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ORIGINAL RESEARCH PAPER

# Performance of the Italian strong motion network during the 2009, L'Aquila seismic sequence (central Italy)

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**Abstract** On April 6, 2009, the town of L'Aquila in the Abruzzo region (central Italy) was struck by a seismic event at 01:32 (UTC), of magnitude $M_W = 6.3$. The mainshock was followed by a long period of intense seismic activity and within seven days after the mainshock there were seven events of magnitude $M_W \geq 5$ that occurred from April 6 to April 13. This long seismic sequence was characterized by a complex rupture mechanism that involved two major normal faults of the central Apennines: the Paganica and the Gorzano faults. The strong-motions of the mainshock were recorded by 64 stations of the Italian Strong-motion Network (RAN) operated by the National Civil Protection Department (DPC). Six stations of a local strong-motion array were working in NW L'Aquila suburb area. One of them, located at about 6 km from the Paganica fault surface tip-line, set up in trigger mode, recorded continuously for more than 20 min the mainshock and the aftershocks. Besides the mainshock, the RAN stations recorded in total 78 foreshocks and aftershocks of $M_L \geq 3.5$, during the period from January to December 2009. The corresponding waveforms provide the most extensive digital strong ground motion data set ever recorded in Italy. Moreover, the 48 three-component observations of events of magnitude $M_W \geq 5$, recorded at a distance less than 15 km from each of the major involved faults, provide a significant increasing of near-field records available for the Italian territory. Six days after the mainshock, the strong-motion dataset, referred to preliminary locations of the events with $M_L \geq 4.0$, was made available on the DPC web site (http://www.protezionecivile.it/) and at the same time it was delivered to the ITACA database (http://itaca.mi.ingv.it/ItacaNet/). This dataset has been used by many authors in scientific papers and by engineers, geophysicists and geologists for professional technical works. In this paper, the present-day available strong-motion signals from the L'Aquila sequence and the performance of the Italian strong-motion network in terms of the number and quality of recorded data, the geometry and data transmission system

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are described. In addition the role of the temporary network that represents an extension of the permanent Italian strong-motion network, supporting the emergency response by civil protection authorities and improving the network coverage has been evaluated.

**Keywords** Strong-motion data · Strong-motion network · RAN · Normal fault · L'Aquila seismic sequence · Apennines · Central Italy

## 1 Introduction

The role of strong-motion seismology is of increasing interest to the engineering and seismological community. Decades ago the accelerometric data were mostly oriented towards earthquake engineering for structural design and had very little impact on seismology. However, since the last 20 years, they have been widely used also in seismological studies. Nowadays, due to the increasing number of seismic networks installed all over the world, as well as to the significant advances in seismometry, in recording systems and in data transmission systems, the strong-motion data also support the emergency response for reliable near-real-time information on potentially damaging ground shaking. The importance of deploying strong-motion instruments has been widely recognized and many instrumentation programs in countries such as in Japan, California—CSMI, Taiwan—TSMIP, Greece, Turkey, and Iran, have been carried out (Kinoshita 1998; Lee et al. 2001; Mirzaei Alavijeh and Farzanegan 2003; Skarlatoudis et al. 2004; Hutton et al. 2006; Polat et al. 2009).

In Italy, the strong-motion network (RAN) has been operating since 1972 (Gorini et al. 2010). The accelerometers distributed all over the national territory recorded strong-motions of the greatest earthquakes that occurred in Italy in the last 40 years, namely: Ancona 1972 ($M_L = 4.7$); Friuli 1976 ($M_L = 6.4$, $M_W = 6.4$); Irpinia 1980 ($M_L = 6.5$, $M_W = 6.9$); Umbria-Marche 1997-1998 ($M_L = 5.8$, $M_W = 6.0$); Molise 2002 ($M_L = 5.4$, $M_W = 5.7$) and their associated sequences.

The Italian Civil Protection Department (DPC) took over the analogue strong-motion network of the national electrical power company (ENEL) in November 1997 and started up a program for its upgrading. The main goal was to collect high-quality digital recordings from earthquakes, in order to take a step forward in the evaluation, prevention and mitigation of seismic risk, but also to optimize the effectiveness regarding the delivery of emergency response services. This purpose was achieved through two important steps: increasing the number of monitoring stations and adopting technical innovations in strong-motion instrumentation.

The DPC started a network development program making reference to the Italian seismic hazard map (Working Group MPS 2004), since the reliability of information on an earthquake in terms of ground response depends on the density of the recording stations. Moreover, the technical innovation in remote sensing, data acquisition and data transmission systems has been carried out, with the aim to determine the strong seismic motion map on the basis of instrumental data (Michelini et al. 2008; Moratto et al. 2009) as soon as possible after a damaging earthquake and to provide an immediate reliable damage assessment.

Additionally, important progress has recently been achieved with the installation, at RAN Data Centre based in Rome, of a new acquisition system that retrieves, processes and archives the recorded digital data automatically. The possibility to retrieve data and to control the stations remotely, made it possible to lower trigger thresholds set to 1mg as a standard and to increase the number of recordings (Fig. 1). All the stations of the RAN network and the whole system are continuously upgraded following the advances in science and technology.

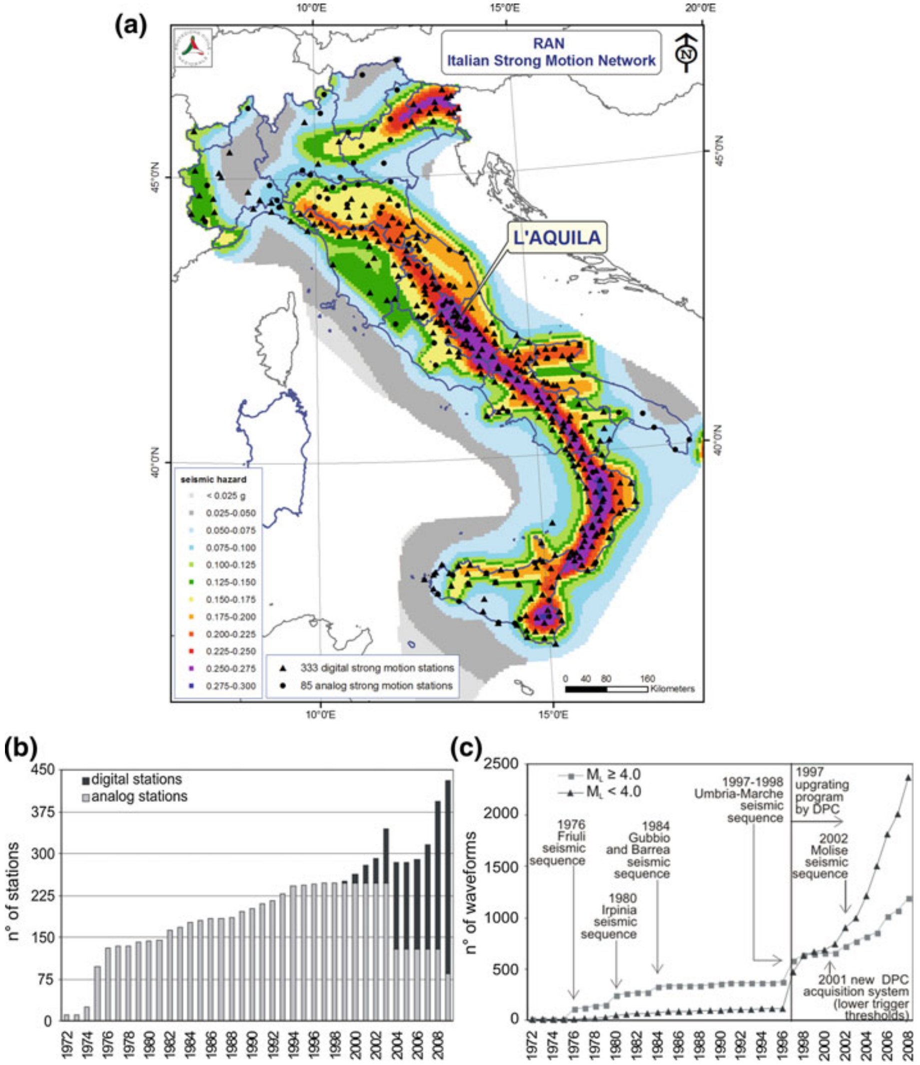

**Fig. 1** **a** Configuration of the Italian strong-motion network (RAN) at the end of 2009. The *black triangular symbols* represent the 333 digital strong-motion stations and the *black circles* the 85 analog stations. The underlying base map is the Italian seismic hazard map (Working Group MPS 2004). Different colors depict Peak Ground Acceleration (PGA) with a 10% chance of exceedance in 50 years (see legend at the bottom left corner). **b** Number of analog and digital stations from 1972 to 2009. **c** Cumulative number of analogue and digital waveforms divided into classes of magnitude ($M < 4$; $M \geq 4$) recorded from 1972 to the end of 2008. The arrows indicate the major seismic sequences (detectable steps in the cumulative curve) and the more important dates for the Italian instrumentation program

The current network geometry follows the criterion to monitor the Italian territory giving priority to urban areas. It is well integrated with about 161 local strong-motion stations and small networks operated by research institutes and universities (Priolo et al. 2005; Weber et al. 2007; Augliera et al. 2009; Costa et al. 2009). Today the RAN counts 422 stations and provides a dense station coverage for all high seismic hazard areas. 85 stations still have analogue instruments, which are however scheduled for replacement with digital accelerometers within 2010. Figure 1 shows the RAN configuration (Fig. 1a), the substantial improvement of the network since 1972 in terms of number of analogue/digital stations (Fig. 1b) and the cumulative number of records, per year and per two ranges of magnitude, from 1972 to 2008 (Fig. 1c). The arrows point out the relationship between the main advances in the system upgrading and the growth of recorded data. Until now RAN has recorded more than 3564 accelerograms, among which 1056 from 1972–1997 and 2508 from 1998–2008.

This paper aims to provided analysis of the following issues: (a) the RAN performance during the April 6, 2009 L'Aquila earthquake and the subsequent Abruzzo seismic sequence, (b) the effectiveness of the instrumentation and the reliability of the data transmission system during the mainshock and the whole seismic sequence, (c) the data quality, their characteristics and the data dissemination. Moreover, the recently launched upgrade of the centralized system for network management, as well as the project for the implementation of new accelerometric arrays in urban areas along the main Italian basins, will be shortly described.

## 2 The L'Aquila seismic sequence

In peninsular Italy, seismic deformation is prevalently concentrated within a narrow extensional belt which extends along the axis of the Apennine mountain chain, from northern Tuscany to Calabria (Lavecchia et al. 1994; Meletti et al. 2008 and references therein). There is a fair agreement in the literature on the geometry and dimension of the intra-Apennine extensional process, as well as on the seismic hazard assessment (i.e. Working Group MPS 2004; Pace et al. 2006, 2010). The intra-Apenninic extensional zone, of high seismicity, is characterized by shallow crustal earthquakes and by a history of destructive earthquakes, as listed in the Italian Parametric Catalogue CPTI04 (Working Group CPTI 2004).

During the last 30 years, four important seismic sequences (1979 Norcia, 1984 Gubbio, 1984 Barrea, 1997–1998 Colfiorito earthquakes) took place in the Central Apennines (Boncio and Lavecchia 2000). Although it was well documented (Guidoboni et al. 2007; Working Group CPTI 2009) that the L'Aquila area was struck in the past by three historical destructive earthquakes (1461, $I_{max} = XMCS$, 1703, $I_{max} = XMCS$, and 1762, $I_{max} = IX - XMCS$), the seismic instrumental activity was extremely scarce and relatively stable in size and time domains (Bagh et al. 2007; Boncio et al. 2009; Papadopoulos et al. 2010). Only 3 minor seismic sequences in August 1992 ($M_{d\ max}3.9$), in June 1994 ($M_{d\ max}3.7$) and in October 1996 ($M_{d\ max}4.0$), and background seismicity were recorded both by the local seismic network (RAC) operated by DPC from 1992 to 2000 and by a temporary network installed from April 2003 to September 2004 (De Luca et al. 2000; Boncio et al. 2004b; Bagh et al. 2007).

Just in this sparse seismicity area, from the beginning of 2009, a weak foreshock sequence was located in the hanging wall of the SW-dipping active normal fault known as the Paganica fault having an estimated length of ca. 20 km in the NW-SE direction (Boncio et al. 2004a; Lavecchia et al. 2009; Boncio et al. 2010). Two events of $M_L$ 4.1 and 3.9 occurred on March 30, and on April 5, 2009, respectively, and the last one just a few hours before the mainshock. The strongest event ($M_W = 6.3$), located close to the dense cloud of foreshocks, near the L'Aquila town, occurred at 01:32:40 UTC on April 6, 2009. It caused nearly 300 deaths and extensive damages that were increased by the following energetic aftershocks. In fact, up to this moment, about 15400 aftershocks have been counted, among which 78 events with $M_L \geq 3.5$, and seven earthquakes with $M_W \geq 5$ occurred within about 7 days. As it is possible to note in Fig. 2, the seismicity migrated southeastwards in the Aterno valley and northwestwards close to the Campotosto area. The area of epicentres covers 700 km$^2$ and the spatial distribution of the aftershocks suggests at least two fault ruptures referred to as the Paganica and Gorzano faults, which are considered as active and seismogenic structures in the literature (Boncio et al. 2004a,b; Pace et al. 2006; Lavecchia et al. 2009; Peruzza et al. 2011). The WSW-dipping Gorzano normal fault extends for 28 km along-strike with a NW-SE mean direction and the Amatrice-Campotosto area, located in the hanging wall of this fault, was struck by one large historical earthquake in October 1639 ($M_W = 6.3$), probably due to the rupture of the northern portion of the fault.

## 3 RAN network configuration in the L'Aquila seismic sequence epicentral area

### 3.1 Permanent stations

In the Lazio-Abruzzi Apennines (central Italy) various seismic instrumentation programs started in the early '90 by the National Seismic Survey (SSN), now Seismic Risk Office of DPC. A local seismic network (RAC), presently operated by INGV, and two strong-motion arrays were installed. The main purpose of these programs was to collect high-quality digital recordings in a high seismic hazard area, characterized by the presence of a deep sedimentary basin and a main town and administrative centre, such as L'Aquila. For these reasons, L'Aquila earthquake occurred in a region exceptionally well instrumented and provided an excellent set of high-quality strong-motion records.

Seven stations of the Italian strong-motion network were running in L'Aquila municipality (AQG, AQA, AQV, AQM, AQF, AQP and AQK) and other two (GSA and GSG) were working at the base of the Gran Sasso mountain, about 15 km far from the city.

The AQG, AQA, AQV, AQM, AQF and AQP stations belong to the strong-motion array of "Valle dell'Aterno"—L'Aquila. This DPC local array has an aperture of $\sim$ 2 km and minimum interstation distance of $\sim$230 m. It has been working since 1994 and it was originally formed by seven stations aligned through the Aterno valley in the NW suburbs of L'Aquila city (Bongiovanni and Marsan 1994). It was designed and installed to investigate site effects due to the presence of deep sedimentary basin and shallow sedimentary deposits, fracture processes at the earthquake source, and spatial variability of earthquake ground motion.

The AQK station is the only still operating station of "Aquilpark"—L'Aquila strong-motion array. The array was installed in 1996 and originally consisted of three strong-motion stations located in the centre of the L'Aquila town (Bongiovanni and Marsan 1994; Bongiovanni et al. 1996). In spite of the high-noise urban environment, the stations of the array successfully triggered and recorded some small local and regional earthquakes that permitted to detect low-frequency amplification in the city of L'Aquila, as described and discussed in De Luca et al. (2005).

The GSA is nearby the external Gran Sasso National Laboratory of INFN (National Institute of Nuclear Physics), while GSG is located in one of the service tunnels of the underground facilities beneath the mountain where the GPS signal is not available.

These strong-motion stations are equipped with three-component strong-motion sensors Kinemetrics Episensor and FBA23, and digital dataloggers of the Kinemetrics Altus series with high dynamic range, from 108 to 130 dB.

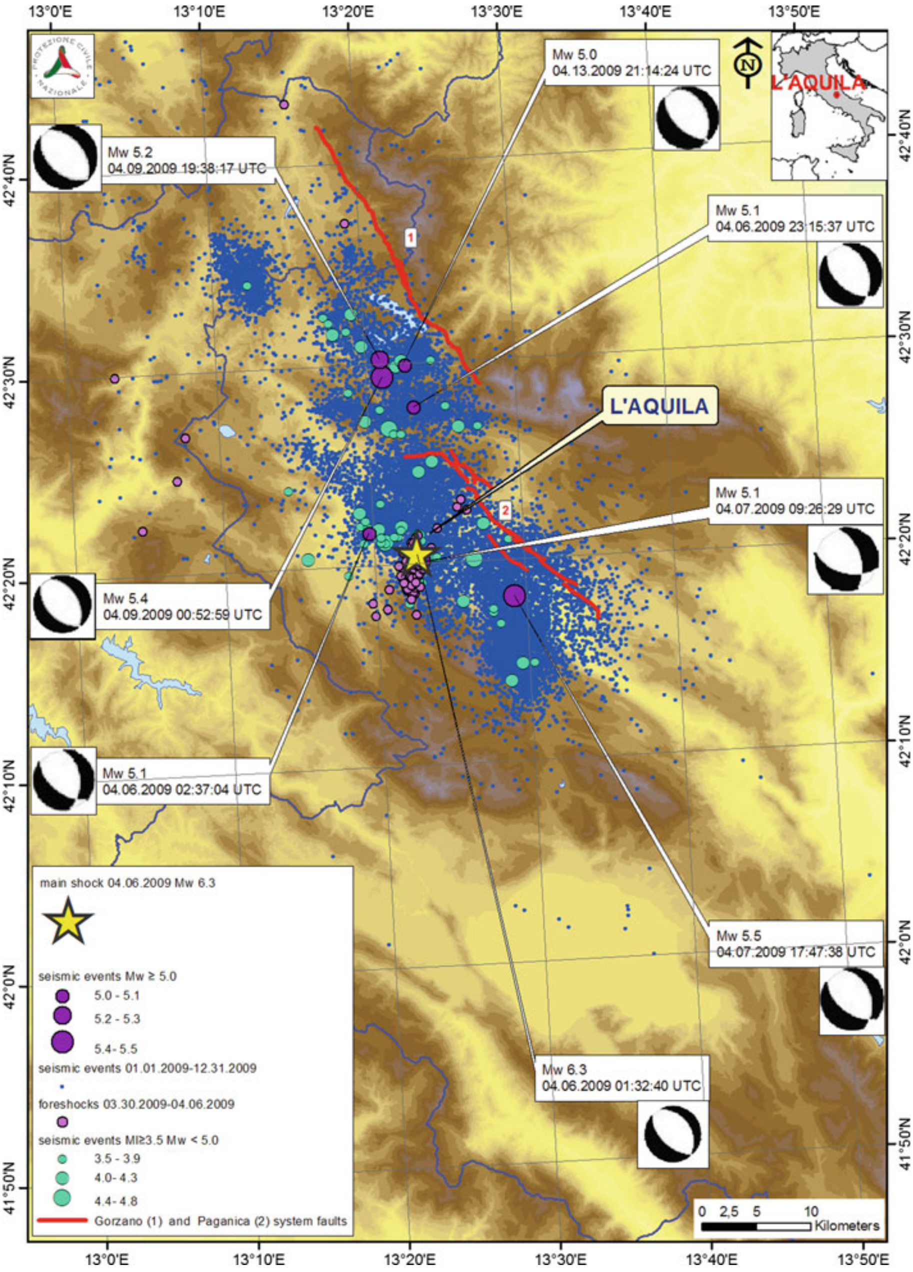

**Fig. 2** Epicentral distribution of the L'Aquila 2009 seismic sequence from January 1 to December 31, with the focal mechanisms of the mainshock and the seven aftershock events with $M_W \geq 5$. The yellow star represents the mainshock epicenter location, the purple circles the aftershock events with $M_W \geq 5$, the light blue circles the events with $M_L < 3.5$, the larger green ones the events with $M_L \geq 3.5$ and the pink little circles the foreshocks. Hypocentral coordinates are drawn from the Italian Seismic Bulletin (2003–2010) and the focal mechanism from Polat et al. (2009).The underlying base map is a shaded DEM image of Italy. The red lines depict the surface projection of the Paganica and Gorzano normal faults as represented in Boncio et al. (2004b) and Boncio et al. (2010). The *inset* at the *upper right corner* represents the location map of the L'Aquila earthquake, and the *inset* at the *bottom left corner* represents the detailed legend

The RAN network configuration in the L'Aquila seismic sequence epicentral area before April 6, 2009 is shown in Fig. 3.

### 3.2 Temporary stations

In case of significant seismic sequence DPC deploys in the field temporary strong-motion stations to increase the density of recording instruments in the epicentral area. DPC thus installed 12 digital plus 2 analogue temporary stations during the 1997–1998 Umbria-Marche seismic sequence (SSN—Monitoring System group 2002) and 9 digital stations in the aftermath of the 2002 Molise seismic sequence (DPC-USSN—Monitoring System group 2004).

The number of RAN stations operating in the L'Aquila area was already considerable when the April 6 mainshock occurred. In spite of this, on April 7, DPC began to install further stations to increase the network coverage in the regions interested by the seismic sequence that followed the mainshock, and in the areas of particular interest for Civil Protection purposes. At present, most of the temporary stations installed on this occasion have become permanent ones.

According to the spatial and temporal evolution of the local seismicity, fifteen digital new strong-motions stations were deployed from April 7 to May 15; all these stations, except for a single one, are still working and they have been integrated to RAN. Figure 3 shows the 9 stations of the temporary network installed in the epicentral area. In the first 2 days after the mainshock four $M_W \geq 5$ earthquakes occurred (Fig. 2). The second one ($M_W = 5.1$, 23:15) was localized at about 15 km northwest of L'Aquila (Campotosto area), while the fourth one ($M_W = 5.5$, 17:47) was localized southeast of L'Aquila, in an area where the main event destroyed Onna and caused extensive damage in other villages. The remaining two $M_W \geq 5$ earthquakes occurred nearby L'Aquila city. Although on April 7 a new station was installed at Bazzano (BZZ) to better monitor the southeastern suburbs of L'Aquila, the DPC was particularly interested in the migration of seismicity northwards to Amatrice—Campotosto area were the seismic activity culminated with a $M_W = 5.4$ seismic event occurred on April 9. This area is delimited by the Gorzano normal fault (Fig. 2) that runs along the western slope of Mt Gorzano and passes underneath the Rio Fucino dam at the eastern end of Lago di Campotosto (Fig. 4). This lake is a man-made water reservoir impounded by other two dams, namely Sella Pedicate and Poggio Cancelli, besides that of Rio Fucino, and represented a further hazard during the seismic sequence.

In order to monitor the ground shaking of the Campotosto lake area, four stations (SPD, PCB, MSC, RFC) were installed, starting from April 8 (Fig. 4a). The SPD and PCB are placed nearby Sella Pedicata and Poggio Cancelli dams respectively, whereas MSC is in a build-up area of Mascioni and the RFC was working from 15/04/2009 to 26/08/2009 inside one of the tunnels at the base of the concrete dam of Rio Fucino (Fig. 4b). Several of the new stations installed after the L'Aquila earthquake, are equipped with the new instrumentation recently acquired by DPC: a three-component Syscom Instruments Force Balance Accelerometer, model MS2007, and a digital data logger Reftek, model 130-01. Table 1 lists the permanent stations in the epicentral area and the temporary stations installed after April 6, 2009.

## 4 Analysis of the RAN performance

During the period January–December 2009, the RAN network recorded a large amount of data that substantially enrich, in terms of number and quality of recordings, the strong-motion

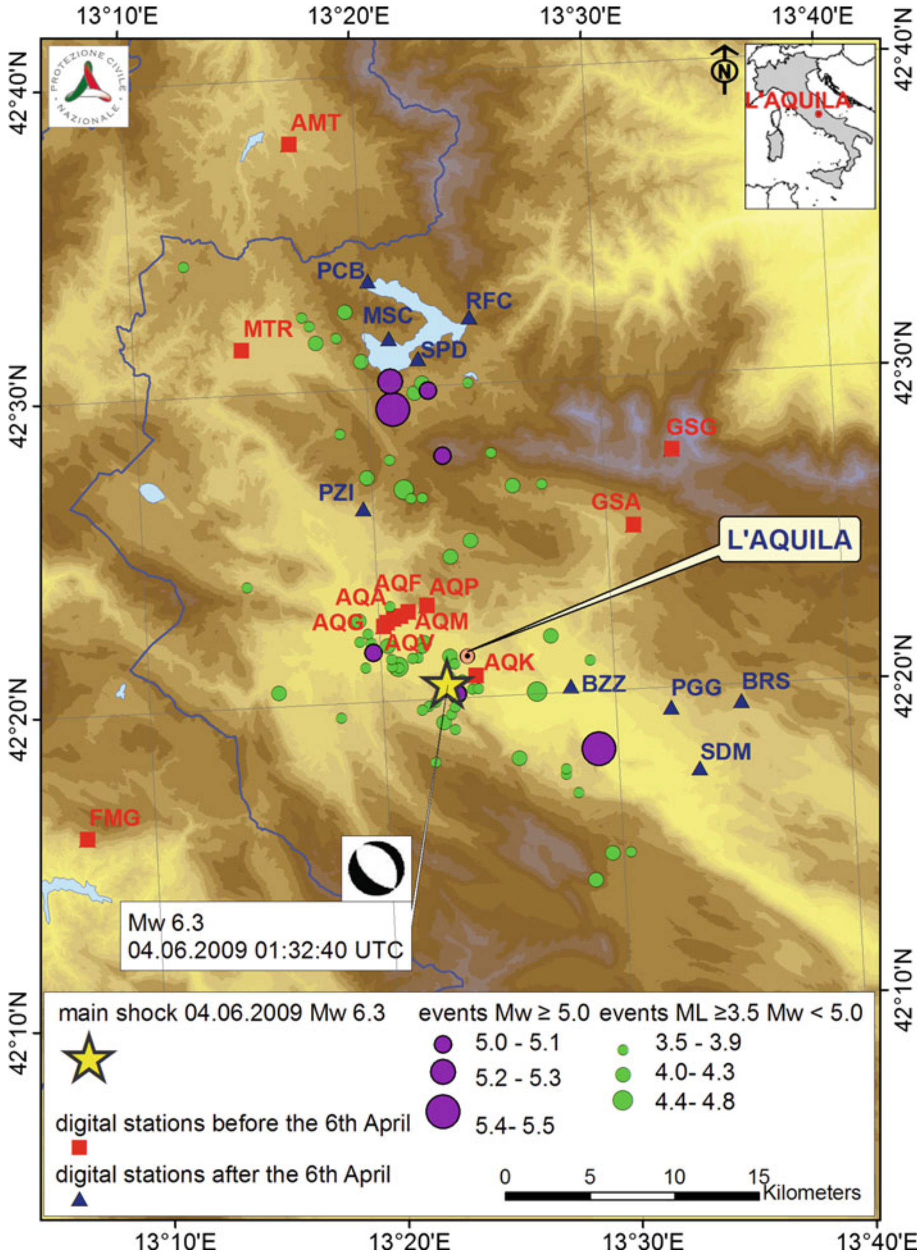

**Fig. 3** RAN configuration in the epicentral area. Distribution of the accelerometric stations in the "Valle dell'Aterno" array and the other permanent strong-motion stations (*red squares*) before April 6, 2009. The *yellow star* locates the mainshock, whose focal mechanism is also provided. The *blue triangular symbols* represent the nine temporary stations installed after April 6 in the selected area. The events of $M_L \geq 3.5$ recorded by these stations are also indicated (see legend at bottom)

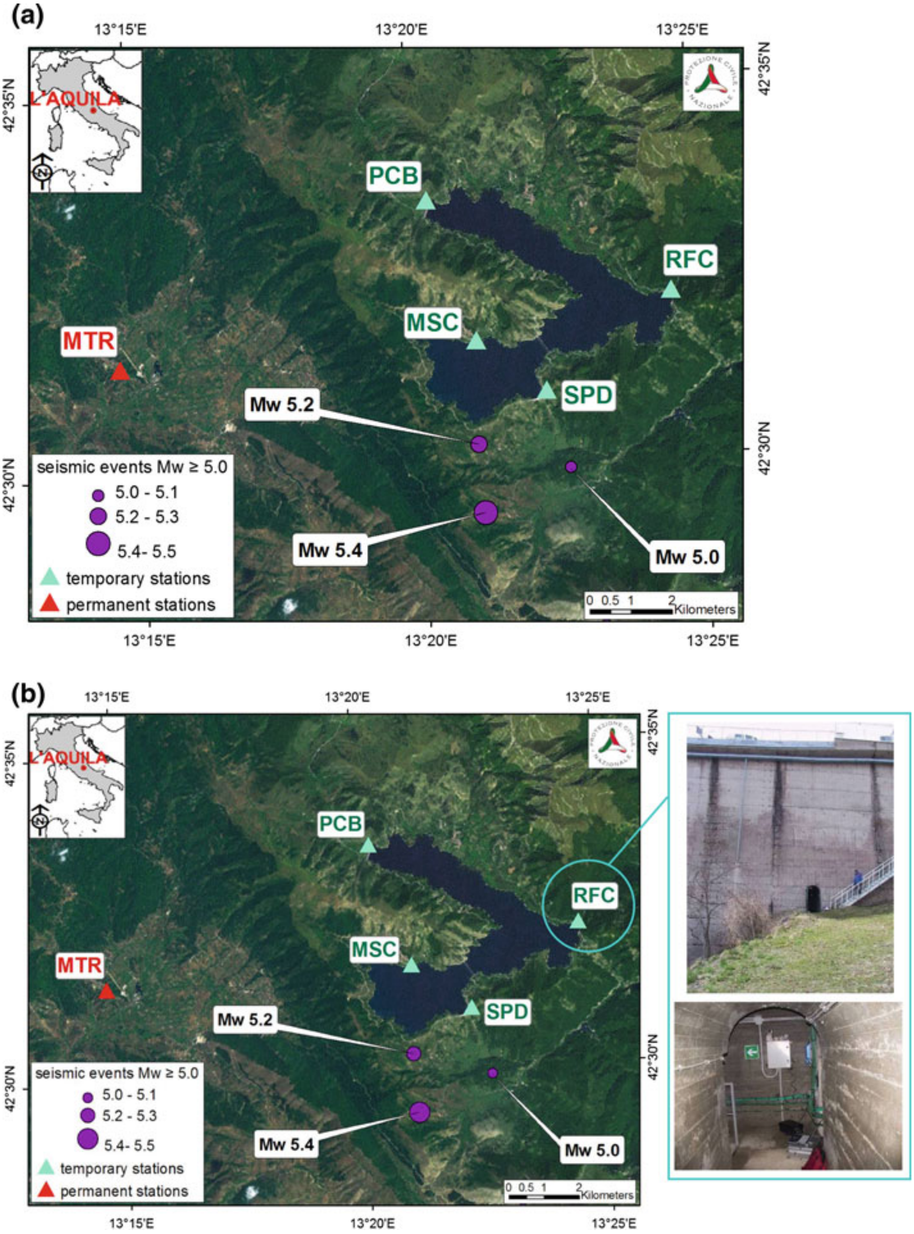

**Fig. 4** **a** Detail of the temporary stations distribution around the Campotosto lake, installed with the purpose of monitoring the dam response. The more significant events ($M_W \geq 5.0$), and the Gorzano normal fault (*red line*) are also shown. **b** Pictures of RFC station installed inside one of the tunnels at the base of the Rio Fucino dam of the Campotosto reservoir

waveforms of the Italian archive. A significant result of the strong-motion network was the successful recording of the foreshocks, mainshock and aftershocks of the L'Aquila seismic sequence in both near and far field and within a wide range of magnitudes (down to $M_L \sim 1$).

**Table 1** List of the permanent stations in the epicentral area and temporary stations installed after April 6, 2009

| No. | Station code | Municipality | Region | Lat | Lon | Elevation (m) | Date deployment/ dismissal |
|---|---|---|---|---|---|---|---|
| 1 | AMT | AMATRICE | Lazio | 42.632 | 13.286 | 950 | 07/04//2003 |
| 2 | AQA | L'AQUILA VALLE ATERNO<br>*Fiume Aterno* | Abruzzo | 42.376 | 13.339 | 693 | 17/04/2001 |
| 3 | AQF | L'AQUILA VALLE ATERNO<br>*Ferriera* | Abruzzo | 42.381 | 13.355 | 36 | 11/11/1999 |
| 4 | AQG | L'AQUILA VALLE ATERNO<br>*Colle dei Grilli* | Abruzzo | 42.373 | 13.337 | 721 | 18/06/2001 |
| 5 | AQK | L'AQUILA<br>*Aquil Park entrance* | Abruzzo | 42.345 | 13.401 | 726 | 17/04/2001 |
| 6 | AQM | L'AQUILA VALLE ATERNO<br>Il *Moro* | Abruzzo | 42.379 | 13.349 | 724 | 17/05/2001 |
| 7 | AQP | L'AQUILA VALLE ATERNO<br>*Monte Pettino* | Abruzzo | 42.384 | 13.369 | 1193 | 06/11/2001 |
| 8 | AQV | L'AQUILA VALLE ATERNO<br>*Centro Valle* | Abruzzo | 42.377 | 13.344 | 692 | 15/05/2001 |
| 9 | CLN | CELANO | Abruzzo | 42.085 | 13.521 | 796 | 30/01/2003 |
| 10 | FMG | FIAMIGNANO | Lazio | 42.268 | 13.117 | 1071 | 12/11/2001 |
| 11 | GSA | GRAN SASSO<br>*(Assergi, INFN external lab)* | Abruzzo | 42.420 | 13.519 | 1062 | 25/08/2001 |
| 12 | GSG | GRAN SASSO<br>*(INFN, underground lab)* | Abruzzo | 42.460 | 13.550 | 1200 | 04/04/2001 |
| 13 | MTR | MONTEREALE | Abruzzo | 42.524 | 13.245 | 975 | 20/02/2001 |
| 1 | BRS | BARISCIANO | Abruzzo | 42.324 | 13.590 | 931 | 08/04/2009 |
| 2 | BZZ | BAZZANO | Abruzzo | 42.337 | 13.469 | 608 | 07/04/2009 |
| 3 | MSC | MASCIONI | Abruzzo | 42.527 | 13.351 | 1335 | 27/04/2009 |
| 4 | PZI | PIZZOLI | Abruzzo | 42.437 | 13.326 | 941 | 14/05/2009 |
| 5 | PCB | POGGIO CANCELLI | Abruzzo | 42.558 | 13.338 | 1315 | 08/04/2009 |
| 6 | PGG | POGGIO PICENZE | Abruzzo | 42.323 | 13.539 | 769 | 22/04/2009 |
| 7 | SDM | S. DEMETRIO NE' VESTINI | Abruzzo | 42.290 | 13.558 | 666 | 22/04/2009 |
| 8 | SPD | SELLA PEDICATE | Abruzzo | 42.515 | 13.371 | 1338 | 15/04/2009 |
| 9 | RFC | RIO FUCINO | Abruzzo | 42.536 | 13.409 | 1374 | 15/04/2009-26/08/2009 |

The last column reports the date of deployment and the date, when the case, of dismissal

With the aim of analyzing the RAN performance during the L'Aquila seismic sequence, the main characteristics of the recorded data are described in the following. Moreover, the effectiveness of the network to provide high-density and high-quality strong-motion waveforms and rapid post earthquake information are discussed.

### 4.1 Recorded ground motions (foreshocks, main and aftershocks)

On April 6, 2009, the "Valle dell'Aterno" array, AQK, GSA and GSG stations were in the very near fault region of the $M_W = 6.3$ L'Aquila earthquake (Chiarabba et al. 2009; Lavecchia

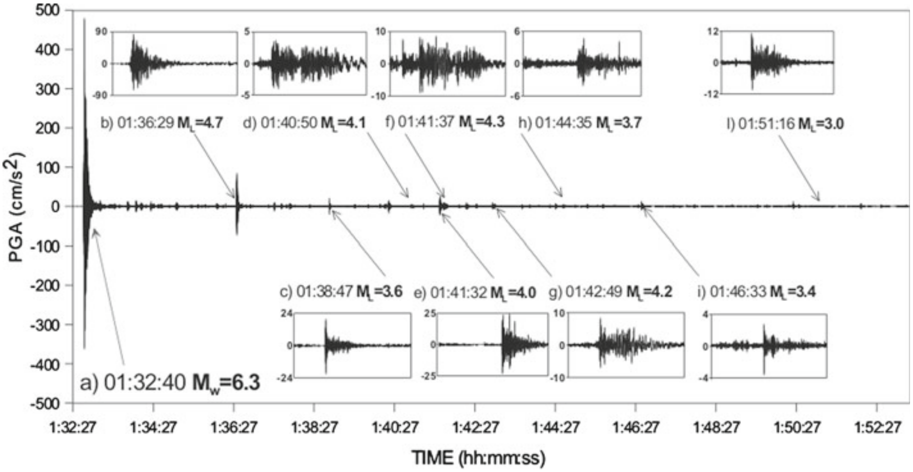

**Fig. 5** The ~21 min of recording at AQA station (“Valle dell’Aterno” array) triggered by the mainshock of the sequence. This record includes the mainshock and the 12 aftershocks as reported by the Italian Seismic Bulletin (2003–2010). Specifically, the arrows indicate 10 well distinguishable earthquakes down to magnitude $M_L = 3.0$

et al. 2009; Walters et al. 2009) and produced high-quality near-source records of intense strong shaking. Four stations of “Valle dell’Aterno” array and AQK were at epicentral distances ranging from about 1.5 to 4.6 km and at a Joyner-Boore distance (Joyner and Boore 1981) $R_{JB} = 0$, while GSG and GSA were located at epicentral distances about 15 km with a $R_{JB} = 4.6$ km. The AQA recorded continuously for about 21 min the mainshock and the following events giving important information on the rupture evolution within its very first minutes. In fact, according to the Italian Seismic Bulletin (2003–2010), 12 events occurred in these first minutes, among which 9 of $M_L \geq 3$. Figure 5 shows the AQA ‘long trace’ and the arrows detect the 10 well distinguishable earthquakes down to magnitude 3.0.

The “Valle dell’Aterno” array recorded peaks of acceleration greater than 300 cm/s$^2$ and specifically 663 cm/s$^2$ (AQV—classified as EC8, Comité Européen de Normalisation (2004)—B site), 504 cm/s$^2$ (AQG classified as EC8—A site), 480 cm/s$^2$ (AQA classified as EC8—A site). High peaks of accelerations were also recorded by AQK station (366 cm/s$^2$ classified as EC8—A site) close to L’Aquila urban area.

On the whole, the mainshock of the L’Aquila earthquake was recorded by 64 RAN instruments located within the 1.7–277 km epicentral distance range and it is, in Italy, the seismic event with the largest number of instrumental observation points.

The RAN network provided also data, from both permanent and temporary stations, for the 7 aftershocks with $M_W \geq 5.0$, mainly associated to either Paganica or Gorzano normal faults.

Quite interesting are, e.g., the earthquakes located at about 6 km from Campotosto dams, occurred on April 9 (00:52 and 19:38 UTC) and on April 13 (21:14 UTC) of magnitude 5.4, 5.2, 5.0 respectively, recorded by two near-source stations (MTR and PCB in Fig. 4) at epicentral distances from 6 to 11 km with a $R_{JB} = 0$ with respect to the Gorzano normal fault.

Table 2 lists, for each event of $M_W \geq 5.0$, the minimum and maximum epicentral distance of the recording stations, the number of available recordings, including the waveforms from temporary stations, and highlights the number of waveforms recorded within 5, 7 and 15 km.

**Table 2** List of seismic events of Mw ≥ 5 occurred up to April 13, 2009 and associated to the Paganica and Gorzano normal faults

| Time | Lat | Lon | Dep. | Ml | Mw | Source | dmin km | dmax km | ntot | nrec1 $0 < d \leq 5$ km | nrec2 $5 < d \leq 7$ km | nrec3 $7 < d \leq 15$ km |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2009/04/06: 01:32:40.4 | 42.342 | 13.380 | 8.3 | 5.9 | 6.3 | P2010-BS | 1.7 | 276.9 | 64 | 5 | 0 | 1 |
| 2009/04/06 02:37:04.3 | 42.360 | 13.328 | 8.7 | 4.6 | 5.1 | P2010-BS | 1.6 | 99.0 | 18 | 3 | 1 | 0 |
| 2009/04/06 23:15:36.8 | 42.463 | 13.385 | 9.7 | 5.0 | 5.1 | P2010-BS | 10.2 | 93.2 | 17 | 0 | 0 | 3 |
| 2009/04/07 09: 26: 28.6 | 42.336 | 13.387 | 9.6 | 4.8 | 5.1 | P2010-BS | 1.4 | 130.0 | 18 | 1 | 5 | 0 |
| 2009/04/07 17: 47: 37.3 | 42.303 | 13.486 | 17.1 | 5.4 | 5.5 | P2010-BS | 4.0 | 215.4 | 45 | 1 | 0 | 7 |
| 2009/04/09 00: 52: 59.7 | 42.489 | 13.351 | 11.0 | 5.1 | 5.4 | P2010-BS | 7.7 | 170.4 | 36 | 0 | 1 | 7 |
| 2009/04/09 19: 38: 17.0 | 42.504 | 13.350 | 9.3 | 5.0 | 5.2 | P2010-BS | 6.1 | 93.8 | 27 | 0 | 1 | 6 |
| 2009/04/13 21: 14: 24.5 | 42.498 | 13.377 | 9.0 | 5.0 | 5.0 | P2010-BS | 7.4 | 90.0 | 24 | 0 | 1 | 5 |

The source of data for the hypocentral parameters and magnitude of the listed earthquakes are Pondrelli et al. (2010) [P2010] and the Italian Seismic Bulletin (2003–2010) [BS]. Key: dmin and dmax = minimum and maximum epicentral distance of the triggered stations; ntot = total number of available recordings per event; nrecX = number of waveforms recorded at an epicentral distanced in km within $0 < d \leq 5$ (nrec1), $5 < d \leq 7$ (nrec2), $7 < d \leq 15$ (nrec3)

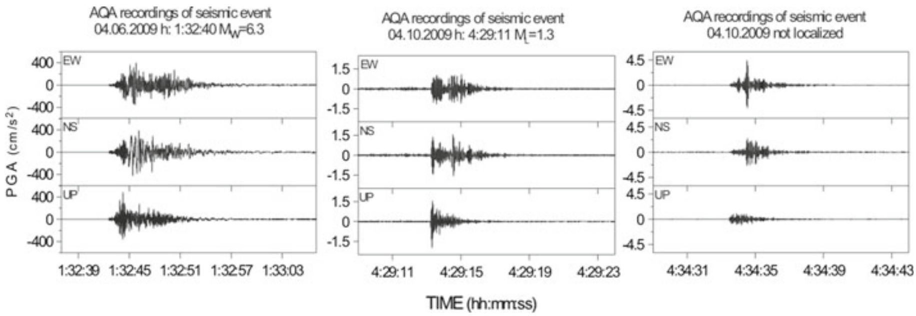

**Fig. 6** Example of high quality three component-recordings recorded at AQA station: the mainshock of $M_W = 6.3$, an aftershock of $M_L = 1.3$ and another event that is not associated to any localized earthquake by the Italian Seismic Bulletin (2003–2010)

The high dynamic range of the strong-motion instruments gave the possibility to record both strong and weak motions down to magnitude $M_L = 1$, so the Italian strong-motion network recorded the foreshocks and the vast majority of the events of the L'Aquila seismic sequence. An example of the high sensitivity of the instruments is shown in Fig. 6 where three-component waveform traces recorded by the same station (AQA) are reported. These strong-motion time histories are referred to the mainshock, to an aftershock of $M_L = 1.3$ and to another event that is not associated to any localized earthquake in the Italian Seismic Bulletin (2003–2010).

The RAN recorded in total 1175 three-component waveforms for events of $M_L \geq 3.5$, with an increment of the number of waveforms of the order of 70% with respect to those contained in the archive. Figure 7a shows the number of recordings, per magnitude interval, versus epicentral distance and Fig. 7b shows the number of recordings for each station located in the epicentral area. This significant growth of the recorded strong-motion signals is also evident when comparing the average of observations (i.e. events with $M_L \geq 3.5$), per magnitude interval, with the one obtained during the Umbria-Marche sequence (Fig. 7c). The comparison with the Umbria-Marche dataset is the only feasible one, because it is the more recent sequence of comparable magnitude for which a digital strong-motion temporary network was deployed.

Figure 8 shows the strong-motion parameters of the records related to the events with $M_L \geq 3.5$. PGA, PGV, Housner and Arias intensity are plotted versus distance (Fig. 8a) and magnitude (Fig. 8b).

## 4.2 Effectiveness of the strong-motion instruments

During the L'Aquila sequence, the Italian strong-motion stations provided a satisfactory percentage of data recovery both on the permanent stations and on the temporary network. An estimate of its effectiveness during this period of intense seismic activity is shown in Fig. 9. It displays the percentage of recordings for each permanent and temporary station in the epicentral area for the $M_L \geq 4.0$ events occurred during the period January–December, 2009. In this specific evaluation, we roughly consider the epicentral area as the one defined by the aftershocks and comprising the surface projection of the two seismogenic fault planes describing the Paganica and Gorzano normal faults (Boncio et al. 2004a). We include in this analysis only the stations located in the epicentral area because in this zone the station trigger is strictly related to the actual functioning of the instrument and

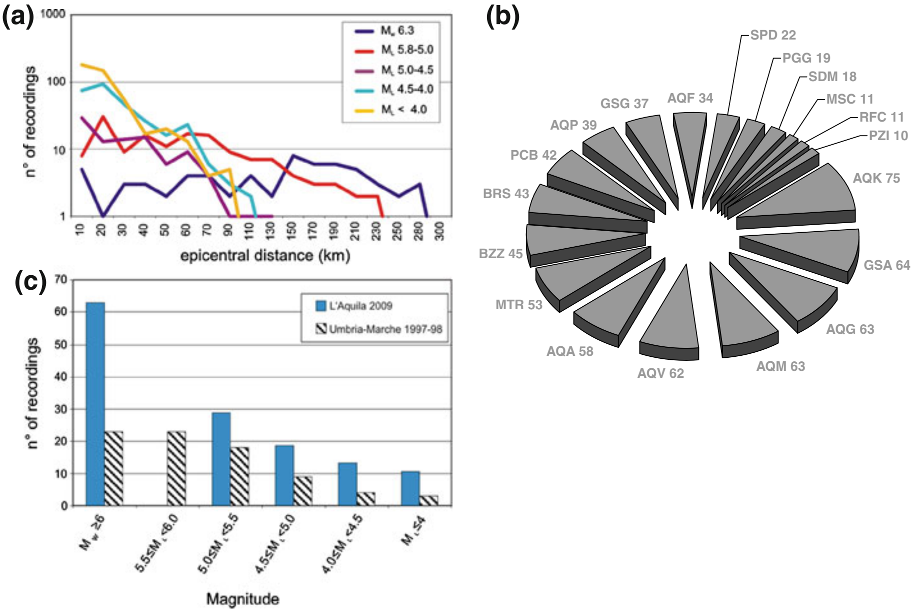

**Fig. 7** Recordings summary of seismic events of $M_L \geq 3.5$. **a** Number of recordings, per magnitude interval, versus epicentral distance. **b** Number of recordings for each station located in the epicentral area. **c** Comparison between the average of observations, per magnitude interval, obtained during the Umbria-Marche and L'Aquila seismic sequences

does not depend on other factors such as magnitude, epicentral distance and local amplification effects. Moreover, because the histogram includes both permanent and temporary stations deployed in different periods, to achieve the data consistency, the percentages of each station are computed with respect to the specific number of events occurred during its deployment.

The RAN stations, on the whole, have recorded more than 70% of the events, except for the AQP, AQF, RFC, MSC and GSG stations that suffered from technical problems like poor power supply and saturation of internal memories. In particular, AQP and AQF were the only stations belonging to the "Valle dell'Aterno" array, located in the epicentral area, which did not record the mainshock because the battery charge was not sufficient to provide the necessary power for their operation during the night. RAN stations, as a standard, have a buffer battery power supply system connected to a power socket provided by the local municipality, but where the electric power line is not available, and this is the case for AQP and AQF, the batteries are recharged by means of solar panels.

As highlighted in Fig. 9, the AQM station have recorded more than 80% of the events, but the related recording of the mainshock is not considered reliable. In fact, the recorded signal exceeded the settled 1g full scale of the RAN stations since the station was severely damaged by the event.

The instrumentation installed at AQM station was protected by a rectangular metal container with its four feet fixed to the ground. The feet were partially corroded by rust at the point of contact with the ground due to atmospheric agents. The earthquake was strong enough to cause the breaking of two of the four feet at the point affected by rust. The two broken feet

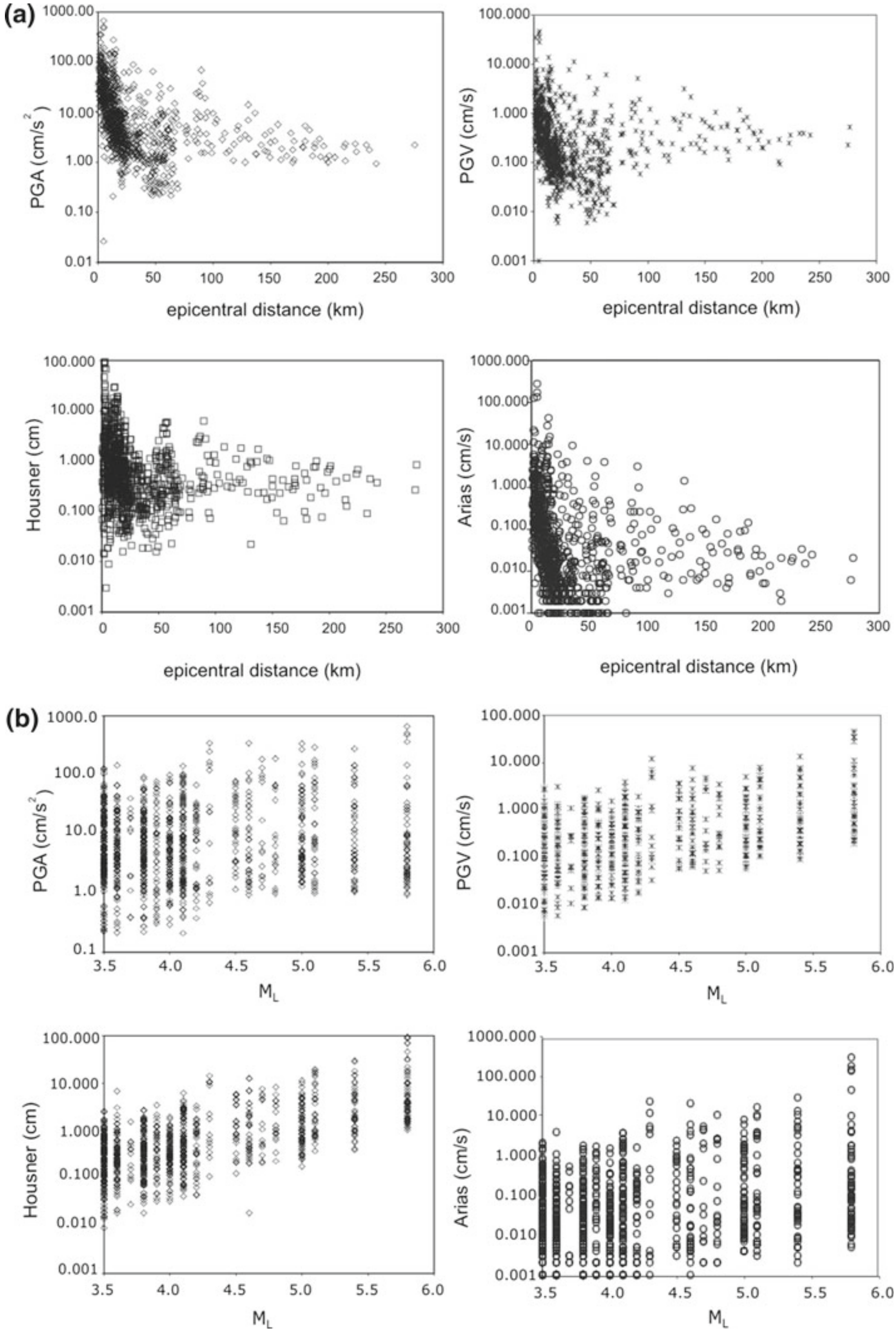

**Fig. 8** Summary of the strong-motion parameters of the waveforms of events with $M_L \geq 3.5$ recorded by RAN in the period January–December 2009. Peak ground acceleration, peak ground velocity, Housner and Arias intensity, for maximum component, plotted versus epicentral distance (**a**) and versus magnitude (**b**)

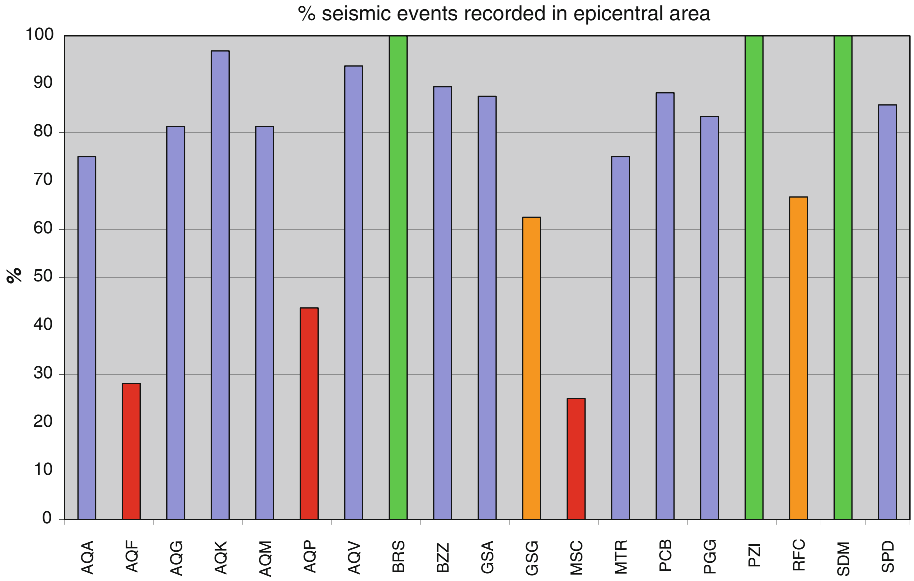

**Fig. 9** Percentage of recordings for each permanent and temporary station in the epicentral area for the events with $M_L \geq 4.0$ occurred during the period January–December, 2009. The percentage of recordings is with respect to the number of earthquakes occurred during the period of deployment

were on the same short side of the container, oriented in the NS direction and this probably allowed the container to rebound on its broken feet.

This hypothesis seems likely after having observed, during laboratory tests on the DPC bidirectional shaking table in which the metallic box was subjected to the AQK mainshock, the lifting and sudden fall of the box itself and its effects on the station recordings.

The AQM recorded waveforms associated to the following seismic event are to be carefully used, although for seismic events of lower energy it can be supposed that no lifting of the box had occurred. This station was removed on September 11, 2009.

### 4.3 Data transmission system

Two of the most critical points of a monitoring network during a damaging earthquake are: the instrumentation power supply, as we have seen in the previous paragraph, and the data communication system, the latter in the case the network should provide real-time information for immediate public safety and emergency response purposes.

The RAN stations use a GSM data transmission system and this choice dates back to more than 10 years ago, when the main purpose of the Italian strong-motion network was only to record data for scientific purposes when a significant seismic event occurred. Moreover, GSM was adopted as a standard for RAN since it could manage both a GSM external modem as well as an SMS service and it was the best cost/benefit compromise. An experimental network with GPRS data transmission was also tested in 2004, but the cost/benefit balance at that time was unfavorable. Presently, DPC is working to optimize the network infrastructures to improve the time response of the network and its reliability in providing information in near-real time.

On April 6, 2009 all the RAN stations were equipped with GSM modems, set in dial up operation mode, with the exception of the GSG station placed in the underground facilities of the INFN National Laboratory, that uses a phone line because of the lack of a GSM signal. Few minutes after the earthquake, the ground motion parameters from the near-source RAN station and full waveforms from farther stations started to arrive to the DPC data centre. The SMS information was the only one available from some of the near-source strong-motion stations during the first hours after the event. As a matter of fact, some stations, due to the low threshold of the station channel triggers and the high level of local seismicity, triggered over and over again for several minutes originating huge record files. These stations did not succeed in transferring the stored waveforms. Probably this was related to the local GSM lines that were already overloaded or to the GSM network instabilities that could have occurred.

Starting from April 7, new stations recently acquired by DPC were installed in the epicentral area. They use GPRS data transmission system instead of the GSM modem to communicate with the RAN data centre. At present the GPRS and GSM coverages of the Italian territory are almost the same, but the GPRS allows retrieving recorded data at higher transmission rates, even if a minimum data transmission rate is not guaranteed like for GSM. The spreading use of this technology in recent years has lead to a remarkable decrease of the costs for data transmission via GPRS.

### 4.4 Waveform characteristics in time domain: permanent displacements

The L'Aquila seismic sequence, specifically the mainshock and the more energetic aftershocks provided the most extensive dataset of near-field data ever recorded in Italy.

The characteristics of the near-source strong-motions are well known in literature, since several major earthquakes occurred in the nineties (1992 Landers, California, 1999 Chi-Chi, Taiwan, 1999 Koaceli, Turkey, etc) and many researchers have extensively studied near-fault ground motion records (Durukal 2002; Chen and Loh 2007; Huang et al. 2008). As a matter of fact, for a strong earthquake the near-field ground motion is largely affected by a permanent static displacement, also called "fling step", due to tectonic slip, and by long-period velocity pulses with large amplitudes on the fault-normal direction caused by directional fault rupture mechanism (Chioccarelli and Iervolino 2010). Moreover, more recent studies indicated that also high-frequency acceleration pulses, caused by fault rupture dynamics, may carry potential damaging effects in the near-source region (Tong et al. 2007).

Evidences of these characteristics are identifiable only in high-quality strong-motion records or achievable through their processing. The pre-event and threshold level parameters set on RAN stations made it possible to record not only the whole waveform, but also several seconds of noise level before the April 6 mainshock anticipating the ability to compute permanent displacements.

The corrected acceleration, velocity and displacement traces recorded during L'Aquila earthquake at the AQG, GSA and AQK near-field stations are shown in Fig. 10. As observed in other large earthquakes such as 1992 Lander earthquake (Abercrombie and Mori 1994) and the 2005 West off Fukuoka prefecture earthquake (Takenaka et al. 2006), the acceleration time histories at these stations exhibit an emergent onset, with about 0.6–0.7s of small but increasing-amplitude wave arrivals followed by the onset of the main energy release. The first label P, on the A, B and C traces of Fig. 10a, is called "initial rupture phase" and denotes the first P arrival time and second label P′ indicates the "main rupture phase" (Takenaka et al. 2006). This feature of near-fault records has been observed also at AQV and AQG stations for the $M_W = 5.4$ event occurred on April 7, 2009 at 17:47 UTC. Even in this case the delay P′–P is 0.6–0.7 s (Fig. 10b).

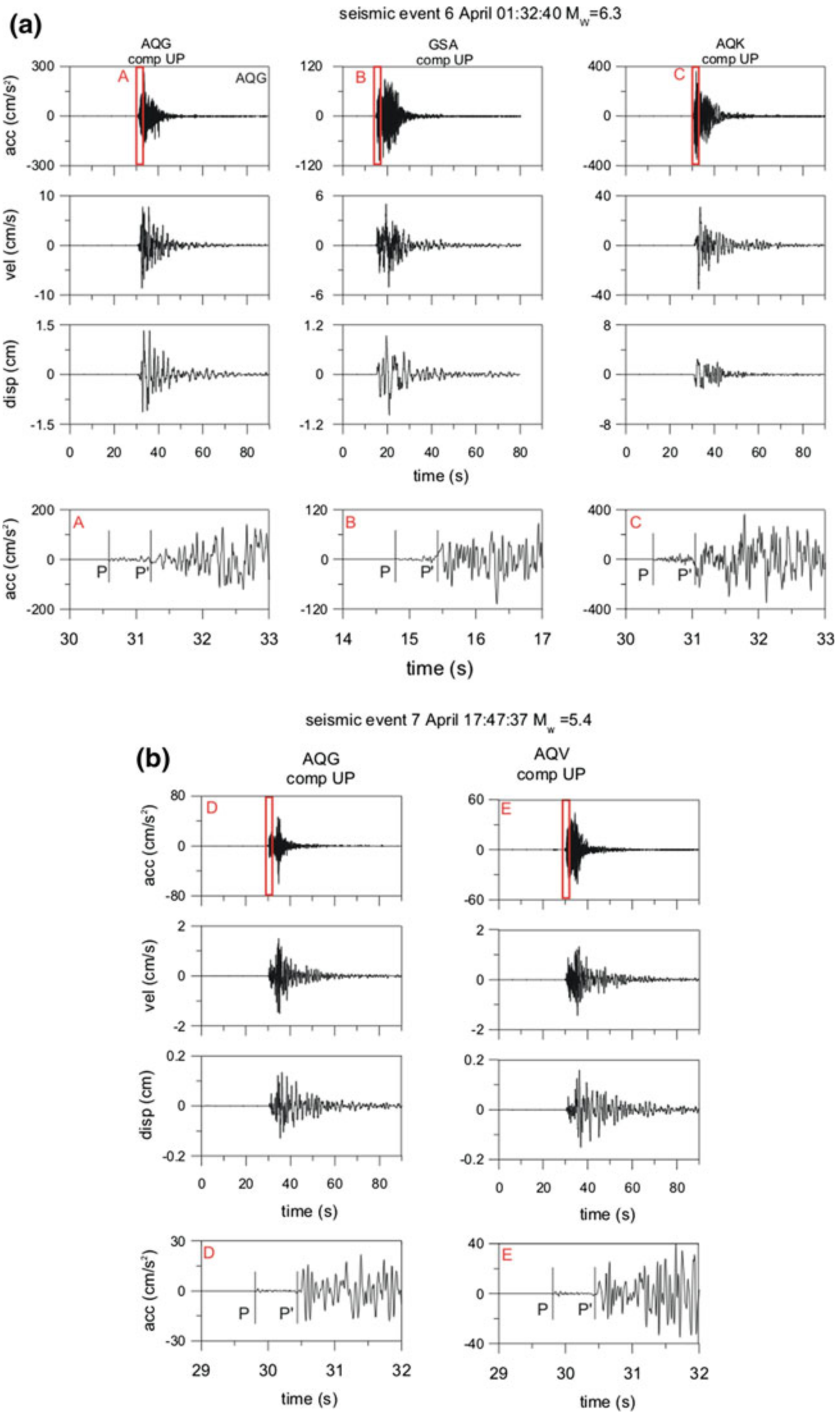

**Fig. 10** **a** Vertical component of the corrected acceleration, velocity and displacement traces of the mainshock ($M_W = 6.3$) recorded by AQG, GSA and AQK stations and **b** the aftershock of the $M_W = 5.4$ event (7 April 17:47) recorded by AQG and AQV stations. The traces A, B, C, D and E are a zoom in the time window indicated on the corresponding acceleration time history of each station. The zoom highlights the emergent onset of the acceleration time history. P indicates the initial rupture phase and P' indicates the main rupture phase

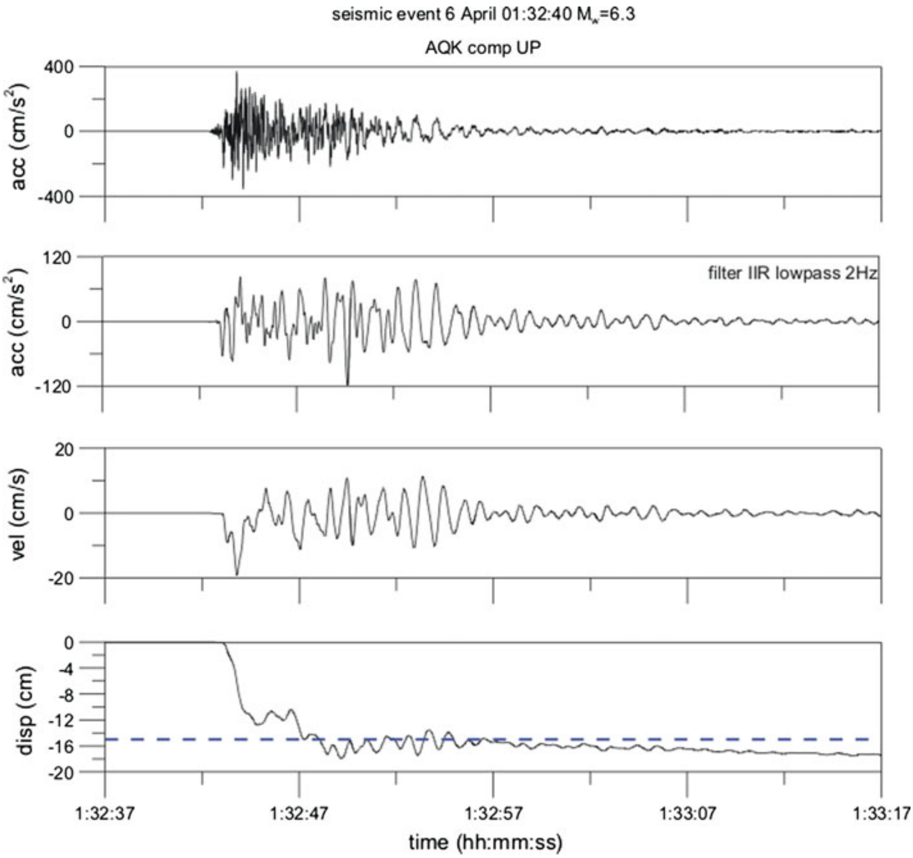

**Fig. 11** Corrected acceleration for station AQK and velocity and permanent displacement obtained by integrating the acceleration time history after filtering it with an IIR low-pass filter at 2 Hz

As shown in Fig. 11 for AQK station, and more in detail observed by Rupakhety and Sigbjörnsson (2010), accelerometric data available at AQA, AQK, AQV and AQG stations can be used to estimate permanent ground displacements caused by the mainshock. More precisely, by means of these waveforms it was possible to estimate a permanent ground subsidence of about 4 cm at AQA, AQV and AQG sites located north-west of L'Aquila town and a permanent downward displacement of about 15 cm at AQK site, located close to the urban area.

### 4.5 Focal depth control

A further proof of the effectiveness of the strong-motion network in the epicentral area was performed utilizing first P and S arrivals of the strong-motion recordings for determining earthquake hypocentral parameters. In fact, as shown in previous sections, the dense network of strong-motion instruments, distributed in the Central Apennines and the array located in the urbanized sedimentary basin, recorded a sufficient number of signals from small, local, to large earthquakes to evaluate the hypocentral parameters.

**Table 3** List of the 9 events of $M_L \geq 4.0$ relocated using the strong-motion data recorded from the Italian accelerometric network

| Date | Time | Lat | Lon | Dep (km) | $M_L$ | $M_W$ | Gap(°) | Rms (s) | seh (km) | Sez (km) |
|---|---|---|---|---|---|---|---|---|---|---|
| 20090406 | 01:32:40.40 | 42N20.93 | 13E21.54 | 9.5 | 5.9 | 6.3 | 72 | 0.15 | 0.4 | 0.5 |
| 20090406 | 01:36:29.18 | 42N21.12 | 13E21.45 | 10.2 | 4.7 | | 73 | 0.06 | 0.4 | 0.6 |
| 20090406 | 02:37:04.35 | 42N22.17 | 13E19.45 | 8.4 | 4.6 | 5.1 | 83 | 0.13 | 0.6 | 0.3 |
| 20090406 | 03:56:45.69 | 42N19.85 | 13E23.61 | 8.9 | 4.1 | | 132 | 0.03 | 0.8 | 0.3 |
| 20090406 | 16:38:10.03 | 42N21.99 | 13E20.15 | 9.4 | 4.0 | | 88 | 0.05 | 1.0 | 1.0 |
| 20090406 | 23:15:36.90 | 42N28.28 | 13E23.21 | 13.3 | 5.0 | 5.1 | 134 | 0.10 | 0.7 | 0.9 |
| 20090407 | 17:47:37.56 | 42N18.76 | 13E28.81 | 13.4 | 5.4 | 5.5 | 68 | 0.26 | 0.4 | 0.7 |
| 20090408 | 22:56:50.37 | 42N30.21 | 13E21.82 | 11.0 | 4.3 | | 137 | 0.06 | 0.6 | 1.3 |
| 20090409 | 00:53:00.02 | 42N29.03 | 13E20.07 | 10.8 | 5.1 | 5.4 | 130 | 0.21 | 0.4 | 0.7 |

The local and moment magnitude are referred to Italian Seismic Bulletin (2003–2010) and Pondrelli et al. (2010), respectively

This test was carried out for 9 events with $M_L \geq 4.0$. P- and S-wave arrival times recorded by the strong motion network were collected and the standard locations were performed using the program HYPOELLIPSE (Lahr 1989). A general velocity model was selected (Italian Seismic Bulletin, 2003–2010) in order to test the accuracy of the hypocenter locations with respect to the geometry and density of the Italian strong-motion network.

Table 3 summarizes the calculated hypocentral parameters using only the strong-motion data. It is very interesting to note that low values of root-mean-square (rms) of the travel-time residuals and errors with respect to the vertical and horizontal coordinates (sez, seh) are obtained for all the examined events. The set of hypocenters has rms travel time residuals less than 0.3 s. Vertical and horizontal location errors are less than 1 km and even smaller. In Table 3, the local and moment magnitude are referred to Italian Seismic Bulletin (2003–2010) and Pondrelli et al. (2010), respectively.

The azimuthal gap, that provides information on the detection capability from station distribution, is less then 137° for all the considered events. The comparison between these locations and the ones obtained from the detailed relocations performed by Chiarabba et al. (2009) integrating data from all national and regional permanent stations and some of the temporary stations installed soon after the main event, does not show significant differences. In fact, the focal depth evaluated with strong-motion data differs at most by 2.5 km only for one event (2009/04/06, 23:15:36.90 UTC) whereas for the others the difference ranges from 0.01 to 1.5 km. As a matter of fact, these discrepancies fall mostly within the uncertainty range.

## 5 Importance of the L'Aquila records for the Italian strong-motion database

As discussed in the previous sections, the most important outcome of the DPC program for RAN upgrading was the network satisfactory performance and the rich set of recorded high-quality strong-motion data.

As a matter of fact, this dataset is unique in Italy for several aspects. The RAN network provided, for the mainshock and the most energetic aftershocks, the highest number of digital waveforms ever recorded in Italy, within a wide distance range: from short distances (less than 1 km) from the surface tip line of the causative faults, to large distances (~300 km), as shown in Fig. 8. Moreover, the 1175 recordings obtained only for the $M_L \geq 3.5$ events provide a 70% increment of waveforms with respect to the previous database within the same magnitude range. As a matter of fact, the Italian strong-motion archive, for the period 1972–2008, consisted of 3564 observations, among which less than 20% have been recorded with analogue instruments.

In particular, for the major seismic sequences (mainshock of $M_L > 5.5$), the database includes:126 waveforms of the 1976 Friuli sequence (Aoudia et al. 2000), 26 of the 1979 Norcia sequence (Brozzetti and Lavecchia 1994; Olivieri and Ekström 1999), 84 of the 1980 Irpinia sequence (Del Pezzo et al. 1983), 53 of the 1984 Sangro Valley sequence (Pace et al. 2002), 799 of 1997–1998 Umbria-Marche sequence (SSN—Monitoring System group 2002) and 62 of the 1998 Mercure sequence (Arrigo et al. 2006; Brozzetti et al. 2009). Table 4 lists, for each sequence, the closest recording stations from the epicentre and the number of available near-field recordings (less than 25 km from the epicenter) and gives information about the maximum recorded PGA and PGV.

The Friuli mainshock was recorded at a minimum epicentral distance of about 22 km (the Tolmezzo accelerogram of the May 6, 1976, 20:00:12 UTC, $M_L = 6.4$, $M_W = 6.4$), while the Irpinia mainshock at an epicentral distance of about 19 km (the Calitri waveform of November 23, 1980, 18:34:53 UTC, $M_L = 6.5$, $M_W = 6.9$) and the Umbria-Marche mainshock at an epicentral distane of about 6 km (the Colfiorito recordings of, September 26, 1997, 09:40:25 UTC, $M_L = 5.8$, $M_W = 6.0$).

Moreover, the AQV station belonging to the "Valle dell'Aterno" array, classified as B site according to Eurocode 8 (EC8, Comité Européen de Normalisation 2004), recorded some of the largest strong-motion parameters (PGA = 662.6cm/s$^2$, PGV = 45.5 cm/s, Arias intensity = 285.6 cm/s, Housner intensity = 94.5 cm) ever recorded in Italy. As a matter of fact, besides the very debated Colfiorito Casermette accelerogram (recorded during the Umbria-Marche seismic sequence, in a C site class, for an earthquake of $M_L 4.5$, at a epicentral distance of 1.7 km), that presents a PGA value of $\sim$ 712cm/ s$^2$, all the others already in the database show lower PGA values. For example, the observations that exceeded 500cm/s$^2$ are only three: the old strong motion signal recorded from the Ancona Rocca station (PGA = 569cm/s$^2$—B site class, at an epicentral distance of 7.7 km, during the Ancona earthquake occurred on 14/06/1972, $M_L = 4.7$), the one of Nocera Umbra station (PGA = 511cm/s$^2$—A site class, at an epicentral distance of 7.8 km, during the Umbria-Marche earthquake on April 3, 1998, $M_L = 5.3$) and Nocera Umbra 2 station (PGA = 538cm/s$^2$—C site class, at an epicentral distance of 10 km, during the Umbria-Marche earthquake on October 6, 1997, $M_L = 5.4$). Conversely, the maximum values of PGA and PGV recorded for the listed sequences in Table 4 are always less then 500cm/s$^2$.

## 6 Current and future work

Following the lesson learned by L'Aquila earthquake, some efforts have been made to further improve the station communication system and the density of stations in urban areas. In fact, in order to obtain as much as possible reliable information on severe earthquakes from instrumental data and to increase the effectiveness of the emergency response a higher number of observation stations and a more robust communication system are needed.

The future developments will mainly concern the transmission system, the installation of new arrays and the geophysical/geotechnical characterization of the station sitings.

Presently, DPC is optimizing the time response of the network and its reliability in providing information in near-real time. Moreover, DPC is evaluating the possibility of promoting a new project at the national scale level to develop local arrays in urban areas subject to a high

**Table 4** List of major (mainshock magnitude $\geq 5.5$) seismic sequences occurred in Italy from 1972 to 2008

| Seismic sequence | Date-Time | Ml Mainshock | ntot | dmin km | dmax km | nrec d < 25 km | PGAmax cm/s$^2$ | PGVmax cm/s |
|---|---|---|---|---|---|---|---|---|
| 1976 Friuli | | | | | | | | |
| 1st Shock | 06/05/1976 20.00.12 | 6.4 | 10 | 21.7 | 195.0 | 1 | 335.640 | 32.602 |
| 2nd Shock | 11/09/1976 16.35.01 | 5.8 | 6 | 19.5 | 91.9 | 2 | 230.902 | 22.859 |
| 3rd Shock | 15/09/1976 3.15.18 | 6.1 | 6 | 11.6 | 180.9 | 3 | 260.731 | 10.845 |
| 4th Shock | 15/09/1976 9.21.18 | 6.0 | 11 | 8.5 | 187.8 | 4 | 345.196 | 24.538 |
| 1979 Norcia | 19/09/1979 21.35.37 | 5.5 | 8 | 9.3 | 50.1 | 2 | 199.159 | 13.208 |
| 1980 Irpinia | 23/11/1980 18.34.53 | 6.5 | 22 | 18.9 | 143.4 | 3 | 185.418 | 36.118 |
| 1984 Sangro Valley | | | | | | | | |
| 1st Shock | 07/05/1984 17.49.43 | 5.9 | 14 | 10.2 | 74.1 | 2 | 144.254 | 12.516 |
| 2nd Shock | 11/05/1984 10.41.48 | 5.7 | 11 | 8.5 | 54.6 | 6 | 198.320 | 9.320 |
| 1997–1998 Umbria-Marche | | | | | | | | |
| 1st Shock | 26/09/1997 0.33.12 | 5.6 | 45 | 2.8 | 125.8 | 7 | 465.751 | 24.536 |
| 2nd Shock | 26/09/1997 9.40.25 | 5.8 | | 5.9 | 101.3 | 5 | 490.172 | 33.780 |
| 3rd Shock | 14/10/1997 15.23.09 | 5.5 | | 11.8 | 113.2 | 11 | 175.092 | 12.671 |
| 1998 Mercure | 09/09/1998 11.28.00 | 5.6 | 5 | 6.6 | 28.4 | 3 | 243.592 | 13.915 |

dmin and dmax = minimum and maximum epicentral distance of the triggered stations; ntot = total number of available recordings for the mainshock seismic event; nrec = number of waveforms of the mainshock recorded at an epicentral distance less than 25 km; PGAmax, PGVmax = peak ground acceleration, peak ground velocity for maximum component referred to the waveforms of the mainshock seismic risk and located in sedimentary basins in order to obtain in the near future valuable information on site effects at such locations.

Further efforts are also underway in order to characterize the station sites by supporting and managing project activities in this field. In fact, even if the RAN stations produced high-quality data, strong-motion site classification according to the geotechnical EC8 classification was based on the Italian geologic map at the 1:100000 scale and only in few cases (e.g., Friuli and in Campania regions or stations which recorded large-magnitude events and for other few stations like AQV station belonging to the Aterno Valley array) on local surveys.

Since the L'Aquila earthquake the DPC is systematically investigating the site-characterization of the strong-motion stations in the Central Apennines. This objective was also part of the microzonation work that has been extended to the Municipalities areas that experienced a macroseismic intensity equal or greater than MCS VII on the occasion of L'Aquila earthquake.

The AQA, AQG, AQV, AQP, AQM and AQK RAN sites, have been investigated during these microzonation studies and some geophysical and geotechnical surveys have been carried out.

## 7 Conclusions

The national digital strong-motion instrumentation program in Italy started in 1997, and significant advances have been made during the past decade by the Department of Civil Protection in upgrading the existing strong motion instrumentation (Gorini et al. 2010), network infrastructures and in making its geographic coverage more dense and uniform.

The April 6, 2009 L'Aquila earthquake has been the first real occasion to evaluate the efficiency of RAN during a severe damaging seismic event and its aftershock sequence. The network density in the epicentral area, the high dynamic range of digital RAN stations, the low values of settled trigger levels and the rapid data recovery with respect to analogue instruments, made it possible to record high-quality strong-motion waveforms of the L'Aquila mainshock, that were preliminary distributed six days after the main event, together with $M_L \geq 4$ event recordings occurred up to April 13, 2009, via the DPC website (http://www.protezionecivile.it/) and via the Itaca website (http://itaca.mi.ingv.it/ItacaNet/).

The features of the recorded near-field waveforms are of great interest to seismologists as well as to earthquake engineers as demonstrated by past studies (Somerville 2005; Yushan et al. 2005; Tong et al. 2007). An estimation of rupture directivity effects and permanent ground displacements, besides the identification of acceleration pulses in near-fault ground motion, are useful for seismic source characterization but also for safe, cost-effective design and construction of structures in earthquake-prone regions. For these reasons the L'Aquila strong-motion dataset has been already used by many authors in scientific papers and in technical works. For example, near-source waveforms were important for the focal depth control and for determining the rupture history, the directivity effects and the slip distribution of the mainshock (Cirella et al. 2009; Pino and Di Luccio 2009; Akinci et al. 2010).

Furthermore, Rupakhety and Sigbjörnsson (2009) evaluated, with strong-motion data, the permanent ground displacements at the stations of the "Valle dell'Aterno" array, whereas other authors investigated site effects (Bindi et al. 2009) and rupture directivity effects that could lead to an increase of the structural seismic demand (Chioccarelli and Iervolino 2010). Recently, near-field features have been shown to cause significant strength, displacement and ductility demand in structures. Moreover these data, recorded in such wide distance range, introduce an important constraint to the attenuation relationships that heavily depend on the extrapolation from larger distances and smaller magnitude earthquakes. Besides, records from the local basins and from the fast-growing urban/industrial areas, along with the data from the temporary network deployed close to the dam, give important information on local site and dynamic structure response.

The rate and high quality of recordings, provided by strong-motion stations, demonstrate that the density and advances in recording systems substantially increase the range of signals that can be recorded by strong-motion instruments. As an immediate consequence, the use of strong-motion data is not restricted anymore to few specific interests in engineering and seismology only.

The number of accesses to the DPC and to the Itaca websites (the number of accesses to Itaca was 18863 during the period from January 2009 to December 2009) witnesses the great interest of the RAN strong-motion data. Such efforts will certainly lead to a further significant improvement in strong-motion monitoring, high-quality data collection and emergency response in Italy.

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