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ORIGINAL RESEARCH PAPER

Horizontal and vertical ground motion prediction equations derived from the Italian Accelerometric Archive (ITACA)

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Abstract A set of Ground Motion Prediction Equations (GMPEs) for the Italian territory is proposed, exploiting a new strong-motion data set become available since July 2007 through the Italian Accelerometric Archive (ITACA). The data set is composed by 561 three-component waveforms from 107 earthquakes with moment magnitude in the range 4.0–6.9, occurred in Italy from 1972 to 2007 and recorded by 206 stations at distances up to 100 km. The functional form used to derive GMPEs in Italy (Sabetta and Pugliese in Bull Seismol Soc Am 86(2):337–352, 1996) has been modified introducing a quadratic term for magnitude and a magnitude-dependent geometrical spreading. The coefficients for the prediction of horizontal and vertical peak ground acceleration, peak ground velocity and 5% damped acceleration response spectra are evaluated. This paper illustrates the new data set, the regression analysis and the comparisons with recently derived GMPEs in Europe and in the Next Generation Attenuation of Ground Motions (NGA) Project.

Keywords Ground motion prediction equation · Strong ground motion · Peak ground acceleration · Peak ground velocity · Acceleration response spectra

1 Introduction

The prediction of the ground motion as a function of source-to-site distance and earthquake magnitude is required for assessing the seismic hazard of a given site or an area. The probabilistic approach to seismic hazard (Cornell 1968) determines the ground motion level at a fixed probability of exceedence over a selected time interval, using the ground motion predicted by a Ground Motion Prediction Equation (GMPE) in terms of mean values and related uncertainties. The GMPEs are generally developed by the regression analysis of a set of observations which results in a set of coefficients of an assumed ground motion model. Besides the earthquake magnitude and the source-to-site distance, the explanatory variables

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of the ground motion model generally include several terms describing the source (e.g. style of faulting, hanging/foot wall effects, etc.) and the site (e.g. soil class, resonant frequency, etc.). The complexity of the model should be suitable to the characteristics of the data set and should return reliable values of the explanatory variables.

The earliest GMPEs in Italy were developed by Sabetta and Pugliese (1987), hereinafter SP87, for evaluating the peak ground acceleration and velocity and subsequently extended to 5% damped pseudo-velocity response spectra (Sabetta and Pugliese 1996, hereinafter SP96). The authors exploited a data set consisting of 17 earthquakes occurred in the period 1976–1984, with a magnitude range 4.6–6.8 (local or surface wave magnitude) and recorded at distances smaller than 115 km from the causative fault.

Further GMPEs have been recently developed for different regions in Italy, considering different explanatory variables and magnitude -distance ranges. For example, regional GMPEs have been calibrated for North-Eastern Italy (Bragato and Slejko 2005; Ml ranges 2.5–6.3 for epicentral or fault distances up to 130 km), for North-Western Italy (Frisenda et al. 2005; Ml up to 4.5 and hypocentral distances up to 200 km), Northern-Italy (Massa et al. 2008a; Ml range 3.5–6.3 and epicentral distances up to 100 km) and Umbria-Marche (Central Italy) region (Bindi et al. 2006; Ml range 4–6 for epicentral and hypocentral distances up to 100 km).

The goodness of fit of the Italian GMPE developed by Sabetta and Pugliese (1987, 1996) has been recently evaluated by considering a subset with the 27 major earthquakes occurred in Italy from 1972 to 2002 (Bindi et al. 2009a). The results showed that SP87 and SP96 GMPEs do not adequately fit the new strong-motion data set, for its small standard deviation and its non-zero bias, especially for rock sites. Moreover, the analysis of the residuals highlighted the inadequacy of the selected functional form to capture the behaviour of the attenuation of the strong motion parameters with distance (Bindi et al. 2009a).

In this study, we exploit the new Italian strong motion archive (ITalian Accelerometric Archive ITACA http://itaca.mi.ingv.it, Luzi et al. 2008) to develop new empirical GMPEs for Italy. The models are developed for peak ground acceleration, peak ground velocity and 5% damped acceleration response spectra, considering both the maximum horizontal and vertical component of motions. The functional form considered by SP96 has been modified introducing a quadratic term for magnitude and a magnitude-dependent geometrical spreading.

2 Data set and data processing

The GMPEs were developed considering the strong motion records processed in the ITACA archive (Luzi et al. 2008). In particular, the raw accelerometric time series has been filtered using a fourth order a-causal Butterworth filter, selecting the corner frequencies by visual inspection of the Fourier spectrum of individual records. Details about data processing and different choices adopted for digital and analogue records can be found in Massa et al. (2008b, this issue).

To develop the new GMPEs, we selected in the database earthquakes with moment magnitude equal to or larger than 4 and distances from the fault smaller than 100 km, recorded at least by two stations. In addition we included the waveforms recorded by the Northern Italy Strong Motion network (*Rete Accelerometrica dell'Italia Settentrionale*, RAIS http://rais.mi.ingv.it/), installed around the Garda lake area, in northern Italy. They correspond to three events occurred in 2006 and 2007 (id's from 105 to 107 in Table 1), with magnitudes in the range 4.2–4.5. Since a detailed geophysical characterization is available only for a small

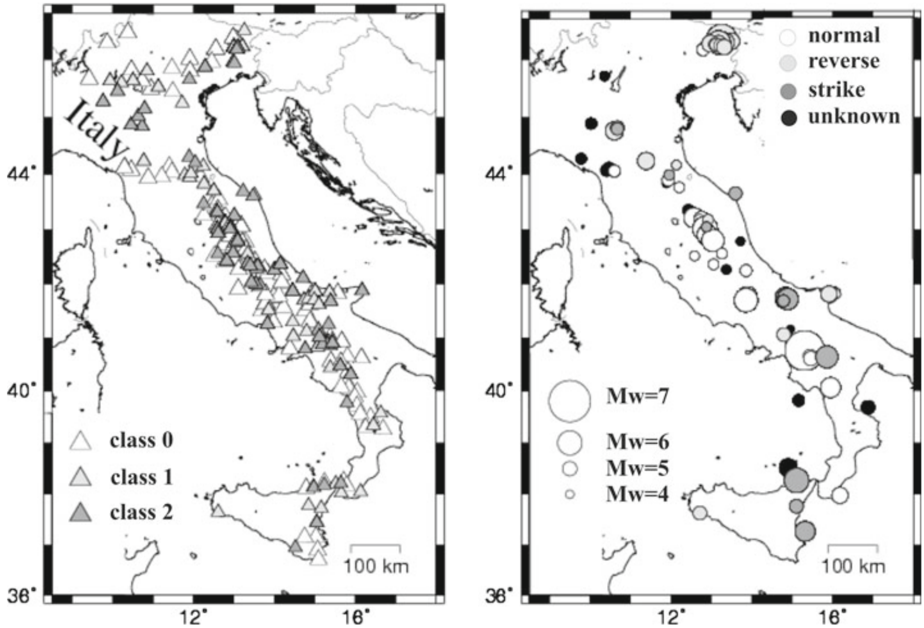

Fig. 1 *Left* Geographic distribution of recording stations, *right* geographic distribution of earthquakes

subset of sites, the stations were grouped according to the site classifications used in SP87, consisting of three classes. The first class (hereinafter referred to as C_0) includes the stations installed on rock; the second class (C_1) includes the stations installed on shallow sediments (thinner than 20 m) while the third class (C_2) is representative of the stations installed on sediments thicker than 20 m, where with the term "sediment" are denoted soils with shear wave velocity lower than 800 m/s. Class C_0 corresponds to classes A and B of NEHRP site classification, while the classification of soil stations using classes C_1 and C_2 (which roughly corresponding to classes C and D of NEHRP, respectively) is simple but efficient in identifying the sites with amplifications occurring at frequencies larger or smaller than about 2-5 Hz.

The selected data set is composed by 107 earthquakes and 206 stations with the geographical distribution shown in Fig. 1. The characteristics of the earthquakes are listed in Table 1, whereas the magnitude versus the horizontal distance to the surface projection of the fault plane (Joyner and Boore distance, R_{jb}) distribution is shown in Fig. 2. The R_{jb} has been computed for the events with $M \geq 5.5$ using the fault geometry reported in the DISS database (DISS Working Group 2006; Basili et al. 2008) while the epicentral distance is used for earthquakes with smaller magnitude. Magnitudes up to 6 are well sampled at distances greater than 5 km, and, in particular, small magnitude events, in the range 4.0–4.6, are well sampled even at smaller distances. Only records at distances greater than 10 km are available for the two earthquakes with magnitude larger than 6, i.e. the 1976 Friuli (id = 2 in Table 1) and the 1980 Irpinia (id = 26 in Table 1).

Figure 3 shows the comparison between the PGA and R_{jb} used in ITACA and those for common records considered by SP87. While the PGA are similar, indicating that the different data processing resulted in consistent results, significant deviations are observed in the R_{jb} values for distances smaller than 20 km. These differences are likely due to the improvement

Table 1 Characteristics of the selected seismic events (Id = earthquake index; Lon = longitude; Lat = latitude; Mech = focal mechanism: 1 = normal, 2 = reverse, 3 = strike-slip, 4 = unknown)

Id	Year	Month	Day	Hour (GMT)	Lon	Lat	Depth (km)	Mw	Mech
1	1972	06	14	18:55:46	13.600	43.650	3.00	4.8	3
2	1976	05	06	20:00:12	13.260	46.350	12.00	6.4	2
3	1976	05	09	00:53:44	13.320	46.220	20.00	5.1	2
4	1976	05	10	04:35:53	13.120	46.260	15.00	4.7	2
5	1976	05	11	22:44:00	12.990	46.290	13.00	5.0	2
6	1976	05	13	13:04:50	12.983	46.233	16.00	4.1	1
7	1976	05	18	01:30:08	12.867	46.250	5.00	4.1	1
8	1976	06	01	17:21:07	12.867	46.217	15.00	4.1	1
9	1976	06	08	12:14:38	13.230	46.300	19.00	4.6	1
10	1976	06	09	18:48:15	13.067	46.350	16.00	4.3	1
11	1976	06	17	14:28:47	12.798	46.177	15.00	4.7	1
12	1976	09	07	11:08:16	12.983	46.300	5.00	4.2	1
13	1976	09	11	16:31:10	13.180	46.290	10.00	5.1	2
14	1976	09	11	16:35:01	13.320	46.300	9.00	5.6	2
15	1976	09	15	03:15:18	13.190	46.300	2.00	5.9	2
16	1976	09	15	04:38:53	13.170	46.270	21.00	4.9	1
17	1976	09	15	09:21:18	13.180	46.300	21.00	5.9	2
18	1977	04	03	03:18:13	13.100	46.267	9.00	4.8	2
19	1977	09	16	23:48:07	12.980	46.280	21.00	5.3	2
20	1978	03	11	19:20:43	16.184	37.979	5.00	5.2	1
21	1978	04	15	23:33:47	15.110	38.270	22.00	6.0	3
22	1979	09	19	21:35:37	13.040	42.800	6.00	5.8	1
23	1980	02	28	21:04:40	12.967	42.800	12.00	5.0	4
24	1980	05	14	09:01:13	13.000	42.855	15.00	4.1	4
25	1980	06	09	16:02:47	13.860	42.246	12.00	4.6	1
26	1980	11	23	18:34:53	15.310	40.760	15.00	6.9	1
27	1980	11	24	00:24:00	15.268	40.811	13.00	5.0	1
28	1980	11	25	17:06:44	15.462	40.609	18.00	5.0	1
29	1980	11	30	07:41:59	15.316	40.761	18.00	4.5	4
30	1980	12	01	19:04:29	15.310	40.890	9.00	4.6	4
31	1980	12	04	00:04:56	15.527	40.746	12.00	4.0	4
32	1980	12	08	02:49:39	15.231	40.821	13.00	4.2	4
33	1980	12	08	04:09:24	15.249	40.785	14.00	4.1	4
34	1981	01	16	00:37:45	15.440	40.840	10.47	5.2	1
35	1981	02	14	17:27:46	14.794	41.060	10.10	4.9	2
36	1982	10	17	06:45:37	12.714	43.162	5.90	4.6	1
37	1984	04	29	05:03:00	12.570	43.210	5.97	5.6	1
38	1984	05	07	17:49:43	13.860	41.700	20.50	5.9	1
39	1984	05	11	10:41:48	13.890	41.780	12.10	5.5	1
40	1984	05	11	11:26:15	13.885	41.705	13.60	4.1	4
41	1984	05	11	13:14:56	13.919	41.754	12.20	4.8	1

Table 1 continued

Id	Year	Month	Day	Hour (GMT)	Lon	Lat	Depth (km)	Mw	Mech
42	1984	05	11	23:35:04	13.883	41.678	8.80	4.0	4
43	1985	01	23	10:10:17	10.415	44.064	24.10	4.7	4
44	1985	05	20	10:00:29	13.372	42.266	11.50	4.2	4
45	1987	04	24	02:30:29	10.674	44.816	23.50	4.9	3
46	1987	05	02	20:43:55	10.678	44.794	23.70	4.7	3
47	1987	07	05	13:12:37	12.208	43.759	15.50	4.4	1
48	1988	02	08	11:24:46	10.465	44.106	27.70	4.6	4
49	1990	05	05	07:21:20	15.860	40.640	22.54	5.8	3
50	1990	12	13	00:24:26	15.320	37.270	7.00	5.6	3
51	1991	01	14	07:38:36	11.891	43.828	14.20	4.0	4
52	1995	09	30	10:14:34	15.914	41.814	27.40	5.2	2
53	1996	04	03	13:04:35	15.442	40.655	11.40	4.9	1
54	1996	10	15	09:56:01	10.605	44.763	25.50	5.4	2
55	1996	10	20	19:06:56	13.263	42.559	11.90	4.4	1
56	1997	09	26	00:33:12	12.890	43.020	3.51	5.7	1
57	1997	09	26	09:40:25	12.850	43.010	9.87	6.0	1
58	1997	09	26	13:30:52	12.905	43.035	13.90	4.5	1
59	1997	09	27	17:13:03	12.812	43.011	6.70	4.2	1
60	1997	09	27	19:56:43	12.826	43.036	8.20	4.3	1
61	1997	10	02	10:59:56	12.778	43.105	8.20	4.7	1
62	1997	10	03	08:55:22	12.824	43.043	12.10	5.2	1
63	1997	10	04	15:07:20	12.918	42.917	5.10	4.4	1
64	1997	10	04	16:13:32	12.906	42.916	6.20	4.7	1
65	1997	10	04	18:47:47	12.904	42.924	6.10	4.4	1
66	1997	10	06	23:24:53	12.847	43.028	3.90	5.4	1
67	1997	10	07	01:24:34	12.846	43.037	4.90	4.2	1
68	1997	10	07	05:09:56	12.859	43.036	1.70	4.5	1
69	1997	10	12	11:08:36	12.920	42.906	0.10	5.2	1
70	1997	10	12	11:12:29	12.922	42.920	0.50	4.2	4
71	1997	10	14	15:23:09	12.900	42.900	7.33	5.6	1
72	1997	10	14	23:23:29	12.872	42.956	4.10	4.1	4
73	1997	10	16	12:00:31	12.884	43.044	2.40	4.3	3
74	1997	10	19	16:00:17	12.848	42.971	3.90	4.2	1
75	1997	11	08	15:31:53	12.974	42.863	0.30	4.1	4
76	1997	11	09	19:07:33	12.988	42.846	1.50	4.9	1
77	1997	11	30	11:24:42	12.990	42.842	3.50	4.0	1
78	1998	02	07	00:59:44	12.823	43.005	0.00	4.3	4
79	1998	04	03	07:26:36	12.757	43.185	1.90	5.1	1
80	1998	04	03	07:59:52	12.755	43.194	3.90	4.3	1
81	1998	04	05	15:52:21	12.767	43.190	4.40	4.8	1
82	1998	06	02	23:11:23	12.786	43.186	3.30	4.3	1
83	1998	08	15	05:18:08	13.056	42.362	2.90	4.4	1

Table 1 continued

Id	Year	Month	Day	Hour (GMT)	Lon	Lat	Depth (km)	Mw	Mech
84	1998	09	09	11:28:00	15.950	40.060	29.21	5.6	1
85	1999	01	25	22:45:58	11.962	43.980	27.90	4.4	3
86	1999	02	14	11:45:53	15.022	38.226	20.70	4.7	1
87	2000	12	16	07:31:07	12.586	42.516	9.20	4.2	1
88	2002	04	17	06:42:54	16.880	39.684	4.00	4.9	4
89	2002	10	27	02:50:27	15.106	37.766	0.00	4.9	3
90	2002	10	31	10:32:59	14.890	41.720	25.15	5.7	3
91	2002	11	01	15:09:02	14.840	41.740	21.36	5.7	3
92	2002	11	04	00:35:46	14.837	41.750	22.20	4.3	4
93	2002	11	04	03:26:30	14.823	41.764	21.10	4.0	4
94	2002	11	12	09:27:48	14.786	41.689	28.90	4.6	3
95	2003	01	26	19:57:04	11.936	43.892	5.80	4.7	1
96	2003	01	26	20:01:16	11.930	43.900	6.80	4.0	4
97	2003	06	01	15:45:18	14.825	41.666	16.20	4.8	2
98	2003	09	14	21:42:53	11.387	44.230	15.80	5.3	2
99	2003	12	07	10:20:33	12.138	44.159	19.60	4.2	2
100	2003	12	30	05:31:38	14.834	41.654	14.90	4.5	4
101	2004	03	03	02:13:26	15.160	39.815	2.30	4.6	4
102	2004	07	12	13:04:06	13.502	46.322	6.20	5.2	2
103	2004	09	03	00:04:13	15.646	40.681	10.10	4.1	4
104	2004	12	09	02:44:25	13.722	42.784	18.20	4.0	4
105	2006	10	20	00:11:12	10.360	45.720	5.00	4.2	4
106	2007	05	09	06:02:56	10.520	44.800	27.20	4.3	4
107	2007	07	30	19:05:04	10.030	44.890	27.80	4.5	4

in the identification of seismogenic source geometries for Italian earthquakes with magnitude larger than 5.5 (DISS Working Group 2006). Finally, the three site classes are sampled as follows: 104 waveforms belong to category C_0, 47 to category C_1 and 55 to C_2, respectively, while about 50% of the events (53) have a normal-slip mechanism.

3 Model

The GMPEs are calibrated considering the following functional (e.g. Akkar and Bommer 2007):

$$\log_{10} Y = a + b_1(M_W - M_{\text{ref}}) + b_2(M_W - M_{\text{ref}})^2 + (c_1 + c_2(M_W - M_{\text{ref}})) \log_{10} \sqrt{(R^2 + h^2)} + e_i S_i + f_j F_j \quad (1)$$

where Y is the response variable; M_{ref} is a reference magnitude; R is the distance; h is the pseudo-depth (km); S_i with $i = 1, 2, 3$ are dummy variables that assume either the value 0 or 1 depending on soil type (rock, class C_0: $S_1 = 1$ and $S_2 = S_3 = 0$; shallow alluvium, class $C_1 : S_2 = 1$ and $S_1 = S_3 = 0$; deep alluvium, class $C_2 : S_3 = 1$ and $S_1 = S_2 = 0$); F_j are

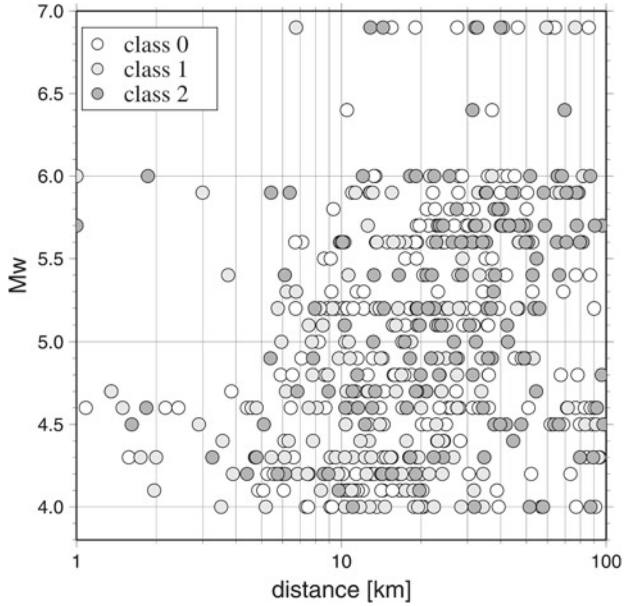

Fig. 2 Magnitude versus distance distribution (*different symbol* indicate soil classes)

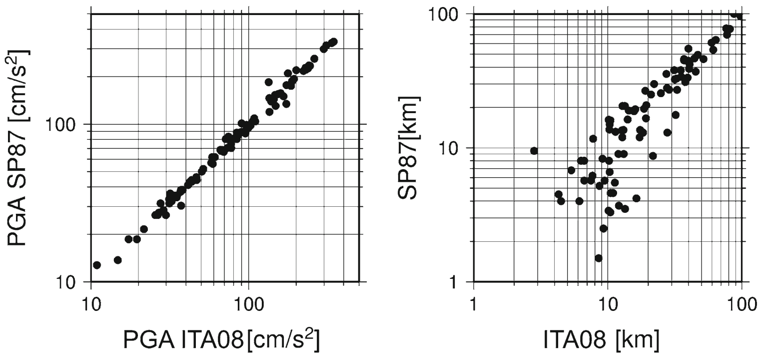

Fig. 3 *Left* Comparison between the PGA (in cm/s^2) computed by Sabetta and Pugliese (1987) and those used in the study (PGA-ITA08). *Right* Comparisons between the Joyner–Boore distance used by Sabetta and Pugliese (1987) and those considered in this study

dummy variables that take either the value 0 or 1 depending on the style of faulting (normal fault: $F_1 = 1$ and $F_2 = F_3 = 0$; strike-slip: $F_2 = 1$ and $F_1 = F_3 = 0$; reverse fault: $F_3 = 1$ and $F_1 = F_2 = 0$); e_i and f_j are the site and the style-of-faulting coefficients, respectively. Two different set of regressions were performed, considering either the epicentral distance (R_{epi}) or considering R_{jb} for $M \geq 5.5$ and R_{epi} for smaller magnitudes. A regression scheme based on the random effect model (Brillinger and Preisler 1985; Abrahamson and Youngs 1992) was adopted to describe the errors that are assumed to be independent and normally distributed. The variability of the errors for different stations that recorded the same event is the inter-event term (σ_{eve}) while the variability of the errors for different earthquakes recorded by the same station is the inter-station term (σ_{sta}), as described by Bindi et al. (2006, 2009b). The regressions were performed for the maximum horizontal (maxH) and vertical peak ground (V) acceleration (PGA) and velocity (PGV), as well as for 5%-damped spectral acceleration (SA) at 21 periods from 0.03 to 2 s. The reference magnitude M_{ref} was fixed to 4.5.

4 Results

The regressions coefficients of Eq. 1 were derived twice, considering or neglecting the style-of-faulting parameter. In the former case, the coefficient f_j for the normal slip earthquakes was assumed as reference and constrained to zero. Since the regression accounting for the style of faulting provided coefficients f_j not significantly different from zero, and their introduction did not significantly reduced the variance of the residuals, only the results obtained without including the style of faulting are further considered. The results of this study will be hereinafter referred to as ITA08.

Table 2a, b list the coefficients obtained for the maximum horizontal and the vertical components for peak ground acceleration and velocity considering the Joyner–Boore and epicentral distance, respectively. The coefficients obtained for the 5% damped acceleration response spectra are listed in Tables 3a and 4a for maxH and for the vertical component, using the Joyner and Boore distance and in Tables 3b and 4b for maxH and for the vertical component and the epicentral distance.

Figure 4 shows the site coefficients versus period considering the maximum horizontal spectral accelerations. The site coefficient for class C_1 is larger than 0.2 for periods smaller than 0.2 s whereas class C_2 is characterized by amplifications at periods larger than 0.4 s. This result confirms that the adopted site classification scheme mainly discriminates between sub-surface geological conditions that led to local site amplification effects either in the low or in the high frequency range, being the transition zone over the 2.5–5 Hz frequency range.

Table 2 (a) Coefficients for the prediction of the horizontal and vertical PGA (cm/s^2) and PGV (cm), considering the Joyner–Boore distance. (b) Coefficients for the prediction of the horizontal and vertical PGA (cm/s^2) and PGV (cm), considering the epicentral distance

	a	b_1	b_2	c_1	c_2	h	C_0	C_1	C_2	σ_{eve}	σ_{sta}	σ
(a)												
Horizontal												
PGA	3.7691	0.0523	−0.1389	−1.9383	0.4661	10.1057	0	0.2260	0.1043	0.2084	0.2634	0.3523
PGV	2.574	0.0496	−0.0982	−2.0846	0.5283	10.4844	0	0.1462	0.2701	0.2314	0.2819	0.3659
Vertical												
PGA	3.2191	0.1631	−0.0765	−1.7613	0.3144	9.1688	0	0.1938	0.1242	0.2080	0.1859	0.3288
PGV	2.0127	0.1069	−0.0619	−1.9206	0.4622	10.2227	0	0.1126	0.1907	0.2270	0.1747	0.3384
(b)												
Horizontal												
PGA	3.750	0.1180	−0.1147	−1.9267	0.4285	10.0497	0	0.2297	0.1022	0.2103	0.2666	0.3555
PGV	2.5830	0.0890	−0.0771	−2.0896	0.5106	10.5886	0	0.1496	0.2673	0.2344	0.2454	0.3707
Vertical												
PGA	3.2015	0.2482	−0.0428	−1.7514	0.2588	9.1513	0	0.1983	0.1230	0.1917	0.1877	0.3241
PGV	2.0141	0.1447	−0.0405	−1.9207	0.4443	10.3378	0	0.1165	0.1879	0.2309	0.1773	0.3442

Table 3 (a) Coefficient for the prediction of horizontal 5% damped acceleration response spectra (cm/s^2), considering the Joyner–Boore distance. (b) Coefficient for the prediction of horizontal 5% damped acceleration response spectra (cm/s^2), considering the epicentral distance

T (s)	a	b_1	b_2	c_1	c_2	h	C_0	C_1	C_2	σ_{eve}	σ_{sta}	σ
(a)												
0.03	3.8802	0.0086	−0.1287	−1.9720	0.4710	10.5940	0	0.2176	0.0866	0.2083	0.2603	0.3521
0.04	3.8569	0.0395	−0.1255	−1.9300	0.4431	10.0362	0	0.2221	0.0764	0.2158	0.2656	0.3648
0.07	4.0050	0.0479	−0.1232	−1.9197	0.4212	10.2414	0	0.2082	0.0390	0.1999	0.2887	0.3649
0.10	4.0176	0.0619	−0.1120	−1.8599	0.3949	10.4222	0	0.2572	0.0580	0.2045	0.2970	0.3734
0.15	4.1000	0.0930	−0.1330	−1.8769	0.4125	10.7824	0	0.2631	0.0632	0.2099	0.2941	0.3832
0.20	4.0808	0.0633	−0.1358	−1.8833	0.4546	10.5949	0	0.2126	0.1212	0.2149	0.2840	0.3924
0.25	3.9805	0.1333	−0.1418	−1.8756	0.4318	10.2248	0	0.1618	0.1454	0.2090	0.2647	0.3815
0.30	3.9016	0.1224	−0.1407	−1.8908	0.4551	9.7928	0	0.1409	0.1630	0.2219	0.2446	0.3750
0.35	3.8185	0.1167	−0.1366	−1.8992	0.4740	9.4714	0	0.1289	0.1892	0.2430	0.2479	0.3842
0.40	3.6578	0.1583	−0.1470	−1.8521	0.4727	9.2690	0	0.1146	0.2190	0.2213	0.2291	0.3740
0.45	3.5972	0.1656	−0.1342	−1.8678	0.4665	9.3437	0	0.0946	0.2632	0.2215	0.2327	0.3744
0.50	3.5304	0.2035	−0.1320	−1.8728	0.4519	9.2842	0	0.0763	0.2741	0.2197	0.2300	0.3713
0.60	3.3531	0.2456	−0.1181	−1.8463	0.4414	9.0307	0	0.0539	0.2973	0.2360	0.2290	0.3732
0.70	3.2126	0.2754	−0.1209	−1.8299	0.4396	8.8794	0	0.0447	0.3217	0.2379	0.2311	0.3761
0.80	3.0980	0.2949	−0.0963	−1.8318	0.4255	8.7481	0	0.0436	0.3406	0.2375	0.2308	0.3756
0.90	3.0472	0.3500	−0.0952	−1.8627	0.3992	9.1414	0	0.0400	0.3663	0.2393	0.2302	0.3784
1.00	3.0311	0.3555	−0.0962	−1.9011	0.4036	9.6044	0	0.0347	0.3791	0.2471	0.2560	0.3907
1.25	2.8210	0.3621	−0.0963	−1.8780	0.4151	9.5829	0	0.0233	0.4091	0.2605	0.2619	0.4119
1.50	2.8348	0.2498	−0.1103	−1.9787	0.5216	9.9923	0	−0.0006	0.4111	0.2223	0.2654	0.4059
1.75	2.8610	0.1834	−0.1040	−2.0899	0.5880	10.8928	0	−0.0002	0.4133	0.2359	0.2390	0.3987
2.00	2.7506	0.2056	−0.1139	−2.0976	0.5953	10.5615	0	−0.0065	0.3836	0.2242	0.2112	0.3790
(b)												
0.03	3.8636	−0.0723	−0.1043	1.9618	0.4346	10.5707	0	0.2211	0.0842	0.2102	0.2638	0.3553
0.04	3.8461	0.1056	−0.0993	−1.9232	0.4040	10.0637	0	0.2260	0.0742	0.2177	0.2690	0.3680
0.07	3.9944	0.1111	−0.0962	−1.9128	0.3835	10.2906	0	0.2122	0.0367	0.2017	0.2926	0.3682
0.10	3.9926	0.1360	−0.0839	−1.8447	0.3492	10.3528	0	0.2609	0.0560	0.2059	0.2781	0.3759
0.15	4.0596	0.1713	−0.1061	−1.8525	0.3646	10.6030	0	0.2667	0.0610	0.2114	0.2971	0.3859
0.20	4.0725	0.1252	−0.1124	−1.8780	0.4187	10.6263	0	0.2158	0.1191	0.2164	0.2859	0.3951
0.25	3.9793	0.1856	−0.1177	−1.8747	0.4025	10.3088	0	0.1654	0.1431	0.2108	0.2671	0.3849
0.30	3.8899	0.1709	−0.1186	−1.8837	0.4298	9.7877	0	0.1448	0.1605	0.2247	0.2474	0.3798
0.35	3.8082	0.1670	−0.1153	−1.8929	0.4480	9.4708	0	0.1329	0.1868	0.2244	0.2506	0.3794
0.40	3.6486	0.2120	−0.1262	−1.8463	0.4439	9.2789	0	0.1185	0.2168	0.2237	0.2314	0.3782
0.45	3.5930	0.2225	−0.1119	−1.8654	0.4352	9.3832	0	0.0983	0.2612	0.2239	0.2146	0.3784
0.50	3.5320	0.2612	−0.1081	−1.8738	0.4193	9.3706	0	0.0802	0.2722	0.2220	0.2322	0.3753
0.60	3.3660	0.3051	−0.0931	−1.8534	0.4061	9.2463	0	0.0581	0.2955	0.2391	0.2121	0.3781
0.70	3.2342	0.3272	−0.0968	−1.8420	0.4096	9.1689	0	0.0489	0.3197	0.2412	0.2141	0.3813
0.80	3.1072	0.3532	−0.0708	−1.8367	0.3911	8.9420	0	0.0481	0.3387	0.2409	0.2138	0.3809
0.90	3.0662	0.4113	−0.0663	−1.8733	0.3612	9.4254	0	0.0445	0.3645	0.2429	0.2333	0.3840
1.00	3.0468	0.4210	−0.0666	−1.9096	0.3627	9.8637	0	0.0389	0.3772	0.2504	0.2386	0.3959
1.25	2.8175	0.4168	−0.0708	−1.8762	0.3838	9.6593	0	0.0285	0.4079	0.2402	0.2444	0.4059
1.50	2.8253	0.2885	−0.0923	−1.9731	0.5055	9.9835	0	0.0035	0.4089	0.2249	0.2477	0.4106
1.75	2.8399	0.2188	−0.0878	−2.0782	0.5756	10.7942	0	0.0041	0.4124	0.2161	0.2424	0.3946
2.00	2.7171	0.2378	−0.0990	−2.0787	0.5868	10.3772	0	−0.0012	0.3830	0.2058	0.1947	0.3758

Considering R_{jb}, the total standard deviation is 0.3523 and 0.3659 for the maximum horizontal PGA and PGV, respectively and 0.3288 and 0.3384 for the vertical PGA and PGV. These values are significantly larger than those evaluated in SP96 (for horizontal components 0.173 and 0.215 for PGA and PGV, respectively), which are, in turn, much smaller than typical GMPE sigma's derived worldwide (generally in the range 0.3–0.4). Bindi et al. (2009a) recalculated the coefficients of the functional form used by Sabetta and Pugliese 1987, 1996 enlarging their data set with the recordings of the strongest earthquakes occurred after

Table 4 (a) Coefficients for the prediction of vertical 5% damped acceleration response spectra (cm/s^2), considering the Joyner–Boore distance. (b) Coefficients for the prediction of vertical 5% damped acceleration response spectra (cm/s^2), considering the epicentral distance. Table 2a

T (s)	a	b_1	b_2	c_1	c_2	h	C_0	C_1	C_2	σ_{eve}	σ_{sta}	σ
(a)												
0.03	3.3378	0.1061	−0.0626	−1.7927	0.3214	9.3650	0	0.1974	0.1137	0.1928	0.1881	0.3259
0.04	3.2871	0.1978	−0.0567	−1.7169	0.2462	8.2612	0	0.2320	0.1198	0.1865	0.1789	0.3405
0.07	3.4305	0.2591	−0.0558	−1.6801	0.1938	8.2858	0	0.2066	0.1146	0.2099	0.2168	0.3548
0.10	3.4767	0.2962	−0.0617	−1.6467	0.1851	8.9225	0	0.1595	0.0933	0.2046	0.2129	0.3458
0.15	3.4249	0.3236	−0.0906	−1.6218	0.2165	9.7569	0	0.1766	0.1149	0.1999	0.2220	0.3378
0.20	3.5314	0.2441	−0.0916	−1.7322	0.2836	10.3065	0	0.1415	0.1378	0.2055	0.2118	0.3474
0.25	3.3264	0.2703	−0.1016	−1.6627	0.2930	9.3620	0	0.1329	0.1402	0.1996	0.1909	0.3375
0.30	3.2307	0.2704	−0.0908	−1.6443	0.2993	8.8936	0	0.0797	0.1296	0.2160	0.1910	0.3415
0.35	3.1481	0.2724	−0.0938	−1.6320	0.3057	9.1088	0	0.0854	0.1396	0.2074	0.1688	0.3279
0.40	3.0705	0.2682	−0.0953	−1.6377	0.3255	8.9782	0	0.0805	0.1582	0.2338	0.1567	0.3485
0.45	3.0589	0.2673	−0.0994	−1.6704	0.3488	9.3007	0	0.0481	0.1709	0.2414	0.1829	0.3599
0.50	3.0721	0.2918	−0.0951	−1.7171	0.3410	9.8103	0	0.0510	0.1709	0.2401	0.1810	0.3580
0.60	2.9603	0.2790	−0.0739	−1.7181	0.3604	9.7820	0	0.0355	0.1677	0.2644	0.1845	0.3739
0.70	2.9058	0.2249	−0.0900	−1.7493	0.4288	10.0439	0	0.0327	0.1803	0.2704	0.1917	0.3823
0.80	2.9774	0.1850	−0.0791	−1.8587	0.4595	11.0579	0	0.0312	0.2003	0.2684	0.2082	0.3795
0.90	2.8355	0.2298	−0.0737	−1.8216	0.4380	10.8397	0	0.0327	0.1876	0.2714	0.1890	0.3839
1.00	2.6846	0.2892	−0.0690	−1.7704	0.4082	10.7126	0	0.0193	0.1894	0.2687	0.2071	0.3800
1.25	2.5013	0.3133	−0.0692	−1.7768	0.4113	10.7505	0	0.0379	0.2424	0.2589	0.2119	0.3859
1.50	2.4435	0.3476	−0.0748	−1.8420	0.4121	10.4345	0	0.0375	0.2842	0.2453	0.2126	0.3879
1.75	2.4401	0.2886	−0.0491	−1.9249	0.4383	11.1435	0	0.0269	0.3001	0.2256	0.2131	0.3813
2.00	2.4825	0.2391	−0.0738	−2.0134	0.5054	11.8535	0	0.0087	0.2702	0.2020	0.1892	0.3688
(b)												
0.03	3.3202	−0.1924	−0.0284	1.7826	0.2648	9.3572	0	0.2018	0.1123	0.1949	0.1720	0.3294
0.04	3.2650	0.2970	−0.0165	−1.7046	0.1784	8.2287	0	0.2374	0.1190	0.1884	0.1805	0.3440
0.07	3.3909	0.3814	−0.0100	−1.6577	0.1074	8.1178	0	0.2120	0.1143	0.2110	0.2179	0.3567
0.10	3.4366	0.4100	−0.0181	−1.6241	0.1054	8.7309	0	0.1643	0.0928	0.2060	0.2141	0.3483
0.15	3.3749	0.4240	−0.0529	−1.5927	0.1479	9.4787	0	0.1809	0.1138	0.2010	0.2236	0.3398
0.20	3.5002	0.3262	−0.0581	−1.7138	0.2297	10.2023	0	0.1455	0.1361	0.2077	0.2138	0.3510
0.25	3.3275	0.3397	−0.0703	−1.6639	0.2480	9.4903	0	0.1370	0.1388	0.2020	0.1923	0.3414
0.30	3.2208	0.3400	−0.0606	−1.6390	0.2549	8.9227	0	0.0841	0.1283	0.1994	0.1746	0.3371
0.35	3.1402	0.3360	−0.0652	−1.6276	0.2657	9.1613	0	0.0896	0.1381	0.2101	0.1707	0.3322
0.40	3.0654	0.3422	−0.0663	−1.6348	0.2777	9.0618	0	0.0845	0.1570	0.2363	0.1578	0.3522
0.45	3.0478	0.3385	−0.0720	−1.6634	0.3036	9.3435	0	0.0521	0.1693	0.2446	0.1645	0.3646
0.50	3.0676	0.3488	−0.0678	−1.7137	0.3060	9.9299	0	0.0552	0.1688	0.2441	0.1833	0.3638
0.60	2.9571	0.3398	−0.0473	−1.7150	0.3224	9.9319	0	0.0396	0.1656	0.2684	0.1867	0.3795
0.70	2.9166	0.2670	−0.0694	−1.7539	0.4055	10.2881	0	0.0363	0.1778	0.2739	0.1938	0.3874
0.80	2.9909	0.2220	−0.0587	−1.8641	0.4399	11.3384	0	0.0347	0.1974	0.2721	0.1910	0.3849
0.90	2.8642	0.2626	−0.0525	−1.8358	0.4202	11.2612	0	0.0363	0.1847	0.2754	0.1915	0.3894
1.00	2.7167	0.3195	−0.0472	−1.7865	0.3915	11.1822	0	0.0230	0.1865	0.2725	0.2102	0.3853
1.25	2.5220	0.3241	−0.0502	−1.7862	0.4095	11.1357	0	0.0426	0.2394	0.2634	0.2159	0.3926
1.50	2.4439	0.3593	−0.0551	−1.8405	0.4119	10.6114	0	0.0422	0.2804	0.2281	0.2175	0.3855
1.75	2.4238	0.3053	−0.0281	−1.9148	0.4353	11.1738	0	0.0321	0.2978	0.2300	0.1970	0.3887
2.00	2.4513	0.2559	−0.0575	−1.9949	0.5060	11.7562	0	0.0147	0.2684	0.2059	0.1932	0.3760

1984 ($M > 5.3$) and obtained values equal to 0.30 and 0.31 for maximum horizontal PGA and PGV, respectively. This result confirms that the standard deviations of the GMPEs developed by Sabetta and Pugliese (1987, 1996) underestimate the observed ground motion variability.

Figure 5 shows the distributions of inter-event variability and inter-station variability for the maximum horizontal and vertical component of PGA. Most of the inter-event errors vary in the range from −0.2 to 0.2. Only some events have significant errors (e.g. 2002 Molise earthquakes, id = 90 and 91 in Table 1), caused by the strong overestimation or underestima-

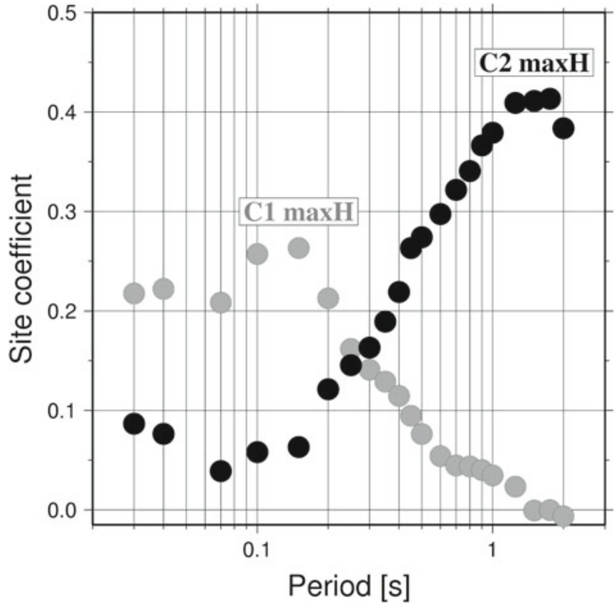

Fig. 4 Site coefficients (see Eq. 1) for classes C_1 (*shallow alluvium*) and C_2 (*deep alluvium*) for maxH spectral acceleration as function of period (s)

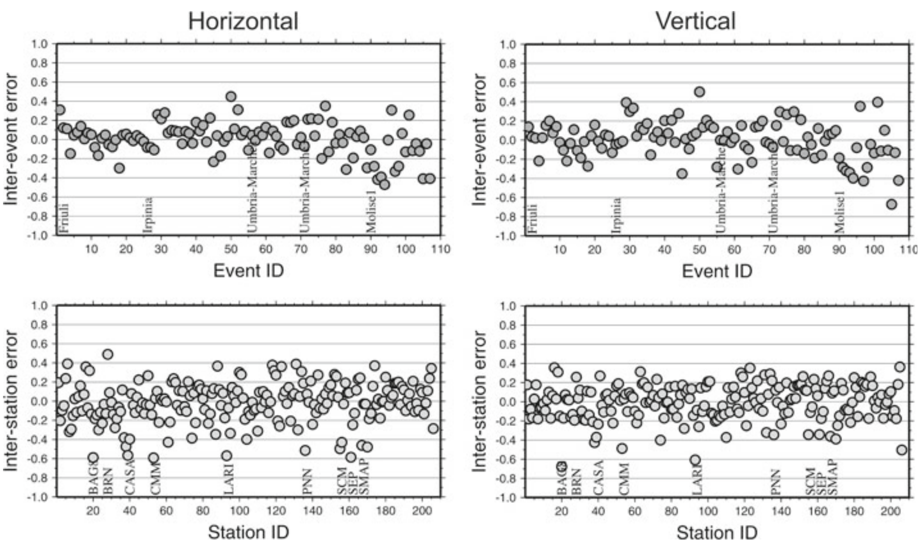

Fig. 5 Inter-event (*top panels*) and inter-station (*bottom panels*) distribution of errors for PGA, considering the maximum *horizontal* (*left*) and *vertical* components (*right*)

tion of the predictions. The inter-station variability is the dominant component of variance for both horizontal PGA and PGV (σ_{sta} in Table 2a, b) but the dominancy of σ_{sta} diminishes with increasing periods (Table 3a, b). For the vertical component (Tables 2a, b and 4a, b), the inter-event standard deviation is larger than the inter-station one, confirming that the vertical

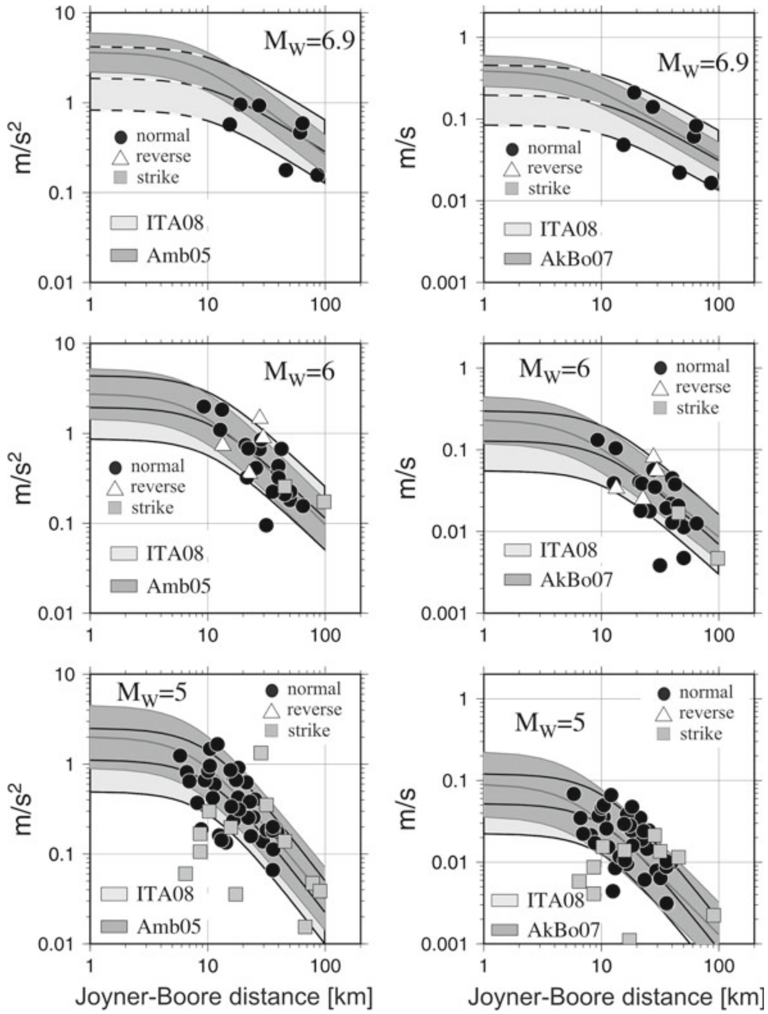

Fig. 6 PGA (*left*) and PGV (*right*) versus distances for rock sites and three different magnitudes: 6.9 (*upper panel*), 6 (*middle panel*) and 5 (*bottom panel*)

component of ground motion is generally less affected by local site amplification effects. These results confirm the conclusion of Bindi et al. (2009b), that evaluate the inter-event and inter-station variability for the Italian strong-motion database (ITACA), computed with a sub-set of strong motion data with respect to this study.

Figures from 6, 7, 8 show the attenuation of horizontal PGA and PGV with distances, comparing the GMPE obtained in this study with global predictive models valid for Europe or worldwide. The comparisons are made for rock sites, for the difficulties in comparing the soil classes of the different predictive models.

Figure 6 shows the attenuation of horizontal PGA and PGV with distances and a comparison with the European models developed by Ambraseys et al. (2005) and Akkar and Bommer (2007) (hereinafter referred to as Amb05 and AkBo07, respectively, whose main characteristics are listed in Table 5). Three magnitude values are considered: 5, 6 and 6.9, and

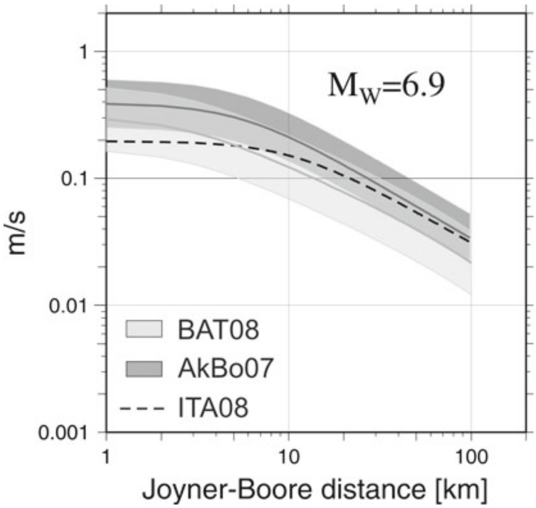

Fig. 7 Comparison between ITA08, Boore and Atkinson (2008), BAT08, and Akkar and Bommer (2007), AkBo07, for peak ground velocity, rock sites and Joyner–Boore distance

the mean plus or minus one standard deviation is plotted using bands of different colours. Different symbols are used for the observations, accordingly to the style of faulting. Since the considered data set does not sample distances smaller than 10 km for magnitudes larger than 6, the comparison for the 6.9 earthquake (Irpinia earthquake) is reliable only for distances >10 km (the ITA08 curves over distances <10 km are plotted with dashed lines). For both PGA and PGV, a good agreement with Amb05 and AkBo07 is observed for distances greater than 10 km. For distances smaller than 10 km, the predictions of ITA08 underestimate those obtained from the European model by a factor up to 2 for both PGA and PGV. Moreover, Amb05 and AkBo07 show smaller dispersion around the mean than ITA08 since their standard deviations are function of magnitude, increasing with decreasing magnitude. Figure 7 shows the mean curve proposed in this study (ITA08) and the mean plus or minus one standard deviation derived by AkBo07 and by Boore and Atkinson (2008), hereinafter referred to as BAT08. The predictions from BAT08 are computed setting the $V_{s,30}$ value to 760 m/s, the threshold value which separates class A (hard rock) from B (rock) in the NEHRP soil classification. At short distances, the ITA08 predictions are between the mean and the mean minus one standard deviation of BAT08, although our data set is poorly sampled at magnitudes greater than 6 (Fig. 2) and 6.9 is the upper magnitude limit of ITA08. For distances larger than 10 km, ITA08 shows a good agreement with AkBo07.

The comparison between ITA08 and the SP96 models is shown in Figs. 8 and 9 for PGA and PGV, considering three different magnitudes. The mean plus or minus one standard deviation is plotted using bands of different grey levels. The main differences are in the magnitude dependence of geometrical spreading, not taken into account by SP96, and in the value of the standard deviation. In particular, a strong over-estimation at large distance is observed with respect to ITA08, in particular for magnitude 5.

The standard deviations of the horizontal component are generally high (>0.35) and the highest values are found for periods larger than 1s (about 0.39–0.40). Vertical components have lower standard deviations than the horizontal, although an increase is observed for periods greater than 0.7 s. Table 3a confirms that σ_{sta} is the dominant component of variability

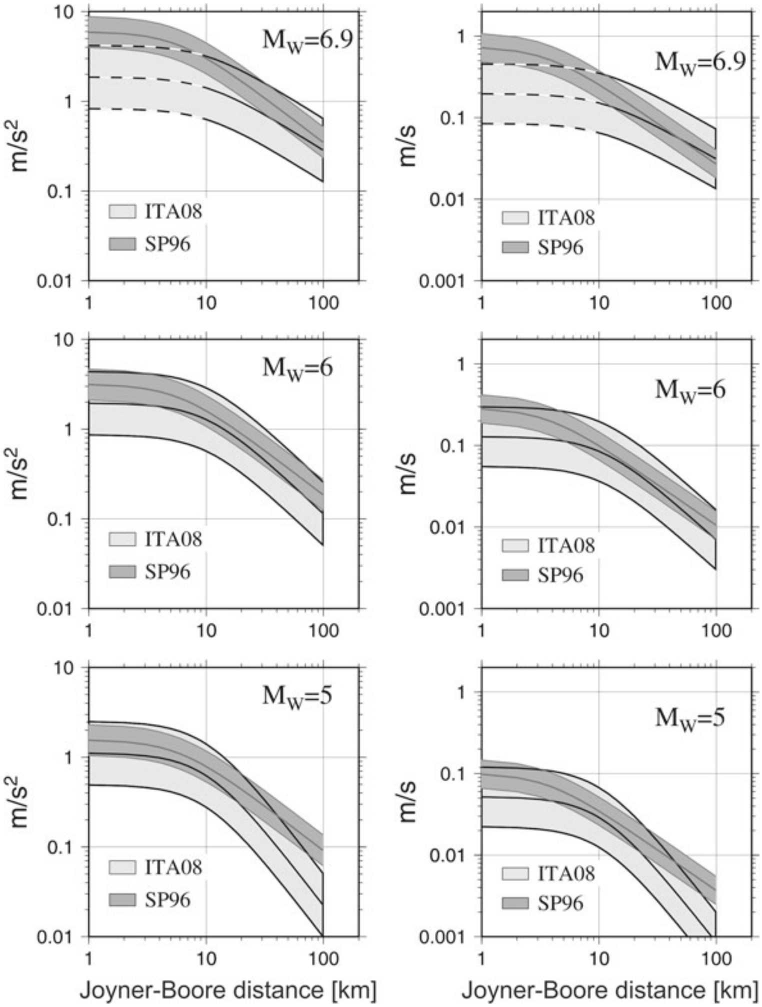

Fig. 8 Comparison between ITA08 and SP96 models for PGA (*left*) and PGV (*right*), rock sites, magnitude 6.9 (*upper panel*), 6 (*middle panel*) and 5 (*bottom panel*) and Joyner–Boore distance

for the horizontal components, with the largest values observed for period between 0.07 s and 0.2 s (i.e., frequencies between 5 and 14 Hz).

Figure 10 compares the horizontal spectral acceleration predicted by ITA08 with the Amb05 predictions for rock sites and normal fault, as the majority of earthquakes in Italy are generated by extensional tectonics. For magnitude 6.5, a good agreement is observed at both 20 and 50 km while for magnitude 5.5 the predictions agree only at 20 km, while at 50 km ITA08 predictions under-estimate those of Amb05 for periods greater than 0.15 s.

Finally, the results for the vertical components are expressed in terms of vertical-to-horizontal response spectra ratio (V/H). A recent study about the engineering characteristics of the vertical ground motion has been published by Bozorgnia and Campbell (2004). They observed that the V/H ratio is a strong function of natural period, source-to-site distance, and local site conditions; and a relatively weak function of magnitude and faulting mecha-

Table 5 Characteristics of the GMPEs used in this study

Study	Parameter	Region	N_{rec}, N_{eve}	Component	M_{range}	M	R_{min}, R_{max}	Dist_type	Style of faulting	Site class
Akkar and Bommer (2007)	PGV	Europe/Middle East	532, 131	L, G	5–7.6	M_w	5–100	R_{JB}	Yes	3
Ambraseys et al. (2005)	PGA, Sa	Europe/Middle East	595, 135	L	6–7.6	M_w	0–100	R_{JB}	Yes	4
Boore and Atkinson (2008)	PGA, PGV, Sa	Worldwide	1574, 58	GMRot	5–8	M_w	0–200	R_{JB}	Yes	$Vs_{,30}$
Sabetta and Pugliese (1987, 1996)	PGA, PGV, PSV	Italy	95, 17	L, V	4.6–6.8	$M_l M_s$	<100	R_{JB}, R_{epi}	No	3

Parameter PGA, peak ground acceleration; PGV, peak ground velocity; SA, acceleration response spectra; PSV, pseudo-velocity response spectra; N_{rec}, N_{eve}, number of records, number of events; component L, larger, G, geometric mean; GMRot, geometric mean determined from the 50th percentile values of the geometric means computed for all non-redundant rotation angles and all periods less than the maximum useable period; V, vertical; M_{range}, magnitude range; R_{min}, R_{max}, minimum distance, maximum distance (km); Dist_type, type of distance; R_{JB} = Joyner–Boore distance (km); R_{epi}, epicentral distance (km); site class, number of site classes

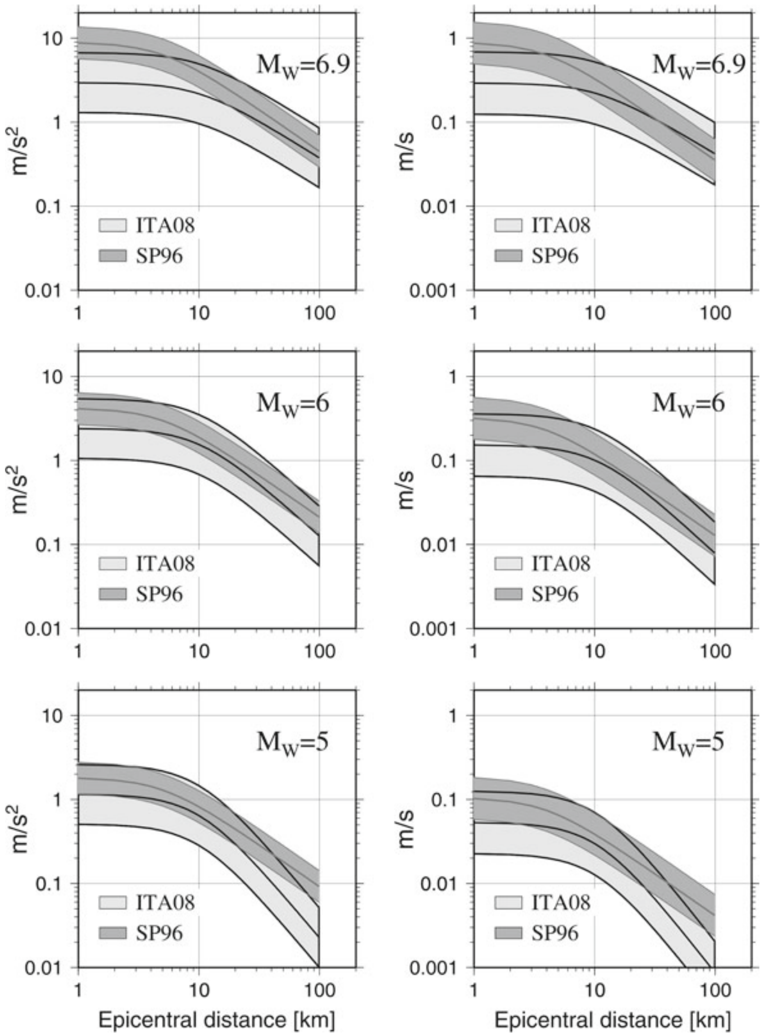

Fig. 9 Comparison between ITA08 and SP96 models for PGA (*left*) and PGV (*right*), rock sites, magnitude 6.9 (*upper panel*), 6 (*middle panel*) and 5 (*bottom panel*) and epicentral distance

nism. Moreover, the dependence of V/H on distance is much different for firm soil than for very firm soil, soft rock or firm rock. In particular, the largest values of V/H (up to a factor of 1.8) are obtained considering predictions for firm soil sites, at short periods, close distances, and large magnitudes. At small magnitudes and large distances, the only significant effect of site conditions observed by Bozorgnia and Campbell (2004) is the tendency for V/H to be higher on firm rock for periods exceeding 0.2 s. Further evidences about the V/H ratio for a recently developed GMPE can be found in Cauzzi and Faccioli (2008).

Figure 11 shows the V/H ratio predicted by the models derived in this study, for two different magnitudes (6.9 and 5.5) and two different distances (10 and 60 km). Our ratios are compared to the curves proposed by Bozorgnia and Campbell (2004) for firm soil (corresponding to classes C_1 and C_2 of this work) and firm rock, soft rock and very firm soil (class

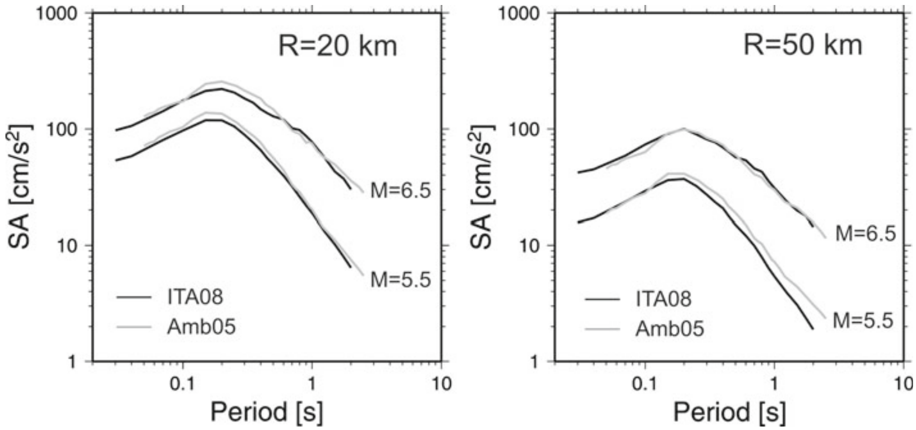

Fig. 10 Comparison between 5% damped acceleration spectra SA obtained with ITA08 and Ambraseys et al. (2005), Amb05: magnitudes 6.5 and 5.5 at 20 km (*left*) and magnitudes 6.5 and 5.5 at 50 km (*right*)

C_0 of this work). The trend of the ratios is consistent with the observations of Bozorgnia and Campbell (2004), characterized by a bump at short periods (<0.2 s) and an almost constant ratio at longer periods (>0.3 s). In particular, a remarkable amplification of the vertical component (ratio greater than 1) is observed for class C_2 and magnitude 6.9 for periods lower than 0.1 s. The results in Fig. 11 suggest that the V/H for class C_1 is more similar to C_0 than C_2, both at short and long periods. Finally, our data set shows a dependence of V/H on the event magnitude more than what observed by Bozorgnia and Campbell (2004).

5 A posteriori validation of GMPEs: the Mw 5.4 Parma earthquake (December, 23 2008)

On December 23, 2008 a Mw 5.4 earthquake occurred in the northern Apennines, close to the town of Parma. The mainshock (origin time 15:24:21 GMT) was followed by a Mw 4.9 (Ml = 4.7) earthquake (origin time 21:58:25 GMT). The two earthquakes have hypocentral depth larger than 20 km and reverse focal mechanism. The mainshock was recorded by 33 strong-motion stations (20 belonging to RAN and 13 to RAIS) with epicentral distances between 32 and 217 km. The Mw 4.9 aftershock has been recorded by 26 strong-motion stations (15 belonging to RAN and 11 to RAIS) in the distance range 9–217 km. The occurrence of these earthquakes represents a good opportunity to validate the predictive equations proposed in this study, although a large number of stations that recorded the two events were installed after 2004 and they were not considered in the development of the GMPE presented in this study. Moreover, as shown in Fig. 2, these events are characterized by Mw values that are well sampled in the data-set used for the GMPE, both in terms of number of records and distance distribution. It is worth noting that in the last 30 years Italy suffered several moderate earthquakes ($5 \leq M \leq 5.5$) which, due to the high degree of vulnerability of many ancient historical villages (Central and Southern Italy) or to the high-rate of industrial facilities (Northern Italy), produced large damages and losses (e.g, the Mw 5.5, 31 October 2002, San Giuliano di Puglia earthquake or the Mw 5.3, 24 November 2004 Salò earthquake).

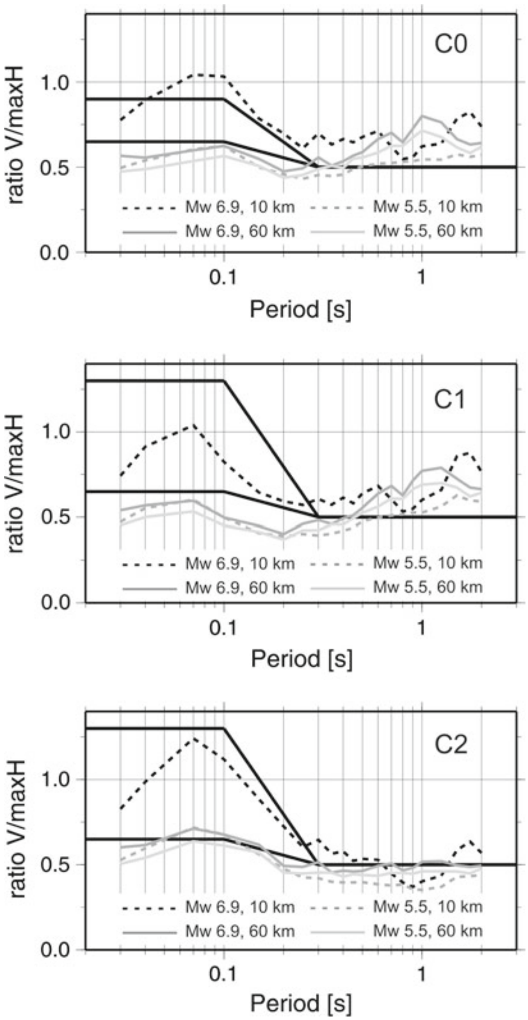

Fig. 11 *Vertical*-to-*horizontal* response spectra ratio (V/H) for magnitudes 6.9 (distance 10 and 60 km) and magnitude 5.5 (distance 10 and 60 km) for rock sites C_0 (*top panel*), shallow alluvium C_1 (*middle panel*) and deep alluvium C_2 (*bottom panel*); black solid lines are the reference curves in Bozorgnia and Campbell (2004)

The data were processed following the same procedure adopted for ITACA database (for details see Massa et al. 2008b, this issue); Fig. 12 shows that the acceleration response spectra ordinates calculated for the Parma earthquakes at the period of 0.1 s, 0.5 s, and 1s fit those reported in ITACA.

In order to check the improvements of ITA08 with respect to previous studies, we compare the observations of the Parma earthquakes (both in term of PGA and PGV) to ITA08 and SP96 predictions. Since detailed geological and geophysical information on the recording stations are currently not available, the comparisons are done only qualitatively, by comparing the mean prediction for rock conditions ($\pm 1\sigma$) to the observations classified as rock and soil.

Figure 13 shows that both ITA08 and SP96 fit the data recorded at station NEVI with distance 10 km. On the contrary, for distances larger than 30 km, SP96 overestimates the observations both in terms of acceleration and velocity. As the SP96 functional form does

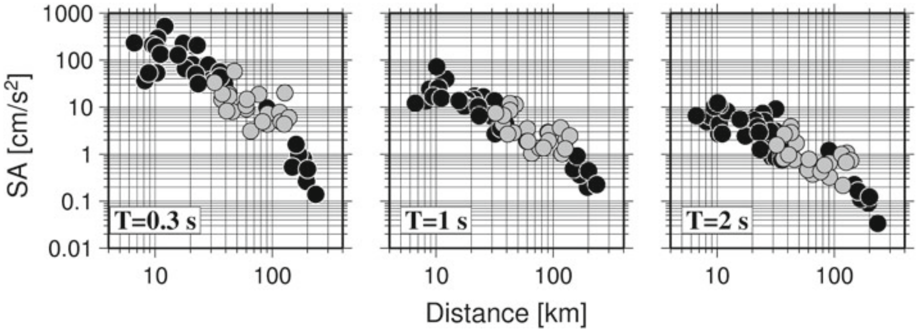

Fig. 12 Acceleration response spectra (SA) ordinates at periods of 03, 1 and 2 s for the events included in ITACA (*black circles*) and for the Mw 5.4 Parma earthquake (*grey circles*), plotted as a function of the epicentral distance

not include the magnitude dependent geometrical spreading, the discrepancies increase with increasing distances. When the Mw 4.9 earthquake is considered the differences with SP96 increases probably as the magnitude of this earthquake (Ml = 4.7) is close to the lowest magnitude threshold of SP96 (Ml = 4.6).

On the other hand, Fig. 13 shows that, for almost all stations, the observations are included in the ITA08 $\pm 1\,\sigma$. Some recordings of the Mw 5.4 earthquake at distances between 30 and 60 km deserve further investigations as strong discrepancies (over-estimation of the predictions up to one order of magnitude) are observed for several rock sites. The sparse trend of rock and soil sites highlights that a reliable site classification is not currently available.

Finally, Fig. 14 shows the good agreement between ITA08 predictions and observations for spectral acceleration (damping 5%) at the three different periods (0.3 s, 1.0 s, 2.0 s) used in Italy for the computation of the ShakeMaps.

6 Conclusions

The accelerometric recordings of the new Italian Strong Motion Archive (ITACA) and the RAIS network database were considered to derive empirical ground motion prediction equations for Italy (ITA08). A larger and more qualified data set than the one used by Sabetta and Pugliese (1987, 1996) was exploited for the regression. The data set qualification was performed through the event relocation, a careful magnitude attribution and the characterization of the recording sites using geological, geophysical and geotechnical investigations and recent seismological studies. The GMPE functional form has been changed respect to SP96 models, including a quadratic term in magnitude and a magnitude dependence of the geometrical spreading. The results of this study show remarkable differences with the SP96 and an agreement, for distances larger than 10 km, with recently proposed GMPEs (Ambraseys et al. 2005; Akkar and Bommer 2007). At distances shorter than 10 km, the underestimation of ITA08 with respect to the European models can be attributed to the scarce data sampling over the short-distance range.

The future developments will be addressed to the improvement of the site classification scheme, which can exploit the results of an ongoing project named "S4 Project—Italian Accelerometric Database", funded by the Italian Civil Protection (http://esse4.mi.ingv.it),

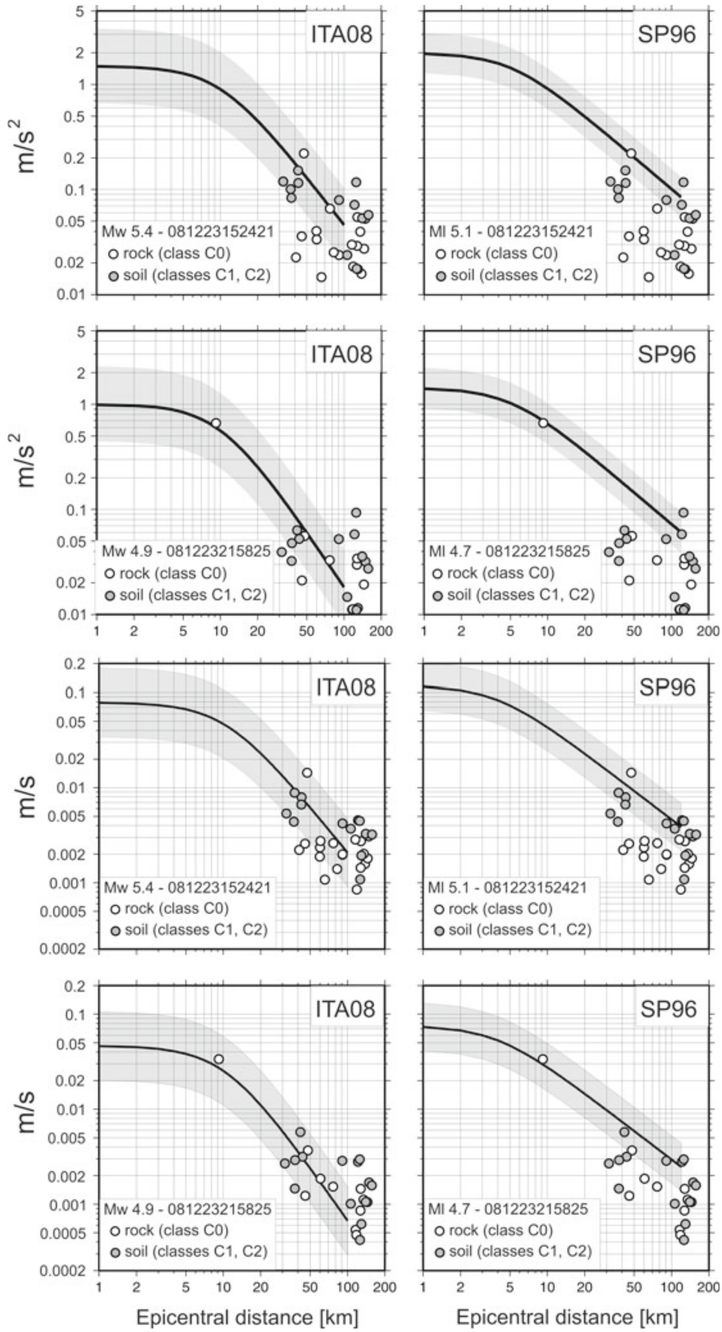

Fig. 13 Parma earthquake observations (Maximum *Horizontal* component of PGA (PGHA) and of PGV (PGHV)) compared to ITA08 (*left panels*) and SP96 (*right panels*) for rock sites. *White circles* are rock sites (C_0 class), *grey circles* indicate soil sites (C_1 and C_2 classes). *Light grey* areas represent the ITA08 standard deviationAnguera03 and distances are calculated from the epicentre

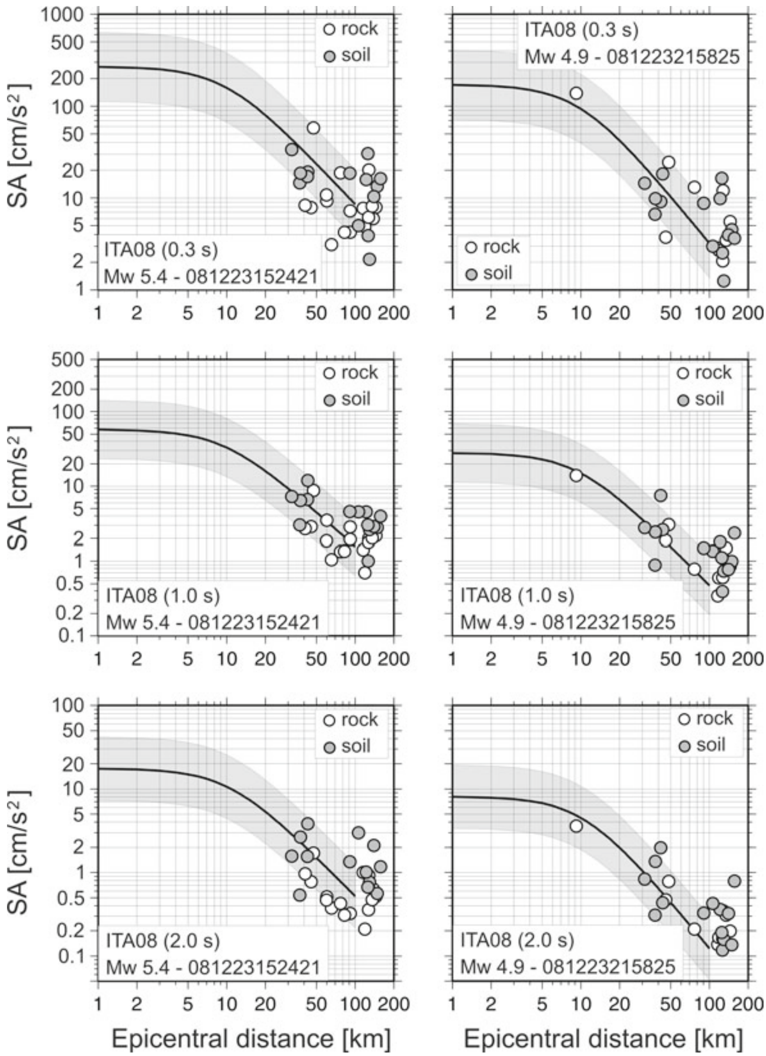

Fig. 14 Comparison between acceleration response spectra ordinates SA (damping 5%) computed for the Parma earthquakes (Mw = 5.4 on the *left* and Mw = 4.9 on the *right*) and ITA08 predictions (*black lines*) for periods of 0.3, 1.0 and 2.0 s. *White circles* are C_0 class observations (rock sites), *grey circles* indicate soil sites (C_1 and C_2 classes). *Light grey* areas represent the ITA08 standard deviation and distances are calculated from the epicentre

whose aim is to acquire a relevant number of shear wave velocity profiles at different sites in Italy. Recent papers have proposed soil classification alternative to the SP96 scheme, based on quantitative parameters, such as the mean shear wave velocity profile at different depths or the fundamental frequency of resonance of the site. We believe that a new soil classification may reduce the GMPE standard deviation, as the inter-station error represents a large component of the variability.

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