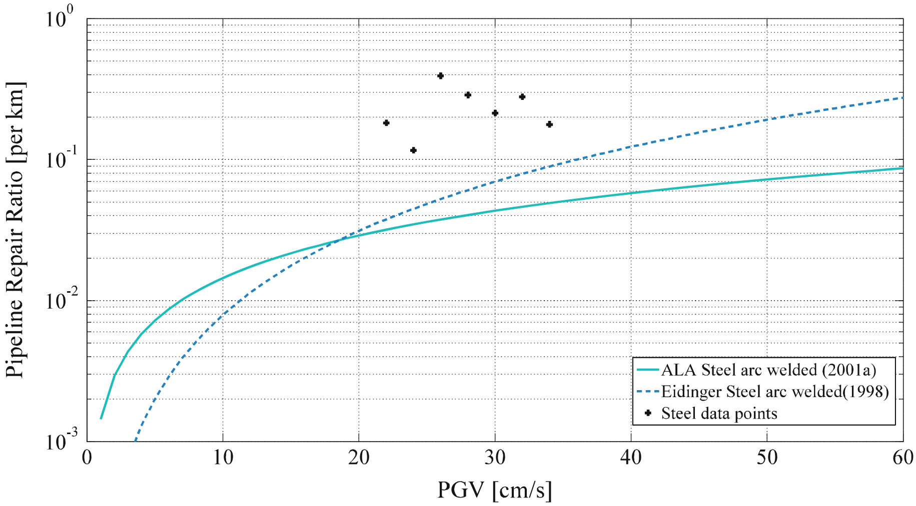

Fig. 10 R_R-PGV with respect to pipe material

Table 5 R_R-PGV pipelines fragility relations considered for L'Aquila gas network

Authors	Fragility relation	Notes
ALA (2001a)	$R_R = K_{1ALA} \cdot 0.002416 \cdot PGV$	Backbone curve ($K_{1ALA} = 1$)[a]
		Steel arc welded curve ($K_{1ALA} = 0.6$)
HAZUS (FEMA 1999)	$R_R = 0.00003 \cdot PGV^{2.25}$	Ductile pipes curve
Eidinger (1998)	$R_R = K_1 \cdot 0.0001658 \cdot PGV^{1.98}$	Best-fit curve ($K_1 = 1$)
		Steel arc welded curve ($K_1 = 0.5$)

[a] Backbone fragility functions represent the average performance of all kinds of pipes in earthquakes. These functions can be used when there is no knowledge of the pipe materials, joint type, diameter, etc

fires, and to secure the safety of emergency vehicles and teams assisting during the initial rescue phase and into the recovery phase. To this aim, the entire network was shut off via the closure of the three operating M/R stations (Dolce et al. 2010). The subsequent closure of the 300 RGs ensured the full securing of the network in less than two hours after the earthquake. Furthermore, in the days following the event, all the gas valves external to each residential property were closed.

6.2 Service restoration and observed resilience

The process to recovery the gas network delivery started few days after the earthquake. The reactivation of the shut-off gas network required the following consequential operations: (1) check of the gas flow in the MP and LP networks; (2) check of each external valve pertinent to each residential building previously closed; (3) replacement of gas-meters in each single residential building.

Operation (1), namely the gas-flow check, was deployed in four steps: (i) seal verification; (ii) nitrogen check; (iii) repair of damaged pipes and/or valves; (iv) reopening of the flow. In the seal verification phase (i), the detection of broken pipes and/or the possible joint slip-off was from node to node, and further segmenting the network when necessary (Dolce et al. 2010). The material and equipment needed for the repairs of damaged pipes and/or valves (iii) was available from the integrated logistics system used by *ENEL Rete Gas*.

To more effectively manage and prioritise the repair activities, during the recovery phase the four different zones discussed in Sect. 4 were identified. In Z1, including L'Aquila downtown, a large number of the collapsed and severely damaged buildings was concentrated. In Z2 a moderate/slight impact on the built environment was observed. Z3, corresponds to suburbs where a large percentage of the buildings resulted collapsed or severely damaged. Z4, includes municipalities less affected by the earthquake.

The less affected areas, (i.e., Z2 and Z4) were the first targeted for the recovery activities. This prioritization strategy ensured in these areas the restoration of the network functionality for 50 % of the end-users, 6 days after the earthquake event.

The reinstatement of the gas service delivery, following the reactivation operations after the gas network shut-off and the required repair/replacements activities, were closely monitored by *ENEL Rete Gas*, in collaboration with the Lifeline Function of the L'Aquila emergency operation center (operated by the *Italian Civil Protection*). Data are summarized in Fig. 11. In particular, the red line in Fig. 11 shows the percentage of the customers that could have been potentially reconnected to the network, following the repair activities as a function of time. However, only a relatively minor fraction of the end-users was actually reconnected (Fig. 11, blue line). The gas service reactivation required, as a prerequisite, that the end-user' building resulted safe following post-earthquake inspections.

From the figure it also emerges that data on potential reconnection and end-user activation was available only since the 6 of May. In fact, from 6 April 2009 to 6 May 2009, when information was not available, a hypothetical trend for the network performance has been assumed (dashed lines in Fig. 11) considering that, immediately after the earthquake, the entire network was shut off.

The restoration curves in Fig. 11, can lead to some preliminary considerations on the L'Aquila gas system resilience to the 6 April 2009 earthquake. For an infrastructural system, a measure of resilience, R, may be related to the area pertaining to the restoration curve in Fig. 11, from the time of shock to that at which the pre-event level of performance is taken back.

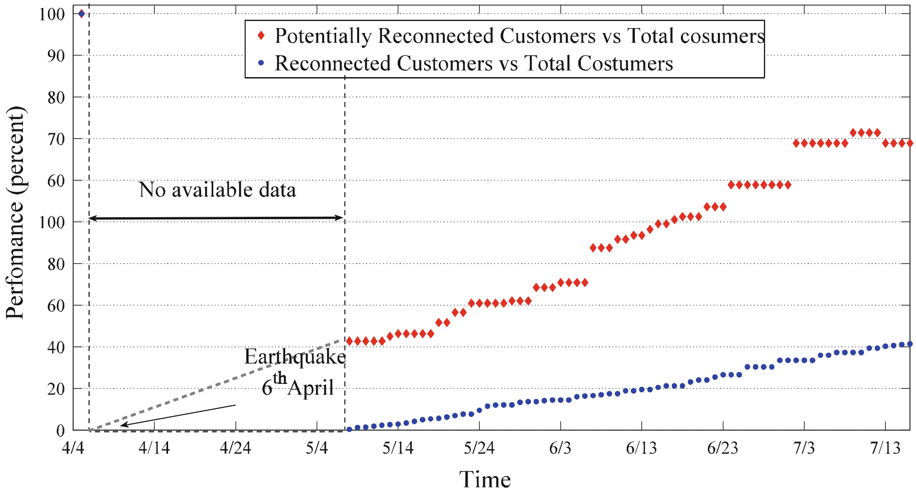

Fig. 11 Observed resilience-related curve for the L'Aquila gas network following the 2009 event

Some considerations can be advanced with respects to the four main attributes of resilience that Bruneau et al. (2003) identify. The system showed a fair level of *Robustness* (defined as the ability of systems, system elements, and other units of analysis to withstand disaster forces without significant degradation or loss of performance): limited damages were observed to above-ground components and were required to buried pipes and elements (85 repairs over 160 km of network for the Zone 1).[5] *Rapidity* (defined by as the capacity to restore functionality in a timely way, containing losses and avoiding disruptions) in restoring costumer connectivity was fair, considering that, following a complete system shut-off, the remediation and testing of more than 70 % of the gas network occurred in three months' time after the earthquake, leading to the provision of the gas supply for all the end-users with a safe home. *Resourcefulness* (defined as the ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological, and human resources) played an important role in the rapidity and effectiveness of restoration operations; particularly effective, in this sense, were the adopted prioritization procedures for the repair activities and the availability of both human and physical resources at national level and the company ability to effectively manage the same resources. Finally, *Redundancy* (the extent to which systems, system elements, or other units are substitutable, that is, capable of satisfying functional requirements, if significant degradation or loss of functionality occurs), although not an attribute of the L'Aquila gas network, was fairly used in the repair process where extension of the pipe network were promptly realized to by-pass of inaccessible zones in cordoned areas of the city center (as part of *E1E.activities*).

7 Conclusions

An investigation of the impact of L'Aquila 2009 earthquake (M_w 6.3) on the performance of the local medium- and low-pressure gas distribution networks, was presented. The motivation is related to the relatively poor availability of damage and functionality reports for gas distribution systems, especially in Europe.

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[5] As mentioned before only for the Zone 1 the dataset is complete.

The analyses included post-earthquake repair-maintenance activities, and a database was created from the joint processing of the technical and addendum economic reports available from *ENEL Rete Gas*, the network's operator. The processed data were collected in a GIS database linked to the digitized maps of the network, together with geometrical and constructive features of the network components. This extended database, including 431 records covering local all the medium- and low-pressure network within L'Aquila, was affected by some incompleteness in the first month period following the earthquake, namely April 2009 and resulted incomplete for some geographical areas. Data resulted complete for a localized area corresponding to L'Aquila downtown. Nevertheless, its analysis allowed for the definition of average time and cost of different inspection and repair operations in the post-event recovery process.

The database also provided a preliminary understanding of the seismic response of both buried and above-ground components of the system. With regard to the latter, the performance of the metering and reduction stations (M/R Stations) and of the Reduction Groups (RGs) was fair overall. The only repair activities that interested the M/R station were related to the repair of their buried input/output system, and or introduction of shut-down systems. The repair/replacement of RGs was mainly due to the problems suffering by building hosting and/or adjacent to the same stations. With regard to the former components, the repair activities addressed their damages in the following proportions: pipelines (37 %), valves (18 %), demand nodes (32 %), mixed (13 %). The largest proportion of repairs to pipes (72 %) interested LP distribution network, which is made of steel pipes with welded joints. Breaks or leaks in correspondence of the same joints were a common issue.

For the area where the repair/maintenance database resulted complete, average repair rate (number of repairs per km) for LP and MP pipes were derived (on a few data) as a function of the transient ground motion, expressed in terms of peak ground velocity. The impact of permanent ground deformation in the selected area, was found to be limited.

Main findings from the estimated repair rate analysis included the following:

- the presence of discontinuities and appurtenances counted for a significant proportion;
- for HDPE pipes, conversely with respect to steel pipes, no damages were observed in the selected area.

The observed repair rates were compared to existing fragility functions. The apparent higher, with respect to predictive models, seismic vulnerability of steel pipes in L'Aquila can be possible related to their welded joints. Moreover, the estimates of repair rates were based on *Shakemap*$^{\text{TM}}$ to retrieve local ground motion intensity; these are large-scale emergency management tools affected by large uncertainty; therefore, their use for point estimates has to be considered with due caution. Finally, it has to be recalled that damages were not directly analyzed, while in fact inferred from repair reports.

The functionality reinstatement process of the L'Aquila gas system showed a fair level of resilience, considering that, following the complete system shut-off of the gas system (executed in the immediate aftermath of the earthquake for safety reasons), the fault identification, damage remediation, safety testing for both the pipes and IDU and substitutions of the gas meter for each single user for more than 70 % of the gas network was completed in three months. Factors that contributed to this fair performance, included the prompt availability of both physical and human resources and a thoughtful prioritization of the recovery operations. However, it is worth highlighting that despite the functionality was restored for 70 % of the network, only 30 % of the costumers were actually reconnected to the systems. A safe home (green-tag) was in fact the prerequisite for the actual reconnection. The analysis of the functionality restatement process for the L'Aquila gas system has made evident that:

(1) numerous operations further than the activities for repairing the physical damage are required to reinstate the functionality of the gas service; (2) the feasibility of reinstating costumer connectivity following the service functionality restoration is influenced by exogenous factor (e.g., building conditions).

It is finally worth highlighting some issues which affected this study and that, if addressed, should improve post-event understanding of gas networks seismic performance. In particular, standardized post-earthquake damage assessment should be developed for lifelines, in an effort similar to what is currently done for buildings. For example, the availability of geo-localized damage descriptions would have allowed, in this study, to deepen the understanding of seismic vulnerability of different components and damage mechanisms with, in turn, the possibility to enhance predictive seismic risk assessment of this kind of systems.

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