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Post-Earthquake Physical Damage Assessment for Gas Networks

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ABSTRACT: This paper describes the assessment of the damage occurred to the local gas network following 6th April 2009 L'Aquila earthquake. The analysis accounts for all the system components that have a critical role for the functionality of the gas network. The physical impact of the earthquake on the system components has been estimated processing the technical reports from Enel Rete GAS (the unique gas network operator in the affected region), describing the repairs and the replacements activities following L'Aquila earthquake.

1 INTRODUCTION

Recent disastrous seismic events have widely documented the crucial role of the lifelines networks in supporting the emergency management and in facilitating the response and recovery phases following an earthquake, thus rising the interest of both the scientific community and the stakeholders in identifying proper risk mitigation and risk management strategies for lifelines 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 (e.g., HAZUS, MAEviz, RISK-UE, LESSLOSS, REDARS) 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 overcome still existing criticalities and shortcomings. The SYNER-G project relies on the collaboration of fourteen research groups from highly qualified Universities and Research Institutes in Europe and the support of international Universities and stakeholders. This paper, developed as part of the SYNER-G project, focuses on the post-earthquake physical damage assessment for gas distributions networks. Gas distribution networks have shown to be prone to damage during past earthquakes, and to have the potentiality to induce significant consequences, including: the disruption of gas services with a resulting severe impact on the affected population and businesses; the triggering of fires; the pollution of waterways.

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), permanent ground deformation (EERI, 1986; O'Rourke and Trautmann, 1981; O'Rourke, 1988) and liquefaction. Empirical data on pipeline failures from past earthquakes have been processed to define empirical correlations, 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 (e.g., permanent ground deformation, PGD) (ALA, 2001). Further research is required to allow for the definition of a more systemic and holistic approach allowing for the estimation of the social and economic consequences caused the lack/reduced functionality of a damaged gas distribution network. This should include the evaluation of: the vulnerability of independent elements (e.g., pipelines); the systemic vulnerability of more complex component (e.g., metering and pressure reduction stations);.the interconnections and interdependencies between the different components of the gas network and between the gas network and the urban context. This paper describes the first stage of a study that, under the umbrella of an European Commission EC funded research project, is trying to address the aforementioned issues focusing the 6th April 2009 L`Aquila (Italy) earthquake case-study. In order to provide a framework of the analysed case-study, the second section of the paper presents a short summary of the seismological, geological and geotechnical data pertinent to the area affected by the 6th April 2009 earthquake; the third section provides a description of the gas networks in the affected region and of the operations undertaken for securing the system following the earthquake and for its restarting during the recovery phase. The processing of the technical data collected by the organization managing the gas distribution network in L`Aquila is presented in Section four and the resulting damage scenario is discussed. Some preliminary conclusions are drawn in the fifth section.

2 THE L`AQUILA EARTHQUAKE

On 6th April 2009, 01:32:40 UTC, a moment magnitude Mw 6.3 earthquake struck the Abruzzo region, in central Italy. The earthquake occurred at 9.5 km depth along a NW-SW normal fault with SW dip, located 6 Km below the city of L'Aquila (INGV, 2009). The maximum observed intensity was IX–X in the MCS scale. 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. The impact on population was devastating: 308 victims, 1600 injured, about 70,000 to 80,000 residents of L'Aquila and its neighbouring municipalities were temporarily evacuated, more than 40.000 were left homeless. This event represents the third largest earthquake (not considering the archaic case of Messina 1908) recorded by strong-motion instruments in Italy, after the 1980 Mw 6.9 Irpinia and the 1976 Mw 6.4 Friuli earthquakes (Luzi et al., 2008). After the main shock of 6th April, 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 epicentres of this sequence were located at a depth between 10 and 12 Km from the surface, exception made for the 7th (Mw=5.3) April event identified at a depth of 15 Km from the surface. The main-shock and its aftershocks were recorded by several digital stations of the Italian strong-motion network (Rete Accelerometrica Nazionale, RAN), owned and maintained by the Department of Civil Protection. Horizontal peak ground accelerations recorded in the near-fault region ranged from PGA=0.33g to PGA=0.65g, the latter representing one of the highest values measured in Italy (Ameri et al., 2009).

The distribution of damage within the affected area was irregular, creating speculation for rupture directivity effects as well as for local amplification phenomena. In the epicentral area, where the city of L'Aquila is located, an evaluation of site effects was obtained from the available strong motion recordings. In the Aterno River valley, where recordings were not available, an assessment of basin/site effects was carried out based on the survey of the variable damage distribution for villages at similar distance from the epicenter, taking into account the different vulnerability of the buildings (Monaco et al., 2009). The geological setting of the affected area is very complex: the city of L'Aquila is settled on cemented breccias having thickness of some tens of meters, overlying lacustrine sediments resting on limestones; the Aterno valley is partly filled with lacustrine deposits, overlying the limestone bedrock and topped by alluvial deposits (Monaco et al., 2009; AA.VV., 2010). No liquefaction phenomena were observed in the affected area, exception made for a negligible case of sand boils and sand volcanoes detected in the area approximately 45 km far from the epicentre (Monaco et al., 2010). Conversely, several soil deformations were identified, surveyed, measured and mapped (AA.VV., 2009).

3 THE GAS NETWORK IN L`AQUILA AND ITS MANAGEMENT DURING THE EMERGENCY 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) 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 one-story reinforced concrete buildings with steel roofs (Figure 2a) hosting internal regulators and mechanical equipment (heat exchangers, boilers and bowls) where the gas undergoes the following operations and processes (Figure 2b): 1) gas preheating; 2) gas-pressure reduction and regulation; 3) gas odorizing; 5) gas-pressure measurement.

In L'Aquila the gas is distributed via a 621 km pipeline network (Fig. 1a): 234 km of pipes 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 pipiline network (mainly gate valves, butterfly valves, check valves, ball valves).

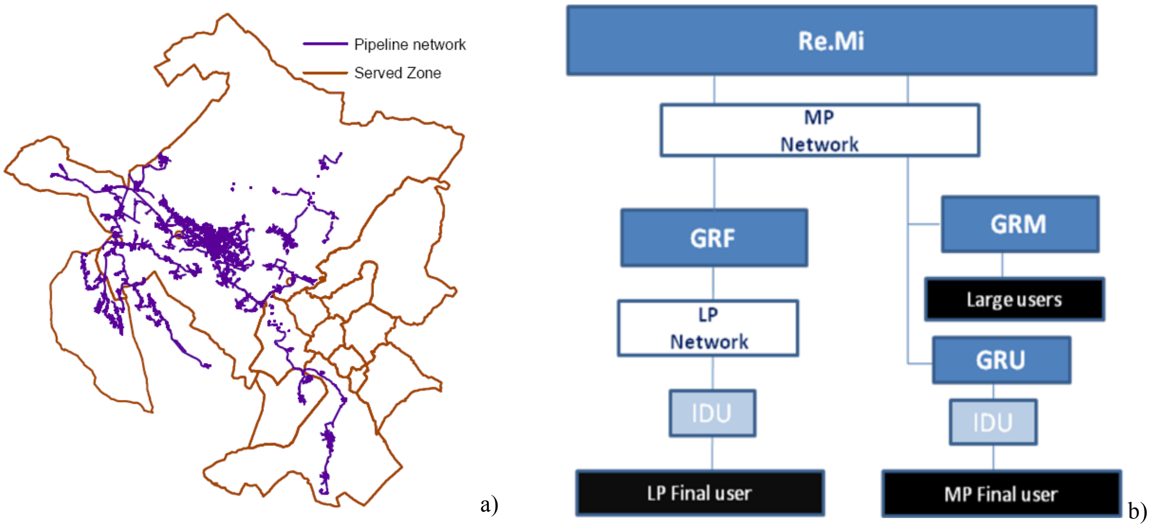


Figure 1. L`Aquila Gas distribution system: a) Map of the gas distribution network and served zone; b) gas system flow chart.

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 MP 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 as shown in Figure 1b: a) GRM, Reduction Groups and Measure along 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 seismically vulnerable.

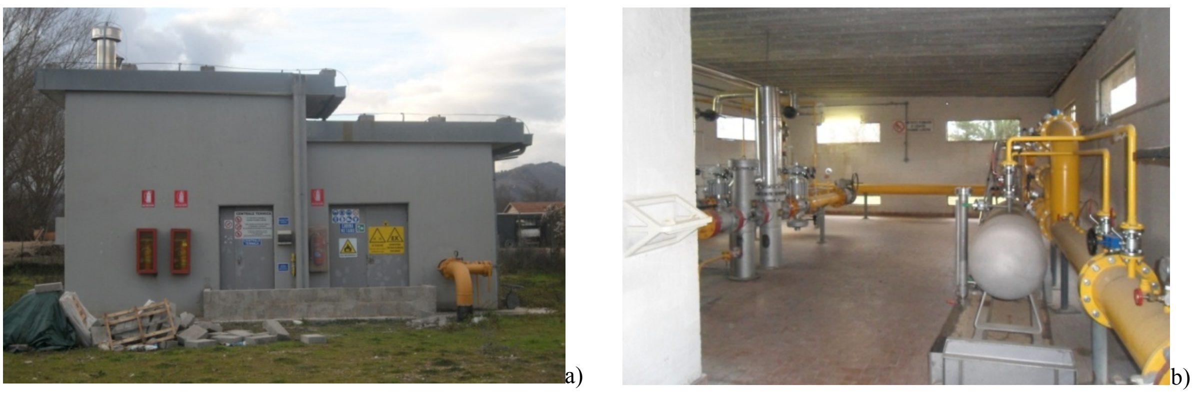
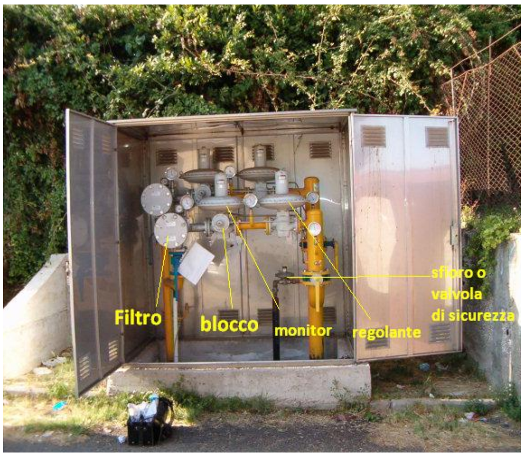


Figure 2. M/R Metering/Pressure reduction stations in Onna (L`Aquila, Italy): a) external view; b) internal view.

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 (Fig. 3a) or housed within/close to a building (Fig. 3b).



a)


b)

Figure 3. Reduction Group in L`Aquila, Italy: a) GR housed in a metallic kiosk; b) GR housed in a masonry kiosk closed to building and damaged following the 6th April 2009 earthquake.

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. 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 reactivation of the shut-off gas network, in the recovery phase following the earthquake, required gradual restoration, first of all, the gas flow into the medium pressure network, secondly the gas flow in the low pressure network, up to each external valve pertinent to each residential building previously closed. It should be highlighted that all the residential and industrial gas-meters were replaced, since Enel Rete Gas was not confident to ensure their reliability after the level of ground-motion sustained. The reactivation of the service 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.

4 POST-EARTHQUAKE PHYSICAL DAMAGE ASSESSMENT FOR THE GAS SYSTEM IN L`AQUILA

In order to assess the physical damage that occurred to the gas network components (described in Section 2), the technical reports from Enel Rete GAS (the single gas network operator in the affected region), describing the repair and replacement activities following L'Aquila earthquake, have been processed over a five month period following the earthquake (from April 2009 to August 2009).

Different maintenance operations have been identified and geocoded. For each component, those 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. 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.

Following the 6th April 2009 earthquake, 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).

4.1 *Repair/restoration activities: processing of technical reports and results*

In order to get an overview of the damage sustained by the gas system networks in L`Aquila, about 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). Aiming to also obtain information on the cost of these maintenance/repair activities, a finite number of delivery work reports (LCL reports, in Italian "Lettere Consegna Lavori") were furthermore processed. The LCL reports contain information related to the total cost of maintenance/repair operations together with a list of codes used in order to liquidate the companies that have undertaken such operations. By cross referencing the economic information contained in the LCL reports with the information described in the technical reports, a database of damage and repair costs has been built. Table 1 shows, as an example, some rows of the database.

Table 1. Some records of the damage-cost database compiled for the L`Aquila gas distribution system.

ID	NUMBER OF MAINTENANCE	DATE	START	END	COMPONENT	NOTE	ADDRESS	INTERVENTION TYPE	COST (€)
4	11085624	11/06/2009	14.00	16.00	53-1	Excavation and valve insertion	Via Pellegrini	V_ins_1	764
1	11086680	19/06/2009	7.30	11.30	52-2	Reconnection network previously disconnected	Via Aldo Moro	P_rec_1	2699
1	11086677	16/06/2009	7.30	10.00	53-1	Gas leak repair	Via Celestino V	P_rec_1	3215

An identification code (ID) has been associated to the component of the network subjected to technical intervention, as follow: ID =1, Pipeline; ID =2, M/R stations (not including, complex equipment and piping between the primary supplier delivery room, and the dielectric joint downstream of the valve outlet); ID =3, Reduction Groups GR; ID =4, Valves; ID =5 Demand Nodes. The "Number of Maintenance" code associated in the technical report to each specific repair activity has been recorded in the database to retrieve the corresponding costs from the LCL reports, as explained above. The date, the start and end times of each technical intervention has been included in the database in order to assess the duration of each operation. Furthermore a column indicated as "Note" with a short description of the technical intervention has been inserted in the database. The column "Component" describes characteristics of the system's element (e.g., 53-1 implies steel pipeline of low distribution network). Information on the "Address" of the intervention has been recorded aiming to geo-reference the technical operations. An "Intervention Type" code has been defined and included in the database to identify specific group of basic operations performed during the technical intervention (e.g., V_ins_1 is the first intervention recognized for valves and it implies an excavation for valve insertion). Finally a column summarising "Cost" (in Euro) for each operation has been added.

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”: 1) testing operations (disconnecting and reconnecting the network); 2) gas leak detection and repair; 3) valve replacement; 4) demand node repair. Unfortunately, for the month of April 2009, in a situation of full emergency, the technical reports describing the repair activities were not compiled; and only the LCL report, reporting the costs of the operations is available. 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 the following month, May 2009, both the economic resume and the technical reports about the repair activities are available, but there is not always easy to link the costs to the undertaken repair activities. Furthermore, for all the analysed period, not all the technical reports contain comprehensive information. In particular in some of the analysed reports information about the address are not provided; in some others the description of the repair intervention is insufficient or unclear. The damage and cost database (495 records) created by processing the technical and the economic reports of the Enel Rete Gas has been cleaned of the incomplete records resulting in a reduced database consisting of 413 records.

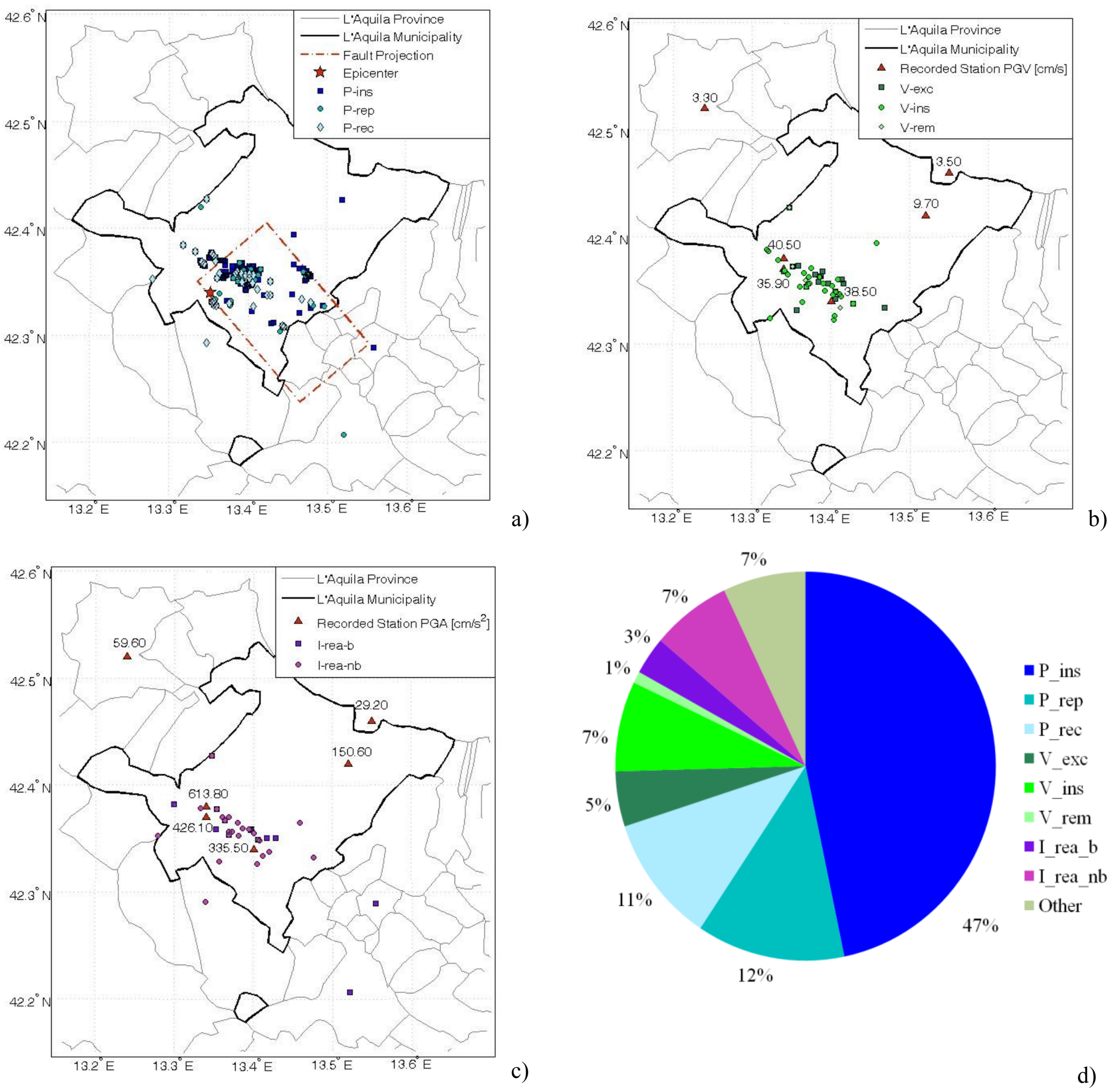


Figure 4. Spatial distribution of the macro categories for repair operations of each component and recorded values of PGV[cm/s^2]: a) pipelines, fault projection and location of the epicentre; b) valves; c) demand nodes; d) pie chart summarising the percentages of the maintenance operations.

More than 80 Interventions Types codes resulted from the processing of the “Rei.activities” reports. In order to get a clearer idea of the damage undertaken by the gas network system, these intervention types have been summarized identifying eight macro categories: three for pipelines (including operation for pipeline inspection, P_isp, pipeline repair, P_rep, pipeline reconnection, P_rec), three for the valves (excavation for valve insertion, 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).

Figures 4a-4c show the spatial distribution of the aforementioned repair macro-categories over the Municipality of L'Aquila. From Figure 4a it is possible to notice the high concentration of the damage to the pipelines and to the other network system components (Figg. 4b and 4c respectively for valves and demand nodes) in the area close to the epicenter of the 6^{th} April L'Aquila main-shock, occurred in proximity of the L'Aquila city centre.

Figure 4d shows a pie chart of these repair activities. Repair interventions involving multiple components correspond to more than one macro-category according to the adopted classification system (e.g., an operation that involves pipeline laying and valve insertion is described as a combination of P_ins and V_ins categories). They represent the 7% of the database (as shown in Figure 4d, those interventions are signed as "Other").

Considering the level of PGV registered in the affected area (Figg.4a-c), the damage scenario resulting from the data processing is coherent with what described in the international literature (ALA, 2001). Continuous pipelines, built with rigid welded joints have shown generally speaking a good performance: P_ins=222 pipelines inspections have been performed over the 621km pipeline networks, requiring P_rep=52 repair interventions and P_rec=44 reconnection interventions. The repair and reconnection interventions have been operated mostly to address leakage problems at the joint locations mainly caused by poor quality welds or the presence of corrosion at the joint location. In very few cases repair/substitution interventions, have been operated because of the deformation of the pipeline affecting the gas flow (ENEL Rete Gas representatives, personal communication). Discontinuities, including in-lines valves and connections to IDU, have shown to represent vulnerability points; 23% of the interventions have addressed problems at valves and IDU (Fig. 4d).

4.2 Reconstruction activities: processing of technical reports and results

Reports related to E1E.activities (Reconstruction of facilities for investments as a result of exceptional operations) were furthermore analyzed and processed over a period of six months (from June 2009 to November 2009) distinguishing between two different typologies of investment operations: 1) re-placement of damaged parts (components cabins, pipelines); 2) extension of the pipe network (e.g to by-pass inaccessible zones in cordoned areas of the city centre, to add missing link, to connect tempo-rary or new urbanised areas, etc.). The results from the processing of "E1E.activities" reports were in-cluded in a distinct database consisting of 51 records. It is important to note that unlike the Rei.activities, E1E.activities include also operations on the M/R and GR stations. Among these, the most relevant interventions are listed below:

- 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;
- M/R station in Centicolella: valve replacements and input/output substation network repair;
- GR in L`Aquila and Onna: replacements concurrently with the laying of new pipe.

Regarding M/R stations, there was no damage to their buildings; according to the AeDES forms ("Agibilità e Danno nell' Emergenza Sismica" form in Italian) used for the post-earthquake building inspection, all the M/R station buildings were classified as "A" (corresponding to a green tag in the US system; i.e., safe building). The regulator and mechanical equipments of the M/R stations were as well undamaged. 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.

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, and to get lessons and best practices on the risk management activities.

Regarding the post-earthquake damage assessment of the gas network in L`Aquila, considering the level of PGV registered in the affected area (Figg. 4a-4c), the damage scenario resulting from the data processing is coherent with what described in the international literature. The merit of this study has been to have given attention to all the components of the distribution networks, including M/R and GR Stations, Demand Node, Gas-meter whose damage can highly impact on the functionality of the network and whose repair/replacement highly influence the time and costs of the restoration phase. To identify seismic vulnerabilities of the system components, and to calibrate/tune existing fragility functions or define new ones, the resulting damage scenario will be overlaid to: the ground motion, the geotechnical conditions, and the induced geotechnical hazards observed in the affected area. A functional study of the network is on-going, including the definition of fault-trees for the whole system and for sub-systems and more complex components (e.g., M/R and GR stations) to assess the residual functionality of the damaged system and to define/calibrate predictive models for that.

This study will allow as well the analysis of the social and economic impact of the reduced functionality of the gas networks in the recovery phase following the quake, since information on costs and the time required for the repair operation has been coupled with the damage data.

An important lesson learnt from this experience has been the need to define together with the stakeholders best practices and standardised procedures (including a proper damage survey form) that could support and inform their operation in emergency/response/reconstruction phases following an earthquake.

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