DATA AND EXPERIMENT DESCRIPTIONS

The July 17, 2011, M_L 4.7, Po Plain (northern Italy) earthquake: strong-motion observations from the RAIS network

Marco Massa*, Paolo Augliera, Gianlorenzo Franceschina, Sara Lovati, Maria Zupo

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano-Pavia, Milan, Italy

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ABSTRACT

On July 17, 2011, at 18:30:23 UTC, a M_L 4.7 earthquake occurred on the east side of the Po Plain (northern Italy), between the towns of Ferrara and Rovigo. The epicentral coordinates provided by the National Earthquake Center of the Istituto Nazionale di Geofisica e Vulcanologia (National Institute of Geophysics and Volcanology, INGV) were 45.01˚N and 11.41˚E (http://iside.rm.ingv.it/iside). The depth of the hypocenter was constrained at 8.1 km, corresponding to a buried active source that existed in the area. The source of the event was characterized by a predominant left-transverse focal mechanism, even if there was also an important reverse component. Although it did not produce relevant damage, the earthquake was clearly felt in an area of about 50 km radius around the epicenter. The maximum observed intensity was V on the Mercalli-Cancani-Sieberg (MCS) scale, with a predominant distribution of damage towards the north-west. This study provides an overview of the strong-motion waveforms of the mainshock as recorded by the RAIS (Rete Accelerometrica Italia Settentrionale) strong-motion network, in particular focusing on the recordings provided by the stations located in the central part of the basin, which were installed in correspondence with hundreds of soft sediments. The preliminary results show the relevant influence of the basin on the seismic wavefield, highlighting in particular a possible site-amplification phenomena, and also affecting the ground motion at long periods (T >1 s). The systematic underestimations provided by the empirical ground-motion predictive models calibrated for Italy in terms of acceleration response spectra up to 2.0 s support this hypothesis. The sharing of the 24 waveforms (in raw sac and ascii formats) recorded by RAIS is assured by the availability of the data at the ftp site: ftp://ftp.mi.ingv.it/download/RAIS-FR_rel01/.

1. Introduction

The July 17, 2011, ML 4.7 earthquake (http://www.ingv.it/primo-piano/2011/07180818/) occurred in a low seismicity area of northern Italy. Figure 1 shows the instrumental and historical seismicity (top and bottom panels, respectively), which indicate that in this region the earthquake epicenters have mainly been distributed in the foothill areas of the central-eastern Po Plain, with major seismicity associated with the Apennine chain. Over the last 30 years, the Po Plain and its surroundings have been characterized by a rate of seismicity of about 200 small events per year, which have mainly been localized at the edge of the alluvial basin (http://csi.rm.ingv.it/; http://iside.rm.ingv.it/iside). The period between 1982 and the end of 2011 was characterized by only two earthquakes with M_L >5.0: the November 24, 2004, M_L 5.2, Salò event, located at the northern edge of the basin, and the December 23, 2008, M_L 5.1, Parma event, located at the southern edge of the basin.

In particular, the area that included the epicenter of the July 17, 2011, earthquake (Figure 1, top panel, black dashed inset) is located inside the basin, and it has been characterized by the occurrence of 91 earthquakes with M_L higher than 3.0. The strongest events were the December 6, 1986, M_L 4.1, Polesine earthquake, and the May 8, 1987, Mantova, M_L 4.0, earthquake. In the black dashed inset in the bottom panel of Figure 1, the red squares indicate the more relevant historical events that have occurred in this area: 1. February 22, 1346, Maw 5.81 (Io 7.5); 2. March 17, 1574, Maw 5.12 (Io 7.0); 3. March 20, 1234, Maw 5.17 (Io 7.0); and 4. November 17, 1570, Maw 5.48 (Io 7.5) (Maw, moment magnitude derived from macroseismic data; Io, Mercalli-Cancani-Sieberg [MCS] epicentral intensity; Gruppo di Lavoro CPTI [2004], http://emidius.mi.ingv.it/CPTI/).

The July 17, 2011, M_L 4.7, event was located 25 km north-west of Ferrara, about 8 km from the December 6, 1986, M_L 4.1, Polesine earthquake. It did not produce particular damage, as the maximum observed intensity was V on the MCS scale, with a felt area of about 50 km around the epicenter and a damage distribution extending to the north-west (http://www.ingv.it/primo-piano/2011/07180818/). In this area, the reference seismic hazard map for Italy calculated for hard rock sites and considering a return period of 475 yr [Gruppo di Lavoro 2004, Ordinanza PCM 3519/2006] shows predictable horizontal acceleration peaks ranging from 0.050 g to 0.125 g.

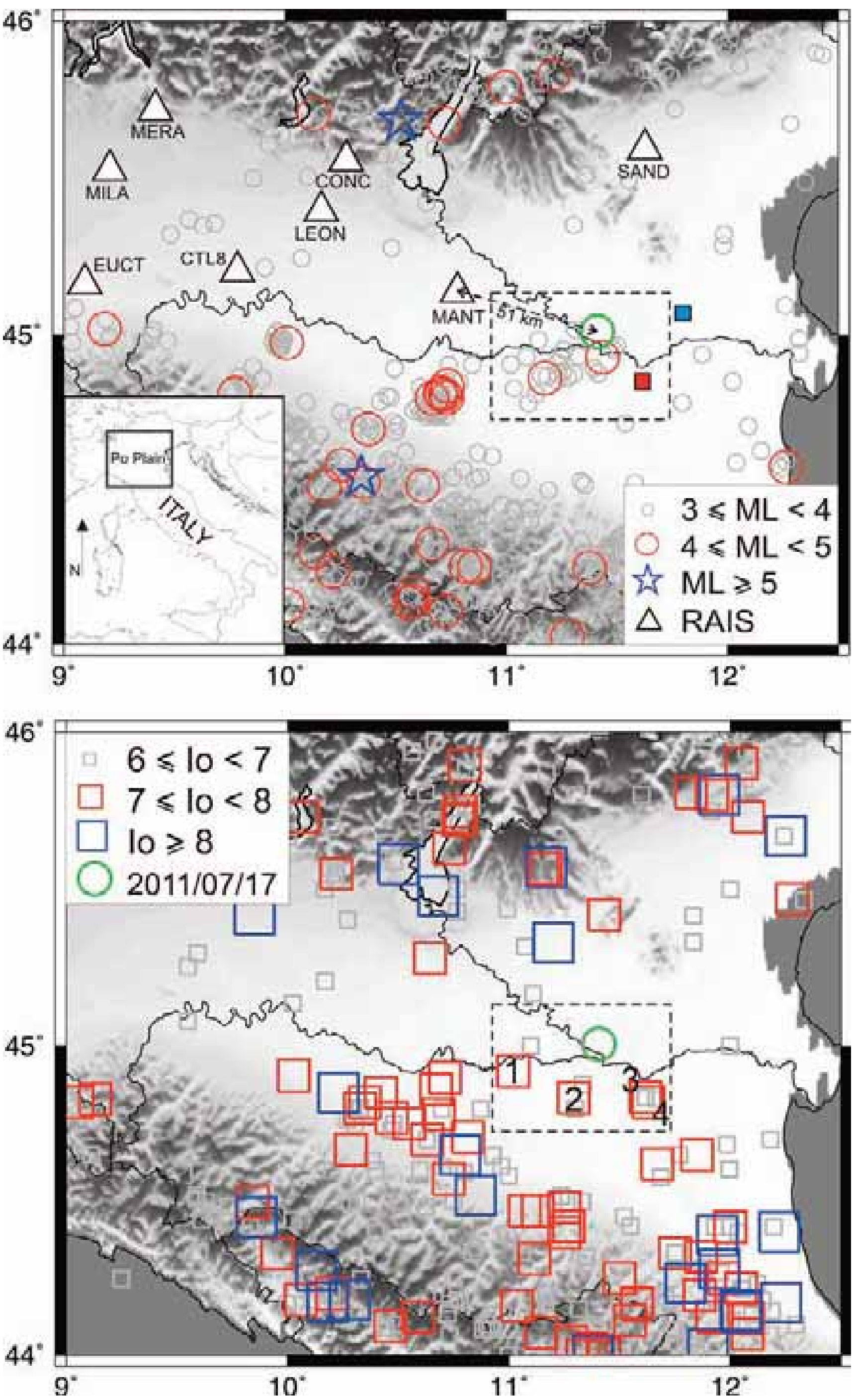


Figure 1. Seismicity of the Po Plain and surrounding areas considered. Top: Instrumental seismicity for the last 30 years (http://csi.rm.ingv.it/; http://iside.rm.ingv.it/iside). White triangles, RAIS stations (http://rais.mi.ingv.it). Red and blue squares, Ferrara and Rovigo, respectively. Inset: location of the study area in Italy. Bottom: Historical seismicity. Green circle, epicenter of the July 17, 2011, M_L 4.7, Po Plain earthquake. See keys for details.

From a geological point of view, the Po Plain represents a syntectonic sedimentary basin that forms the in-fill of the Pliocene-Pleistocene Apenninic foredeep, and is characterized by sediment thickness ranging from 1,000 m to 1,500 m [Picotti et al. 1997, Scardia et al. 2006]. According to the Italian Database of Individual Seismogenic Sources [Basili et al. 2008, DISS Working Group 2010], the central-eastern part of the basin is bordered by several composite seismogenic sources, the structures of which are generally inferred based on regional surface and subsurface geological data. The July 17, 2011, event was characterized by a left-transverse focal mechanism (with a nonnegligible inverse component; http://autorcmt.bo.ingv.it/QRCMT-on-line/E1107171830B.html), and by a hypocentral depth that is, unfortunately, ill-constrained by the available seismological data. However, both the focal parameters and the epicentral coordinates can be considered reliable enough to be able to associate this event to the "ITCS050 – Poggio Rusco-Migliarino" composite source of DISS 3.1.1, an extended seismogenic area that is 70 km long and is characterized by a maximum depth of 8 km

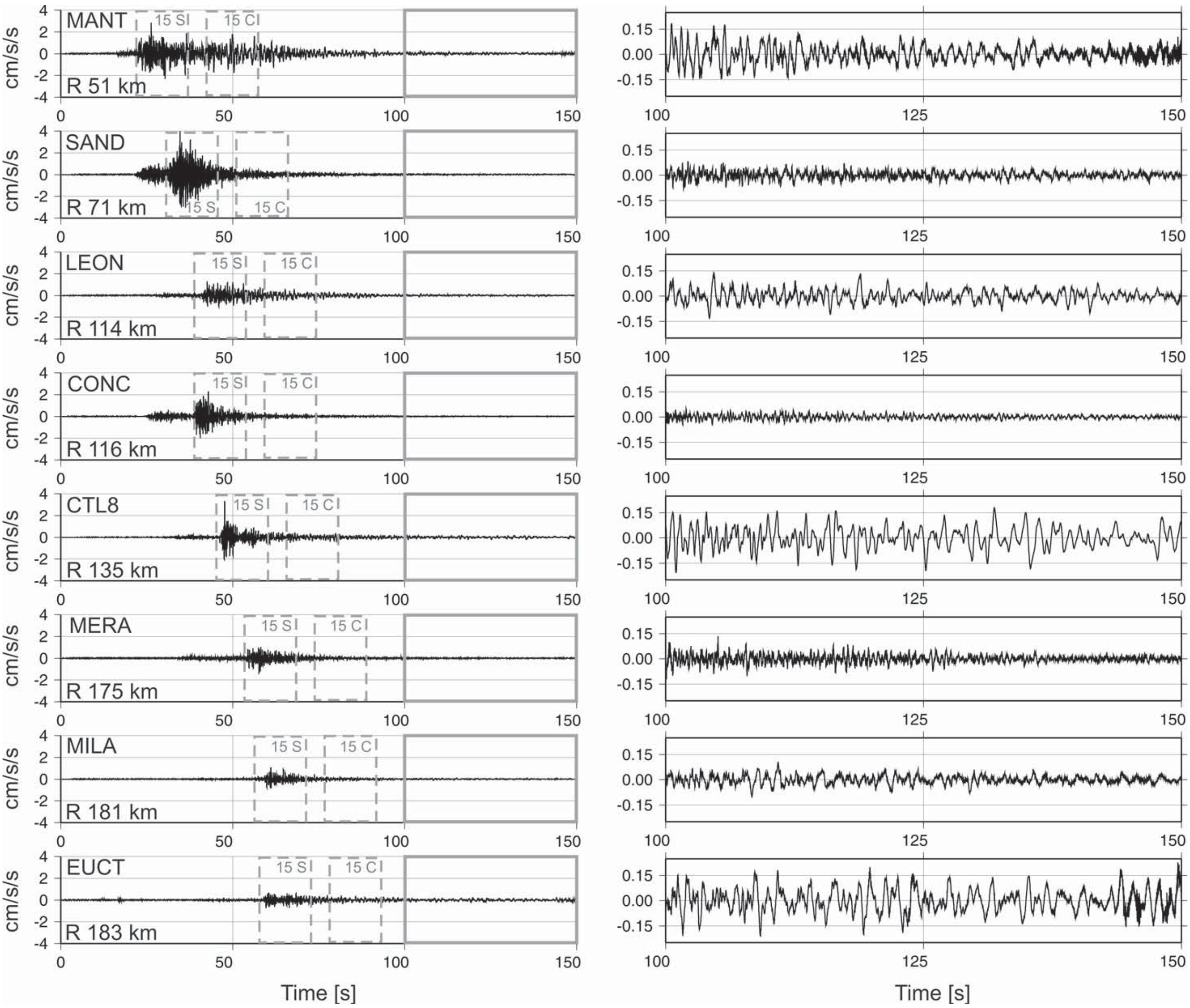


Figure 2. Strong-motion recordings at the RAIS stations analyzed. Left: North-south components of the July 17, 2011, event. Recordings are shown in relation to their arrival times. Gray dashed insets, portions of the signals (15 s of S and coda phases) considered during the spectral analysis. Right: Particular of coda windows indicated by the gray solid inset in the left panels.

Code	City	Latitude (°)	Longitude (°)	Elevation (m)	Sensor	Recorder	Time	Eurocode8
LEON	Capriano C.	45.4582	10.1234	92	episensor	Reftek 130	GPS	C
CTL8	Castelleone	45.2763	9.7622	66	episensor	Gaia2	GPS	C
CONC	Concesio	45.606	10.217	126	episensor	Gaia2	GPS	C
MANT	Mantova	45.1495	10.7897	36	episensor	Gaia2	GPS	C
MERA	Merate	45.6725	9.4182	350	episensor	Gaia2	GPS	B
MILA	Milano	45.4803	9.2321	125	episensor	Gaia2	GPS	C
EUCT	Pavia	45.2026	9.1349	82	episensor	Gaia2	GPS	C
SAND	Sandrigo	45.6399	11.6099	51	episensor	Reftek 130	GPS	C

Table 1. Main features of RAIS stations considered in the present study.

Station	Component	Epicentral distance (km)	PGA (cm/s^2)	PGV (cm/s)	SA 0.3 s (cm/s^2)	SA 1.0 s (cm/s^2)	SA 3.0 s (cm/s^2)	Arias intensity (cm/s)	Housner intensity (cm)
MANT	E	51.98	2.46981	0.20883	5.44374	3.38349	0.17664	0.015767	0.810978
	N	51.98	2.87259	0.269297	4.52401	3.16835	0.271577	0.015912	0.905395
	Z	51.98	2.22253	0.130075	4.8086	1.37493	0.066882	0.010562	0.39714
SAND	E	71.73	3.96209	0.085448	3.63173	0.571226	0.03167	0.02038	0.202407
	N	71.73	3.35872	0.089847	4.74157	0.421781	0.038124	0.018657	0.231281
	Z	71.73	1.11557	0.028732	1.01985	0.224593	0.019009	0.002352	0.090029
LEON	E	114.3	1.25589	0.124055	3,85825	1.70462	0.084326	0.004625	0.460844
	N	114.3	1.16181	0.105747	3.14127	1.54128	0.090736	0.003828	0.427069
	Z	114.3	0.622325	0.044272	1.52349	0.811842	0.043697	0.001151	0.176712
CONC	E	116.1	2.29351	0.107125	6.30756	1.18898	0.044852	0.007953	0.321172
	N	116.1	2.9453	0.146983	7.52268	0.634902	0.040865	0.010303	0.300469
	Z	116.1	1.87299	0.054024	2.01732	0.309395	0.016135	0.003414	0.123725
CTL8	E	135.1	3.31139	0.177278	8.64181	3.50759	0.158861	0.007339	0.69093
	N	135.1	2.55576	0.183904	6.09347	2.80033	0.177472	0.005986	0.647067
	Z	135.1	0.511999	0.0312	1,34122	0.378218	0.020032	0.000699	0.101747
MERA	E	175.5	1.3146	0.064391	3.32264	0.599027	0.026341	0.002542	0.179364
	N	175.5	1.29529	0.080054	2.77246	0.517417	0.03342	0.003345	0.221608
	Z	175.5	0.774228	0.027724	1.57142	0.338607	0.017968	0.00078	0.101602
MILA	E	181.9	1.0497	0.043298	2.7326	0.375714	0.014724	0.001272	0.130091
	N	181.9	0.756287	0.038253	2.05313	0.417281	0.26605	0.000933	0.137395
	Z	181.9	0.392454	0.013322	1.0888	0.121308	0.005855	0.000414	0.045442
EUCT	E	183.3	0.753942	0.059794	2.18877	0.648491	0.032238	0.00128	0.20693
	N	183.3	1.09421	0.060059	2.39014	0.942975	0.059796	0.001482	0.260645
	Z	183.3	0.377386	0.017494	0.97581	0.360262	0.022404	0.000319	0.071847

Table 2. Ground-motion parameters calculated from the collected recordings.

and a maximum magnitude of 5.5.

From the engineering point of view, it must be considered that the superficial quaternary alluvial deposits present everywhere in the Po Plain are expected to strongly modify the seismic wavefield, in terms of both signal duration and amplification. As a consequence, a detailed study of the waveforms recorded during small to moderate events that can occur in the area might be useful to validate the capability of predictive models that can not usually be tested in such a complicated geological setting. These are recorded with broad-band strong-motion sensors installed in the central part of the basin. In such an area, the estimation of the long-period local site effects is a fundamental issue. Indeed, the disaggregation of the Italian probabilistic hazard [Barani et al. 2009] highlights that the expected ground shaking for the area is stronger for events with relevant low-frequency content, with magnitudes in the range 6.0 to 6.5 and epicentral distances between 100 km and 150 km.

It is also worth noting that the Po Plain represents a high exposure area, as it is characterized by the highest density of industrial facilities and municipalities in Italy, some of which have invaluable artistic relevance. Moreover, in this region there are decommissioned nuclear power plants, the Italian high-speed railway, waste oil reservoirs, and important skyscrapers and bridges.

In the present study, 24 three-component recordings collected by eight RAIS (Rete Accelerometrica Italia Settentrionale) strong-motion stations are analyzed (Figure 1, white triangles; http://rais.mi.ingv.it), paying particular attention to stations installed in the central part of the basin. Preliminary results are presented in terms of spectral ratios (both horizontal-to-vertical spectral ratios [HVSRs] and

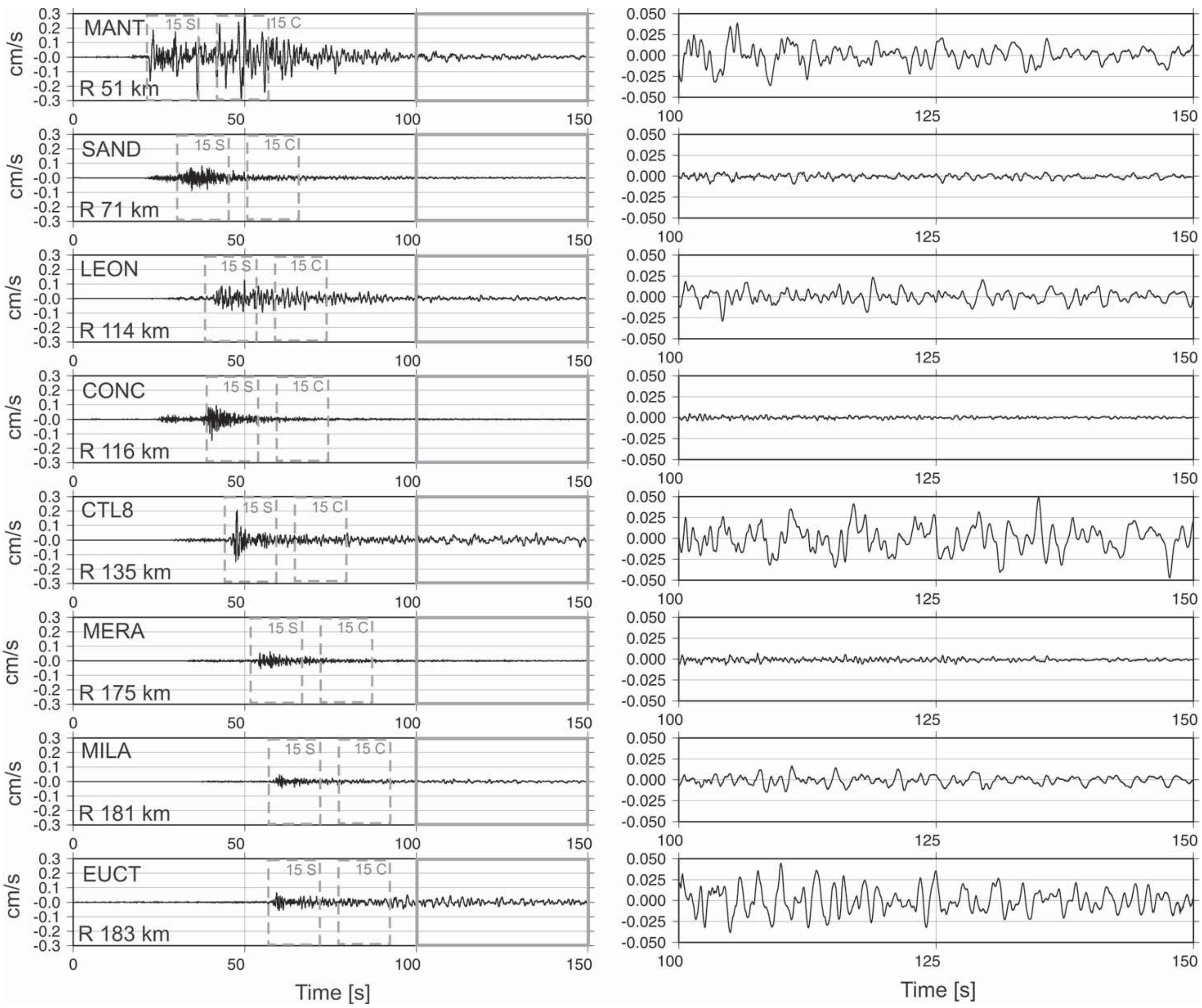


Figure 3. Velocimetric waveforms obtained after integral of the acceleration time series shown in Figure 2 for the eight RAIS strong-motion stations analyzed. Left: North-south components of the July 17, 2011, event. The gray dashed inset define portions of the signals (15 s of S and coda phases) considered during the spectral analysis. Right: Particular of coda windows indicated by the gray solid inset in the left panels.

standard spectral ratios [SSRs]) and comparisons with the empirical ground-motion prediction equations (GMPEs) that are available at present for Italy. These also consider the new Italian seismic code for building, with comparisons made to investigate the predictive capabilities of existing ground-motion models.

2. The RAIS network and data processing

The data presented and analyzed in this study were recorded by eight strong-motion stations (see Figure 2 for the north-south components) that belong to RAIS [Augliera et al. 2010, 2011]. The stations considered are equipped with Kinemetrics EpiSensor FBA ES-T force balance accelerometers coupled with 24-bit digital recorders (Reftek 130 or Gaia2; see Table 1). At present, these stations send data to the INGV acquisition center in Milan in real-time using TCP/IP protocol or Wi-Fi links. The management of the data, which is recorded in MiniSEED format at a sampling frequency of 100 Hz, is achieved using the SeisComP package with the SeedLink protocol. The geological conditions of the RAIS station sites were investigated on 1:25,000 geological maps provided by the Lombardia region [CARG project 2003] or 1:100,000 Italian geological maps [SGI 1984]. Considering the relationship between the superficial geology and the Vs30 (the shear-wave velocity estimated in the first 30 m of depth), as reported in Bordoni et al. [2003], the stations can be classify following Eurocode8 [CEN 2003]: as shown in Table 1, two stations (CONC and MERA) are classified in the B soil category (360 m/s <Vs30 <800 m/s), while the other six are classified in the C soil category (180 m/s <Vs30 <360 m/s).

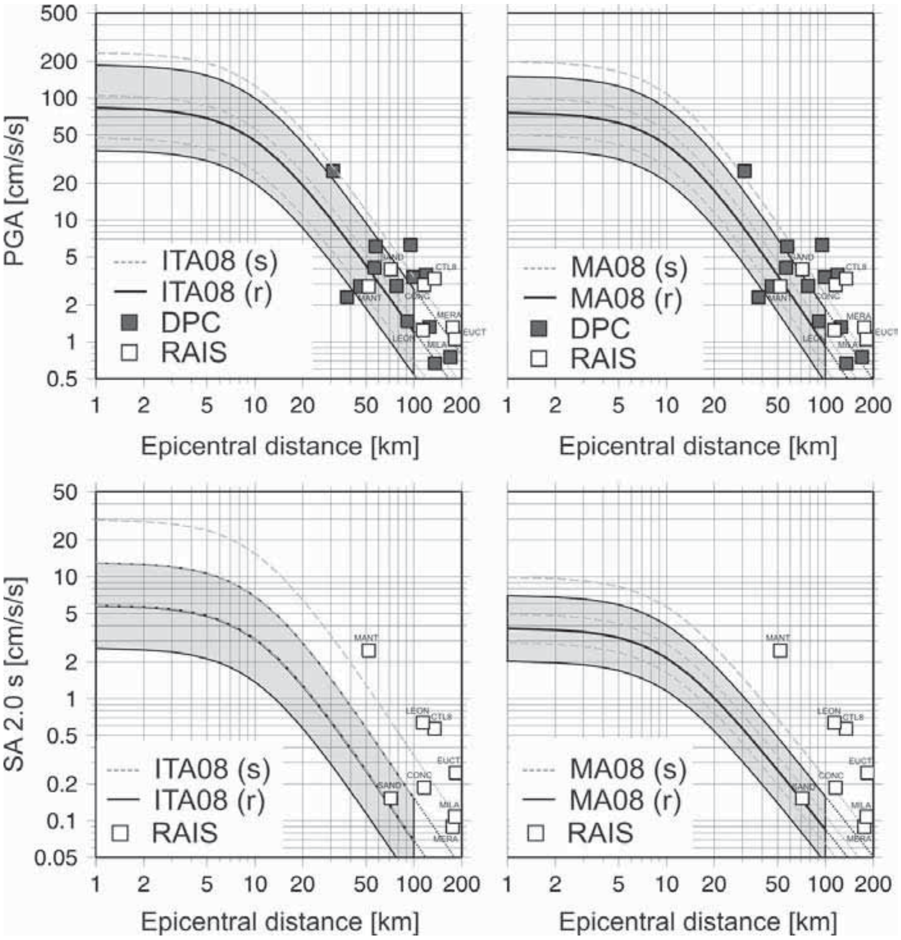


Figure 4. Comparisons between the recorded PGA (top) and SA at 2.0 s (bottom) related to the July 17, 2011 event (considering the maximum horizontal component) and the empirical GMPEs available for the area. Left: Comparisons considering the Italian GMPEs calibrated by Bindi et al. [2010] (ITA08). Right: Comparisons considering the regional relationships calibrated by Massa et al. [2008] (MA08). Solid black lines, dashed grey lines, models (median ±1v) calibrated for hard rock and soft soil, respectively. For both empirical models, the explanatory variable for distance was valid up to 100 km, and was extrapolated up to 200 km. Labels for the RAIS stations are shown.

Each strong-motion waveform is processed using a standard procedure, as described in Massa et al. [2010], which includes: baseline correction, performed by least-squares regression; mean removal, considering the whole signal; application of a 5% cosine-taper function; and application of an acasual 4th order Butterworth digital filter, selecting both low and high pass thresholds by visual inspection of the recorded data. While at high frequencies a good signal-to-noise ratio is assured up to 35 Hz, considering both the available instrumentation (accelerometric sensors) and the characteristic levels of the background noise of the sites (in particular in the central part of the Po Plain), at low frequencies the low-cut threshold for filtering was fixed at 0.4 Hz.

For all of the processed waveforms, peak ground acceleration (PGA) and acceleration response spectra (SA, 5% damped) for periods of up to 2 s were calculated, together with the Arias intensity [Arias 1970] and the Housner intensity [Housner 1952] (see Table 2). Finally, after the integration of the acceleration time series, velocity waveforms were obtained (see Figure 3 for north-south components) and the peak ground velocities (PGVs) were determined.

3. Ground-motion parameters

The ground shacking produced by the July 17, 2011, earthquake in correspondence with the eight RAIS and 13 RAN (Italian Accelerometric Network; http://www.protezionecivile.gov/) strong-motion stations was compared with the empirical GMPEs at present available for Italy, on both the national [Bindi et al. 2010] and regional [Massa et al. 2008] scales. The comparisons were performed in terms of amplitude, and spectral and duration parameters. For the RAN, due to the waveforms not being available, the comparisons were possible only in terms of the PGA (available at: http://www.protezionecivile.gov.it/jcms/it/view_rst.wp?contentId=RST26698).

At the national scale, new GMPEs were recently calibrated by Bindi et al. [2010], considering all of the Italian strong-motion data collected in the Italian Accelerometric Archive (ITACA) [Pacor et al. 2011] recorded from 1972 to 2009 by RAN, and from 2006 by RAIS. Considering data with $4.0 \geq M_w \geq 6.9$ and with distances (Joyner-Boore or epicentral) of up to 100 km, Bindi et al. [2010] developed empirical relations for prediction of the maximum horizontal and vertical PGA, PGV and SA (5% damping) from 0.04 s to 2 s.

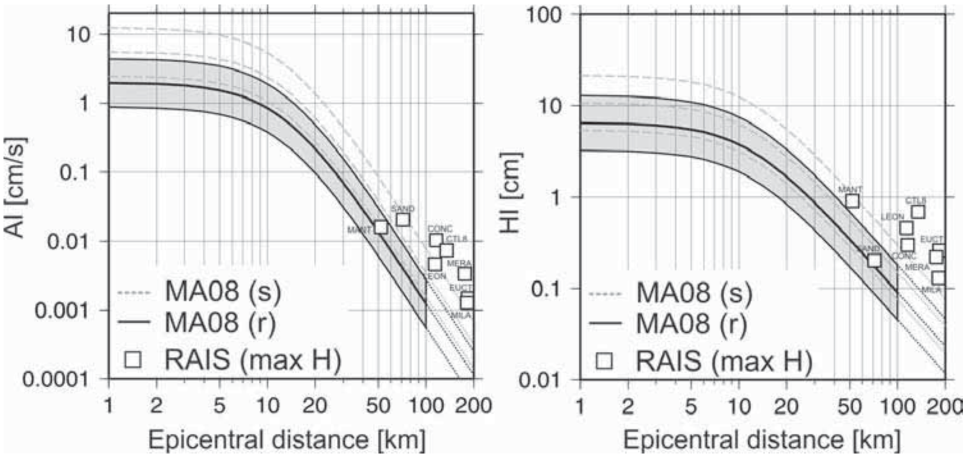


Figure 5. Comparisons between the Arias (left, AI) and Housner (right, HI) intensities calculated from the July 17, 2011, recordings (considering the maximum horizontal component) and the related relationships calibrated for northern Italy by Massa et al. [2008] (MA08). Solid black lines, dashed gray lines, models (median ±1v) calibrated for hard rock and soft soil, respectively. For both empirical models, the explanatory variable for distance was valid up to 100 km, and was extrapolated up to 200 km (black and gray dots). Labels for the RAIS stations are shown.

Massa et al. [2008] calibrated the regional GMPEs for northern Italy using both weak-motion and strong-motion data. In this case, considering the local magnitude ($3.5 \geq M_L \geq 6.3$) and the epicentral distance (up to 100 km) as explanatory variables, Massa et al. [2008] developed a set of empirical relationships in terms of amplitude (PGA, PGV), and spectral (SA, up to 2s) and duration (Arias and Housner intensities) parameters.

Figure 4 shows the comparison between the experimental and predicted PGA (top panels) and SA at 2.0 s (bottom panels), considering in all cases the maximum horizontal component; in the left panels the July 17, 2011, data are compared considering the Bindi et al. [2010] empirical relationships, while in the right panels the comparison was performed considering the Massa et al. [2008] regional relationships. In all cases, the predicted median values are reported together with the related ±1 standard deviations, both for hard rock (Figure 4, black solid lines) and soft soil (Figure 4, gray dashed lines). The median GMPE calibrated for the soft soil reflects the Italian technical standards for construction [Norme Tecniche per le Costruzioni, NTC 2008] and/or the Eurocode8 [CEN 2003] C soil category (360 m/s $<V_s30<$ 180 m/s) for Bindi et al. [2010], while it groups B (800 m/s $<V_s30$ $<$360 m/s) and C soil categories for Massa et al. [2008] (for details about soil classifications adopted in each GMPE, see Bindi et al. [2010], and Massa et al. [2008]). In general, Figure 4 shows that both at high (PGA) and at low (SA, 2.0 s) frequencies the median GMPEs underestimate the experimental values. For the RAIS stations, the bias increases moving from high to low frequency, in particular for the stations located in the central part of the Po Plain (MANT, LEON, MILA, EUCT, CTL8); on the contrary, the values recorded by the stations located near to the edge of the basin are included in the standard deviation range.

The same results are obtained for the regional GMPE calibrated by Massa et al. [2008] for the duration parameters (the Arias and Housner intensities), which are, as already demonstrated by Masi et al. [2006], the ground-motion parameters that capture the potential destructiveness of an earthquake well, as they are integral parameters of a time history. The comparisons between the observed and predicted ground-motion parameters in terms of the Arias [Arias 1970] and Housner [Housner 1952] intensities are shown in Figure 5. In both cases, the underestimation of the predictive models is evident with respect to the observed data for stations MANT, LEON, EUCT and CTL8.

In particular, the underestimation is more evident for the Housner intensities (Figure 5, right panel), in agreement with the comparison performed considering the SA at 2.0 s of the period (Figure 4, bottom panels). Figure 6 shows the SA (5% damping; gray lines) for the four RAIS stations located in the central part of the Po Plain, as obtained from the recordings of the July 17, 2011, event, together with the predicted SA from Bindi et al. [2010]. Especially in the low frequency band (T >1s), the sites where these stations are installed appear to amplify the ground motion with respect to the GMPE predictions. For CTL8, the model underestimates the experimental data also at high frequencies. The other four stations that are not reported in Figure 6 agree better with the trend of the empirical model, with, in any case, the real SA included in the ±1v interval.

4. Spectral ratio analyses

The knowledge of the resonance frequency of a soil, coupled to information about the predominant period of a structure, can give us an idea of the potential damage that we can expect for a site in the case of an earthquake. To analyze earthquake data recorded at a single station, the most commonly used technique at present is the so-called single station HVSR for earthquakes [Lermo and Chavez

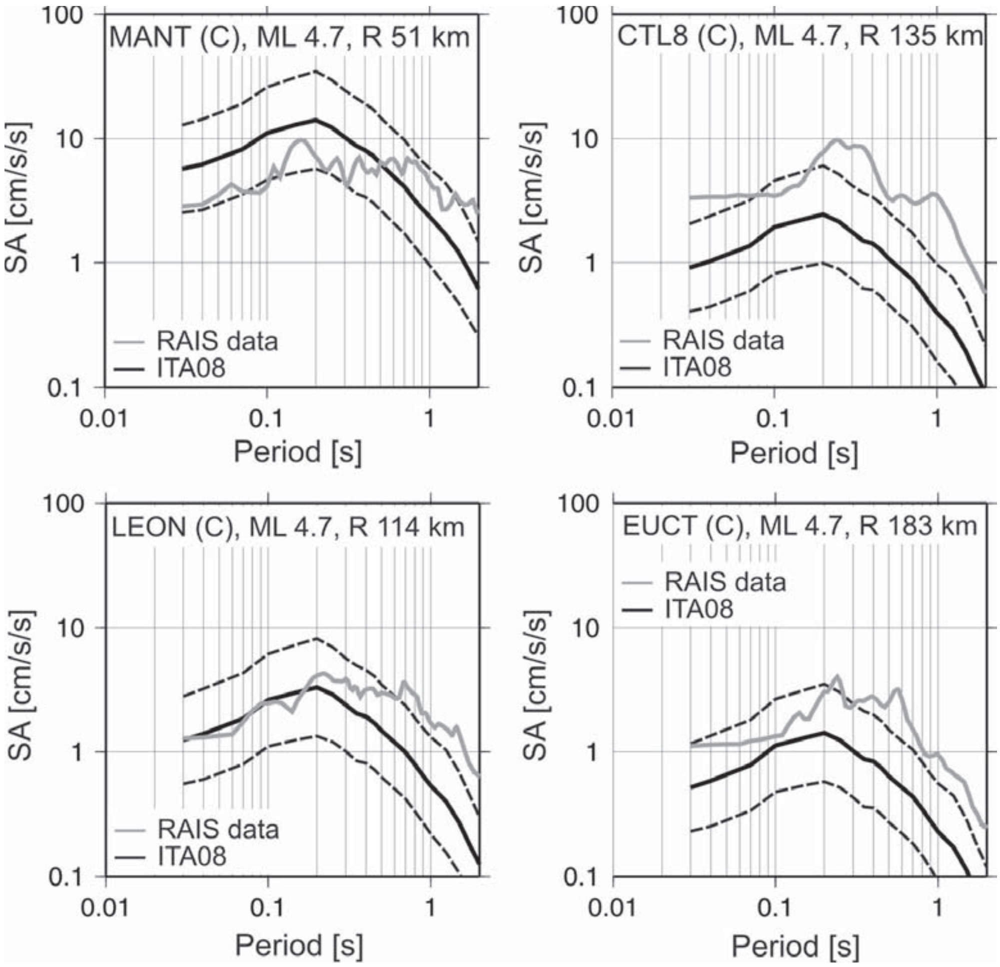


Figure 6. Comparisons between the SA (5% damping) obtained from the recordings of the July 17, 2011, event (gray lines) for the stations located in the central part of the Po Plain and those predicted by Bindi et al. [2010] (ITA08). Solid black lines, dashed black lines, median and ±1ν of the model, respectively.

Garcia 1993]. In Figure 7, the results obtained for all of the analyzed RAIS stations are presented in terms of the rotated HVSRs, considering 15 s of S-phase, starting from the S onset. In each panel of Figure 7, a single amplification function represents the ratio between the rotated north-south horizontal component and the vertical component, considering 36 directions between 0° and 175° (steps of 5°): each color groups an interval of 20° as the results obtained for four consecutive directions. All of the computed Fourier spectra were smoothed using the Konno and Ohmachi [1998] smoothing algorithm, fixing the b parameter at 20.

In the top panels of Figure 7, the results obtained for the CONC (left) and MERA (right) stations are presented, both of which are located at the edge of the Po Plain. In these cases, the spectra highlight the presence of amplified peaks for frequencies higher than 1 Hz, without any evidence of a preferential direction of amplification (i.e. the HVSRs obtained for each of the 36 analyzed directions show similar amplification values). For the other stations, and also in agreement with the previous considerations, while MILA and SAND do not appear to suffer particular effects of amplification at low frequencies (between 1 Hz and 2 Hz for MILA, and between 2 Hz and 3 Hz for SAND), stations MANT, EUCT, LEON and CTL8 show relevant amplification effects for frequencies lower than 1 Hz. The common peaks observed between 0.5 Hz and 1.0 Hz lead us to assume the presence of a regional site response that affects the central part of the basin. In this case, no particular polarization effects were observed.

As previously highlighted, the signal-to-noise ratio at low frequencies for these stations does not allow considerations for frequencies lower than 0.4 Hz. To support these results, the same analyses were performed considering a portion of the 15 s selected on coda (starting from a time equal to twice the S travel time from the origin time), the part of the seismogram that is less affected by radiation pattern effects. The results of the HVSR performed on these coda are presented in the top panels of Figure 8 for one station located at the edge of the basin (CONC, top panel) and for one station located in the central part of the basin (CTL8, bottom panel). As previously seen for the S phase, for both of the stations, the results reflect well the presence of amplification, at high frequencies for CONC (between 1 Hz and 2 Hz) and at low frequencies for CTL8 (at around 0.5 Hz). Also for the other stations not reported in Figure 8, the HVSR on the coda agree well with those obtained from the S phase.

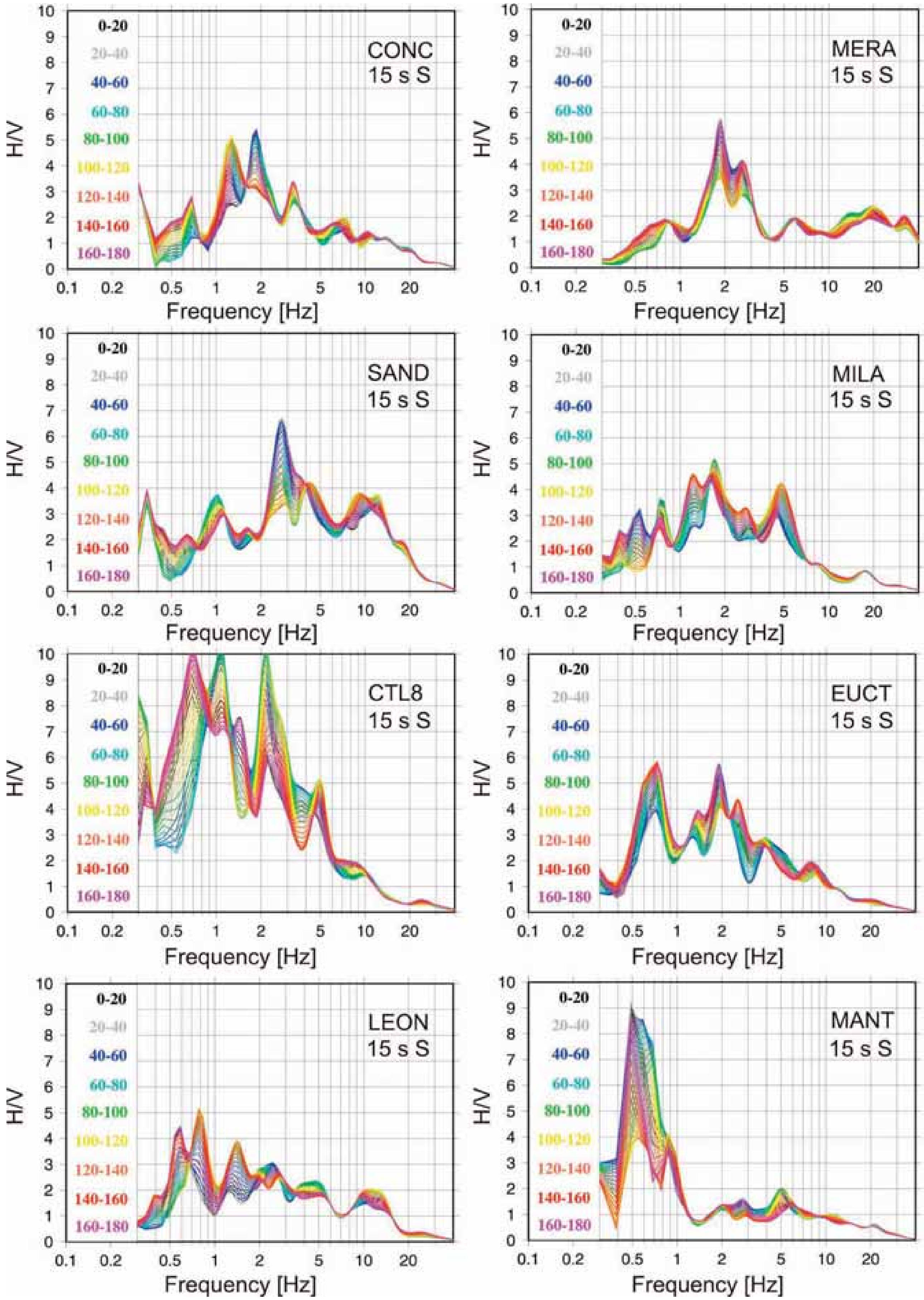
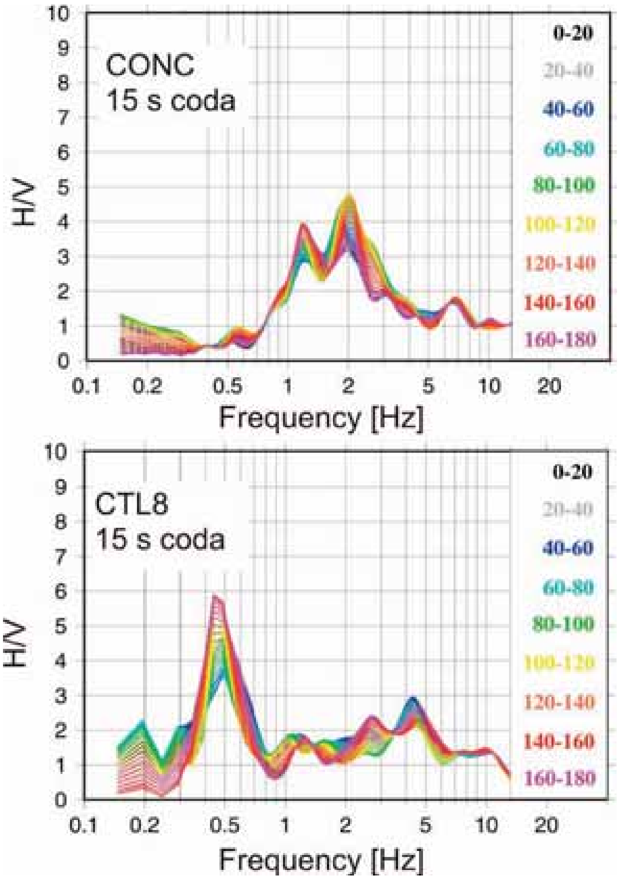


Figure 7. Directional (36 rotations, steps of 5°, between 0° and 175°) HVSRs for the stations considered, computed considering 15 s of S-phase. Different colors indicate consecutive directional HVSRs, grouped according to 20° intervals.



A preliminary estimate of the amplification factors was achieved using, when possible, the SSR technique [Borcherdt 1970] at the regional scale. The basic concept is: if the hypocentral distance of the selected event is large compared to the considered station inter-distances, then the seismic wave field can be considered uniform with respect to the heterogeneity of the area. In this case, it is possible to assume that the differences in the observed waveforms are only correlated to the differences in the local structures. Considering the location of the RAIS network with respect to the epicenter of the July 17, 2011, event, we performed directional SSR selecting on the basis of the source-to-site distances, for two groups of stations: the first composed of CTL8 (135 km), LEON (114 km) and CONC (116 km), and the second composed of EUCT (183 km), MILA (181 km) and MERA (175 km). As the present study is particularly focused on possible anomalous low frequency site responses, CONC and MERA were chosen as the reference sites,

Figure 8 (left). Directional (36 rotations, steps of 5°, between 0° and 175°) HVSRs for CONC, at the edge of the basin, and CTL8, in the central part of the basin, computed considering 15 s of coda for these two representative stations. Different colours indicate consecutive directional HVSRs, grouped every 20° interval.

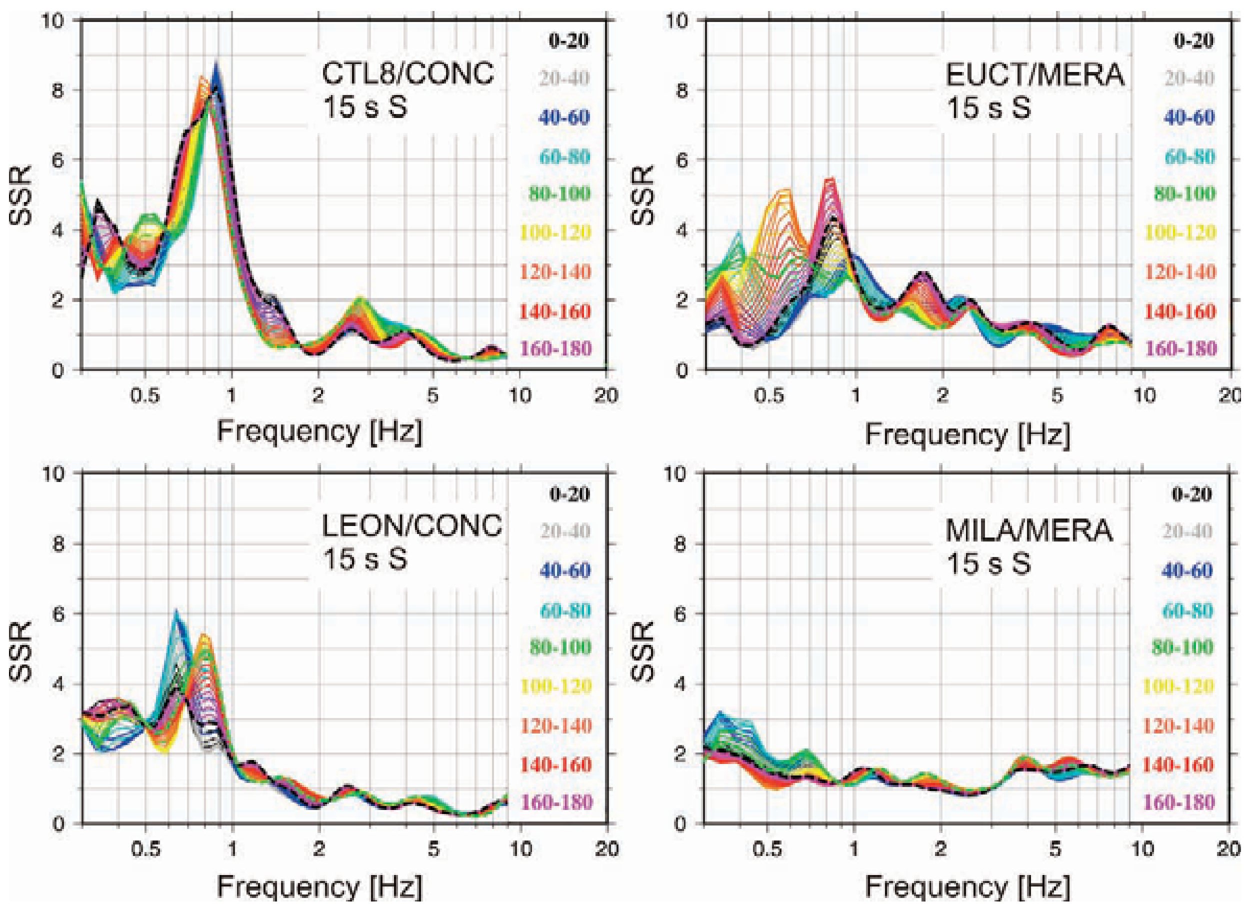


Figure 9. Directional (36 rotations, steps of 5°, between 0° and 175°) SSRs computed for the stations located in the central part of the Po Plain, considering as reference the stations located at the edge. Different colors indicate directional SSRs grouped by according to 20° intervals.

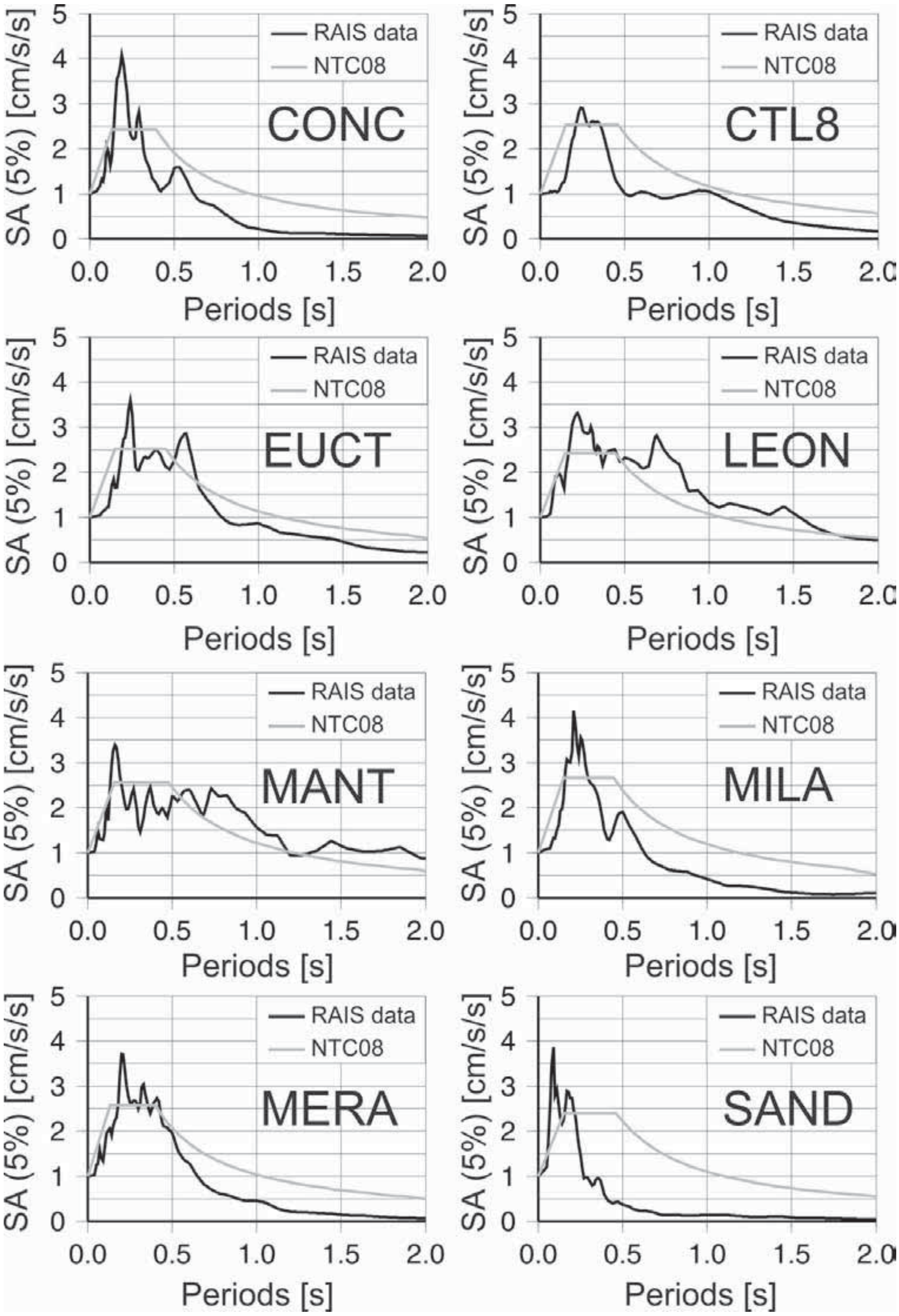


Figure 10. Comparisons between desing elastic SA as provided by the new Italian seismic code for building [NTC 2008, NTC08, gray lines] and the SA (5% damping) obtained at each station considered, from the July 17, 2011, recordings (considering the maximum horizontal component, black lines). All of the spectra were normalized considering the related values at the zero period.

considering that: 1. they are classified in the Eurocode8 B soil category; and 2. they show flat HVSRs (amplification factors <2) for frequencies in the range of 0.5 Hz to 1.0 Hz. It is worth noting that the SSRs in the range of 1.5 Hz to 3.0 Hz might be biased by the amplified peaks observed at CONC and MERA (see Figure 7, top panels, HVSRs). For the analyses, 15 s of S waves were selected. from the S phase onset.

The results here are reported in Figure 9. Considering the first group of stations (CTL8, LEON and CONC), for both of the sites located in the central part of the basin, there is a clear amplification peak between 0.5 Hz and 1.0 Hz. In this case, the amplification factor appears to increase if we move from the north side (amplification up to 6 for LEON) to the central part of the basin (amplification up to 9 for CTL8). Considering the second group of stations (EUCT, MILA and MERA), while EUCT reflects the behavior of LEON and CTL8 (amplification between 0.5 Hz and 1.0 Hz, with an amplification factor of up to 5.5), station MILA does not show particular amplification peaks. Also in this case it is worth mentioning that the amplification increases moving towards the center of the basin.

5. Discussion and conclusions

In this study, the strong-motion recordings were analyzed from the July 17, 2011 (18:30:23 UTC), M_L 4.7, earthquake, as recorded by eight RAIS stations. The 24 waveforms are downloadable in both the raw sac and ascii formats, from ftp://ftp.mi.ingv.it/download/RAIS-FR_rel01/.

The earthquake analyzed was located in the central part of the Po Plain (northern Italy), between the towns of Ferrara and Rovigo, in an area characterized by a low degree of seismicity, both historical and instrumental (see Figure 1). The presence of the RAIS stations, and in particular those installed in the area of the alluvial basin (Table 1, MANT, LEON, CTL8, EUCT, MILA, SAND), gave us the opportunity to test the capability of empirical predictive models for areas where particular amplification, and in particular periods greater than 1 s, can be expected due to the geological setting (very deep sedimentary basin). These preliminary analyses show relevant differences in the site responses considering the stations located at the edge of the basin (Table 1, MERA, CONC) with respect to those in correspondence to the basin. The comparisons with the available GMPEs highlight that the empirical models underestimate the true conditions.

Moving from the stations located at the edge of the basin to those installed in the central areas, this underestimation increases: this evidence involves, in particular, the measured SA at high periods (up to 2.0 s), and the measured duration parameters (the Arias and Housner intensities), which are highly correlated to possible structural damage.

These considerations can generally have relevance for the construction standards for buildings in these areas. At present, the design SA are defined by the new technical Italian regulations for buildings [NTC 2008]. In particular, the elastic SA (5% damping) is defined through a spectral shape that is multiplied by the maximum horizontal acceleration, a_g, for a generic horizontal hard-rock site. Both a_g and the spectral shape vary as a function of the probability of exceeding the reference period. To consider the seismic site amplification, the Italian regulations, the NTC, include five soil categories defined on the basis of the Vs30 [NTC 2008, chapter 3]. To compare the NTC elastic SA and the SA calculated from the July 17, 2011, event, the calculated spectra were normalized by the related PGA values for each station. In this way, it is possible to perform a comparison between the spectral shapes, but not between the amplitudes. The comparisons in terms of the normalized SA are reported in Figure 10. As reported in Table 1, CONC and MERA are included in the B soil category, while the other six stations are in the C soil category. As can be noted, the flat part of the NTC elastic SA (Figure 10, gray) agrees well with the actual SA (Figure 10, black) for many of the stations, and in particular for MERA and CONC, which are located at the edge of the basin. The normalized SA calculated for the CTL8, MILA and SAND stations are well covered by the shape of NTC spectra. On the contrary, for EUCT, and in particular for the MANT and LEON stations, the flat part of the NTC spectra underestimates the normalized SA in the period range of 0.5 s to 1.0 s.

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*Corresponding author: Marco Massa,
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano-Pavia, Milan, Italy; email: marco.massa@mi.ingv.it.