Agreement INGV-DPC 2007-2009

Project S4: ITALIAN STRONG MOTION DATA BASE

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Deliverable # 14

Ground Motion Prediction Equations (GMPEs) derived form ITACA

June 2010

edited by:

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1. Scope and Description of the Deliverable

1.1 Data set

The ground motion prediction equations have been derived over the magnitude range 4-6.9, considering epicentral distances up to 200 km and hypocentral depths smaller than 30 km. The moment magnitude and the distance form the fault (Joyner-Boore distance) have been considered as explanatory variables. When these values were not available, the epicentral distance and the local magnitude have been used. The number of considered recordings is 1213, from 218 earthquakes recorded by 353 stations. The stations have been classified into 5 classes accordingly to EC8 (class A: 524 records; class B: 347; class C: 260; class D: 26; class E: 56) and the focal mechanisms have been categorized into four classes (Normal, 696 records; Reverse, 145; Strike Slip, 87; Unknown, 285). Figure 1 shows the magnitude versus distance scatter plot of the considered recordings.

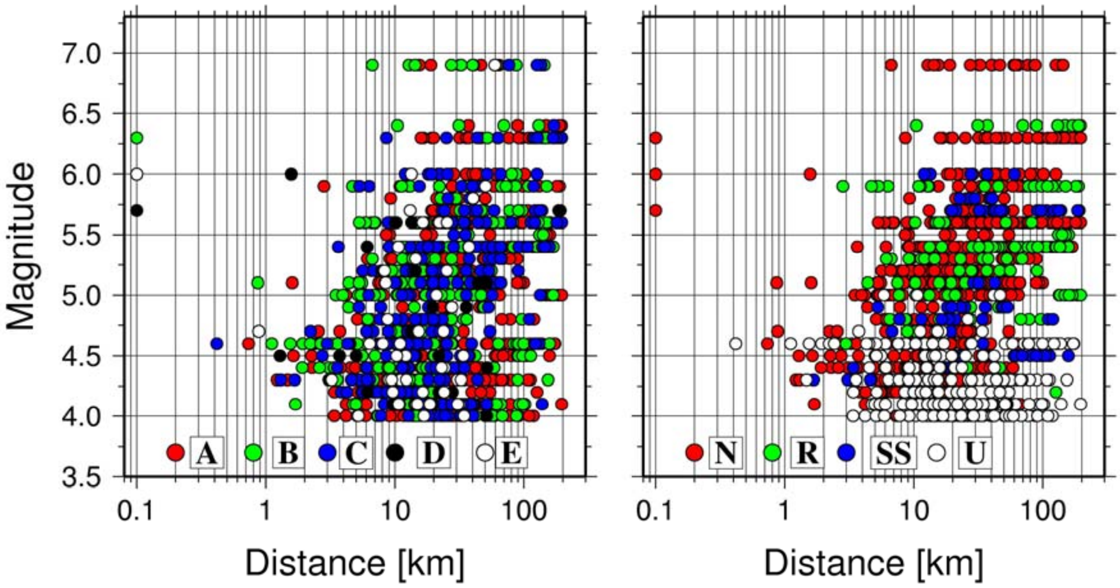

Figure 1. Magnitude versus distance scatter plot (points with Joyner-Boore distance less than 0.1km plotted at 0.1 km). Left: the circle colors indicate the EC8 site classification. Right: the circle colors indicate the style of faulting.

1.2 Functional form

The functional form used for the regression is the same considered by Boore and Atkinson (2008) to derive their equations for NGA, but considering the EC8 site classifications and not including the non-linear site terms. The functional form is the following

$$\log_{10} Y = e_1 + \left[c_1 + c_2\left(M - M_{ref}\right)\right]\log_{10}\left(\sqrt{R_{JB}^2 + h^2} / R_{ref}\right) + c_3\left(\sqrt{R_{JB}^2 + h^2} - R_{ref}\right) + \quad (1)$$
$$+ F(M) + F_S + F_{sof}$$

where e_1, c_1, c_2, c_3, h, M_{ref}, R_{ref} are coefficients to be determined in the analysis. Rjb is the Joyner-Boore distance [km] and M the magnitude. The strong motion parameters Y considered for the regressions are the peak ground acceleration, PGA (gal) and velocity, PGV (cm/s) and 5% response spectra in acceleration, SA (cm/s^2). The functional F(M) is given by:

$$F(M) = e_5(M - M_h) + e_6(M - M_h)^2 \quad \text{for } M \le M_h$$
$$F(M) = e_7(M - M_h) \quad \text{otherwise} \tag{2}$$

where e_5, e_6, e_7 and M_h are coefficients to be determined in the analysis. The functional form F_S represents the site amplification and it is given by F_S=s_jC_j, for j=1,...5, where s_j are the coefficients to be determined during the analysis while C_j are dummy variables used to denote the different EC8 site classes (i.e., A, B, C, D, E).
The functional form Fsof represents the style of faulting corrections and it is given by Fsof=fjEj, for j=1,...4, where fj are the coefficients to be determined during the analysis while Ej are dummy variables used to denote the different site classes. We considered 4 style of faulting classes: normal (E1), reverse (E2), strike slip (E3) and unknown (E4).
After some trials and following some of the results of Boore and Atkinson (2008), the following choices have been performed: Rref=1 km; Mref=5; Mh=6.75; e7=0. In developing the analysis, the site coefficient s_1 of class A was constrained to zero and used as reference for the other coefficients. We also constrained to zero the style of coefficient f4 for the unknown class, as well as the average of the style of faulting coefficient (f_1+ f_2+ f_3=0). In all, we calibrated the model over 13 parameters (e_1, c_1, c_2, h, e_5, e_6, s_2, s_3, s_4, s_5, f_1, f_2, f_3).
The regressions are performed by applying a random effect approach (Abrahamson and Youngs, 1992) to the geometrical mean of the horizontal components (GeoH) and for the vertical one (Z).

1.3 Results

The values of the coefficients obtained for the GeoH and Z components are listed in Table 1 and Table 2 of the Appendix. They are also listed in the enclosed Excel file.
Figures from 2 to 6 show the comparisons between predictions and observations for the strongest earthquakes occurred in Italy since 1972 (i.e., Irpinia 1980, L'Aquila 2009, Molise 2002, Friuli 1976, Umbria-Marche 1997), considering the SA ordinates at 0.1 and 1s. The comparisons are shown for three soil classes (A, B, and C). A general good agreement is observed. Regarding the Friuli earthquake, the fours class A stations exceeding the predictions at the period 0.1s are ASG, FLT, MLC and TRG. The inter-station errors, ε_{sta}, normalized to the inter-station standard deviation, σ_{sta} (see Deliverable D9, Appendix A) have been calculated for these stations. The results, shown in Figure 7, confirm that large errors affect the predictions at high frequencies, with the exception of station BRC, corresponding to the observation at 37 km, which does not show any significant error.
The derived GMPEs are also compared to models previously derived. Figure 8 show the comparison with the Sabetta and Pugliese (1996) model, considering the PGA for a Mw 6.3 earthquake (normal faulting). In order to avoid the application of conversion parameters, a further GMPE has been derived for the maximum of the two horizontal components.
Finally, Figure 9 shows the comparison between the model derived in this study and the GMPE of Boore and Atkinson (2008). The comparison is performed for a Mw 6.3 earthquake considering the spectral acceleration SA at 1 s (left) and PGA (right). This comparison confirms that the NGA model well predicts the Italian data at long periods but underestimates the decay with distance at high frequency.

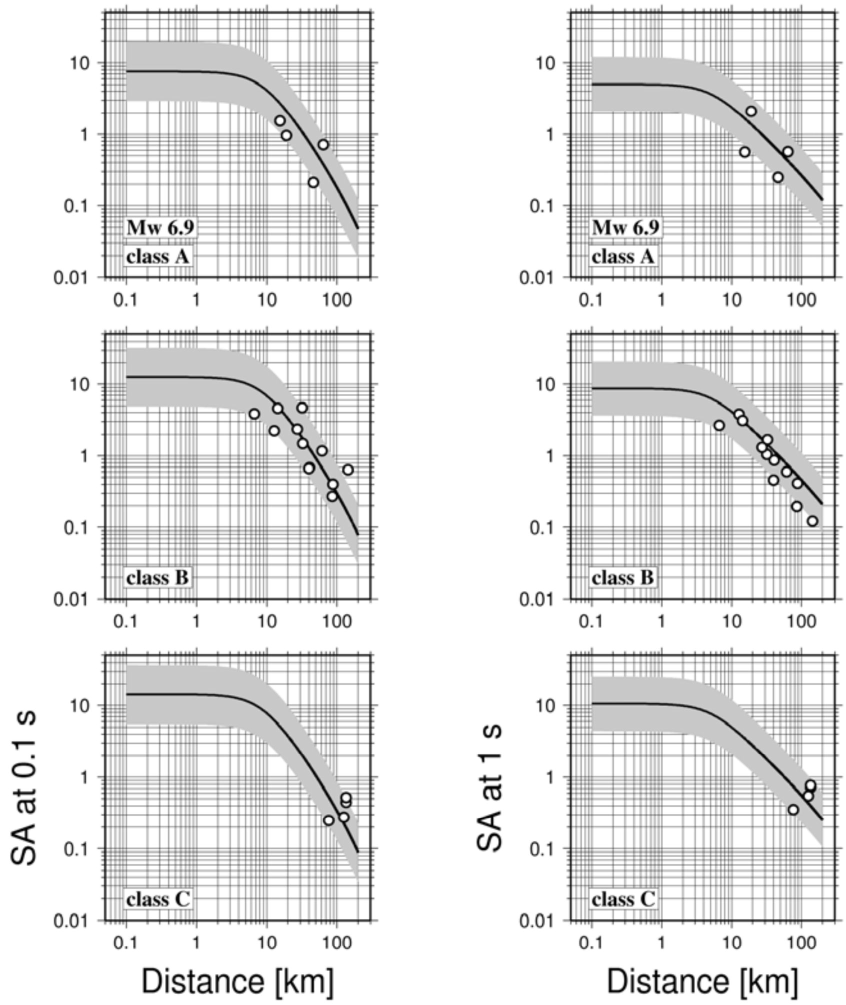

Figure 2. Comparison between median (black line) ±1σ (gray area) prediction and observations (white filled circles) for the Mw 6.9 Irpinia earthquake (normal faulting). Left: results for spectra acceleration at 0.1 s; right: results for spectral acceleration at 1 s. Three different soil classes (A, B, C of EC8) are considered from top to bottom, respectively.

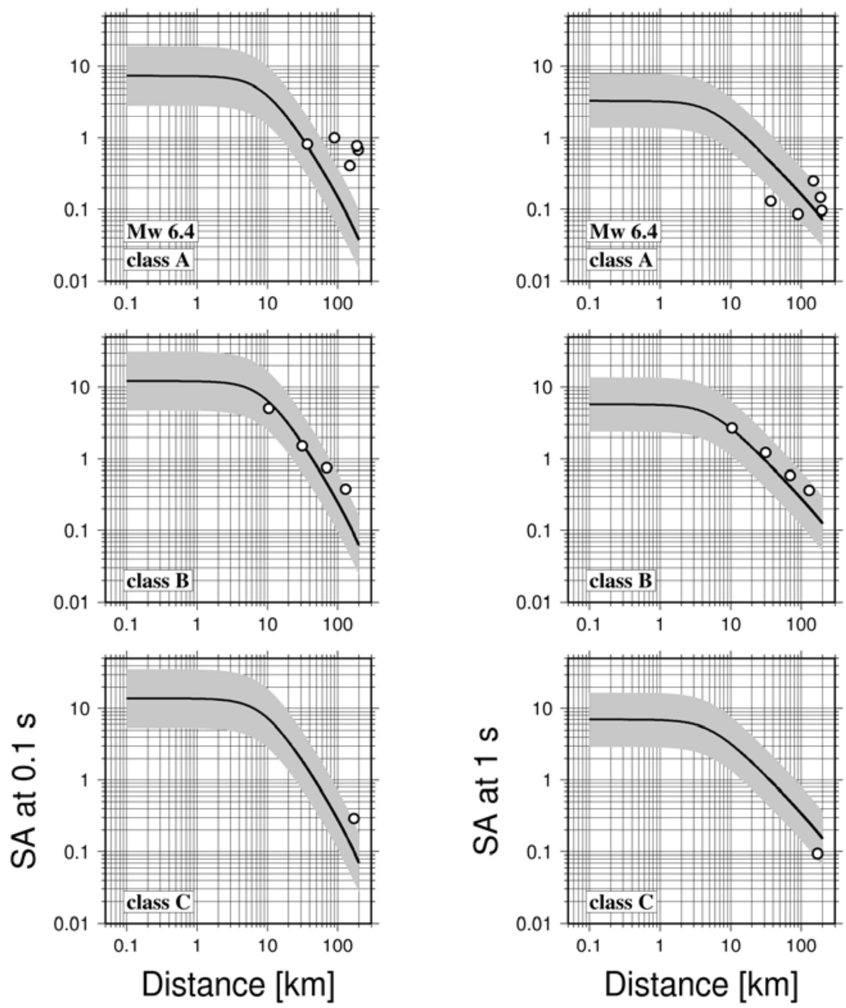

Figure 3. The same as for Figure 2 but considering the Mw 6.4 Friuli earthquake (reverse faulting).

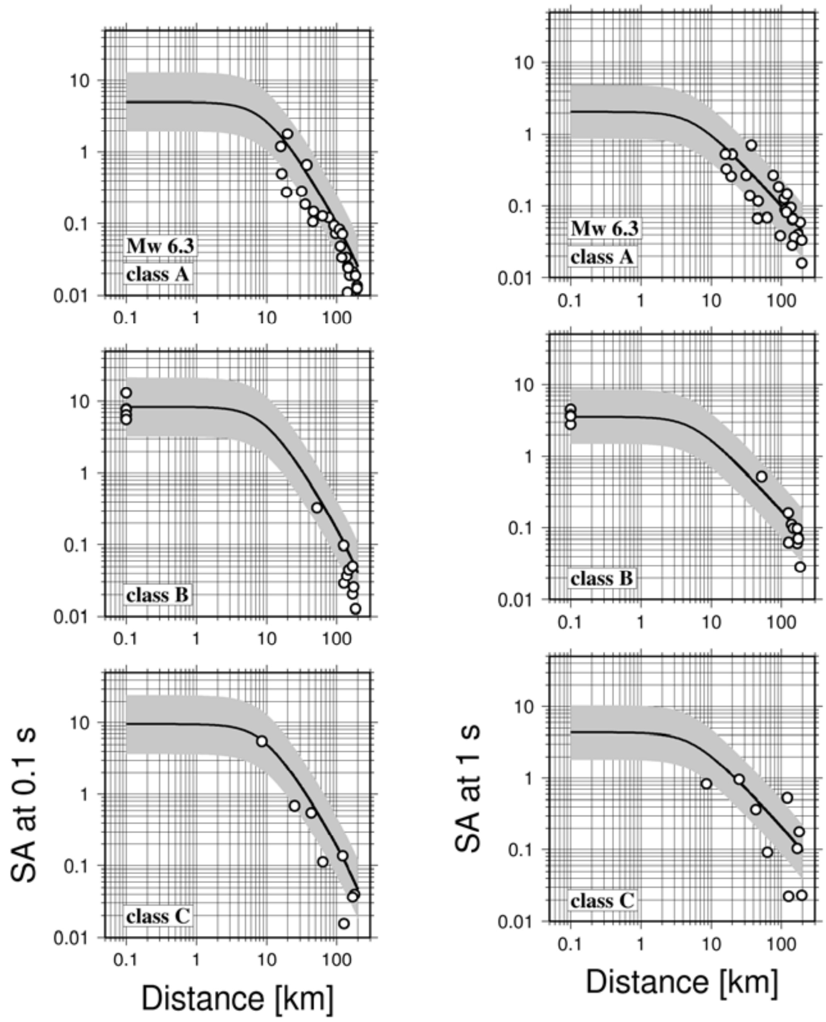

Figure 4. The same as for Figure 2 but considering the Mw 6.3 L'Aquila earthquake (normal faulting).

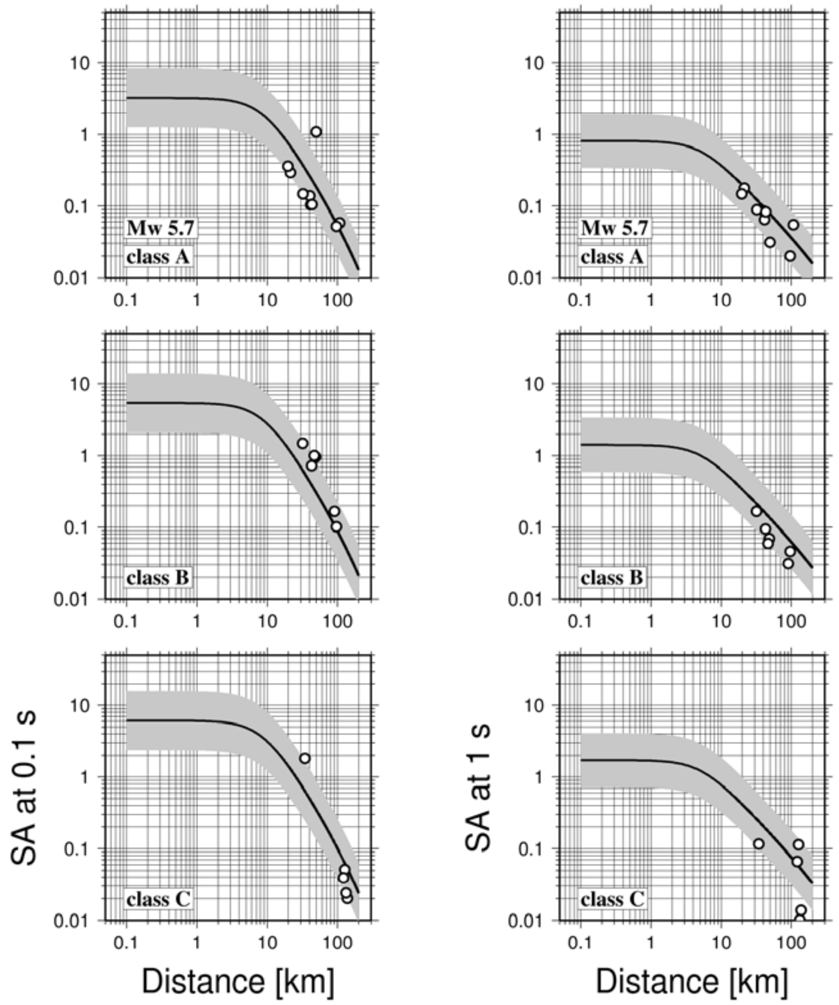

Figure 5. The same as for Figure 2 but considering the Mw 5.7 Molise earthquake (strike slip faulting).

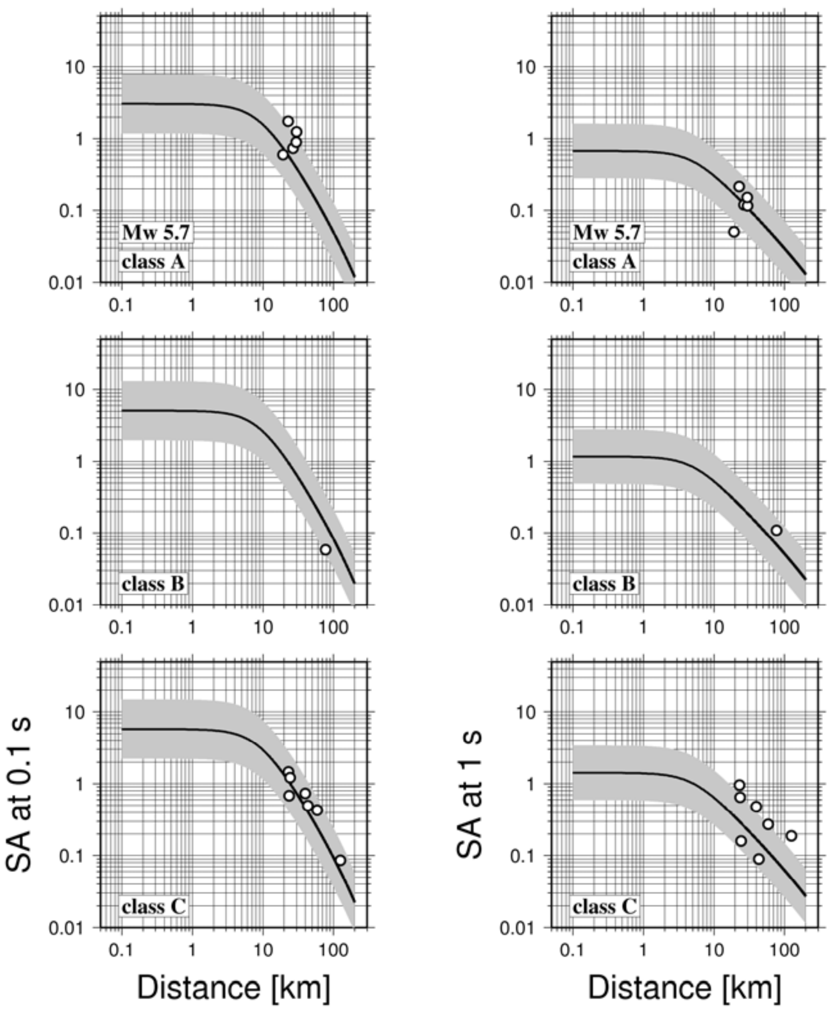

Figure 6. The same as for Figure 2 but considering the Mw 5.7, Umbria-Marche earthquake (normal faulting).

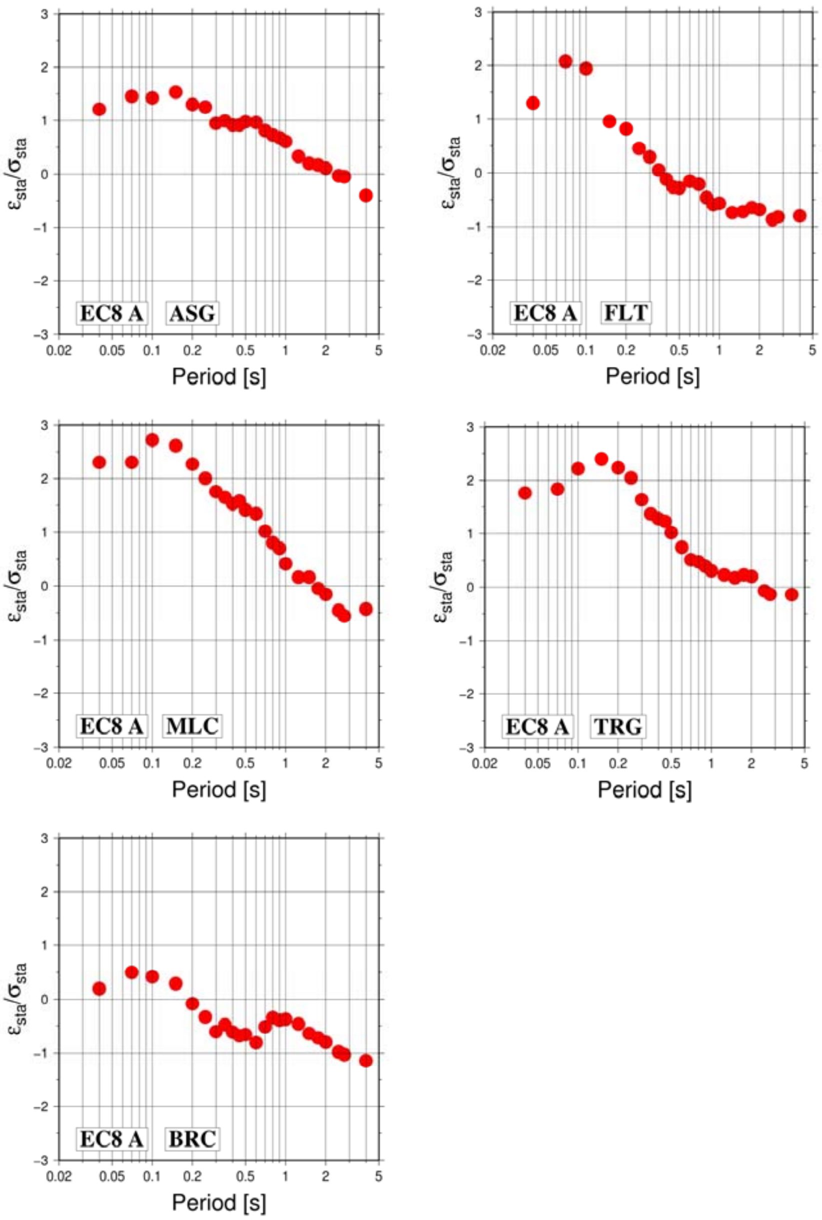

Figure 7. Inter-station error, ε_{sta}, normalized to the inter-station standard deviation, σ_{sta} for 5 class A stations that recorded the Friuli mainshock (see Figure 3). Station ASG, FLT, MLC and TRG show large errors over the high frequency range (short periods), while the normalized error for BRC is bounded between ±1, in agreement with the comparison shown in the top panels of Figure 3 (the BRC station has a distance of 37 km from the fault projection).

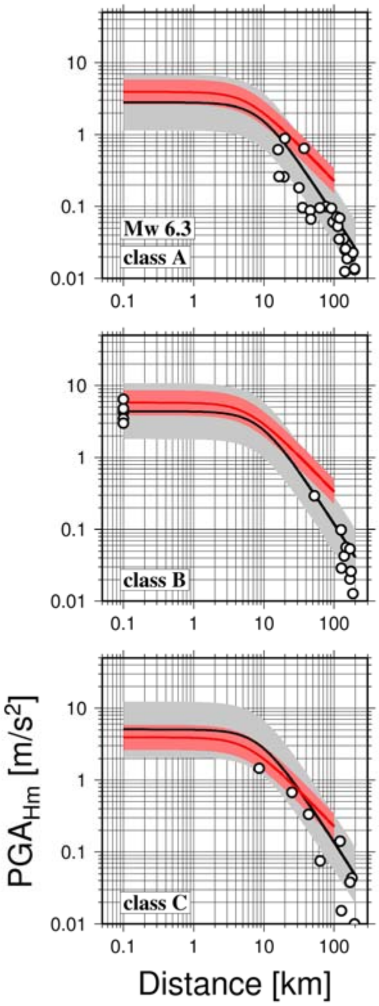

Figure 8. Comparison between the median ±1σ PGA predicted by Sabetta and Pugliese (1996), in red, and this study (gray area and black line). Observations (circles) are shown as well.

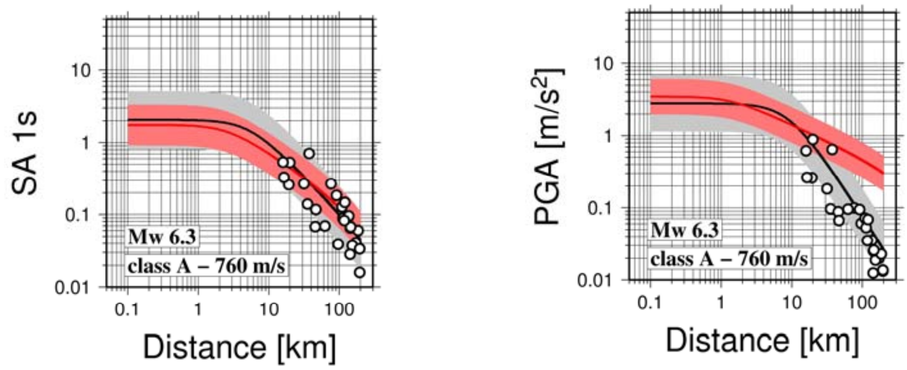

Figure 9. Comparison between median ±1σ SA at 1s (left) and PGA (right) predicted by Boore and Atkinson (2008), in red, and this study (gray area and black line). Observations (circles) are shown as well.

1.3 References

Abrahamson, N.A. and Youngs, R.R. (1992) “A stable algorithm for regression analyses using the random effects models, Bull. Seismol. Soc. Am., 82, 505-510.

Boore, D. M. and G. M. Atkinson (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, Earthquake Spectra 24, 99--138.

Sabetta, F. and Pugliese, A. (1996) “Estimation of Response Spectra and Simulation of Nonstationary Earthquake Ground Motions”, Bull. Seismol. Soc. Am., 86(2), 337-352.

2. Availability/Restrictions and contact person

The Deliverables and the electronic version of the tables are available at http://esse4.mi.ingv.it. Several researchers contributed to this Deliverable: D. Bindi (UR 8), L. Luzi (UR 1) F. Pacor, M. Massa, R. Puglia (UR 1); R. Paolucci (UR 3), A. Rovelli (UR 2). The analyses have been performed by D. Bindi (bindi@gfz-potsdam.de). The Figures have been drawn with the GMT software [Wessel and Smith (1991). Free software helps map and display data, EOS 72, no. 41, 441, 445–446].

3. Relevance for DPC and/or for the scientific community

Since GMPEs are a fundamental tool for any seismic hazard oriented study, this Deliverable is of particular interest for those parts of both the seismological and engineering community dealing with hazard assessment in Italy.

4. Changes with respect to the original plans and reasons for it

Due to its relevance for other research activities within Project S4, the development of new GMPEs for Italy using strong motion data from ITACA has been decided during the second year of project and the Deliverable D14 has been added to the list of expected Deliverables.

Appendix

Table 1. coefficients for the Geometrical mean of the horizontal components (acceleration in cm/s^2, velocity in cm/s)

T [s]	0	0.04	0.07	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.6	0.7	0.8	0.9	1	1.25	1.5	1.75	2	2.5	2.75	4	PGA	PGV
e1	3.87065	3.99922	4.29422	4.25358	4.12979	3.99917	3.88984	3.88389	3.87019	3.71329	3.63222	3.7391	3.63407	3.57729	3.49926	3.4519	3.45762	3.20907	2.95997	3.00271	2.98763	2.87296	2.6667	2.39006	3.99923	2.80809
c1	-1.62571	-1.66649	-1.78982	-1.63552	-1.37719	-1.19514	-1.17658	-1.21002	-1.21385	-1.11009	-1.07415	-1.1272	-1.08393	-1.05732	-1.03144	-1.04357	-1.05018	-0.98827	-0.9513	-1.06106	-1.08389	-1.17981	-1.14717	-1.1892	-1.68074	-1.54632
c2	0.15943	0.145208	0.139926	0.126529	0.082283	0.059165	0.071457	0.076947	0.079467	0.077104	0.08041	0.061179	0.067864	0.059566	0.060053	0.065989	0.04895	0.07398	0.100515	0.097517	0.088079	0.109969	0.131909	0.153783	0.161383	0.172063
h	8.58315	7.81436	8.71227	8.68313	7.90121	6.88591	6.66419	6.57604	6.61929	5.71073	5.2991	5.74521	5.52107	5.16418	4.80725	5.13103	5.19366	4.99159	4.67194	5.82249	5.83565	6.70733	6.4452	6.80357	8.80552	8.05191
c3	0.000427251	0.000403	0.000339	0.001583	0.002841	0.003392	0.003086	0.002342	0.00197	0.002292	0.002238	0.00159	0.001642	0.001374	0.001192	0.000926	0.00054	0.000567	0.000657	-0.00021	-0.00055	-0.00132	-0.00112	-0.00125	0.00018	-0.00098
e5	0.221108	0.228667	0.190881	0.231714	0.313982	0.390613	0.37805	0.407369	0.43695	0.465658	0.495758	0.561348	0.603865	0.692641	0.759184	0.762043	0.827764	0.847682	0.843118	0.886389	0.921832	0.903624	0.884766	0.878922	0.213122	0.544755
e6	-0.00999798	-0.00898	-0.01551	-0.0081	-0.01147	-0.00646	-0.0118	-0.01023	-0.00895	-0.0109	-0.00756	-0.00157	0.004162	0.016651	0.027243	0.025864	0.034674	0.040009	0.042466	0.049143	0.053697	0.055011	0.058093	0.068734	-0.01068	0.04429
e7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
sA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
sB	0.206374	0.201312	0.193027	0.220321	0.237039	0.217988	0.231068	0.236585	0.241061	0.244622	0.236276	0.233124	0.235773	0.228327	0.230264	0.233587	0.238516	0.247724	0.253573	0.255297	0.251608	0.248832	0.24208	0.22221	0.197717	0.231711
sC	0.26585	0.266855	0.258709	0.275835	0.260031	0.248074	0.25764	0.257305	0.265758	0.261138	0.268796	0.276165	0.290821	0.297893	0.303457	0.311081	0.322613	0.343738	0.349344	0.334788	0.331602	0.318464	0.317493	0.29715	0.257494	0.295738
sD	0.049203	0.008196	-0.00356	-0.03873	0.036795	0.001668	0.073495	0.153402	0.168895	0.190825	0.223331	0.263232	0.358604	0.510675	0.627849	0.683314	0.722159	0.717613	0.673899	0.625283	0.599055	0.550063	0.530868	0.481197	0.046975	0.345571
sE	0.522494	0.559583	0.50279	0.569641	0.680347	0.485812	0.325866	0.220337	0.156797	0.128971	0.113994	0.101562	0.083841	0.070963	0.08656	0.090462	0.091733	0.109274	0.130743	0.144143	0.151601	0.153999	0.157695	0.175	0.527619	0.371954
fN	-0.0530851	-0.04145	-0.03298	-0.05161	-0.06517	-0.07859	-0.07204	-0.07665	-0.07741	-0.08347	-0.08723	-0.09099	-0.08738	-0.08344	-0.08095	-0.07575	-0.06794	-0.05761	-0.05002	-0.03879	-0.03458	-0.03259	-0.02637	-0.01499	-0.06276	-0.06702
fR	0.0704092	0.068771	0.069651	0.075595	0.083879	0.074898	0.081412	0.074232	0.075658	0.078358	0.076512	0.073009	0.073161	0.075745	0.065703	0.060381	0.053838	0.038853	0.029687	0.017857	0.011204	0.003759	0.00314	0.001076	0.073439	0.051021
fS	-0.0173447	-0.02734	-0.03669	-0.024	-0.01873	0.003672	-0.00939	0.002394	0.001725	0.005091	0.010694	0.017956	0.014198	0.007671	0.015216	0.015345	0.014071	0.01873	0.020303	0.020904	0.023353	0.028802	0.023209	0.013892	-0.0107	0.015975
fU	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
σSta	0.273789	0.282578	0.315057	0.313839	0.321051	0.3165	0.289257	0.267819	0.259664	0.24935	0.243097	0.242382	0.237383	0.233406	0.226284	0.226894	0.22719	0.228615	0.238206	0.241965	0.242377	0.242074	0.249219	0.237359	0.251227	0.254553
σRec	0.263048	0.271492	0.268102	0.267066	0.262137	0.26933	0.277909	0.278754	0.281339	0.281305	0.285673	0.284833	0.290734	0.298137	0.301713	0.302526	0.30292	0.30482	0.304269	0.30907	0.309597	0.309209	0.30523	0.303186	0.295226	0.275801
σTot	0.379677	0.391865	0.413691	0.412091	0.414476	0.415585	0.401128	0.386563	0.382854	0.37591	0.375106	0.374003	0.375336	0.378634	0.377141	0.378157	0.37865	0.381025	0.386422	0.39252	0.393188	0.392696	0.39405	0.385047	0.387651	0.375317

Table 2. coefficients for the vertical component (acceleration in cm/s^2, velocity in cm/s)

T [s]	0	0.04	0.07	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.6	0.7	0.8	0.9	1	1.25	1.5	1.75	2	2.5	2.75	4	PGA	PGV
e1	3.88302	4.2385	4.49449	4.34476	4.02541	3.96226	3.91492	3.78434	3.5701	3.43118	3.38739	3.4474	3.39	3.22826	3.26928	3.16979	3.07185	2.93616	2.94693	2.73168	2.60986	2.35938	1.99848	1.89455	3.88569	2.4672
c1	-1.59677	-1.7439	-1.75182	-1.54613	-1.26112	-1.30163	-1.27469	-1.24102	-1.15602	-1.14506	-1.14287	-1.19607	-1.15179	-1.07805	-1.15216	-1.08425	-1.02503	-1.01181	-1.0043	-0.91917	-0.89091	-0.87065	-0.73263	-0.87179	-1.60462	-1.48919
c2	0.0898335	0.053635	0.028896	0.017492	-0.00595	0.025887	0.022499	0.053828	0.072092	0.105407	0.103565	0.104632	0.106685	0.104862	0.106501	0.101129	0.101489	0.115892	0.084534	0.088485	0.0862	0.113507	0.142459	0.154251	0.092365	0.181624
h	8.01046	7.38522	8.16331	8.36231	7.29372	8.02077	7.95873	7.77702	7.26814	7.24999	7.03739	7.5145	7.258	6.58664	7.53227	6.73143	6.23694	6.62612	7.03161	6.20264	5.72852	5.13893	3.47082	4.85937	8.10218	8.94676
c3	0.000439128	-7.44E-05	0.000613	0.001854	0.00305	0.002473	0.0021	0.00203	0.002269	0.002109	0.001744	0.001205	0.001261	0.001157	0.000395	0.000584	0.000665	0.000484	0.000478	0.000656	0.000736	0.000663	0.001585	0.000653	0.000405	-0.00093
e5	0.460173	0.505022	0.506409	0.508367	0.508065	0.459002	0.500854	0.498135	0.448976	0.412585	0.423542	0.45607	0.540955	0.597566	0.641821	0.684373	0.735757	0.789045	0.922946	0.964589	0.950327	0.946325	0.881924	0.910312	0.45358	0.590828
e6	0.0298923	0.03619	0.029325	0.022066	0.003294	-0.00259	-0.00055	0.002666	-0.01012	-0.01468	-0.02076	-0.01533	0.000584	0.008528	0.015995	0.020626	0.030275	0.042259	0.058602	0.067993	0.060739	0.064414	0.054068	0.064595	0.029102	0.058468
e7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
sA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
sB	0.186512	0.191581	0.188345	0.210714	0.221657	0.225657	0.210203	0.197685	0.189346	0.179872	0.18385	0.179693	0.176545	0.188237	0.195315	0.199276	0.191629	0.191736	0.171545	0.163832	0.171872	0.173671	0.16774	0.145999	0.186629	0.179744
sC	0.210073	0.238815	0.239906	0.197473	0.195233	0.188896	0.167011	0.184582	0.184023	0.174602	0.189205	0.186561	0.193058	0.211	0.213948	0.212811	0.222597	0.237137	0.242966	0.242113	0.24511	0.218256	0.202403	0.182227	0.210084	0.209719
sD	0.11516	0.062423	0.065326	0.061628	0.145491	0.149956	0.213828	0.270736	0.313791	0.414663	0.461604	0.500931	0.498721	0.522767	0.532211	0.53372	0.519984	0.480982	0.480146	0.442661	0.4134	0.409158	0.419102	0.419067	0.115666	0.333195
sE	0.305698	0.384482	0.28403	0.301139	0.336794	0.245955	0.189018	0.129289	0.133531	0.115243	0.107827	0.100817	0.098921	0.097452	0.113288	0.111281	0.100653	0.091472	0.110277	0.098898	0.095819	0.080353	0.073799	0.046736	0.305785	0.194236
fN	-0.0647816	-0.05085	-0.07437	-0.07264	-0.06494	-0.07284	-0.071	-0.08199	-0.08296	-0.08026	-0.07687	-0.07793	-0.06867	-0.05393	-0.04702	-0.04023	-0.03388	-0.02921	-0.0234	-0.02188	-0.01931	-0.004	-0.00133	0.011445	-0.06478	-0.04394
fR	0.0424443	0.04111	0.062162	0.046657	0.043143	0.057498	0.059308	0.043714	0.050843	0.065397	0.062253	0.063599	0.058728	0.05219	0.045138	0.039055	0.034438	0.034808	0.027181	0.020935	0.019483	0.010166	0.006674	0.007574	0.0424	0.037916
fS	0.0223173	0.009722	0.012194	0.025964	0.021774	0.015318	0.011669	0.038256	0.032097	0.014838	0.014601	0.014314	0.009917	0.001713	0.001863	0.001155	-0.00058	-0.00562	-0.0038	0.000926	-0.0002	-0.00619	-0.00536	-0.01904	0.02236	0.005998
fU	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
σSta	0.234989	0.248132	0.274576	0.280574	0.282023	0.266277	0.240707	0.218186	0.207288	0.201494	0.203826	0.203642	0.193134	0.192085	0.193572	0.185069	0.193004	0.197148	0.203012	0.214473	0.21628	0.208952	0.208818	0.196401	0.240975	0.236158
σRec	0.265103	0.27993	0.274576	0.269566	0.260296	0.266277	0.271554	0.278696	0.276383	0.280734	0.283982	0.283726	0.295017	0.308021	0.310406	0.312222	0.309494	0.31614	0.325543	0.327613	0.330374	0.335069	0.334854	0.331339	0.271856	0.245801
σTot	0.354259	0.374073	0.388309	0.389086	0.383785	0.376572	0.362879	0.353944	0.345479	0.34556	0.349558	0.349243	0.352613	0.363006	0.365817	0.36295	0.364743	0.372575	0.383656	0.391572	0.394872	0.394883	0.394629	0.385174	0.363283	0.340865