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Comparison between empirical predictive equations calibrated at global and national scale and Italian strong-motion data

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ABSTRACT In the last few years in Italy many ground motion prediction equations (hereinafter GMPEs) were calibrated both at national and regional scale using weak and strong motion data recorded in the last 30 years by several networks. Moreover, many of the strongest Italian earthquakes were included in global data sets in order to calibrate GMPEs suitable for the prediction of ground-motion at very large scale. In the last decade, the Sabetta and Pugliese (1996) relationships represented a reference point for ground motion predictions in Italy. At present all Italian strong-motion data, recorded from 1972 by Italian Accelerometric Network, and more recently by other regional networks (e.g., RAIS, Strong motion network of northern Italy), are collected in ITACA (ITalian ACcelerometric Archive). Considering Italian strong-motion data with $M_w \geq 4.0$ and distance (Joyner-Boore or epicentral) up to 100 km, new GMPEs were developed by Bindi *et al*. (2010), aimed at replacing the older Italian relationships. The occurrence of the recent December 23, 2008, M_w 5.4, Parma (northern Italy) earthquake and the April 6, 2009, M_w 6.3, L'Aquila earthquake, allowed us to upgrade the ITACA data set and gave us the possibility of validating the predictive capability of many GMPEs, developed using Italian, European and global data sets. The results are presented in terms of quality of performance (fit between recorded and predicted values) using the maximum likelihood approach as explained in Spudich *et al*. (1999). Considering the strong-motion data recorded during the L'Aquila sequence, the considered GMPEs on average, overestimate the observed data, showing a dependence of the residuals with distance in particular at higher frequencies. An improvement of fit is obtained comparing all Italian strong-motion data included in ITACA with the European GMPEs calibrated by Akkar and Bommer (2007a, 2007b) and the global models calibrated by Cauzzi and Faccioli (2008). In contrast, the Italian data seem to attenuate faster than the NGA models calibrated by Boore and Atkinson (2008), in particular at higher frequencies.

Key words: ground motion prediction equations, Italian strong motion data, residual evaluation, ITACA.

1. Introduction

Empirical Ground Motion Prediction Equations (hereinafter GMPEs) are critical for seismic hazard studies in any region. However, the reliability of all GMPEs is strongly influenced by the characteristics of the data set used to calibrate them. The optimal condition to obtain stable regressions would be to have a large amount of data with a wide distribution of magnitudes, distances, and source mechanisms (Douglas, 2003). Unfortunately, this is rarely the case; in fact prediction equations are usually limited to the typical magnitude range observed in the study region that, in general, allows one to derive empirical relationships only for strong motion data (e.g., Sabetta and Pugliese, 1996; Ambraseys *et al*., 2005a, 2005b; Akkar and Bommer, 2007a, 2007b; Boore and Atkinson, 2008) or weak motion data (Frisenda *et al*., 2005; Massa *et al*., 2007).

The data sets used to calibrate many GMPEs are often characterized by an irregular distribution of data, resulting in a non homogeneous representation of all magnitude-distance ranges. This may lead to erroneous predictions since the final results are governed by the bulk of the distribution (Crouse *et al*., 1988; Molas and Yamazaki, 1995). Moreover, the spatial distribution of events and stations may introduce an azimuthal effect on the amplitudes of the ground motion (Campbell and Bozorgnia, 1994).

Sabetta and Pugliese (1996) GMPEs (hereinafter SP96), calibrated on 95 strong motion waveforms from 17 Italian earthquakes with magnitude 4.6-6.9 (M_L or M_s) and distance [Joyner-Boore (1981), hereinafter R_{JB} or epicentral, hereinafter R_{epi})] up to 100 km, represent one of the GMPEs considered in the calculation of the seismic hazard map of Italy in terms of maximum expected horizontal acceleration [10% probability of exceedence in 50 years, MPS Working Group (2004)] and acceleration response spectra from 0.1 to 2 s (Montaldo and Meletti, 2007). The extremely limited data set, recorded by analogue instruments, on which these GMPEs were based, needed to be updated and, for this reason, under the agreement between the Italian Civil Protection (DPC) and the Italian National Institute for Geophysics and Vulcanology (INGV) the Italian strong–motion database (ITalian ACcelerometric Archive, ITACA, http://itaca.mi.ingv.it) has been developed over the past five years.

At present ITACA includes records of 1017 earthquakes, 1002 relative to the period range 1972 - 2004 ($1.1< M \leq 6.9$), the December 2008 Parma earthquakes (M_w 4.9 and M_w 5.4) and 13 events of the April 2009 L'Aquila (central Italy) sequence ($4 \leq M_w \leq 6.3$). Using a selection of events recorded up to 2004, a set of GMPEs was recently derived for Italy [Bindi *et al*. (2009), hereinafter ITA08], for the prediction of maximum horizontal and vertical peak ground acceleration, peak ground velocity and acceleration response spectra (5% damping) from 0.04 s to 2.0 s. The ITA08 data set is composed of 561 three-component records from 107 earthquakes with M_w in the range 4.0–6.9, recorded by 206 stations with R_{JB} up to 100 km.

On April 6, 2009, 01:32:40 UTC, an M_w 6.3 earthquake occurred in the Abruzzo region (central Italy), at a 9.5 km depth along a NW-SE normal fault with SW dip (e.g., Ameri *et al*., 2009), very close to L'Aquila, a town of about 70,000 inhabitants. The mainshock was followed by seven aftershocks of moment magnitude larger than or equal to 5, the two strongest ones occurred on April 7 (M_w=5.6) and April 9 (M_w=5.4). The data set related to the L'Aquila sequence was used to verify the prediction capabilities of 5 selected GMPEs, calibrated at national [ITA08: Bindi *et al*. (2010); SP96: Sabetta and Pugliese (1996)], European [AKBO07: Akkar and Bommer (2007a, 2007b)] and global scale [BOAT08: Boore and Atkinson (2008); CF08: Cauzzi and Faccioli (2008)].

The AKBO07 data set consists of 532 three-component records, from 131 earthquakes, with M_w from 5.0 to 7.6 and R_{JB} up to 100 km, from the European strong motion database (http://www.isesd.cv.ic.ac.uk/ESD/). The CF08 models were calibrated from about 1,000 digital accelerometric records, many of which coming from Japanese strong-motion data sets (url: http://www.k-net.bosai.go.jp/k-net/index_en.shtml), recorded at hypocentral distances up to 150 km

Table 1 - Data set used to calibrate the GMPEs considered in this study. *M* is moment magnitude, with the exception of SP96 where the local magnitude is for $M<5.5$ and the surface-waves magnitude is for $M\geq5.5$. For ITA08 as well as for SP96 the upper bound of magnitude is represented by the November 23, 1980, M_w 6.9 (M_s 6.8) Irpinia earthquake. *R* is the Joyner-Boore distance, with the exception of CF08 where *R* is the hypocentral distance and of ITA08 for events with $M<5.5$ (in this case *R* is the epicentral distance). In the last column Hm is the maximum between the two horizontal components, Gm is the geometric mean and GmRot50 is the geometric mean determined from the 50th percentile values of the geometric means computed for all non-redundant rotation angles.

GMPE	N events	N rec (x3)	*M*	*R* [km]	Response variables	Comp
ITA08	107	561	4.0 - 6.9	up 100	PGA, PGV, SA up 2s	Hm, V
SP96	17	95	4.6 - 6.8	up 100	PGA, PGV, PSV up 4s	Hm, V
AKBO07 (a,b)	131	532	5.0 - 7.6	up 100	PGA, PGV, RD up 4s	Gm
CF08	60	1155	5.0 - 7.2	up 150	PGA, RD up 20s	Gm
BOAT08	58	1574	5.0 - 8.0	up 400	PGA, PGV, PSA up 10s	GmRot50

and M_w in the range 5.0-7.2. The BOAT08 is derived from an extensive strong-motion database compiled by the PEER NGA project (Pacific Earthquake Engineering Research Center's Next Generation Attenuation project, http://peer.berkeley.edu/products/nga_project.html). The data set consists of about 1,500 accelerometric records relative to 58 worldwide events recorded at distances up to 400 km and M_w in the range 5.0-8.0. The characteristics of the GMPEs considered in this study are reported in Tables 1 and 2.

Finally, the comparison was extended to the whole, recently updated, ITACA strong-motion database.

2. Fit of the L'Aquila data set to the Italian, European and global GMPEs

The L'Aquila sequence data set is composed of 305 three-component accelerometric

Table 2 - Single term for each functional form used to calibrate the GMPEs considered in this study. The coefficients are reported in each column as indicated in the relative paper. Column 2 = scaling for magnitude; column 3 = saturation with distance; column 4 = geometrical spreading attenuation term; column 5 = anelastic attenuation term; column 6 = site correction term; column 7 = style of faulting correction term. For *S* and *SF* terms, S_i and F_i are dummy variables that assume either value 0 or 1 depending on soil type or fault mechanism. For BOAT08 the saturation term (column 3) disappears for $M\geq M_h$ (M_h is the "hinge magnitude" that has to be set during the analysis in order to consider the shape of the magnitude scaling) while for the site correction term (column 6) it is also possible to consider the non-linear site effects [see Boore and Atkinson (2008) for details].

GMPE	M term	Sat. term	Geom. Spread. term	AA term	S term	SF term
ITA08	b_1*(M-Mr)	b_2*(M-Mr)^2	[c_1+c_2*(M-Mr)]*log[(R^2+h^2)$^{0.5}$]	-	e*S_i	-
SP96	b*M	-	c*log[(R^2+h^2)$^{0.5}$]	-	e*S_i	-
AKBO07	b_2*M	b_3*(M)^2	[b_4+(b_5*M)]*log[(R^2+b_6^2)$^{0.5}$]	-	b*Si	b*F_i
CF08	a_2*M	-	a_3*log[R]	-	a*S_i	-
BOAT08	e_5*(M-Mh)	e_6*(M-Mh)^2	[c_1+c_2*(M-Mr)]*ln[(R^2+h^2)$^{0.5}$/R_r]	c_3*(R-R_r)	b(I)*[ln(V_{s30}/V_r)]	e*S_i

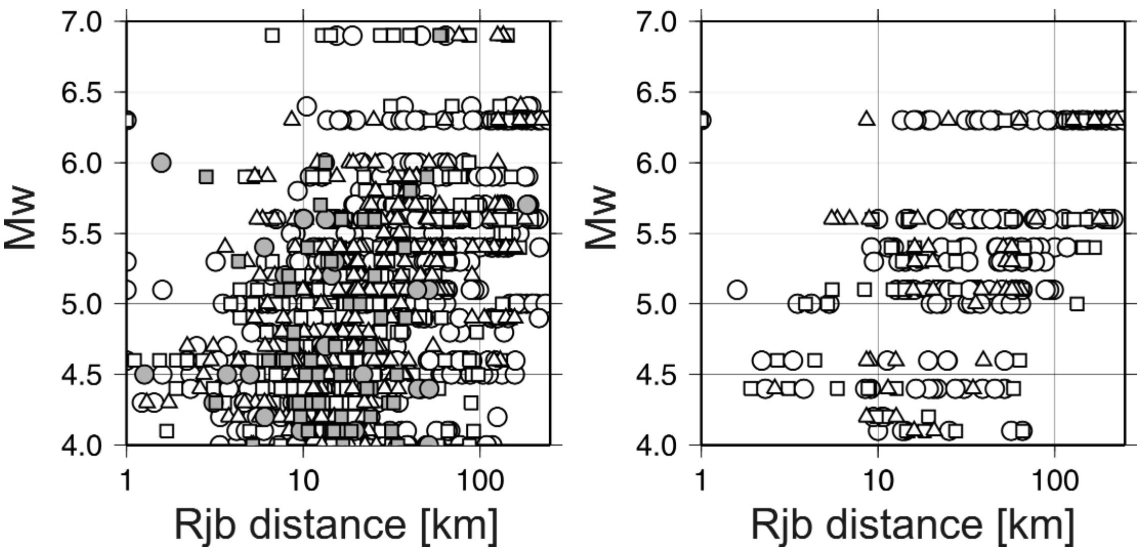

Fig. 1 - Left: subset of ITACA data set showing records with M_w from 4.0 to 6.9 and R_{JB} up to 250 km. Right : L'Aquila sequence data set. EC8 A-class = white circle; EC8 B-class = white square; EC8 C-class = white triangle; EC8 D-class = gray circle; EC8 E class = gray square.

waveforms from events in the M_w range 4.0-6.3 recorded at an R_{JB} in the range 0-250 km (Fig. 1, right panel). All data are available at the ITACA web site (http://itaca.mi.ingv.it). The accelerometric waveforms were recorded by several stations belonging to the Italian Accelerometric Network (RAN), generally equipped by Kinemetrics three-component accelerographs (full scale set to 1 or 2 g) coupled to 24-bit digitizers (with sampling frequency of 200 Hz) and by five temporary strong-motion stations installed in the epicentral area by the INGV, department of Milano-Pavia (RAIS, url: http://rais.mi.ingv.it) after the mainshock occurrence. These stations were equipped with Kinemetrics ES-T Episensors coupled with 24-bit Reftek-130 digitizers. The stations that recorded the events that are included in the L'Aquila data set are classified following the EC8 soil classes (CEN, 2004). Most of the stations, 6 of which installed inside the surface projection of the mainshock fault plane (R_{JB}=0), belong to class A or B (class A has V_{s30}≥800 m/s, class B has 360≤V_{s30}<800 m/s) and only a few sites are classified as class C (180≤V_{s30}<360). All data were processed following the Massa *et al*. (2010) procedure that includes the removal of the linear trend fitting the entire record, a cosine taper and band pass filtering with a time-domain acasual 4th order Butterworth filter. Both the high-pass and low-pass frequencies were selected through the visual inspection of the Fourier spectrum. The peak ground accelerations relative to the mainshock in the near-fault area are characterized by values higher than 300 cm/s^2. However, the largest acceleration peak (670 cm/s^2) was recorded for the April 7 (17:47 UTC), M_w 5.6, aftershock, at an epicentral distance of 5 km (MI05 station, class B). The highest value of peak ground velocity (43 cm/s) is related to the April 6 (01:32 UTC), M_w 6.3, mainshock, recorded at an epicentral distance of 4.9 km (AQV station, class B).

In Fig. 2 (top panels), the maximum between the horizontal components (PGAs, Hm) for the

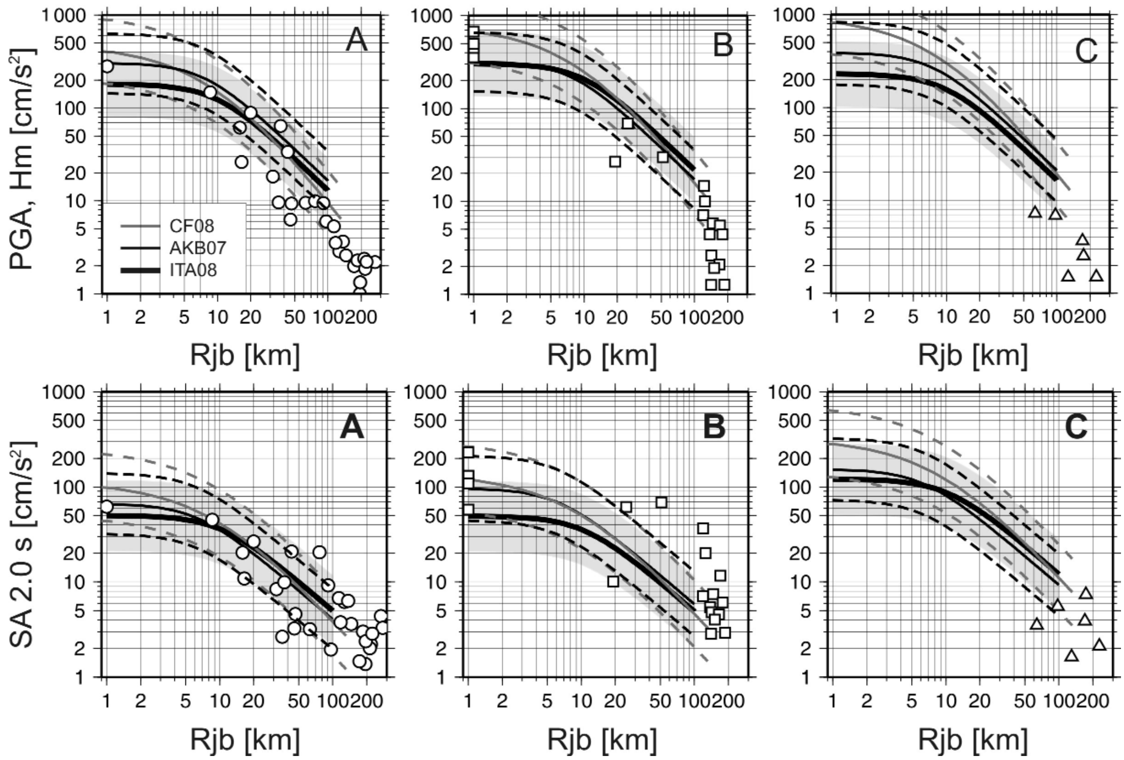

Fig. 2 - Top panels: PGAs for maximum horizontal component (Hm) versus R_{JB} recorded for the April 6, 2009, M_w 6.3, L'Aquila main-shock. Left panel: EC8 A-class. Central panel: EC8 B-class. Right panel: EC8 C-class. The shaded area represents $\pm 1\sigma$ for ITA08. The black and grey dashed lines represent $\pm 1\sigma$ for AKBO07 and CF08 respectively. Note that points with R_{JB} less than 1 km are plotted at 1 km. Bottom panel: the same as in top panels but for acceleration response spectral ordinates at 2.0 s.

April 6, M_w 6.3, L'Aquila mainshock is plotted as a function of R_{JB} along with the attenuation curves predicted by the considered GMPEs, for different EC8 site classes (L'Aquila sequence does not include records in class D or E). For comparisons the original distance measurement of the CF08, that is the hypocentral distance, was converted into R_{JB}, through an ad-hoc empirical relation calibrated with the Abruzzo earthquake records, while the geometrical mean between the two horizontal components was converted into the largest value using the relationships proposed by Beyer and Bommer (2006). On average, for PGA, the GMPEs calibrated using European and global data sets fit the data well, at least for distances where the empirical models are defined (100 km for AKBO07 and 150 km for CF08). In particular, the median values of AKBO07 and CF08 equations match the near-source data recorded at rock sites reasonably well, even if an increasing overestimation with distance is observable. On the contrary, ITA08 predicts lower median PGA values, due to the adopted Italian data set that poorly samples the near-fault distances (a subset of the ITACA data set is shown in the left panel of Fig. 1). Similar considerations can be made regarding the PGVs (not reported here). The bottom panels of Fig. 2 show the comparisons between the same GMPEs and the acceleration response spectral ordinates at 2.0 s. The Italian GMPE reasonably fits the recorded data for class A over the entire distance

Table 3- Bias values obtained comparing the considered GMPEs to the data relative to the 13 events of the L'Aquila sequence with $M_w \geq 4.0$. ITA08 and SP96 (Italy); AKBO07 (Europe); CF08 and BOAT08 (global). The comparisons were made considering the related independent variables (magnitude, distance, site classification and style of faulting) for each GMPEs. CF08 does not consider PGV.

GMPE	Bias PGA (Hm)	Bias SA (1.0s)	Bias SA (2.0s)	Bias PGV
ITA08	-0,318	-0,121	-0,144	-0,192
SP96	-0,504	-0,465	-0,406	-0,486
AKBO07	-0,391	-0,226	-0,244	-0,261
CF08	-0,301	0,104	0,081	/
BOAT08	-0,382	-0,221	0,237	-0,254

range while the near-source records for class B are, on average, better predicted by the CF08 and AKB07.

In order to provide more quantitative results, the comparisons were performed in terms of bias (Spudich *et al.*, 1999), that is the mean value of the residuals evaluated by the maximum likelihood formalism. The residual is computed as the difference between the logarithm of the observations and the logarithm of the predictions. Moreover, for these analyses, the distribution of residuals was decomposed into the inter-event (η) and intra-event (ε) components, which are assumed to be independent, normally distributed with variances σ^2_{eve} (inter-event component of variance) and σ^2_{rec} (intra-event component of variance), respectively (Abrahamson and Youngs, 1992). The goodness of fit was evaluated considering the maximum horizontal peak ground acceleration (PGA), velocity (PGV) and for response spectra (SA, %5 damping) ordinates at 1.0 s and 2.0 s. An example of the results obtained for ITA08 is reported in Fig. 3, where the goodness of the fit for the PGA values recorded during the L'Aquila sequence to the new Italian predictive model is shown.

For ITA08 the overall bias for PGA (Hm) is negative (-0.318, Table 3 and Fig. 3a), denoting a general overestimation of the predictions. Fig. 3b shows the results in terms of inter-event errors [i.e., the error obtained considering the variability of all recordings related to a single event, Strasser *et al*. (2009)]: all the examined events of the L'Aquila data set have negative inter-event errors and this is independent from magnitude (Fig. 3d). As observed for ITA08, negative inter-event errors are also obtained considering the other predictive models, as shown for PGA in Fig. 4. Similar results (not reported here) were obtained for acceleration response spectral ordinates at 1.0 s and 2.0 s, with the exception of CF08 models that show positive, or very close to zero, inter-event errors.

In Fig. 3c, the ITA08 residuals are plotted as a function of the R_{JB}: in this case a non-negligible slope is observed, indicating a general dependence of the error with distance. In particular, an underestimation is observed in the near source area (R_{jb} up to about 10 km) and an overestimation for distance higher than 10 km. The same analysis, performed on PGV (not reported in the figure) provides a negative bias (-0.192) for ITA08, confirming the general overestimation of the predictions.

The biases obtained for PGA, PGV and response spectra ordinates at 1.0 s and 2.0 s are shown in Table 3 for the GMPEs considered in this study.

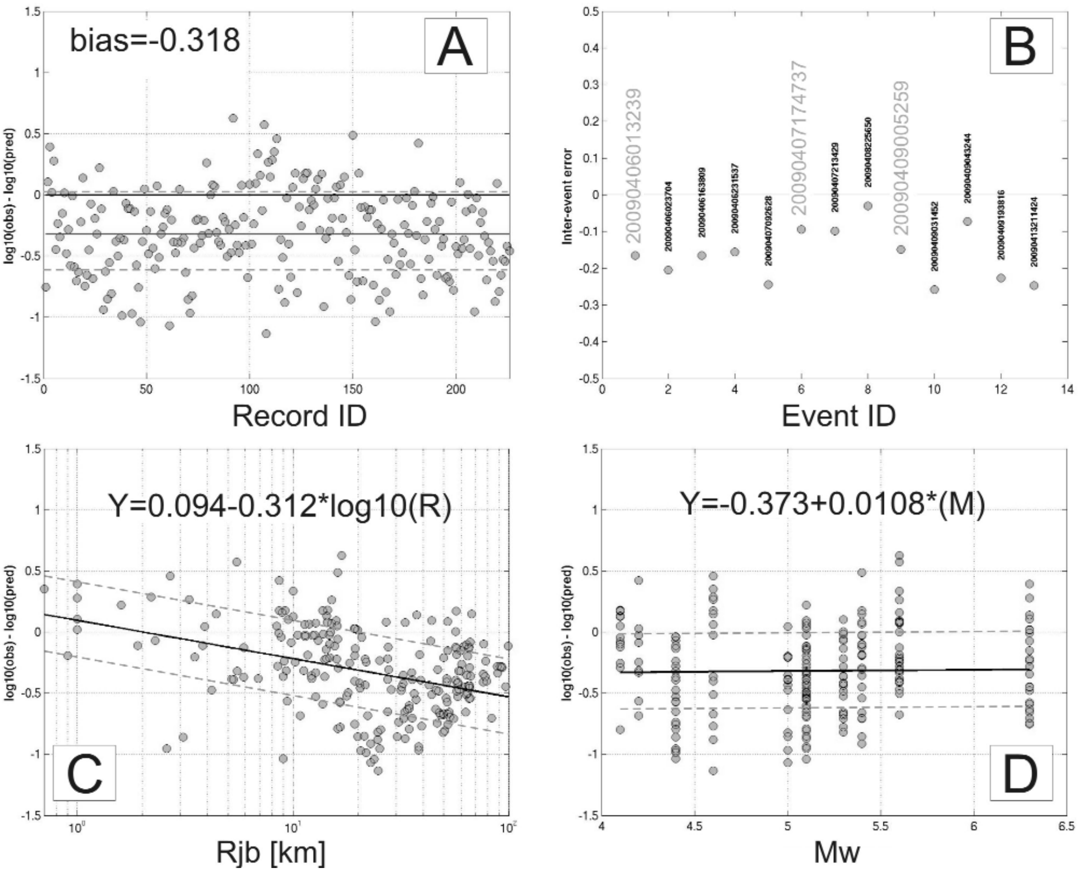

Fig. 3 - Results for PGA (maximum horizontal component) comparing ITA08 vs. L'Aquila data (13 seismic events with M_w≥4.0). Top left-hand panel: residuals (i.e., differences between the logarithm of the observations and logarithm of the predictions, grey circles). The bias (black solid line) and its plus/minus one standard deviation (dashed gray lines) are reported. Top right-hand panel: inter-event errors related to the L'Aquila sequence (the M_w 6.3 L'Aquila mainshock and the two strongest aftershocks, M_w 5.6 and 5.4, are indicated). Bottom panels: residuals as a function of R_{JB} distance (left) and M_w (right). In both panels, solid and dashed grey lines represent the fit function and $\pm 1\sigma$ respectively.

Fig. 5 shows the dependence on magnitude and distance of the PGA residuals obtained with the other predictive models. All the considered predictive models show a variable dependence with distance and magnitude. The strongest dependence of residuals with distance is detected for the SP96 model (slope -0.546, panel A of Fig. 5), but this can be explained by the lack of magnitude-dependent geometrical spreading term in the functional form (Table 2). However, also the other models show a negative dependence of the residuals with distance, that means a general overestimation of the predictions with increasing distances. In particular, the European model (AKBO07) has a dependence of the residuals on distance very close to ITA08 (slopes -0.321 for AKBO07, panel C of Fig. 5, and -0.318 for ITA08, panel C of Fig. 3). The new Italian (ITA08) and European GMPEs were calibrated by using the same functional form and a possible cause of the overestimation with distance could be the absence of the anelastic attenuation term in both

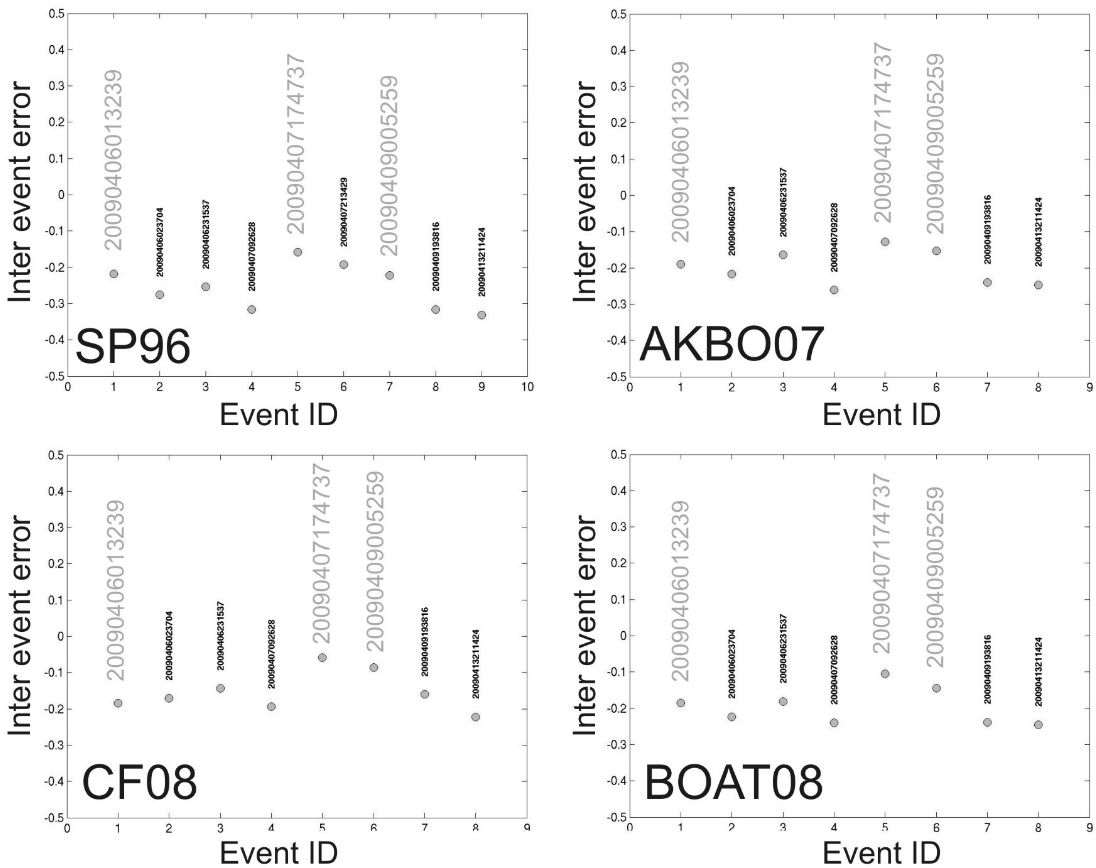

Fig. 4 - Inter-event errors for PGA (grey circles) related to the L'Aquila sequence obtained analysing the predictive models considered in this study (the results for ITA08 are reported in the top right-hand panel of Fig. 3). The M_w 6.3 L'Aquila mainshock and the two strongest aftershocks (M_w 5.6 and 5.4) are indicated.

models (Table 2). The CF08 models, obtained through a simplified functional form (Table 2), suffer a remarkable dependence of residuals with distance (slope -0.412, panel E of Fig. 5). The model developed in the framework of the NGA project (BOAT08), although calibrated by using a functional form that includes both the magnitude-dependent geometrical spreading and the anelastic attenuation terms (Table 2), shows a remarkable dependence of the residuals with distance (slope -0.499, panel G of Fig. 5) as well. It has to be remarked that the residual analysis has been performed in the range of validity of each model, in terms both of magnitude and distance.

As shown in the right-hand panels of Fig. 5, all models show a stronger dependence of the residuals on magnitude than ITA08 (see panel D of Fig. 3). In this case, the results probably reflect the distribution of magnitude values of each single data set. Both the European (AKBO07) and the global (BOAT08 and CF08) GMPEs are, in fact, obtained considering a minimum M_w value of 5.0, that might lead to an overestimation of the prediction for recorded data related to the

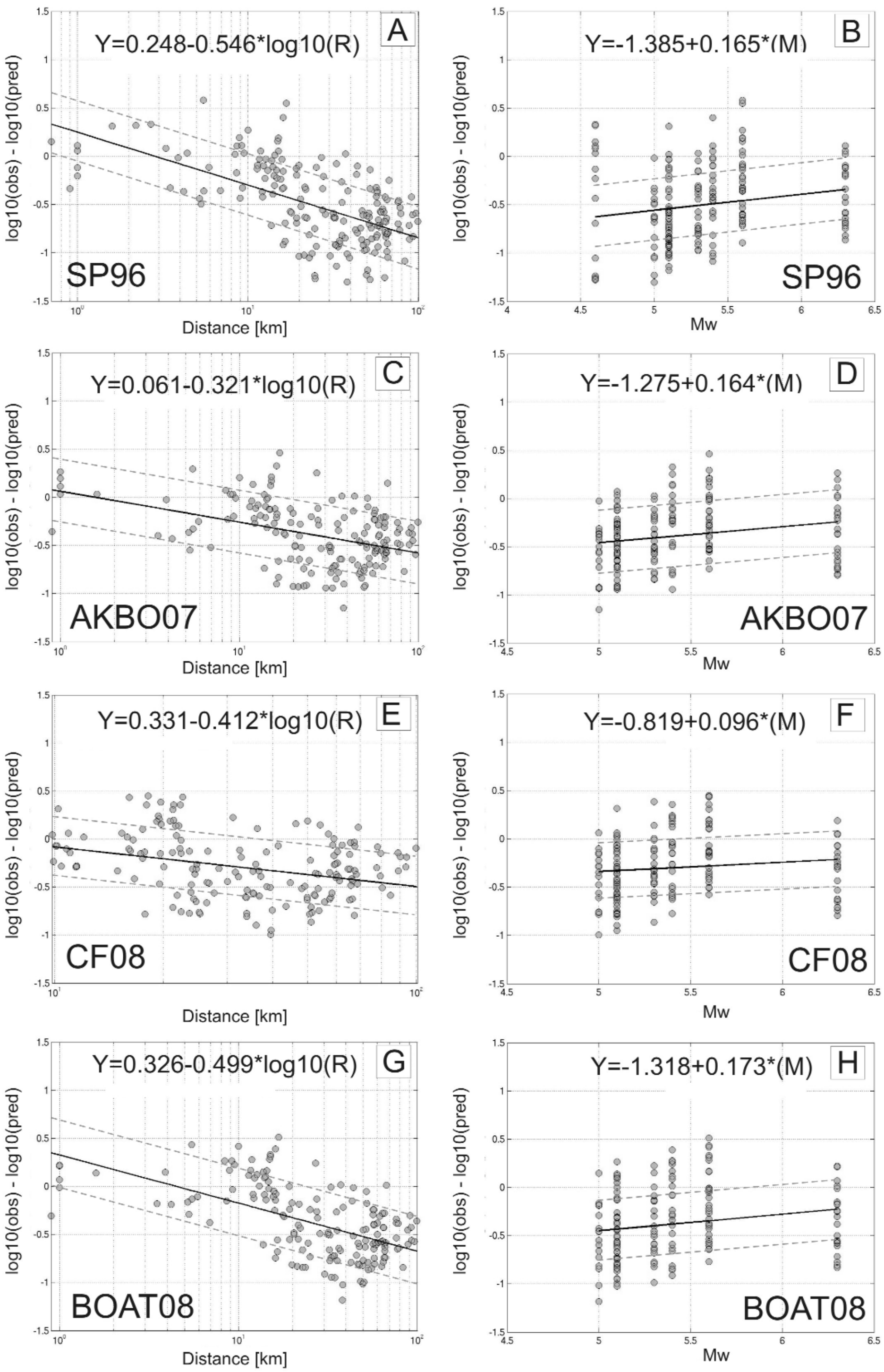

Fig. 5 - Comparisons between the predicted values and the PGAs (maximum horizontal component for SP96 and geometric mean between the two horizontal components for the others GMPEs) recorded during the L'Aquila sequence (grey circles). In the left-hand panels are the residuals plotted as a function of distance (hypocentral for CF08 and R_{JB} for the other GMPEs), while those as function of M_w are in the right panels. The fit functions and related $\pm 1\sigma$ are represented by solid and dashed lines, respectively. The results for ITA08 are reported in the bottom panels of Fig. 3.

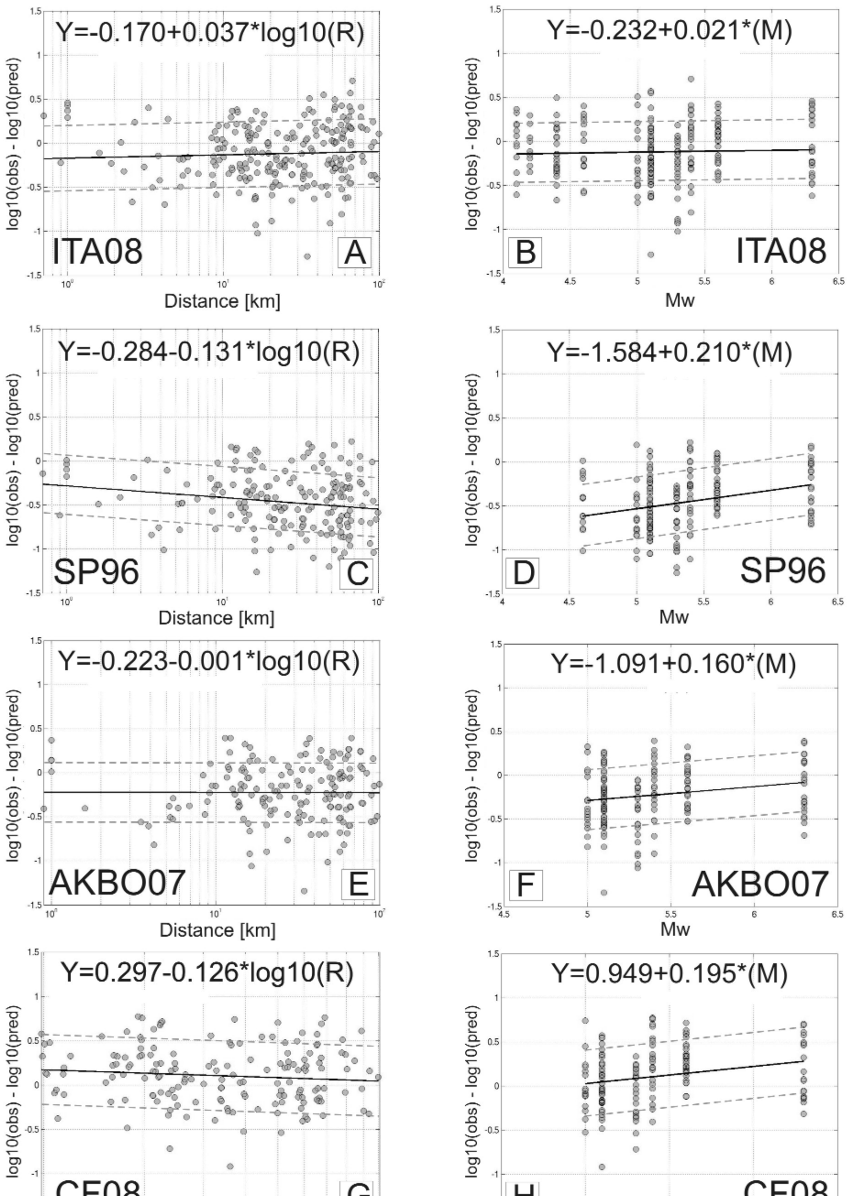

Fig. 6 - The same as in Fig. 5 but for acceleration response spectra ordinates at 1.0 s.

events having magnitudes close to the lower magnitude bound of those GMPEs (Bommer *et al*., 2007). The highest magnitude dependence (slope 0.173, panel H of Fig. 5) is observed for the BOAT08 model that is calibrated considering the highest magnitude range (5.0-8.0).

In Fig. 6, the results obtained for SA ordinates at 1.0 s are shown. Only ITA08 and AKBO07 have a negligible trend of residuals with distance (panels A and E of Fig. 6), while a significant dependence is observed for the other models (slope of -0.131 for SP96, panel C, and of -0.126 for CF08, panel G) and, in particular, for BOAT08 (slope of -0.185, panel I). On the other hand, all models, with the exception of ITA08 and AKBO07, show a stronger dependence on magnitude of SA residuals than PGA (from 0.165 to 0.210 for SP96, from 0.096 to 0.195 for CF08, from 0.173 to 0.257 for BOAT08). This indicates a general decrease of the overestimation with increasing magnitude and periods. Similar results were obtained for PGV and for spectral ordinates at 2.0 s (not shown here).

3. Fit of the ITACA data set to the European and global GMPEs

The Italian strong-motion database, ITACA, was created in the framework of the research agreement between DPC and INGV and is still in progress.

At present, ITACA contains 2550 three-component waveforms, 1821 relative to 1002 earthquakes (maximum M_w 6.9 for the November 23, 1980, Irpinia earthquake) occurring in the period 1972-2004, 363 of which related to the December 23, 2008, M_w 5.4 and M_w 4.9, Parma (northern Italy) sequence and to the April 6, 2009, M_w 6.3, L'Aquila (central Italy) sequence (13 events with M_w in the range 4.0-6.3). Acceleration, velocity and displacement time series and the acceleration response spectra (121 periods up to 4.0 s, 5% damping) related to these records are downloadable from the web site http://itaca.mi.ingv.it. The magnitude values (M_w and/or M_L) range from 1.1 to 6.9 with the best sampled distance interval from 5 to 100 km (R_{JB} or R_{epi} for $M < 5.5$). To calculate R_{JB} distances the fault geometries data available in the DISS database (DISS Working Group, 2009; Basili *et al*., 2008) were considered. The focal mechanisms were assigned to the seismic events following the classification described in Luzi *et al*. (2008). About 350 accelerometric waveforms have PGA > 50 cm/s^2 while 155 have PGV > 1 cm/s. The STR (Sturno) station recorded the largest PGV (70 cm/s) during the November 23, 1980, M_w 6.9, Irpinia earthquake, while the largest PGA (670 cm/s^2) value was recorded during the strongest aftershock (April 7, 2009, M_w 5.6) of the L'Aquila sequence at station MI05.

The strong-motion data collected in ITACA were recorded by 665 strong-motion stations, the

Table 4 - Bias values obtained comparing the European (AKBO07) and global (CF08 and BOAT08) GMPEs to all data included in the ITACA at the end of 2009. The comparisons were made considering the independent variables in their range of validity for each GMPE. CF08 does not consider PGV.

GMPE	Bias PGA (Hm)	Bias SA (1.0s)	Bias SA (2.0s)	Bias PGV
AKBO07	-0,123	-0,064	-0,098	-0,056
CF08	-0,064	0,311	0,214	/
BOAT08	-0,132	-0,036	-0,075	-0,049

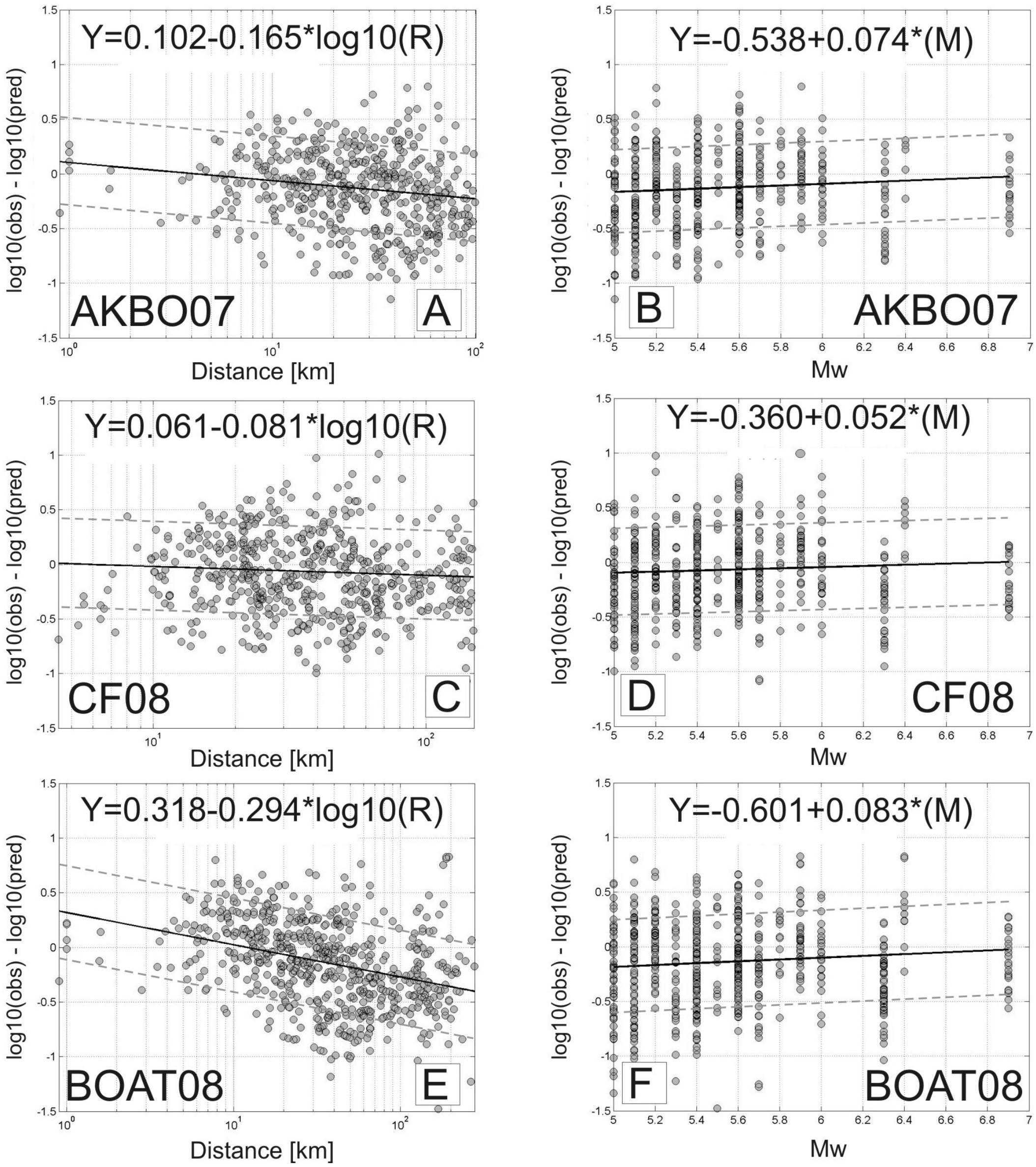

Fig. 7 - Comparisons between the European (AKBO07) and global models (CF08 and BOAT08) predicted values and PGAs (geometric mean between the two horizontal components) currently collected in the ITACA. In the left-hand panels, the residuals are plotted as a function of distance (hypocentral distance for CF08 and R_{JB} for AKBO07 and BOAT08), whereas in the right-hand panels as a function of M_w. The fit functions and related $\pm 1\sigma$ are represented by solid and dashed lines, respectively.

majority belonging to the RAN network (managed by DPC). All stations are classified following the EC8 soil classes (CEN, 2004). When the V_{s30} values were not available, the stations were classified on the basis of the geological information (S4 Project, Deliverable D4, 2009, http://esse4.mi.ingv.it).

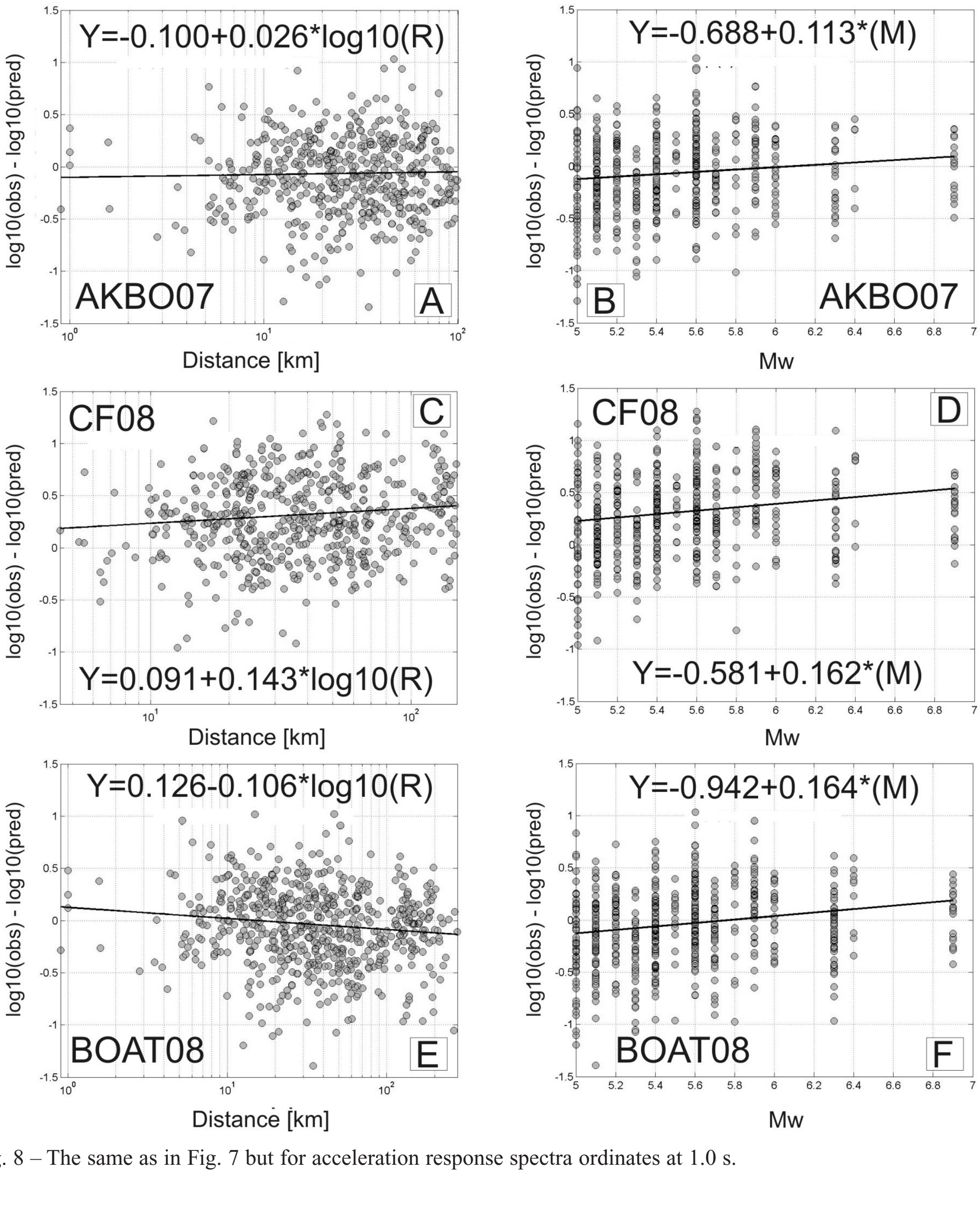

Fig. 8 – The same as in Fig. 7 but for acceleration response spectra ordinates at 1.0 s.

The same approach used to compare the L'Aquila strong-motion data set to the GMPEs considered in this study, was adopted to verify the performance of the European (AKBO07) and global models (CF08 and BOAT08) in predicting the strong-motion data recorded in Italy since 1972. Magnitude and distance were selected according to the ranges of validity of each model (Table 1). The main result is that the bias and the dependence of the residuals on distance and magnitude are lower than those obtained for the L'Aquila data set. At high frequencies (Table 4 and Fig. 7 for PGA), the bias resulting from the European model

(AKBO07) decreases from -0.391 to -0.123, but also the global models, in particular CF08, shows a relevant decrease of the mean values of the residuals (from -0.382 to -0.132 for BOAT08 and from -0.301 to -0.064 for CF08). Concerning the distribution of the PGA-residuals with distance, the CF08 is the model that shows the best improvement, changing the slope of the fit-function from -0.412 (Fig. 5, panel E) to -0.081 (Fig. 7, panel C). BOAT08 confirms to have the highest dependence of residuals with distance (slope -0.294, Fig. 7, panel E), although weaker than that obtained for the L'Aquila sequence (slope -0.499, panel G of Fig. 5). Considering the right-hand panels of Fig. 7, the result is a general decrease of the residuals dependence with magnitude. Also in this case the CF08 (panel D) is the model that shows the lowest dependence (slope 0.052), whereas the model with the highest dependence (slope 0.083, panel F) is BOAT08, although an improvement is obtained with respect to panel H of Fig. 5 (slope 0.173).

At higher periods both AKBO07 and BOAT08 improve their capacity of prediction, whereas the bias resulting from the CF08 shows an increase with increasing periods (see bias values in Table 4 at 1.0 s and 2.0 s).

Considering the period of 1.0 s (Fig. 8), the European model (AKBO07) does not show particular dependence of the residuals with distance (slope -0.026, panel A), even if its negative bias (Table 4) indicates a general overestimation of the predictions. A negligible dependence (slope -0.106, panel E) that leads to an increase of the overestimation of the predictions with increasing distance is still present for BOAT08, whereas an opposite trend is detected for CF08 (slope 0.143, panel C): in this case the positive bias (Table 4) values obtained both for 1.0 s (0.311) and 2.0 s (0.214) periods indicate an underestimation of the predictions. Considering the dependence of the residuals with magnitude (right-hand panels of Fig. 8), for all models, there is an improvement with respect to the comparisons with the L'Aquila sequence (from 0.160 to 0.113 for AKBO07, from 0.195 to 0.162 for CF08, from 0.257 to 0.164 for BOAT08), but also a significant increase of the magnitude dependence of the residuals if we compare the results obtained for 1.0 s to those obtained for PGAs (from 0.07 to 0.113 for AKBO074, from 0.052 to 0.162 for CF08, from 0.083 to 0.164 for BOAT08, see Figs. 7 and 8).

4. Conclusion

The April 6, 2009 (M_w 6.3) L'Aquila earthquake, that occurred in the central Italian Apennines, gave us the opportunity to validate the predictive capability of the newly developed Italian GMPEs (Bindi *et al*., 2010) and make some comparisons both with the older Italian models (Sabetta and Pugliese, 1996) and the recent predictive equations calibrated from European (Akkar and Bommer, 2007a, 2007b) and global data sets (Boore and Atkinson, 2008; Cauzzi and Faccioli, 2008).

The analyses were performed in two steps: at first, the predictive models were compared to the records of the L'Aquila mainshock and 12 aftershocks with $M_w \geq 4.0$ recorded at R_{JB} (or R_{epi}) up to 250 km. In the second phase, the comparisons were extended to all strong-motion data currently collected in the ITACA [http://itaca.mi.ingv.it; Luzi *et al*. (2008), Paolucci *et al*. (2010)].

In general, all models analysed in this study overpredict the ground motions observed during the L'Aquila sequence, especially at high and intermediate (1.0 Hz) frequencies. The overestimation of the predictions for ITA08, AKBO07 and CF08, observed from distances greater than 10 km could be partially justified by the lack of the anelastic attenuation coefficient in the functional form of the considered GMPEs (see Table 2). In particular, the lack of magnitude-dependent decay rate in the geometrical spreading attenuation term in SP96 could be responsible for the higher overestimation of this model with respect to the other GMPEs calculated using the same type of distance. The only analysed model that includes the anelastic attenuation term is BOAT08: the results obtained for the NGA predictions, even if in terms of bias values are comparable with the AKBO07 models (both for low and high frequencies, see Table 3), show a significant dependence of the residuals distribution on distance, in particular for higher frequencies.

Considering all Italian strong-motion data, the European GMPEs (AKBO07) and also the global model developed for PGA by CF08 well fit the recorded values without showing particular dependence of the residuals on distance. In this way, the best results were obtained for acceleration response spectral ordinate at 1.0 s for AKBO07 and for PGA considering the CF08 global model. On the contrary, also considering all Italian data the model calibrated by Boore and Atkinson (2008) confirms, in particular for higher frequencies, the dependence of the residuals with distance, showing a negative slope of the fit-function that means underestimations in near-source area and overestimations for distances greater than 10 km. This general behaviour of the NGA models with respect to the Italian strong-motion data was already observed in Scasserra *et al.* (2009).

Considering all analysed models, with the exception of CF08 for SA in the case of the whole ITACA database, both bias values and residual dependence with distance are weaker when we move from higher to lower frequencies: Figs. 6 and 8 and Tables 3 and 4 confirm this result. Concerning the residual dependence on magnitude, with the exception of the ITA08 models, the other predictive equations show positive slopes of the residual fit-functions which means over predictions that decrease with increasing magnitude: this phenomenon is more evident if we consider only the L'Aquila data set but, more in general, if we move from higher to lower frequencies. In this case, an increase of magnitude dependence of the residuals is observed with the exception of the ITA08 and AKBO07 models.

In general, the results obtained considering all Italian data with respect to the L'Aquila sequence, show a general decrease both of the bias values and the dependence of the residuals on distance and magnitude. This evidence could be interpreted as a peculiarity of the waves propagation (or regional attenuation) of the Abruzzo region if compared to the worldwide areas investigated to calibrate the other models (e.g., Japan for CF08, West Coast of United States for BOAT08, Europe and Middle East for AKBO07), in particular, if we consider BOAT08 where no omissions in the functional form are present (Table 2).

A preliminary attempt to evaluate the regional differences of the ground motion attenuation in Italy was made in a recent paper by Luzi *et al*. (2010): in that paper the authors demonstrate that, taking into account the different tectonic framework of each zone (homogeneous style of faulting), a distance metric that includes the source depths (hypocentral distance) and supposing a homogeneous site classification, no evident differences in ground motion attenuation were found for different areas of Italy (i.e., eastern Alps and northern Apennines, central Apennines, strike slip areas of southern Italy).

Thanks to the 2007-2009 INGV-DPC agreement (S4 Project, url: http://esse4.mi.ingv.it), from May 2010 a new version of ITACA (Paolucci *et al*., 2010) is now available at the web site http://itaca.mi.ingv.it.

Using the new database, in a short time a revised version of ITA08 models, including a complete revision of data for the period 1972-2007 (including the December 23, 2008 Parma earthquake and the April 2009 L'Aquila sequence) and a revised site classification based on the EC8 code (CEN 2004), will be available (Bindi *et al.,* 2011).

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