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# Abruzzo earthquake of April 2009: seismic sequence, ground motion attenuation, simulation scenario and losses

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***ABSTRACT*** The April 6, 2009 Abruzzo earthquake was the third strongest earthquake recorded in Italy since 1972, after the 1976 Friuli ($M_w$ 6.4), and 1980 Irpinia ($M_w$ 6.9) ones. This event, considering also the long aftershock sequence, produced the largest amount of experimental data ever obtained in Italy for a single earthquake, including broad-band and strong ground motion recordings, GPS and interferometry data, macroseismic surveys, microzonation mapping, damage surveys, etc. Globally, the earthquake affected a territory of about 2,400 km$^2$ with a population of 140,000, causing high death toll (308 victims and 1,600 injured) and damage (about 23,000 unusable buildings), in particular, to the largest town in the area, L'Aquila, where the macroseismic intensity reached IX degree of the EMS-98 scale. The main shock was recorded close to the centre of L'Aquila by fifty-eight digital accelerometers with very high values of PGA (0.3-0.65 g). The strong motion recordings are clearly affected by source effects and show a SE directivity, with a systematic decrease of PGA and PGV at sites located in the backward direction of the rupture propagation. The predictive equations available in literature, underestimate the PGA values closest to the epicenter and overestimate those in the backward directivity direction. The overestimation of the far data is reduced when considering PGV and lower frequency response spectral values. The response spectra of the recordings closest to L'Aquila town, show very high values of acceleration in the interval 2-10 Hz, corresponding to the fundamental frequencies of most of the buildings in the area. The acceleration spectra, in the short period range, are higher than those considered by the new Italian building code NTC-08. The simulation scenario, available about 30 minutes after the main shock and giving preliminary estimates of the expected damage and losses, underestimates the effective losses subsequently obtained from the field. In this paper, the characteristics of the strong ground motions recorded during the Abruzzo seismic sequence and of their attenuation with distance are presented together with a comparison of the loss simulation scenario with the damage building surveys performed after the earthquake.

**Key words:** strong motion records, GMPE, response spectra, loss simulation scenario.

## 1. Introduction

An earthquake of $M_w$ 6.3 occurred on April 6, 2009, at 03:33 a.m. local time, in the Abruzzo region (central Italy), close to the city of L'Aquila. The earthquake nucleated at a shallow depth of 9 km and ruptured a NW-SE oriented normal fault dipping about 55° towards the SW and passing

 

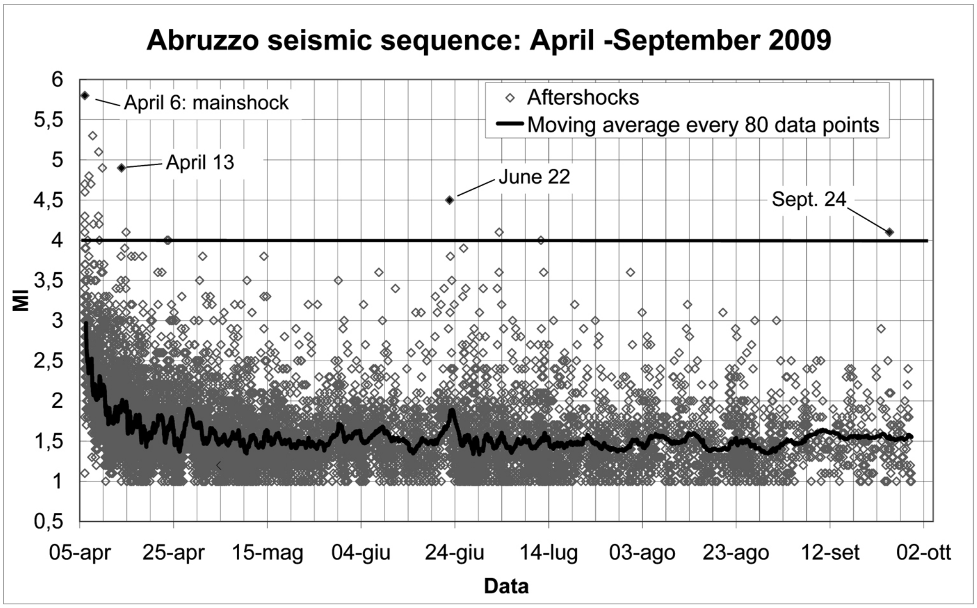


Fig. 1 - Distribution of the 11,617 aftershocks with $M_L \geq 1$ in the period April-September 2009. Highlighted some of the $M_L \geq 4$ events. Aftershocks with $M_L > 3$ are 198, with $M_L > 4$ are 20, and with $M_L > 5$ are 2.

directly beneath the town of L'Aquila, lying on the hanging wall at about 5 km from the epicenter (http://portale.ingv.it; Chiarabba *et al*., 2009; Messina *et al*., 2009).

This event, considering also the long aftershock sequence, produced the largest amount of experimental data ever obtained in Italy for a single earthquake: broad-band and strong ground motion recordings, GPS and interferometry data, macroseismic surveys, damage surveys, etc.

The close proximity of the causative fault to the city of L'Aquila caused several collapses of historical masonry buildings in the town centre, including the prefecture and many major historic churches. While most of L'Aquila's medieval structures were badly affected by the earthquake, many of its modern buildings suffered also a significant level of damage.

Smaller villages, within about 50 km from the epicenter were also heavily damaged. The historic centers of villages in the Aterno River Valley SE of L'Aquila (Onna, Paganica, and Castelnuovo) were very badly damaged, with shaking intensities of up to IX degree on the EMS scale (Galli *et al*., 2009). On the contrary, the damage did not exceed EMS intensity VI nearly anywhere in the area NW of L'Aquila. This south-eastward elongation of the damage pattern probably reflects a combination of rupture directivity and lithostratigraphic amplification effects (Akinci *et al*., 2009).

Globally, the earthquake affected a territory of about 2,400 km$^2$ with a population of 140,000 causing high death toll (308 victims and 1,600 injured) and damage (about 23,000 unusable buildings). One month after the main event, a total of about 64,800 people where displaced from their homes with approximately 32,100 people living in tents and 32,700 lodged in hotels along the Adriatic coast (www.protezionecivile.it).

L'Aquila is well known as an area of high seismic hazard (Stucchi *et al*., 2004; Pace *et al*., 2006); over the past 700 years at least 5 damaging earthquakes occurred in the region, including the two

Table 1- Aftershocks with local magnitude above 4 in the period April-September 2009.

| Date and time (UTC) | Lat. N (°) | Lon. E (°) | Depth (km) | $M_L$ | Source |
|---|---|---|---|---|---|
| 2009-04-06 01.32.41 | 42.348 | 13.380 | 8.8 | 5.8 | Paganica fault |
| 2009-04-06 01.36.29 | 42.355 | 13.342 | 9.7 | 4.7 | Paganica fault |
| 2009-04-06 01.40.51 | 42.418 | 13.408 | 11.0 | 4.1 | Paganica fault |
| 2009-04-06 01.41.33 | 42.387 | 13.316 | 9.1 | 4.3 | Paganica fault |
| 2009-04-06 01.42.50 | 42.300 | 13.429 | 10.5 | 4.2 | Paganica fault |
| 2009-04-06 02.37.04 | 42.366 | 13.340 | 10.1 | 4.6 | Paganica fault |
| 2009-04-06 16.38.09 | 42.362 | 13.333 | 10.2 | 4.0 | Paganica fault |
| 2009-04-06 23.15.37 | 42.451 | 13.364 | 8.6 | 4.8 | Monti della Laga fault |
| 2009-04-07 09.26.28 | 42.342 | 13.388 | 10.2 | 4.7 | Paganica fault |
| 2009-04-07 17.47.37 | 42.275 | 13.464 | 15.1 | 5.3 | Paganica fault |
| 2009-04-07 21.34.29 | 42.380 | 13.376 | 7.4 | 4.2 | Paganica fault |
| 2009-04-08 22.56.50 | 42.507 | 13.364 | 10.2 | 4.3 | Monti della Laga fault |
| 2009-04-09 00.52.59 | 42.484 | 13.343 | 15.4 | 5.1 | Monti della Laga fault |
| 2009-04-09 03.14.52 | 42.338 | 13.437 | 18.0 | 4.2 | Paganica fault |
| 2009-04-09 04.32.44 | 42.445 | 13.420 | 8.1 | 4.0 | Monti della Laga fault |
| 2009-04-09 19.38.16 | 42.501 | 13.356 | 17.2 | 4.9 | Monti della Laga fault |
| 2009-04-13 21.14.24 | 42.504 | 13.363 | 7.5 | 4.9 | Monti della Laga fault |
| 2009-04-14 20.17.27 | 42.530 | 13.288 | 10.4 | 4.1 | Monti della Laga fault |
| 2009-04-23 15.14.08 | 42.247 | 13.492 | 9.9 | 4.0 | Paganica fault |
| 2009-04-23 21.49.00 | 42.233 | 13.479 | 9.3 | 4.0 | Paganica fault |
| 2009-06-22 20.58.40 | 42.446 | 13.356 | 14.2 | 4.5 | Monti della Laga fault |
| 2009-07-03 11.03.07 | 42.409 | 13.387 | 8.8 | 4.1 | Paganica fault |
| 2009-07-12 08.38.51 | 42.338 | 13.378 | 10.8 | 4.0 | Paganica fault |
| 2009-09-24 16.14.57 | 42.453 | 13.330 | 9.7 | 4.1 | Monti della Laga fault |

largest events in the area: in the year 1461 with *I* =X MCS and in the year 1703 with *I*=XI MCS (Rovida *et al*., 2009).

In this paper, the characteristics of the strong ground motions recorded during the Abruzzo seismic sequence and of their attenuation with distance are presented together with a comparison of the response spectra with former and recent Italian building codes. Loss simulation scenarios and damage assessment are also described.

## 2. Seismic sequence

The main shock was preceded by a prolonged swarm-like sequence of foreshocks that began in December 2008, and was followed by several medium-high magnitude aftershocks. Fig. 1 shows the time distribution of the aftershocks of the Abruzzo sequence (http://iside.rm.ingv.it/iside/standard/index.jsp). The majority of the aftershocks with $M_L$ above 4

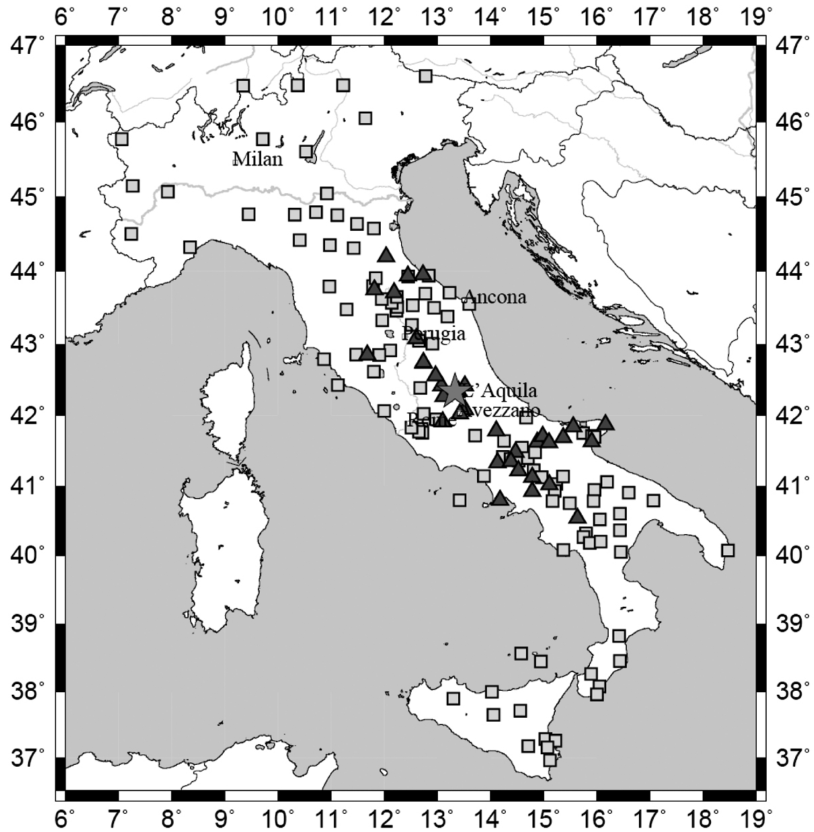


Fig. 2 - Distribution of the stations recording the main shock: 58 strong motion stations (RAN network) are indicated by triangles and 112 broad-band seismometers (INGV network), are indicated by squares.

occurred in the first three days after the main event; the decay of size and frequency with time, occurred with a pattern that follows Omori's law (Omori, 1894) closely enough, with significant reprises at the end of June and September 2009. Table 1 lists the aftershocks with local magnitude above 4 differentiating between two sources: the Paganica fault (Messina *et al*., 2009) generating the main shock, and already described in the introduction, and the Monti della Laga fault (Galadini and Galli, 2003), another NW-SE oriented normal fault activated starting from the afternoon of April 6 and giving rise to an aftershock pattern located about 15 km NE of L'Aquila. In the period April-September 2009, the two strongest aftershocks occurred on April 7 (17:47 UTC, 11 km SE of L'Aquila, $M_L$=5.3, $M_w$=5.6) and on April 9 (00:52 UTC, 14 km NE of L'Aquila $M_L$=5.1, $M_w$=5.4). A month after the main event, the records counted more than 100 significant aftershocks ($3.0<M_w<5$), and several thousand events of lower magnitude. The threshold of local magnitude 4, after April 23, was exceeded only four times in June, July and September (highlighted in grey in Table 1).

## 3. Strong motion records

As shown in Fig. 2, the main shock was recorded by 57 accelerometric stations belonging to the Italian Strong Motion Network (RAN, http://itaca.mi.ingv.it/ItacaNet), with epicentral distances between 4 and 280 km, plus an accelerometer belonging to the Istituto Nazionale di Geofisica e

Table 2 - Strong motion parameters for the largest horizontal component of the 15 recordings with PGA> 25 cm/s$^2$ sorted in descending order of PGA.

| Station Name | Station code | Rjb distance (km) | Repi distance (km) | EC8 site class | PGA (cm/s$^2$) | PGV (cm/s) | Arias Intensity (cm/s) | Housner Intensity (cm) | Duration Vanm. (s) | Duration Trif. (s) |
|---|---|---|---|---|---|---|---|---|---|---|
| V. Aterno - Centro Valle | AQV | 0 | 4.9 | B | 646.1 | 42.83 | 285.7 | 94.5 | 3.1 | 7.8 |
| V. Aterno - Colle Grilli | AQG | 0 | 4.4 | A | 506.9 | 35.54 | 137.0 | 92.2 | 2.9 | 8.6 |
| V. Aterno - F. Aterno | AQA | 0 | 4.6 | A | 435.6 | 32.03 | 175.0 | 86.1 | 4.8 | 7.7 |
| Aquila parcheggio | AQK | 0 | 5.6 | B | 347.2 | 36.21 | 128.9 | 68.1 | 4.8 | 15.5 |
| Aquila Castello (INGV) | AQU | 0 | 5.8 | A | 309.5 | 35.00 | 71.0 | 78.0 | 5.0 | 7.5 |
| Gran Sasso (Assergi) | GSA | 8.6 | 18.0 | A | 148.2 | 9.84 | 44.0 | 17.8 | 3.6 | 8.9 |
| Celano | CLN | 20.0 | 31.6 | A | 89.1 | 6.64 | 9.5 | 14.3 | 3.9 | 7.7 |
| Avezzano | AVZ | 25.1 | 34.9 | C | 67.7 | 11.28 | 9.7 | 27.3 | 6.5 | 19.0 |
| Ortucchio | ORC | 37.3 | 49.3 | A | 64.2 | 5.86 | 7.4 | 17.8 | 5.2 | 12.3 |
| Montereale | MTR | 15.9 | 22.4 | B | 61.6 | 3.53 | 5.8 | 9.7 | 6.9 | 15.4 |
| Sulmona | SUL | 43.4 | 56.4 | A | 33.6 | 3.73 | 1.0 | 7.0 | 6.7 | 17.7 |
| Chieti | CHT | 52.2 | 67.0 | B | 29.4 | 7.91 | 3.8 | 10.3 | 9.5 | 31.7 |
| Gran Sasso (Lab. INFN) | GSG | 13.7 | 22.6 | A | 29.4 | 3.04 | 0.9 | 4.9 | 4.9 | 11.7 |
| Famignano | FMG | 16.6 | 19.3 | A | 26.3 | 2.61 | 1.2 | 6.4 | 8.4 | 21.0 |
| Antrodoco | ANT | 19.3 | 23.0 | A | 26.0 | 2.47 | 1.8 | 6.9 | 8.9 | 22.7 |

Vulcanologia (INGV) and located in the center of L'Aquila, close to the castle (light blue triangle in Fig. 3). In addition, the broad-band seismometers of the INGV network (http://cnt.rm.ingv.it) provided 112 not saturated recordings, in the distance range 50-720 km. All accelerometric stations were equipped with digital instruments (Kinemetrics Episensor FBA-3 with ETNA 18 bits or K2-Makalu 24 bits digitizers). Fig. 3 shows the location of the strong motion stations closest to the epicenter together with the surface projection of the ruptured fault (Cirella *et al*., 2009). It has to be remarked that all these eight stations fall inside the hanging wall of the fault surface projection (Joyner-Boore distance equal to zero) and, apart from AQU and AQK, correspond to the Valle dell'Aterno array. Only two of the eight stations, AQF and AQP (black triangles in Fig. 3) did not record the main shock due to low power supply of the solar panels during the night of April 6. The stations AQP and AQF recorded the following aftershocks starting from April 7. The AQM station deserves particular mention since, just for the main shock, it went off scale above 1g both in the vertical and horizontal directions. Recent tests revealed that the metal box containing the instrument was rusty and interacting with the pillar supporting the sensor, so that the main shock time histories of the AQM cannot be considered reliable and have not been taken into consideration in the present study.

Strong-motion parameters of the main shock for the 15 recordings with a peak ground acceleration (PGA) larger than 25 cm/s$^2$ sorted in descending order of PGA are reported in Table 2. The first five columns report the station name, station code, distance from the surface projection of the fault (Joyner-Boore distance Rjb), epicentral distance (Repi), and soil condition of the stations, according to the Eurocode EC8 classification, derived from the available geological/geophysical

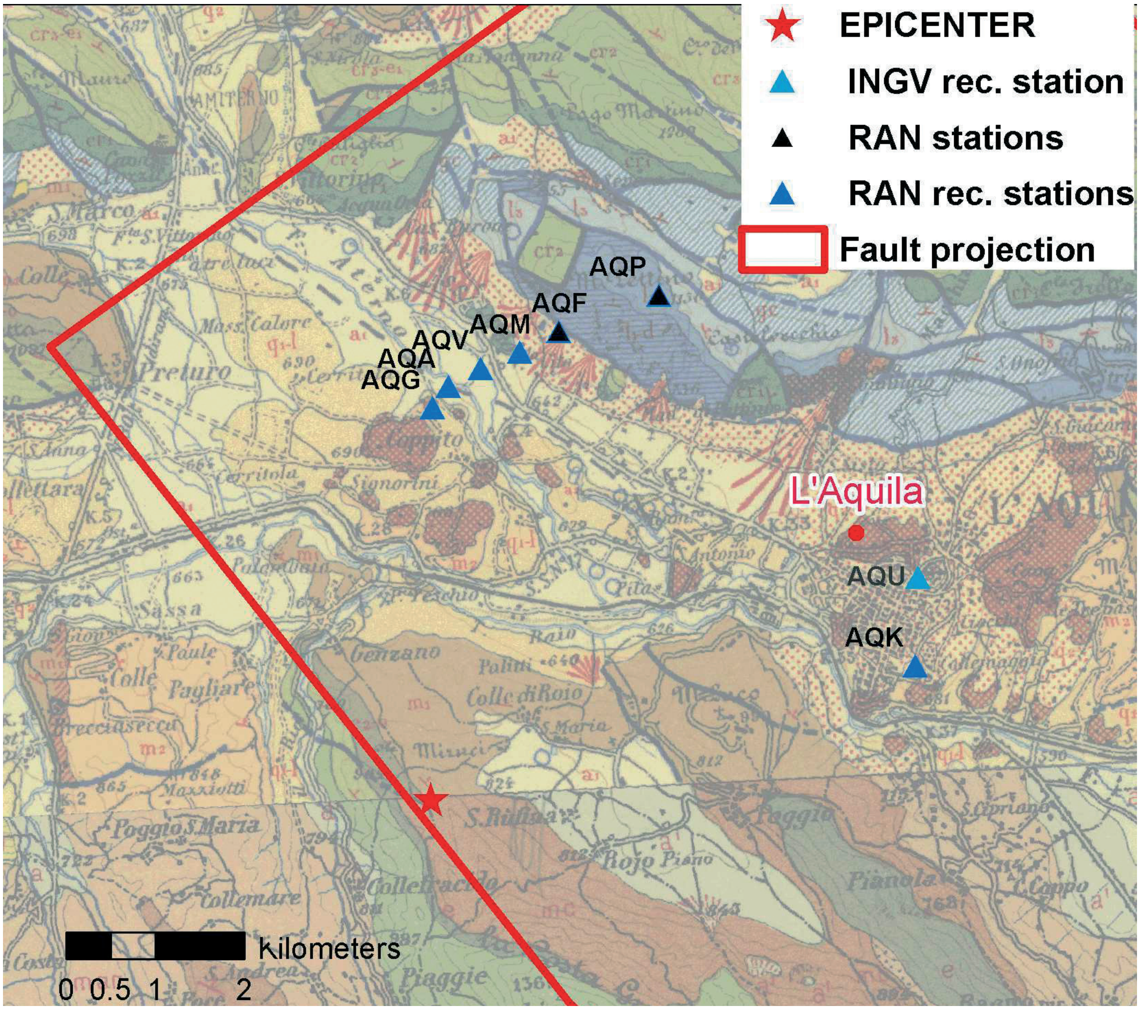


Fig. 3 - Strong motion stations closest to the epicentre (triangles) together with the surface projection of the ruptured fault [red line from Cirella *et al*. (2009)] and the epicentre of the main shock (star).

information (Ameri *et al*., 2009). The strong-motion parameters, for the largest value of the horizontal components, are PGA, PGV, Arias Intensity (Arias, 1970), Housner Intensity (Housner, 1952) and two significant durations according to the definition of Vanmarcke (Vanmarcke and Lai, 1980) and Trifunac (Trifunac and Brady, 1975). The high value of PGA (> 0.3 g) for all the stations at zero distance from the fault and the very short duration (2-5 s according to the Vanmarcke definition that does not overestimate the strong phase duration as the Trifunac definition does) compatible with a high frequency content of the recordings that will be confirmed from the response spectra analysis should be remarked.

## 4. Ground motion prediction equations

The horizontal PGAs and response spectra values from processed data of the L'Aquila earthquake

Table 3 - Main features of the selected GMPEs.

| GMPE | R-range type. | M-range type | Style of faulting | H comp. selection | Response variables | N° of records. | Area |
|---|---|---|---|---|---|---|---|
| **SP96 - Sabetta & Pugliese BSSA (1996)** | 1.5 -100 km Repi, $R_{jb}$ | 4.6-6.8 Ms(>5.5) ML(≤5.5) | strike-slip 7% normal 49% reverse 44% | larger PGA larger PSA | PGA, PGV PSA 0.25-25 Hz | 95 | Italy 1976-1984 |
| **AB07 - Akkar & Bommer EESD (2007)** | 1-100 km $R_{jb}$ | 5.0-7.6 Mw | strike-slip, normal, reverse (scale fact. incl.) | geom. mean | PGA, PGV PSA 0.25 -20 Hz | 532 | Europe Middle East 1973-2003 |
| **MAL08- Malagnini et al. GRL (2008)** | 10-200 km $R_{hypo}$ | 2.0-6.0 Mw | normal | both components | PGA, PGV PSA 0.3, 1, 3.3 HZ | 6000 (mostly seismograms Brune model, RVT) | Central Italy weak and s.m. data |
| **BA08 - Boore and Atkinson NGA (2008)** | 0 - 400 km $R_{jb}$ | 4.2-7.9 Mw | strike-slip, normal, reverse (scale fact. incl.) | geom. mean | PGA, PGV, PSA 0.1-100 Hz | 1574 | World, mainly WNA and Taiwan 1940-2007 |
| **CF08 – Cauzzi and Faccioli J. Seism (2008)** | 5-150 km $R_{hypo}$ | 5.0-7.2 Mw | strike-slip, normal, reverse (scale fact. incl.) | both components | PGA, Disp spect 0.05-20 Hz | 1155 | Worldwide DIGITAL (82% K-NET) 1995-2005 |

have been compared with some ground motion prediction equations (GMPEs), selected on the basis of the following criteria: wide use for attenuation studies in Italy (Sabetta and Pugliese, 1996 - SP96); most recent equation for the European and Middle East area (Akkar and Bommer, 2007 - AB07); implementation of the Italian INGV shake maps (Malagnini *et al*., 2008 - MAL08); Next Generation Attenuation (NGA) models in California (Boore and Atkinson, 2008 - BA08); use of a large number of worldwide digital data (Cauzzi and Faccioli, 2008 - CF08). The main features of the above relationships are summarized in Table 3.

Fig. 4 shows the largest horizontal PGAs (displayed with different symbols according to the EC8 site classification of the station) recorded for the main shock by the 58 strong motion stations (RAN+INGV) and by the 112 INGV broad-band stations that did not saturate. The recorded values are compared with the GMPEs adopting the epicentral distance as reference measure [hypocentral distance in case of Cauzzi and Faccioli (2008) and Malagnini *et al*. (2008)]. In this and the following figures as well, appropriate empirical conversion rules have been adopted to ensure consistency among different GMPEs in terms of distance definition, magnitude scale and selection of horizontal components of ground motion (Scherbaum *et al*., 2004; Sabetta *et al*., 2005). All the GMPEs are computed for rock site conditions and the soil classification is applied only for the RAN stations. The first remark about Fig. 4 is the very good agreement between strong motion and broad-band data converted into PGA. Secondly, although the soil classifications are derived from geological/geophysical information (Ameri *et al*., 2009) and not based directly on Vs30 measurements, a sistematic trend of PGA due to the EC8 soil type classification (the limits of a site classification only based on Vs30 are by now well-known) is not evident. Thirdly, there is a remarkable over prediction by GMPEs of the data between 20 and 100 km becoming stronger at distances of more than 100-200 km that are the limit of applicability for the majority of GMPEs. Concerning large distance data, it is interesting to note that the simple inclusion of an anelastic

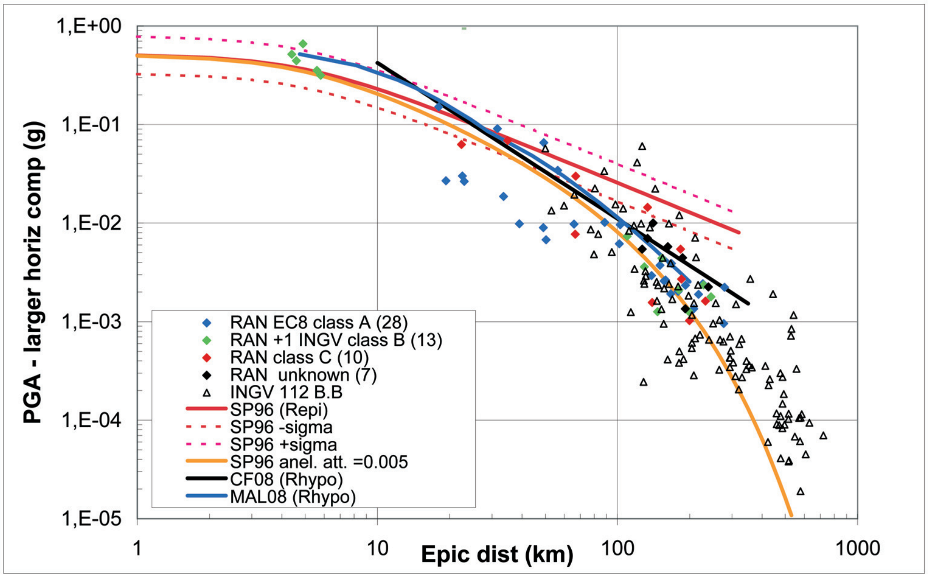


Fig. 4 - PGA values of the main shock recorded by the 58 accelerometers of the RAN network (http://itaca.mi.ingv.it/ItacaNet) and by the broad-band seismometers of the INGV network (http://cnt.rm.ingv.it) compared with some GMPEs computed for rock site conditions (see Table 3 for details).

coefficient (0.005·distance) in the SP96 (orange curve in Fig. 4) gives rise to a very good fit with data of distances of up to and more than 500 km where in fact only the PGAs derived from seismometers are available. In practice, only recently did the availability of high sensitivity digital instruments make very low ground accelerations recorded at large epicentral distances accessible; they also show the effect of the anelastic attenuation, generally not considered in common GMPEs using strong motion data up to distances of 100-200 km.

In Fig. 5a, the largest horizontal PGA values are plotted as a function of the fault distance (Rjb) and compared with the values of the empirical regressions predicted by SP96, BA08, and AB07 with their confidence limits. All GMPEs are plotted for stiff soil and normal fault conditions. The use of a more appropriate distance measurement for the near field stations, emphasizes the large PGA values at zero fault distance compared to the GMPE prediction. The data lying at zero distance on the hanging wall of the fault, are under-predicted by all the GMPEs, even if they are included in the uncertainty bounds of the AB07 equation. In the intermediate and large distance range (10-300 km), the recorded data are overestimated by all the GMPEs, with the BA08 equation providing the best fit at large distances because it includes an anelastic attenuation coefficient. This overestimation can be partially explained by a backward directivity effect because many of the low PGA values correspond to stations located along the NW direction with respect to the fault slipping in the SE direction (Akinci *et al*., 2009). The agreement of the GMPEs with the recorded data is much better in the case of the PGV (Fig. 5b) because less affected by the high frequency anelastic attenuation. This effect is even more evident in Fig. 6 where the attenuation of the response spectral values at two different periods, 0.1 and 1 s, compared with SP96 and AB07 are shown. The behaviour of 0.1 s data (Fig. 6a) is, as expected, quite similar to that of the PGA while the 1 s spectral values (Fig. 6b) are in good

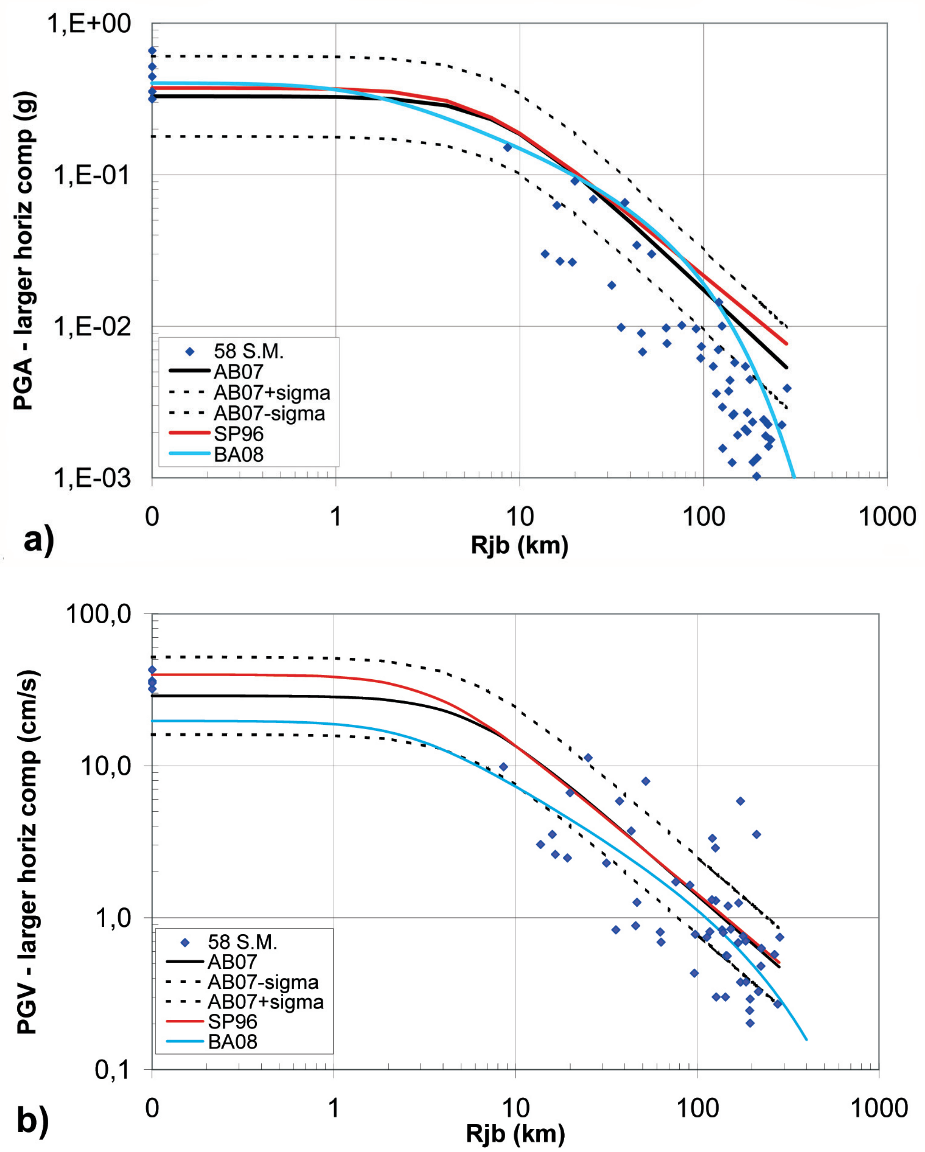


Fig. 5 - PGA and PGV values of the main shock recorded by the 58 accelerometers of the RAN network plotted as a function of the distance from the surface projection of the fault (Rjb) and compared with attenuation equations SP96, BA08, and AB07 with its confidence limits (dashed lines).

agreement with the GMPEs. Once again the effect of anelastic attenuation, acting mainly on high frequencies is recognizable.

## 5. Acceleration response spectra and comparison with the Italian building code

The E-W component of the pseudo-acceleration response spectra at 5% damping for the two stations closest to L'Aquila (AQK and AQU) and for some stations of Valle dell'Aterno array (AQG

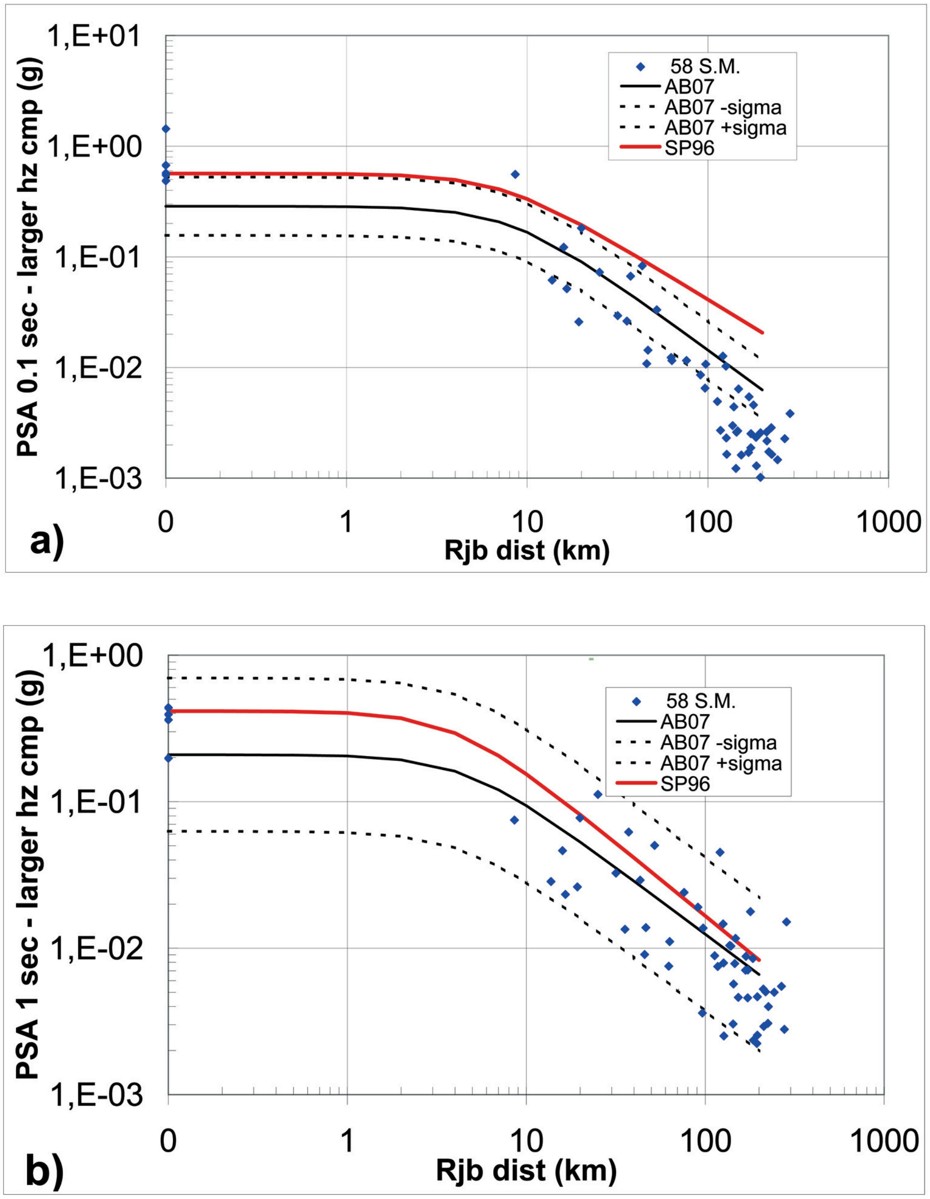


Fig. 6 - Pseudo acceleration response spectral values at periods of 0.1 (a) and 1 s (b) compared with attenuation equations SP96 and AB07 with their confidence limits (dashed lines).

and AQV), are shown in Fig. 7 together with the response spectrum derived from the SP96 for the same magnitude and distance. The large variability of the response spectra of stations located at zero distance from the fault is remarkable; this is probably due not only to different site conditions but also to source effects and to the interference of seismic waves in the near field. Except for a two-story building in the immediate vicinity of the AQV station, the parts of the Aterno Valley close to the AQG and AQV are not built up, and the motions recorded at these two stations may not be representative

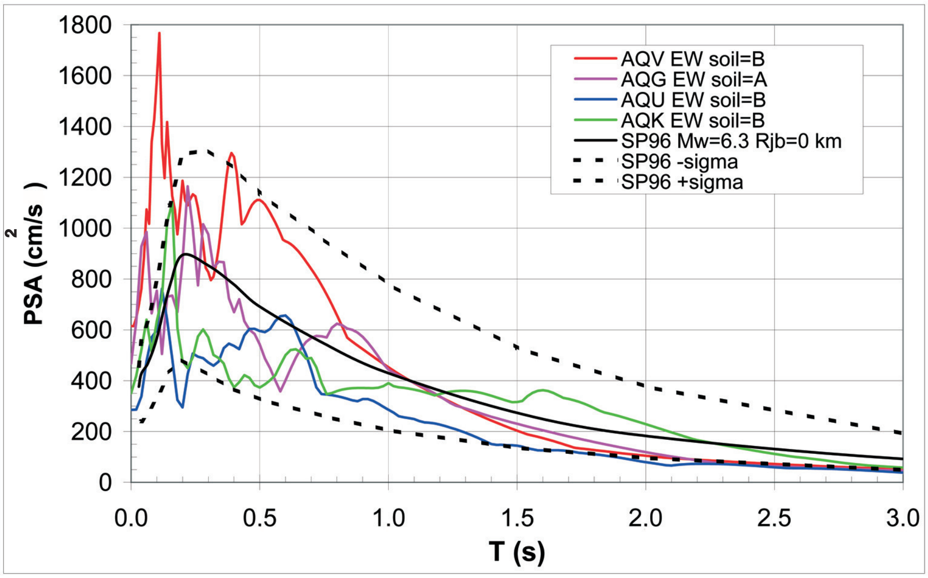


Fig. 7 - Pseudo-acceleration response spectra of some of the stations closest to the epicentre (AQG, AQV) and to L'Aquila downtown (AQU, AQK) compared with the spectrum derived from SP96 for the same magnitude and distance. Dashed curves correspond to the confidence limits of ± 1 standard deviation of the SP96 spectrum.

of the motions in L'Aquila. Therefore, in the absence of data from the historical centre, the ground motions that the structures within the town of L'Aquila most likely experienced, are best represented by those recorded at stations AQK and AQU, both within the perimeter of the town and only ~1 km apart (Fig. 3). Station AQV provides very high values at short periods, reaching about 1.8 g at 0.1 s, while AQK, with more moderate values at short periods, exhibits large values at long periods, in agreement with the site amplification at 0.6 Hz (1.66 s) resulting from the literature (De Luca *et al.*, 2005) and from the H/V spectral ratios obtained for the main shock and aftershocks (Ameri *et al.*, 2009). The response spectra indicate that the shaking is particularly strong at periods (0.1-0.5 s) that are typical of the 1-5 story buildings, both in L'Aquila and throughout the region. Such large values of shaking at short periods are probably due to source effects at zero distance from the fault because, at distances larger than 10 km, they decrease below the values predicted by the GMPEs (Fig. 6a). Finally, Fig. 7 shows that the spectrum predicted by the SP96, which shows a quite lower median value with respect to the recorded spectra, includes even the highest spectral values recorded in the near field well inside ± 1 sigma bounds.

Fig. 8 shows the acceleration response spectra of the stations providing the highest values, compared to the Italian building code NTC-08 (Decreto, 2008) which is based on uniform hazard spectra (UHS) calculated for a grid of 11,000 points covering all the national territory. The spectra presented in the figure correspond to a smoothing of the UHS for the city of L'Aquila calculated for different site conditions (A,B,C as EC8 classification) and return periods of 475 and 2475 years. As most of the modern buildings in the area likely used the 1996 code and not the recent 2008 code, the former Italian code (Decreto, 1996) for the 2$^{nd}$ category to which L'Aquila was assigned, is also shown with appropriate adjustments to make it comparable with elastic spectra and NTC-08. It

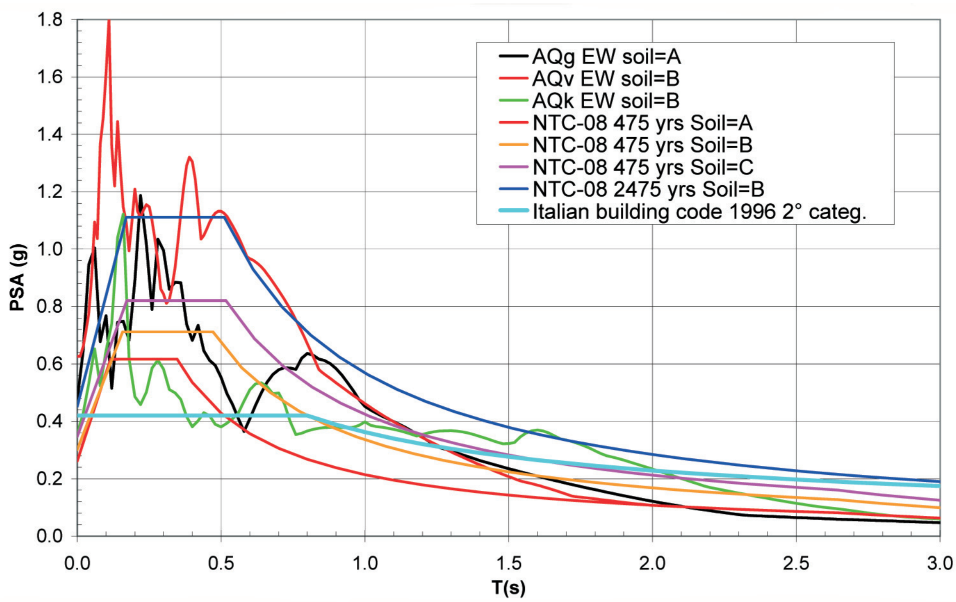


Fig. 8 - Response spectra at 5 % damping for the 3 highest PGA recording stations and comparison with 1996 and 2008 Italian code spectrum for different return periods and soil classes. Assumptions for the adjustment of 1996 code spectrum are: ductility factor 4 and limit state conversion factor 1.5.

appears evident how the recorded spectra largely exceed the design spectra, particularly in the high frequency range and even for a return period as large as 2475 years.

## 6. Simulation scenario and losses

A simulation scenario (SIGE), which is routinely performed by the Italian Department of Civil Protection (Bramerini *et al*., 2006), giving preliminary estimates of the expected damage and losses, was available about 30 minutes after the main shock. Fig. 9 just shows an example of the maps and data produced by the simulation; it has to be remarked that, due to the large uncertainties in the ground motion attenuation, building inventory and Damage Probability Matrices, the simulation scenario aims only at giving the order of magnitude of the expected losses and provides a large difference between minima and maxima of the estimates, as better illustrated in Table 4 where the estimates are compared with the values resulting from the extensive damage assessment performed after the earthquake. After completion of the building inspection (February 2010), more than 80,000 building surveys were performed for a total of 71,302 private buildings giving a percentage of about 52% safe and 32% unsafe buildings (www.protezionecivile.it). In fact, some of the values provided in the last column of Table 4 are estimates themselves, because the scenario provides the number of inhabitants and dwellings whereas the damage surveys (Baggio *et al*., 2007) give the number of buildings belonging to different classes of usability (from A usable to E and F unusable). We considered, therefore, the mean ratios of dwellings/building and inhabitants/building resulting from the ISTAT 2001 census of population and dwellings (ISTAT, 2005) for the 57 municipalities of the

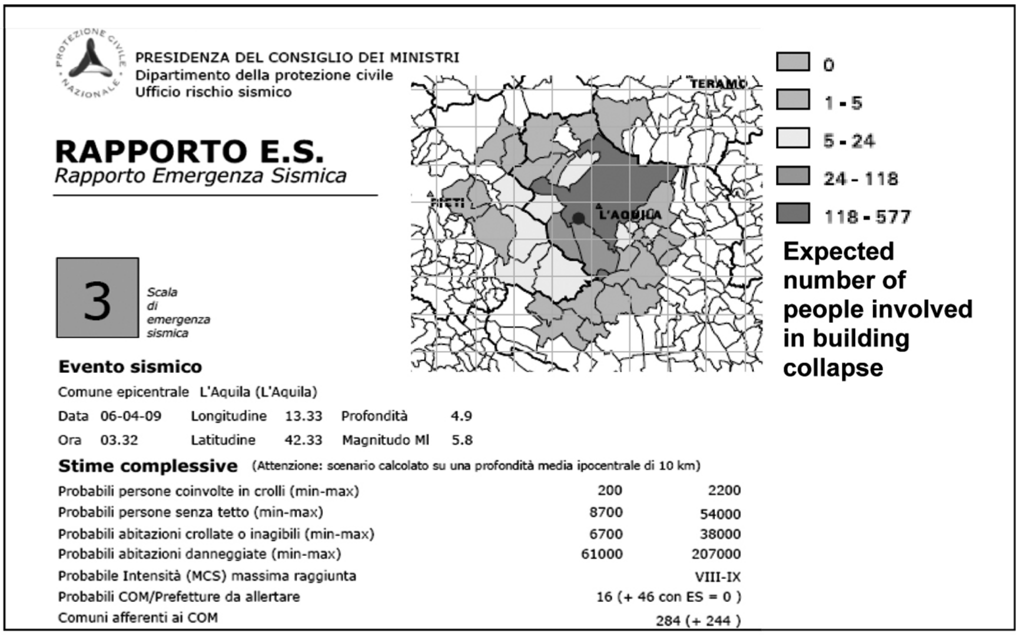


Fig. 9 - Examples of the outputs provided by the simulation scenario (SIGE) generated by the Italian Civil Protection about 30 minutes after the main event. The scenario gives average estimates of about 1,200 people involved in building collapse (mainly concentrated in L'Aquila as shown in the figure box), 31,000 homeless, 22,000 unusable dwellings, and 134,000 damaged dwellings.

epicentral area with a macroseismic intensity $I \geq$VI MCS. To compare it to the scenario, we considered 64,000 persons homeless as resulting from the 22,867 private buildings classified as unusable, without taking into account the percentage of dwelling occupation in the area [84% in L'Aquila, 51% in the surrounding villages, ISTAT (2005)] that brings the real number of homeless close to 40,000.

As illustrated in Table 4, the scenario catches, as desired, the order of magnitude of the expected losses but underestimates all the values, in particular, the ones such as the expected number of homeless. This is probably due to the fact that the scenario was run with the first magnitude estimate provided by the INGV that was $M_L$ 5.8 instead of $M_W$ 6.3. In fact, the simulation scenario calculates the losses on the basis of the macroseismic intensity derived from $M_S$ value through the relationship proposed by Rebez and Stucchi (1996). For a magnitude around 6, $M_S$ and $M_w$ are, in practice, coincident (Ambraseys and Free, 1997) and there should not be a difference greater than 0.2 units also between $M_L$ and $M_w$. With a difference of 0.5 units, the resulting intensity, used as input in the scenario, is IX-X for $M_w$=6.3 and VIII-IX for $M_L$=5.8. In any case, considering the earthquake magnitude, rather high for a country with a real estate like Italy, and the large values of ground acceleration illustrated previously, it has to be remarked that the overall behaviour of the buildings in L'Aquila can be considered satisfactory enough. This could be partially explained by the high frequency content (very high accelerations and moderate displacements) and very short duration of the ground motion, reflecting pronounced source effects typical of near field conditions. As

Table 4 - Comparison between the losses predicted by the simulation scenario (SIGE) and the real values obtained from the field

| **Estimates of the Simulation scenario** | **Estimates of the Simulation scenario** | | | **Real data (source DPC www.protezionecivile.it)** |
|---|---|---|---|---|
| | **Min** | **Max** | **Mean** | |
| Maximum Mercalli Intensity (MCS) | | VIII-IX | | IX |
| People involved in building collapse | 200 | 2200 | 1200 | 1900* |
| Homeless | 8700 | 54000 | 31000 | 64000** |
| Unusable dwellings | 6700 | 38000 | 22000 | 36000*** |

* Sum of injured and victims.
** Obtained from the 22,867 private buildings classified as unusable (usability classes E and F) multiplied by a mean ratio of 2.8 inhabitants/building resulting for the 57 municipalities with $I \geq$VI MCS.
*** Obtained from the buildings classified as unusable multiplied by a mean ratio of 1.6 dwellings/building resulting for the 57 municipalities with $I \geq$VI MCS.

illustrated in Table 2, the significant duration (according to Vanmarcke definition) of strong-shaking of the near field stations, is between 3 and 5 s. In particular, in the case of station AQV, about 80% of the energy has been released within the first 3 s (Sabetta *et al*., 2009). Hence, as is remarkable in the displacement time histories of several strong motion recordings, the strong shaking damaged the majority of deficient structures within few cycles rather than sustained/prolonged displacement excursions.

## 7. Conclusions

- The April 6, 2009 L'Aquila earthquake is the third strongest earthquake recorded in Italy since 1972, after the 1976 Friuli ($M_w$ 6.4), and 1980 Irpinia ($M_w$ 6.9). The earthquake produced one of the largest number of experimental data ever obtained in Italy for a single earthquake.
- The GMPEs available in literature, underestimate the observed PGA values closest to the epicenter and overestimate those in the backward directivity direction (NW sites). The overestimation of far data is reduced when considering PGV and lower frequency response spectral values.
- The earthquake produced high accelerations at all the stations close to the fault, reaching up to 0.63 g at station AQV. The recordings of the main shock are strongly affected by source and site effects with the PGAs at sites very close to the source ranging between 646 and 310 cm/s$^2$. Furthermore, they show a directivity effect in a SE direction with a systematic decrease of PGA and PGV at sites located in the backward direction of the rupture propagation.
- Elastic response spectra of the recordings closest to L'Aquila town, show very high values of acceleration in the interval 2-10 Hz, corresponding to the fundamental frequencies of most of the buildings in the area. The acceleration spectra evaluated in the short period range are higher than those considered by the new Italian building code NTC-08 for the collapse prevention performance target.

- The significant duration of strong-shaking of the near field stations is between 3 and 5 s. This implies a strong, high-frequency pulse, hitting the structures within a few cycles rather than sustained/prolonged excursions; this pulse has been recorded also in the vertical component of the motion that, although not generally considered in the design, played an important role for this event, having often, as is quite common in many cases of near field records, vertical accelerations higher than the horizontal ones.
- The majority of non-ductile, non-engineered and un-reinforced masonry buildings (including historical structures) and a significant percentage of semi-engineered to engineered reinforced concrete buildings did not have the capacity to resist the level of shaking experienced.
- The simulation scenario (SIGE), available about 30 minutes after the main shock and giving preliminary estimates of the expected damage and losses, underestimated the effective losses subsequently obtained from the field.

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