# Addressing ground-shaking-induced damage of the gas distribution network in the 2009 L`Aquila earthquake

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## ABSTRACT

This paper describes the assessment of the damage of the local gas network in the 2009 L'Aquila earthquake (Mw 6.3). The analysis focuses on the main components of the low and medium distribution networks, namely pipes, valves, and demand nodes. The processing of the technical reports from Enel Rete GAS (the unique gas network operator in the affected region), describing the repairs and replacements activities following L'Aquila earthquake is presented, and the resulting damage scenario is discussed. In particular, the density of repairs activities have been overlaid to the ground motion in the affected area, described in terms of peak ground velocity. Finally, the repair ratios (number of repairs per km) for the pipelines were compared with repair ratio fragility functions available in literature.

## 1 INTRODUCTION

Recent disastrous seismic events have widely documented the role of lifeline networks in supporting the emergency management and in facilitating the response and recovery phases (*resilience*) following an earthquake, thus rising the interest of both the scientific community and the stakeholders in identifying proper risk management strategies for this kind of systems (Pitilakis et al. 2006).

Building on the results from past international research projects and existing tools for the vulnerability assessment and seismic risk analysis of lifelines systems the SYNER-G "Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain", has been funded by the European Commission (2009-2012) with the aim to address criticalities.

This paper, developed as part of the SYNER-G project, analyses the impact of the 6th April 2009 L`Aquila earthquake, in Italy, on the gas network with particular focus on the damage induced by the transient ground deformation on the pipeline distribution network. In fact, in the event of an earthquake, buried pipeline can be subjected to both transient ground deformation caused by the passage of seismic waves (ground shaking) which is felt over a wide geographical area, and permanent ground deformation (PGD) caused by surface faulting, liquefaction, landslides which determine localised ground failure.

Exception made for surface faulting phenomena, limited PGD were, in fact, observed following the L`Aquila earthquake. Therefore, the damage to the pipelines, has been correlated with the experienced ground shaking.

The first part of the paper presents relevant information on the 6th April 2009 L`Aquila earthquake and the assessment of the peak ground velocity (PGV), virtually experienced by the gas network.

The second part provides a description of the gas networks in the affected region and of the operations undertaken for securing of the system following the earthquake and for its restarting during the recovery phase.

Finally, data processing and analysis for assessing the physical impact of the earthquake on the pipelines of the distribution network is presented comparing the results with existing predictive relationships of repair ratios per km.

## 2 THE L'AQUILA EARTHQUAKE

On April 6th 2009, 01:32:40 UTC, a moment magnitude (Mw) 6.3 earthquake struck the Abruzzo region, in central Italy. The earthquake occurred at about 10 km depth along a NW-SW normal fault with SW dip, located below the city of L'Aquila (INGV 2009).

Considerable damage to structures and infrastructures was detected over a broad area of approximately 600 square kilometres, including the city of L'Aquila and several villages in the Aterno River valley.

After the main shock, 3 aftershocks with moment magnitude Mw > 5 were recorded (6th April, Mw 5.8; 7th April, Mw 5.3; 9th April, Mw 5.1), and 31 with a range of moment magnitude from Mw 3.5 and Mw 5.

The main shock and its aftershocks were recorded by several digital stations of the Italian strong-motion network (Rete Accelerometrica Nazionale, RAN; Zambonelli et al. 2011), owned and maintained by the Italian Department of Civil Protection.

Horizontal peak ground accelerations (PGA) recorded in the near-source region ranged from 0.33g to 0.65g, the latter representing one of the highest values measured in Italy (Chioccarelli et al. 2009).

Regarding geological effects induced by the earthquake, evidence of coesismic surface faulting was found in correspondence of the Paganica fault (Blumetti *et al*. 2009). A set of well aligned ground ruptures was found (traced for a length of about 2.6 km), reaching in some sites vertical offsets of 7-8 cm. Moreover, numerous rock falls occurred especially near the village of Fossa and within the Gran Sasso mountain. Evidence of liquefaction were found in a quarry near Bazzano (industrial area) and in Vittorino (near Sulmona), relatively far from the epicentre.

### 2.1 *Peak Ground Velocity map from L`Aquila earthquake ground motion records*

A continuous map of the ground motion, for all the extension of the analysed gas network, has been derived from the available records, using *ShakeMap*(TM) (Wald et al. 2006)

The ShakeMap processing system has provided PGV values as a grid of points with associated intensity values of the shaking parameter. Figure 1 shows the resulting PGV values, contoured for the maximum horizontal velocity (cm/sec) at each station, with contour intervals of 2 cm/sec.

Those values have been obtained interpolating recorded values and estimated amplitudes obtained considering available information about local geology.

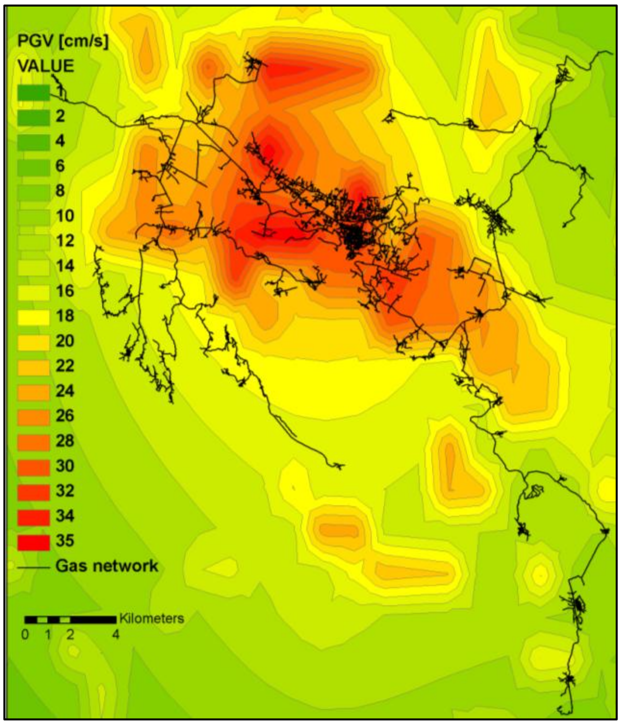

Figure 1. Map of PGV (cm/s) contours relative to L'Aquila earthquake (from http://shakemap.rm.ingv.it) overlapped to the L'Aquila gas network.

## 3 THE GAS NETWORK IN L`AQUILA AND ITS MANAGEMENT DURING THE POST-EVENT PHASE

Principal components of a nationwide gas supply system include: (1) high-pressure transmission lines; (2) Metering/Pressure reduction stations (M/R stations); (3) medium-pressure distribution networks; (4) Reduction Groups; (5) low-pressure distribution networks; (6) demand nodes; (7) gas meters.

In Italy the high-pressure transmission lines (operated at a national level by SNAM http://www.snamretegas.it/) are made of welded–steel pipes, with an internal diameter of 103.9 mm and a thickness of 5 mm. The connection of the L'Aquila distribution medium-pressure network (MP = 64bar) to the national high-pressure transmission lines is operated via three Metering/Pressure Reduction Stations, M/R Stations (Re.Mi. "Regolazione e Misura" stations, in Italian).

The three M/R stations (Re.Mi. stations) of the L`Aquila distribution system are cased in one-story reinforced concrete structures with steel roofs (Figure 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.

In L'Aquila region the gas is distributed via a 621 km pipeline network (Figure 1): 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 – 0.035 bar).

The pipelines of the medium and low pressure distribution networks are either made of steel or HDPE (*High Density Polyethylene*). HDPE pipes have nominal diameters ranging from 32 to 400 mm, whereas diameter of steel pipes is usually between 25 and 300 mm. Different types of in-line valves are found along the pipeline network (mainly gate valves, butterfly valves, check valves, ball valves).

Figure 2. M/R Metering/Pressure reduction station in Onna (L`Aquila, Italy)

The transformation of the medium distribution pressure into the low distribution pressure (LP) is operated via 300 Reduction Groups (GR). Generally along the low pressure network (in some cases also along medium distribution pressure network), there are several demand nodes (IDU, "Impianto di Derivazione Utenza" in Italian) consisting of buried and not buried pipes and accessory elements to supply natural gas to utilities. Moreover, depending on the type of final client of the network and whether there is an IDU system, there are three types of GR: (a) GRM, Reduction Groups and Measure along medium distribution pressure (MP) network and direct connected to large users (e.g., industrial facilities); (b) GRU, Reduction Groups smaller than GRM for medium pressure Users connected to a medium pressure IDU system; (c) GRF, Final Reduction Group connected to low pressure network.

It is worth noting that all the components contained in both the L'Aquila M/R stations and Reduction Groups are unrestrained, and therefore especially seismically vulnerable.

The 300 Reduction Groups, that in the L`Aquila gas distribution allow for the transformation of the medium distribution pressure into the low distribution pressure are either buried, sheltered in a metallic kiosk or housed within/close to a building (Figure 3).

Figure 3. GR housed in a masonry kiosk closed to building and damaged following the 6th April 2009 earthquake.

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### 3.1 *Emergency management of the gas network following the L'Aquila earthquake*

The first priority identified for the management of the gas network, in the first phase of the emergency immediately after the L`Aquila earthquake, was the timely securing of the network in order to avoid explosions, gas leaks and fires and to allow emergency vehicles and Search and Rescue USAR teams to act in the safest possible way. To ensure this priority, the entire network managed by ENEL Rete Gas S.p.A. (http://www.enel.it/it-IT/reti/enel_rete_gas/) in the affected area was shut off via the closure of the three operating M/R stations (Dolce et al. 2010). Thanks to this decision, it was possible to timely and significantly reduce the gas pressure and to avoid the occurrence of secondary effects of the earthquake. The subsequent closure of the 300 GR Reduction Groups ensured the full securing of the network in less than two hours after the earthquake. In the days following the event, all the gas valves external to each residential building were closed as well.

The process to recovery the gas network started few days after the earthquake. To more effectively manage and prioritise the repair activities, during the recovery phase, four different areas, in the region served by the gas network, were identified, namely: Central Area (Z1); West Area (Z2), East Area (Z3), Sud-East Area (Z4).

The Central Area, Z1, included the historical centre of the city and the surrounding where a large number of the collapsed and severely damaged buildings was concentrated.

The West Area, Z2, includes the west suburbs and the municipalities of Lucoli and Tornimparte, where a moderate/slight impact on the built environment was observed. The East Area, Z3, corresponds to the east suburbs, including Onna e Paganica, where a large percentage of the buildings resulted collapsed or severely damaged. The Sud-East Area, Z4, includes municipalities less affected by the earthquake (i.e. Ocre, Rocca di Cambio and Rocca di Mezzo).

The areas Z2 and Z3 were the first ones to be targeted for the recovery activities. In these areas, six days after the earthquake event, the network was restored to allow for 50% of the end-users to be potentially reconnected. The reactivation of the shut-off gas network required: the check of the gas flow in the medium and low-pressure networks; the check of each external valve pertinent to each residential building previously closed; the substitution of each gas-meter.

The check and reactivation of low and medium pressure networks was managed in the following four steps: (1) seal verification; (2) nitrogen check; (3) repair of damaged pipes and/or valves; (4) reopening.

In the seal verification phase, the detection of broken pipes and/or the possible joint slip-off was made, acting in the first instance, from node to node, and further segmenting the network when necessary (Dolce et al. 2010).

The material and equipment needed for the repair was immediately available from the integrated logistics system used by Enel Rete Gas. The adopted strategy ensured the remediation and testing of more than 90% of the gas network in three months time after the earthquake and the provision of the gas supply for all the end-users with a safe home.

Figure 4 (red line) shows the percentage of the customers that could have been potentially reconnected to the network for all the four zones. In fact, a relative minor percentage of the end-users was reactivated to the service, (Figure 4, blue line), since the reactivation required a safe building for the supply; i.e., green tagging by the civil protection.

It is worth highlighting that data on potential reconnection and end-user activation were recorded and reported in Figure 4 starting only from 6th of May. Because data were not available for the month after the earthquake, dashed lines in Figure 4 represent an hypothetical trend of serviceability of the network considering that immediately after the earthquake the entire network in the affected area was shut off by the operator.

## 4 PHYSICAL DAMAGE ASSESSMENT FOR THE GAS SYSTEM

In order to assess the physical damage that occurred to the gas network components (described in Section 3), the technical reports from Enel Rete GAS (the only gas network operator in the affected region), describing the repair and replacement activities following L'Aquila earthquake, have been processed.

In particular, Enel Rete GAS was involved in two types of technical activities: (1) activities to recovery the system efficiency to its state before the earthquake (referred to as “Rei.activities”, recover system efficiency as a result of exceptional events); (2) reconstruction activities to improve the gas network efficiency beyond its original condition (referred to as “E1E.activities”, reconstruction of facilities for investments as a result of exceptional operations).

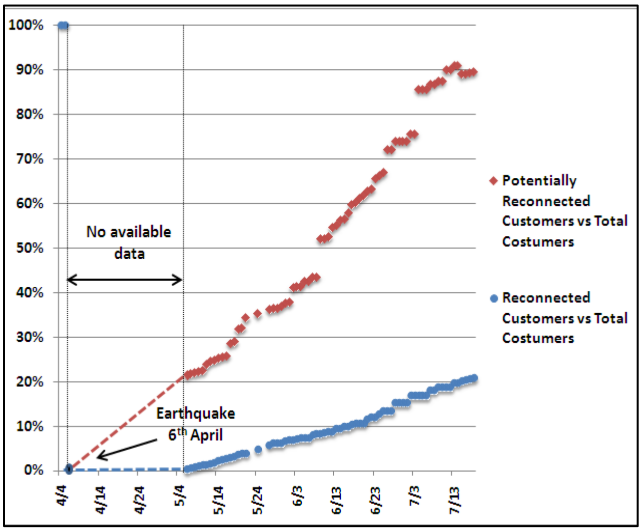

Figure 4. Percentage of the customers potentially reconnected (red line) and reconnected (blue line) to the networks for all the four zones in the months following the earthquake referring time period when data were available.

More than 500 technical reports from Enel Rete GAS related to “Rei.activities” maintenance/repair activities following the earthquake were analyzed and processed, over a period of five months (from April 2009 to August 2009). Starting from those reports different maintenance operations have been identified and geocoded.

(For April 2009, in a situation of full emergency, the technical reports describing the repair activities were not compiled; and only costs of the operations are available for that period. However, assistance and emergency support interventions were the main operations undertaken during the month of April, with a limited activity of repair/restoration of the gas network.)

For each component, operations where gathered in macro categories that are not exactly associated with a particular damage level, since the extent and description of the damage sustained by the network components were insufficiently reported in the technical reports, which scope was more related to price the repair activity rather than to report the damage. However, from processing of technical and economic reports, it has been possible to get an aggregate quantification of: (1) the damage to the network system’ components; (2) the aggregate cost associated with different types of repair operations; (3) the time required for different types of repair operations. A more detailed description of the maintenance operations was illustrated in a previous paper of the authors (Esposito et al. 2011).

Reports related to “E1E.activities” were furthermore analysed and processed until November 2009 but more than two years after the earthquake, the “E1E.activities” activities are still on-going. Further reports will be processed, extending the observation period, to get a clearer overview on these activities and on how they have impacted in the recovery process following the earthquake.

### *4.1 Processing of technical reports and results*

The processing of damage reports allowed for a classification of maintenance operations. In particular the list below illustrates the typology of maintenance operations for “Rei.activities”:

- testing operations (disconnecting and reconnecting the network);
- gas leak detection and repair;
- valve replacement;
- demand node repair.

As mentioned, the reports were compiled by field crews with the main objective to restore the gas system to service as rapidly as possible and price the repair; documenting damage was of secondary importance. As a results repair records have some inaccuracies, including omitted address indication, vague damage description and multiple repairs at a single site combined into one record. For these reasons, processing 513 technical reports and excluding incomplete ones, a dataset consisting of 431 records has been obtained. In order to get a clear idea of the damage undertaken by the gas network system, maintenance intervention types have been summarized identifying eight macro categories: three for pipelines (including operation for pipeline inspection or screening, P_scr, pipeline repair, P_rep, pipeline reconnection, P_rec), three for the valves (excavation for valve inspection, V_exc, valve insertion, V_ins, valve removal, V_rem); and two for the demand nodes, IDU (realization of buried, I_rea_b, and unburied demand node, I_rea_nb).

Figure 5 illustrates the number of interventions included in each of the considered macro categories.

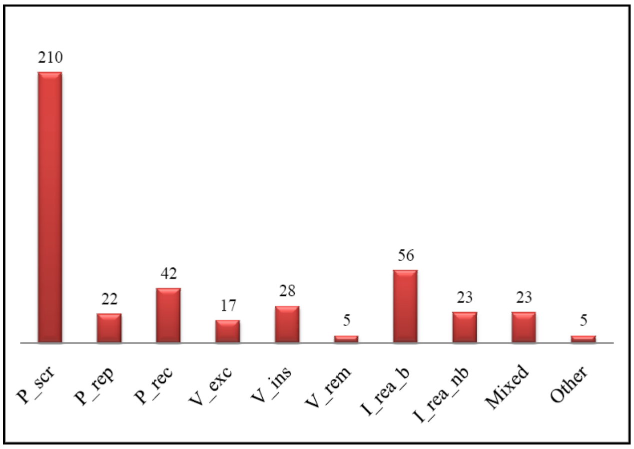

Figure 5. Number of maintenance operations.

The aim of this work is to obtain pipelines damage curves, expressed in number of repairs per km, overlaying density of repairs activities to the ground motion observed in the affected area in terms of peak ground velocity. Therefore, the database obtained was further purified of all records related to screening operations (P_scr), valve excavation (V_exc), realization of unburied nodes (I_rea_nb) and the interventions indicated as "other" that refer to transport operations or closure of excavations previously made.

At the end of this process a reduced dataset consisting of 176 maintenance records was obtained. Figure 6 illustrates the composition of the reduced database used for damage analysis.

Damage reports of maintenance operations involved pipes operating at medium (MP) and low (LP) pressure. Moreover the pipelines of the medium and low pressure distribution networks are either made of steel or HDPE.

Figure 7 illustrates this operations included in the dataset distinguished in relation to pressure level and pipe material.

### 4.2 *Density of repairs activities versus ShakeMap PGV values*

Earthquake damage to buried pipelines can be attributed to transient ground deformation (caused by ground shaking) or to permanent ground deformation, PGD (including surface faulting, liquefaction, landslides, and differential settlement from consolidation of cohesionless soil) or both (Toprak and Taskin 2006).

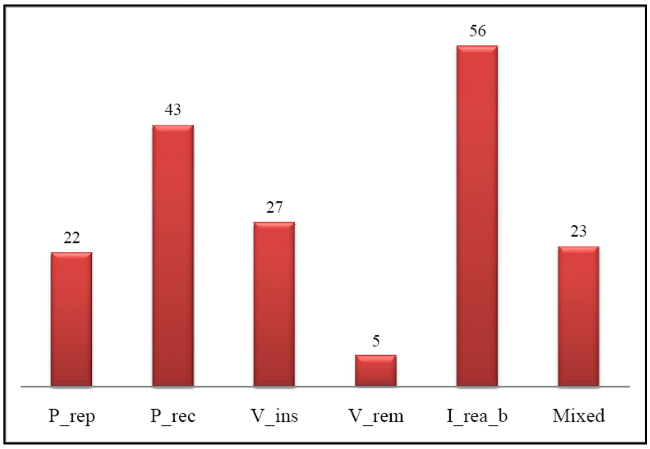

Figure 6. Reduced database of maintenance operations.

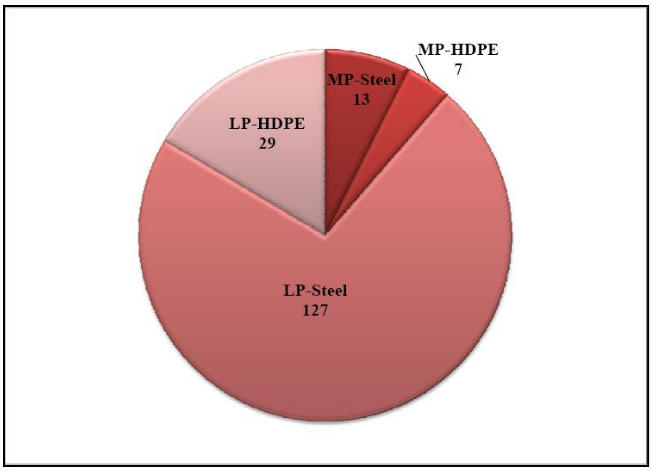

Figure 7. Dataset distinguished in relation to pressure level and pipe material.

The earthquake impact on the pipeline is commonly measured in term of the Repair Rate, $R_R$, which is 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 correlations, able to predict the number of repairs per unit length of pipe required as a function of a parameter representative of ground shaking (e.g., peak ground velocity or acceleration, PGV and PGA, respectively) or ground failure (i.e.,, PGD) (ALA 2001). A concise summary of "Repair Rate" fragility curves for buried pipes due to ground shaking can be found in Tromans (2004) including the dataset used and the range of applicability for each relation.

This study aims to derive Repair Rate values for the gas network following the L`Aquila earthquake as a function of the PGV.

Exception made for surface faulting phenomena, limited PGD were, in fact, observed following the L`Aquila earthquake (as reported in Section 2). Therefore, the damage to the pipelines, deduced from the analysed repair activities, has been correlated with the experienced ground shaking. Moreover, among the various seismic parameters used to correlate the ground motion effects to the damage suffered by buried pipeline, the peak ground velocity, PGV, has been identified as the one having a more direct physical interpretation (O'Rourke et al. 1998).

Actually, PGV is correlated with the ground strain, that can be transferred to the pipeline, depending on the slippage developed between the pipe and the surrounding soil. Therefore a good correlation between PGV and pipeline damage is expected.

In order to evaluate $R_R$ data points based on L'Aquila earthquake, both the network and the damage data have been mapped using a Geographical Information Systems (GIS). For the evaluation of pipeline $R_R$-PGV points, the PGV values from the *ShakeMap* of Figure 1 were used.

It this worth noticing that, although the repairs activities dataset covers four distinct areas, as explained in Section 3.1, only the data belonging to the Zone 1 have been considered and processed for deriving the $R_R$-PGV points. Actually, in the emergency management phase, following the earthquake, several repairs activities were carried out without completing the reporting documentation. Zone 1 was the only one where the repair data were completely reported, for the observation period considered in this analysis. Therefore, in order to avoid an underestimation of the repair ratio, data from the other Zones have been eliminated.

Moreover since the network belonging to the historical center has been completely replaced, repairs data belonging to this zone (referred to as the "Red Zone") have been, equally eliminated, from the dataset. The resulting study area, is shown in Figure 8, together with the L'Aquila gas distribution system and the repairs occurring in the analysed zone.

The repairs dataset used for repair ratio evaluation is composed of 85 data repairs distinguished in six macro categories, as illustrated in Figure 9. This dataset includes 8 repair operations on pipes operating at medium pressure and 77 on pipes operating at low pressure. As concern to material, only 11 repair operations included in the dataset were on HDPE pipes and the remaining 74 were on steel pipes.

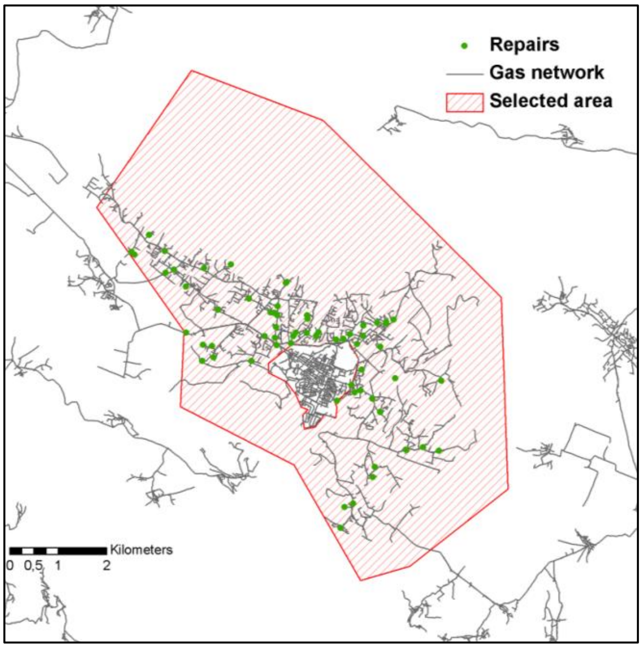

Figure 8. Selected area for the evaluation of Repair Ratio

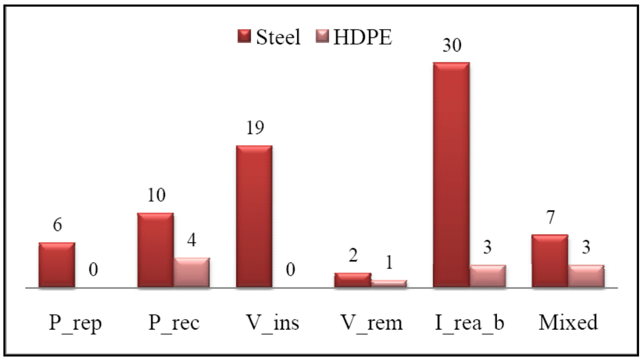

Figure 9. Dataset for repair ratio evaluation distinguished in relation to pipe material.

Using the GIS software, repair rate of the selected area have been calculated for each PGV zone combining repairs location, pipeline network and PGV contours. For each PGV zone, number of repairs and pipeline length has been calculated.

The resulting points (Figure 10) are compared with pipeline fragility relations suitable for the L'Aquila gas network reported in Table 1[1].

Note that data obtained from the analysis consider PGV as the maximum horizontal velocity (cm/sec); even if some fragility curves consider the geometrical mean horizontal component for PGV, no conversion has been applied (see Beyer and Bommer 2006, for a discussion).

Results shows that the trend is somehow comparable with existing pipeline-fragility curves; although the fragility curves seems to be

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[1] Fragility relations reported in Table 1 were converted by Tromans (2004): $R_R$ was converted from 1/feet*$10^3$ to 1/km and PGV from inch/s to cm/s.

conservative on respect to the observed damage, it must be highlighted that the scatter associated with the empirical fragility relations is quite high since those fragility curves have been obtained combining data from different kinds of pipes (e.g. ALA 2001a).

Table 1. $R_R$ - PGV pipelines fragility relations suitable for L’Aquila gas network.

| Author | Fragility relation | Notes |
|---|---|---|
| ALA (2001a) | $R_R = K_{1ALA} \cdot 0.002416 \cdot PGV$ | “backbone[2]” curve ($K_{1ALA}$=1) |
| 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) |

It is important to note that L’Aquila gas pipelines are made of steel and HDPE. HDPE is not well studied in current literature as no empirical fragility curves have been developed specifically for this material. However, The $R_R$ resulting seems to be comparable with the fragility curve derived by Eidinger (1998).

When looking at Figure 10 it is to recall that, as in some of the case studies reported in the literature, the repair rate following the L’Aquila earthquake incorporate the damage from both the ground shaking and the ground deformations, including PGD effects and surface rupture (ALA 2001b).

Unfortunately data available from L’Aquila earthquake does not make possible to derive an empirical curve because of the limited PGV range [22-34 cm/s]; anyway it could be useful to include repair data obtained in this work in a pipe damage database to develop new fragility curves.

## 5 CONCLUSIONS

This paper presents the preliminary results of the data processing activities that are on-going on the L`Aquila case study to understand the impact of the earthquake on the gas distribution system.

In particular the ground shaking induced damage to the gas distribution network following the April 6th 2009 earthquake was analysed.

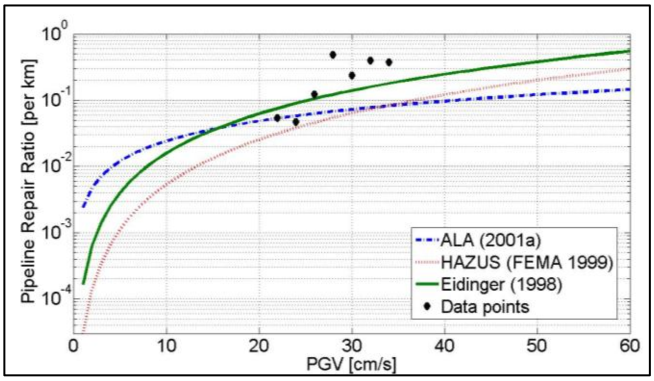

Figure 10. $R_R$-PGV points compared with some fragility curves suitable for the L’Aquila gas network

To this aim the technical reports from the repair activities following the earthquakes were processed to obtain the repair rate (number of repairs per km) as a function of the level of ground shaking experienced, expressed in terms of PGV.

In fact, while it is expected pipelines suffer damage (mostly) from ground displacements, insufficient PGD data were available for the region at the time of the study and therefore damage was correlated to PGV only (as in some of the literature studies at the basis of the existing fragility functions for networks’ components).

The selected period refers to May 2009 - August 2009 since repair activities related to the month of April were not reported technically. However, assistance and emergency support interventions were the main operations undertaken during the month of April, with a limited activity of repair/restoration of the gas network. Many repair reports from the network operator were discarded because of incomplete or unsuitable information. Moreover, although the repair dataset covers four distinct areas, only the data belonging to the Zone 1 have been considered and processed since this area was the only one where the repair data were completely reported, for the observation period considered in this analysis.

This whole set of issues resulted in a limited data available. Nevertheless, the resulting repair rates were finally compared with those ones available from the literature to assess whether these function can be applied in the assessment of gas distribution networks of similar types.

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[2] 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.

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