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An evaluation of the applicability of the NGA models to ground-motion prediction in the Euro-Mediterranean region

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Abstract The first phase of the Next Generation Attenuation (NGA) project has now finished, resulting in the publication of five new sets of empirical ground-motion models for PGA, PGV and response spectral ordinates. These models mark a significant advancement in the state-of-the-art in empirical ground-motion modelling and include many effects that are not accounted for in existing European equations. Under the assumption that the Euro-Mediterranean database from which the European relationships are derived is unlikely to drastically change in the near future, a prudent question to ask is: can the NGA models be applied in Europe? In order to answer this question, the NGA model of Boore and Atkinson (PEER Report 2007/01, Pacific Earthquake Engineering Research Center, Berkeley, CA, 234 pp., 2007), which is shown to be representative of the NGA models as a suite, is compared with the dataset used for the development of the most recent European empirical ground-motion models for response spectral ordinates and peak ground velocity. The comparisons are made using analyses of model residuals and the likelihood approach of Scherbaum et al. (Bull Seism Soc Am 94(6):2164–2185, 2004). The analyses indicate that for most engineering applications, and particularly for displacement-based approaches to seismic design, the NGA models may confidently be applied within Europe. Furthermore, it is recommended that they be used in conjunction with existing European models to provide constraint on finite-fault effects and non-linear site response within logic-tree frameworks. The findings also point to the potential benefits of merging the NGA and European datasets.

Keywords Attenuation · Europe · Ground-motion prediction · Likelihood · Mediterranean · Middle East · NGA · Strong ground-motion

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1 Introduction

The first phase of the Next Generation Attenuation (NGA) project (Power et al. 2006; http://www.peer.berkeley.edu/products/nga_project.html) has now drawn to a close and resulted in the publication of five new ground-motion models to predict PGA, PGV and response spectral ordinates for periods up to 10 s (Abrahamson and Silva 2007; Boore and Atkinson 2007; Campbell and Bozorgnia 2007; Chiou and Youngs 2006; Idriss 2007). These models are intended as updates of a previous generation of models published a decade ago (Abrahamson and Silva 1997; Boore et al. 1997; Campbell 1997; Sadigh et al. 1997; Idriss 1991). A significant amount of effort has been devoted to the collection and reappraisal of the metadata associated with the strong-motion records considered in the NGA project. The marked increase in the number of strong-motion records and this thorough re-evaluation of the metadata has allowed the inclusion of additional terms in the equations, which could not have been constrained previously. In particular, new features include accounting for effects such as the influence of the depth-to-top-of-rupture, as well as more comprehensive models for non-linear site response, sediment depth and hanging wall effects. This new suite of equations thus represents a significant development in the state-of-the-art of empirical ground-motion modelling, although the level of sophistication achieved for the functional forms of the equations also renders their practical implementation far more challenging than was the case for the previous generation of models.

Although the purpose of the NGA project was to derive equations for the prediction of mainshock ground-motions in the Western United States, these new equations might also benefit ground-motion prediction in other parts of the world, such as the region encompassing Europe, the southern Mediterranean and the Middle East, which is henceforth referred to as Euro-Mediterranean. Indeed, the number of indigenous strong-motion recordings of engineering interest currently available to developers in Europe is significantly smaller than the NGA dataset, as a result of a shorter strong-motion recording history and a high level of political fragmentation. In particular, there is a scarcity of accelerograms recorded at short distances from moderate-to-large events, due to the relatively sparse nature of the strong-motion recording arrays. This is clearly shown in Fig. 1, which compares the distribution in magnitude and distance of the NGA dataset and the data available from the Internet Site for European Strong-Motion Data (Ambraseys et al. 2002, 2004). For magnitudes ranging from 4.0 to 8.0, there are 2,418 accelerograms from the Euro-Mediterranean region compared to 3,551 in the NGA dataset. Only 1,344 of the Euro-Mediterranean records have been recorded within 100 km of the source, compared to 2,770 in the NGA dataset. The combination of sparse networks and the relatively infrequent occurrence of large earthquakes in the Euro-Mediterranean region means that even if a series of large earthquakes were to occur in the near future, the number of near-field recordings would most likely be limited.

Another issue is the availability of reliable estimates of the predictor variables and associated metadata, such as fault geometries and site conditions. Focal mechanism solutions are also lacking for a large proportion of the Euro-Mediterranean database, since such solutions are generally only computed for larger events. The lack of reliable metadata has an impact on the functional forms that can be adopted for predictive equations based on Euro-Mediterranean data. Table 1, which is based on the compilation by Douglas (2003, 2004a, 2006), summarises pan-European and regional equations for response spectral ordinates based on indigenous data that have been published over the last decade. Due to the limited number of moment tensor solutions available, only the most recent among these equations consider moment magnitude (M_w); many use surface-wave magnitude (M_S), local magnitude

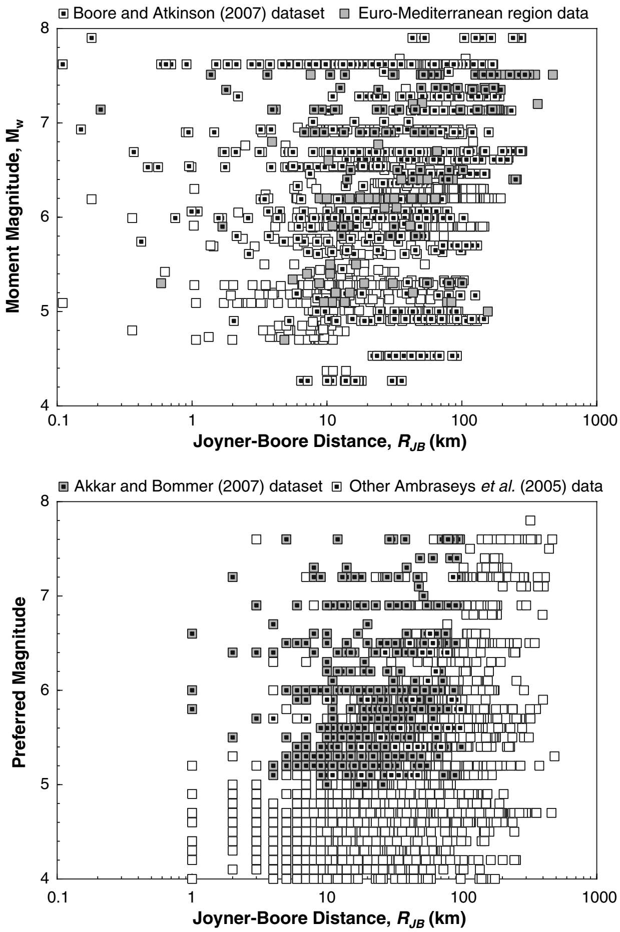

Fig. 1 Comparison of NGA (*upper panel*) and European datasets (*lower panel*). In the upper panel, symbols with a central square indicate records included in the Boore and Atkinson (2007) regression dataset, and grey-shaded symbols identify records from the Euro-Mediterranean region. In the lower panel, symbols with a central square indicate records included in the Ambraseys et al. (2005) regression dataset, with the subset used by Akkar and Bommer (2007a) highlighted in grey. Empty white squares correspond to other strong-motion records available from the Internet Site for European Strong-Motion Data. The magnitude scale is a hybrid scale which uses M_w whenever available and an M_S–m_b hybrid otherwise (M_S for events with $m_b > 6.0$ and m_b for events with $m_b \leq 6.0$), and R_{epi} is used as a proxy for R_{JB} for small-magnitude events with unknown fault geometries

(M_L), or a hybrid magnitude scale. Similarly, the absence of reliable fault geometries results in the frequent use of point-source distance metrics (epicentral distance, R_{epi}, and hypocentral distance, R_{hyp}). For many small earthquakes models of the rupture surface do not exist and point-source distances are often used as proxies for the finite-fault distance metrics. The most common proxy is to assume an equivalence between epicentral distance and the closest distance to the vertical projection of the rupture surface, or Joyner–Boore distance, R_{JB}. In view of the small rupture dimensions involved for these small events, this assumption is reasonable. Finally, all the models listed in Table 1 that include terms to adjust for varying site conditions consider generic site classes, which are generally based on geological criteria

Table 1 Summary of predictive equations for response spectral ordinates for the horizontal component of ground motion published for the Euro-Mediterranean region over the past decade, based on the compilation by Douglas (2003, 2004a, 2006)

Study	Region[a]	N^{d}_{WF}	N^{f}_{EQ}	Y^{g}	T^{h}_{max}	C^{j}	M^{k}	$[M]^{q}$	R^{r}	$[R]^{u}$	SoF[v]	Site[w]
Ambraseys et al. (1996)	Europe, Mediterranean & Middle East	422	157	SAa	2.0	LHe	M_S	4.0–7.9	R^{s}_{JB}	0–260	0	3 [RK, ST, SF]
Sabetta and Pugliese (1996)	Italy	95	17	PSV	4.0	LHa	Hybrid[l]	4.6–6.8	R^{s}_{JB}	1.5–180	0	3 [RK, ST, SF]
Bommer et al. (1998)	Europe, Mediterranean & Middle East	121–183	34–43	SD	3.0	LHe	M_S	5.5–7.9	R^{s}_{JB}	3–260	0	3 [RK, ST, SF]
Smit et al. (2000)	Caucasus	84	26	SAa	1.0	LHe	M_S	4.0–7.1	R_{hyp}	4–230	0	1
Gülkan and Kalkan (2002)	Turkey	93[e]	19	PSA	2.0	LHe	M_w	4.5–7.4	R^{s}_{JB}	1.2–150	0	3 [RK, ST, SF]
Khademi (2002)	Iran	160	28	SA	4.0	LHe	Hybrid[m]	3.4–0.4	R^{s}_{JB}	0.1–180	0	2 [RK, SO]
							M_S	4.0–6.9	R_{JB}	0–110		
Manic (2002)	Former Yugoslavia	153	19	PSV	4.0	B	M_L	4.2–7.0	R_{epi}	0–150	0	2 [RK, SO]
Schwarz et al. (2002)	NW Turkey	683	n/a	SA	2.0	n/a	M_L	0.9–7.2	R_{epi}	0–250	0	3 [RK, ST, SF]
Zonno and Montaldo (2002)	Italy	161	15	PSV	4.0	LHe	M_L	4.5–5.9	R_{epi}	2–100	0	2 [RK, SO]
Berge-Thierry et al. (2003)	Europe, Mediterranean & Middle East[b]	965	138	PSA	10.0[i]	B	M^{n}_{S}	4.0–7.9	R_{hyp}	4–330	0	2 [RK, SO]
Bommer et al. (2003)	Europe, Mediterranean & Middle East	422	157	SAa	2.0	LHe	M_S	4.5–5.9	R^{s}_{JB}	0–260	3 [N,S,R]	3 [RK, ST, SF]
Fukushima et al. (2003)	Europe, Mediterranean & Middle East[c]	740	50	PSA	2.0	B	M^{o}_{w}	5.5–7.4	R^{t}_{hyp}	0.5–235	0	2 [RK, SO]
Kalkan and Gülkan (2004)	Turkey	112	57	PSA	2.0	LHe	M_w	4.0–7.4	R^{s}_{JB}	1.2–250	0	3 [RK, ST, SF]
Özbey et al. (2004)	NW Turkey	195	17	SA	4.0	GM	M^{p}_{w}	5.0–7.4	R^{s}_{JB}	5–300	0	3 [RK, ST, SF]

Table 1 Continued

Study	Region[a]	N_{WF}^{d}	N_{EQ}^{f}	Y^{g}	T_{max}^{h}	C^{j}	M^{k}	$[M]^{q}$	R^{r}	$[R]^{u}$	SoF[v]	Site[w]
Ambraseys et al. (2005)	Europe, Mediterranean & Middle East	207–595	59–135	SAa	2.5	LH	M_w	5.0–7.6	R_{JB}^{s}	0–100	4 [N,S,R, O]	3 [RK, ST, SF]
Bragato and Slejko (2005)	Eastern Alps	1402	240	SAa	2.0	RS	M_L	2.5–6.3	R_{JB}^{s}	0–130	0	1
Bindi et al. (2006)	Umbria-Marche	144–239	45	PSV	4.0	LHe	M_L	4.0–5.9	R_{epi}, R_{hyp}	1–100	0	4 [RK, SC SA, DA]
Zaré and Sabzali (2006)	Iran	89	55	SA	4.0	n/a	M_w	2.7–7.4	R_{hyp}	4–167	4 [R,S, RO, U]	4 [RK, ST, SA, DA]
Akkar and Bommer (2007a)	Europe, Mediterranean & Middle East	532	131	SD	4.0	GM	M_w	5.0–7.6	R_{JB}^{s}	0–100	3 [N,S,R]	3 [RK, ST, SF]
Danciu and Tselentis (2007)	Greece	335	151	PSA	4.0	AM	M_w	4.5–6.9	R_{epi}	0–136	2 [N, S+R]	3 [RK, ST, SF]

[a] Geographical coverage of dataset; [b] Supplemented by data from California; [c] Supplemented by data from California; and Japan; [d] Number of records in dataset; [e] 93 waveforms from 47 triaxial records; [f] Number of events in dataset; [g] Predicted ground-motion parameter: SAa = absolute spectral acceleration; PSA = pseudo-spectral acceleration; SA = unspecified spectral accelerarion; PSV = pseudo-spectral velocity; SD = spectral displacement; [h] Longest response period considered, in seconds; [i] Predictions are severely distorted beyond 3 s; [j] Horizontal component definition: AM = arithmetic mean; B = both; GM = geometric mean; LHa = larger PGA; LHe = larger horizontal (envelope); RS = resolved; [k] Magnitude scale in equation; [l] M_S–M_L hybrid; [m] M_S–m_b hybrid considered equivalent to M_w; [n] M_w for Californian events; [o] Estimated from M_S when unavailable; [p] Estimated from M_L when unavailable; [q] Range of magnitudes in dataset; [r] Distance metric in equation: R_{epi} = epicentral distance; R_{hyp} = hypocentral distance; R_{JB} = closest distance to vertical projection of fault rupture plane; [s] Use R_{epi} as a proxy when unavailable; [t] Closest distance to rupture (R_{rup}) when available; [u] Range of distances in dataset, in km; [v] Mechanism classes considered for style-of-faulting term (0 when no style-of-faulting term in equation): N = normal; O = odd; R = reverse; RO = reverse-oblique; S = strike-slip; U = unknown; [w] Site classes considered in equation (1 when no site classification): RK = rock; SO = generic soil; ST = stiff soil; SF = soft soil; SA = shallow alluvium; DA = deep alluvium; SC = shallow colluvium

due to the small number of borehole data available. Confident estimates of the average shear-wave velocity over the upper 30 m (V_{s30}) could only be obtained at the considerable cost of conducting site-specific geotechnical analyses of all of the recording stations throughout the Euro-Mediterranean region. Similarly, constraining the fault geometries of European events would in many cases require the deployment of additional instruments.

As a result, various effects have been included into the NGA models that could simply not be constrained by the Euro-Mediterranean dataset, and are therefore absent from European predictive models; typical examples include the effects of non-linear site response and terms to account for hanging-wall effects. Since it would appear that the number of Euro-Mediterranean strong-motion recordings is unlikely to drastically change in the near future, and that the metadata associated with currently available records can only be improved at considerable cost, deriving European models with a level of sophistication similar to that of the NGA models will remain unfeasible in the short-term. Furthermore, the NGA models have the advantage of extending to much longer periods (10 s) than currently available European models. With the exception of the Berge-Thierry et al. (2003) model, which has been shown to be severely distorted beyond 3 s (Boore and Bommer 2005), all of the models listed in Table 1 derive coefficients for a period range limited to 4 s or less. Akkar and Bommer (2006) performed a rigorous analysis of the usable period range of accelerograms in the Euro-Mediterranean database recorded on both analogue and digital instruments. As one considers longer response periods the number of records that fulfil the quality requirements stipulated by Akkar and Bommer (2006) decreases drastically. When developing the latest models for response spectral ordinates Akkar and Bommer (2007a) did not derive any equations for response periods beyond 4 s as the numbers of usable records had decreased to the point that the model could not be adequately constrained. The NGA equations therefore represent the only available empirical models for prediction of ground motions for long-period structures with natural periods longer than 4 s, such as bridges, tall buildings and storage tanks. In view of this situation, a pertinent question that may be asked is: can the new NGA models be applied in Europe?

A preliminary analysis of precisely this issue has been conducted by Campbell and Bozorgnia (2006), who compared the Campbell and Bozorgnia (2007) NGA model with the Ambraseys et al. (2005) model for Europe. They found that the NGA model of Campbell and Bozorgnia (2007), and indirectly also the other NGA models, agreed reasonably well with the predictions of Ambraseys et al. (2005) over the magnitude and distance range for which the latter model was relatively well constrained. However, it was noted that a more thorough analysis is required before firm conclusions may be made. The purpose of the present article is to conduct a more rigorous analysis into the ability of the NGA models to predict ground motions from earthquakes occurring in Europe and the Middle East. The analysis is primarily based upon an application of the likelihood approach of Scherbaum et al. (2004) whereby measures of the goodness-of-fit of a model to a given dataset may be used to judge the suitability of the model for application in the region from which the dataset was compiled. Similar approaches have previously been implemented for relatively small numbers of records from parts of Europe (Bindi et al. 2006; Hintersberger et al. 2007; Drouet et al. 2007).

2 Regional differences in strong ground-motion

The applicability of the NGA equations to Europe hinges on the question of whether the models used for the prediction of ground motions in a given region need to be derived from strong-motion data recorded in that region (indigenous data), or whether good-quality data from other tectonically compatible regions (allogenous data) can be used to constrain models for physical processes for which indigenous data are insufficient. A corollary question is whether ground motions vary on a regional scale. This latter question is particularly relevant to Europe, where the comparatively small extent of political entities has led to the derivation of a number of country- or region-specific prediction equations, which represent about two thirds of the equations for response spectral ordinates based on Euro-Mediterranean data that have been published over the last decade (Table 1). Bommer (2006) discusses differences between regional and pan-European prediction equations for peak ground accelerations, and finds that differences between regional equations can be more pronounced than differences between a pan-European and a regional equation.

Similarly, Douglas (2004b) found no regional differences within Europe for ground motions from small-to-moderate events, using an approach based on analysis of variance. Douglas (2004c) extended this approach in an attempt to identify differences in ground motions between California, New Zealand and Europe and found that the ground motions from Californian earthquakes were significantly (in a statistical sense) higher than those from European events. However, the approach taken in this work requires relatively large datasets of accelerograms to be subdivided into relatively small groups of records that share various seismological characteristics. Although Douglas (2004c) was able to identify a systematic trend over a number of these groups, the numbers of records in these groups prevents one from drawing decisive conclusions about the existence of genuine regional differences. If the analysis of Douglas (2004c) were to be repeated now the same problems associated with a restricted number of accelerograms would exist and the potential for identifying differences in ground motions using this approach is therefore limited. An alternative approach is to compare empirical models that have been developed by using the full available dataset rather than the small subsets used in the Douglas (2004b,c) approach.

The NGA dataset itself contains large amounts of allogenous data. Firstly, it is heavily dominated by records from the 1999 Chi-Chi sequence, which represent more than 50% of the total number of records in the flatfile. Secondly, as highlighted in the upper panel of Fig. 1, it includes a non-negligible proportion of events from the Euro-Mediterranean region (35 out of 173 events), which contribute between 20% (Abrahamson and Silva 2007) and 40% (Boore and Atkinson 2007) of the events included in the regressions, and it is therefore to be expected that the source scaling of the equations developed as part of the NGA project reflect at least in part the scaling properties of European earthquakes. Abrahamson and Silva (2007), while developing their model, performed random effects regression analyses on a dataset including records from worldwide earthquakes. Before finalising the dataset to be used for their final model they inspected the inter-event residuals from events foreign to the western US and did not find any systematic regional differences within 100 km of the source. Beyond this distance, they decided to use exclusively data from the Western United States, since differences in regional attenuation characteristics might have an impact on ground-motion levels at larger distances. Such differences may originate from variations in the thickness of the crust, as well as from variations in the propagation characteristics of the bedrock. However, at the distances of most interest for seismic hazard analysis ($\leq$100 km), the influence of the propagation path is marginal compared to that of the source process or site characteristics, for which no significant differences have been determined between tectonically similar regions.

3 Selection of ground-motion models for comparison

A key issue that must be addressed when making comparisons between empirical ground-motion models is parameter compatibility (Bommer et al. 2005; Beyer and Bommer 2006). Both the NGA models and recent European models use the moment magnitude scale to characterise earthquake size but most of the NGA models adopt the closest distance to the rupture surface rather than the Joyner–Boore distance most commonly used in Europe. This presents a potential barrier to direct comparisons. However, the NGA model of Boore and Atkinson (2007) uses the Joyner–Boore distance measure as well as including the smallest number of independent variables. This model is consequently a logical choice for making comparisons. For the subsequent analysis it is assumed that conclusions may be drawn on the basis of comparisons made between European relations and data with the model of Boore and Atkinson (2007). In order to justify this assumption the general scaling of four of the NGA models (Abrahamson and Silva 2007; Boore and Atkinson 2007; Campbell and Bozorgnia 2007; Chiou and Youngs 2006) was compared using the hypothetical test scenarios specified by Campbell and Bozorgnia (2007, Sect. 7.1, p. 79) over a more complete range of distances (Fig. 2). Figure 2 indicates that the general scaling with respect to magnitude and distance over a wide range of spectral ordinates, and PGV, is very similar for the four models. The largest differences appear for the small (M_w 5.0) magnitude cases at short response periods. With the exception of the model of Abrahamson and Silva (2007), and that of Campbell and Bozorgnia (2003) under certain circumstances, the aleatory variability of these models is independent of the predictor variables and of the ground-motion amplitude. The values of aleatory variability associated with the four NGA models considered are also similar and show a degree of variation akin to that of the median ground-motion estimates shown in Fig. 2. Given these findings, it is reasonable to assume that the Boore and Atkinson (2007) model is representative of the suite of NGA models for the subsequent analyses. However, it should be noted that this model does tend to estimate lower short-period spectral amplitudes for small earthquakes at distances up to approximately 20 km. Further support of this assumption is provided by Campbell and Bozorgnia (2007, Sect. 6.4) who discuss the problems associated with using the suite of NGA models in order to account for the epistemic uncertainty in ground-motion prediction. They highlight the fact that for many scenarios there is very close agreement among the NGA models and that this agreement does not necessarily reflect low epistemic uncertainty but may rather reflect the fact that similar datasets were used by the developers. While the treatment of epistemic uncertainty is an important issue in its own right, for the present study the fact that this issue has been raised strongly supports the idea that a single model—in this case, Boore and Atkinson (2007)—can be taken as being representative of the whole suite of NGA models.

When making visual comparisons of the scaling of models under hypothetical scenarios, such as those in Fig. 2, there is no reason why European models may not be compared directly with the NGA models. Issues associated with parameter compatibility are irrelevant in this case as one simply specifies a particular rupture scenario and then calculates all of the corresponding predictor variables that are associated with this scenario such as the various distance metrics or the depth to the top of the rupture. However, the more quantitative analyses that are presented herein deal directly with the performance of the models when predicting observed ground-motions from earthquakes in Euro-Mediterranean region. In order to obtain model predictions under these circumstances all of the predictor variables used in the ground-motion models must be available. For the Euro-Mediterranean dataset that is used herein details of finite-fault models are often not included in the metadata and consequently rupture distances, depths to the top of rupture, rupture widths and dips are not directly available. In addition,

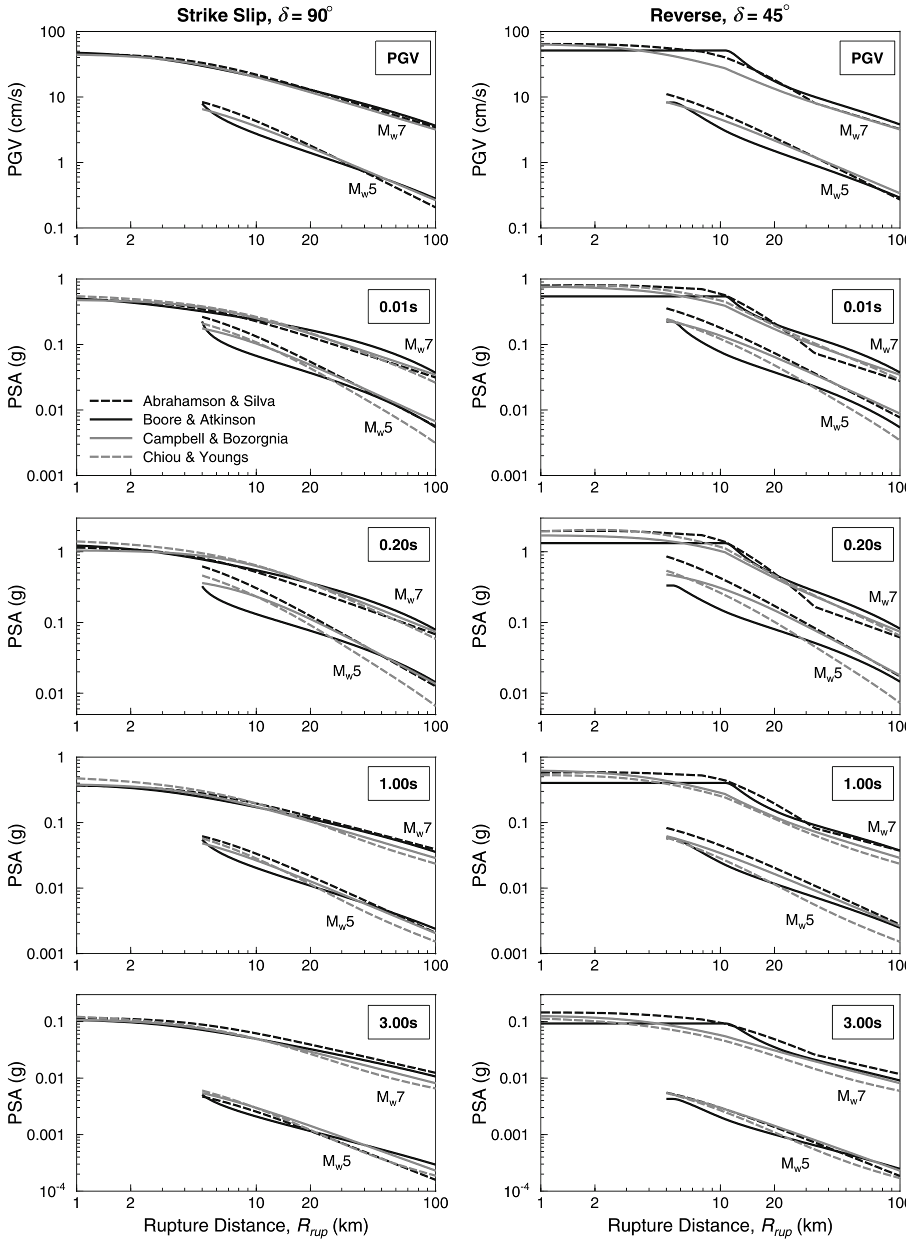

Fig. 2 Comparison of the NGA models of Abrahamson and Silva, Boore and Atkinson, Campbell and Bozorgnia, and Chiou and Youngs for the test scenarios given in Campbell and Bozorgnia (2007). The panels on the left are for a strike slip fault dipping at 90° while the panels on the right correspond to a reverse fault dipping at 45°. Sites are located perpendicular to the strike of the fault and are on the hanging wall side for the reverse scenario. The depths to the top of rupture are 5 and 0 km for the M_W 5.0 and 7.0 events, respectively. The average shear-wave velocity over the upper 30 m is 760 m/s in all cases. The depth to the base of the seismogenic layer is 15 km and fault dimensions are obtained using Wells and Coppersmith (1994). Depths to the 1,000 and 2,500 m/s shear-wave velocity horizons are 412 and 2,000 m, respectively

the specification of site conditions is also incomplete with over half the available records not having estimates of the shear-wave velocity at the recording site and no estimates of depths to the 1,000 and 2,500 m/s shear-wave velocity horizons, which are predictor variables used in some of the NGA models. As previously mentioned, the Boore and Atkinson (2007) model uses the smallest number of predictor variables of the NGA models considered herein and those that are used are consistent the European models of Ambraseys et al. (2005) and Akkar and Bommer (2007a,b). Another issue associated with parameter compatibility between the NGA and European equations is the definition of style-of-faulting classes (Bommer et al. 2003). Conveniently, the definitions of the boundaries between different classes of style-of-faulting used by Boore and Atkinson (2007) are the most consistent with those used for the European models. Finally, the Ambraseys et al. (2005) model prescribes spectral ordinates in terms of the larger horizontal component of motion and therefore had to be adjusted in the current study to allow comparison with the Boore and Atkinson (2007) and Akkar and Bommer (2007a) models, which are both expressed in terms of the geometric mean of the two horizontal components of motion. The empirical adjustment factors of Beyer and Bommer (2006) were used for this purpose. Strictly speaking, the 'geometric mean' that is used by Boore and Atkinson (2007) and Akkar and Bommer (2007a) are different (Boore et al. 2006). However, Beyer and Bommer (2006) found the practical difference between the two definitions to be very small. Consequently, for the purposes of the present analysis no adjustment is made to convert the orientation-independent definition used by Boore and Atkinson (2007) to that used by Akkar and Bommer (2007a).

A comparison between the NGA model of Boore and Atkinson (2007) and the European models of Ambraseys et al. (2005) and Akkar and Bommer (2007a) for spectral ordinates and Akkar and Bommer (2007b) for peak ground velocity is presented in Fig. 3. For this comparison, the same rupture geometry as that used for Fig. 2 is assumed but the comparison is made over different spectral periods. A key issue when making these comparisons between the NGA models and those for Europe is the very different treatment of site effects. All NGA models predict site response on the basis of the average shear-wave velocity over the upper 30 m whereas all European relationships adopt dummy variables for qualitatively different site categories of rock, stiff soil and soft soil. These categories, at least for the recent relationships, are defined on the basis of shear-wave velocity and in some cases, such as in Akkar and Bommer (2007b), a comparison is made with typical soil classification schemes adopted in the US. The European models considered herein use three generic site classes that are defined by ranges of shear-wave velocity with $V_{s30} < 360$ m/s, $360 \leq V_{s30} \leq 750$ m/s, and $V_{s30} > 750$ m/s corresponding to soft soil, stiff soil and rock sites, respectively. For the purpose of creating Fig. 3, stiff soil conditions were assumed for the European equations and the geometric mean of the shear-wave velocities defining this site class were used for the Boore and Atkinson (2007) model. This convention enables comparisons to be made in a systematic manner.

The treatment of possible non-linear behaviour is another issue associated with the modelling of site response. All of the NGA equations account for the strength of the input rock motion when determining the modification (amplification or reduction) of ground motions associated with site response. This is an effect that is not included in any European model although Akkar and Bommer (2007b) and Bommer et al. (2007) have both looked for it in the distributions of residuals. The model of Boore and Atkinson (2007) contains separate terms for both linear and non-linear site response and it is therefore possible to isolate the parts of the model that relate to linear site response and to make comparisons on the basis of these modified predictions. However, it should be noted that although the European equations do not directly model soil non-linearity, the developers will implicitly have included

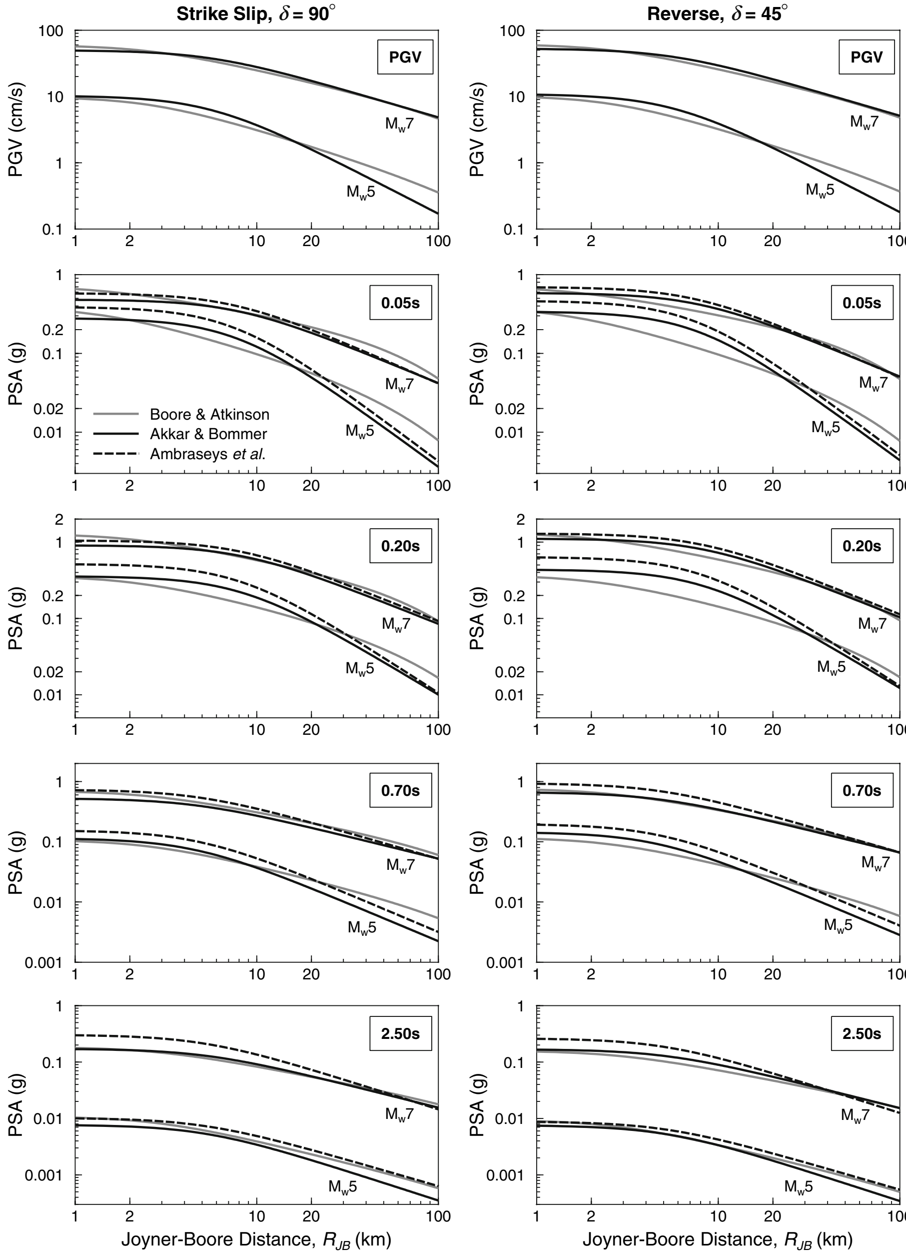

Fig. 3 Comparisons between the NGA model of Boore and Atkinson with the European models of Akkar and Bommer (2007a,b) and Ambraseys et al. (2005). The rupture scenarios considered are the same as those detailed in Fig. 2

ground motions that contain effects associated with this process. For example, the recent work of Scasserra et al. (2006) provides evidence of non-linear site response from moderate magnitude Italian earthquakes that have been used in the development of regional European ground-motion models. Therefore, the linear site response that is predicted using the European equations is not directly analogous to the linear amplification functions used in the Boore and Atkinson (2007) model, or in any of the other NGA models for that matter.

The comparisons made in Fig. 3 indicate that the largest differences in the ground motions between the Boore and Atkinson (2007) model and those of Ambraseys et al. (2005) and Akkar and Bommer (2007a,b) occur at short periods and distances. There is also more variability in the predictions for the small magnitude cases. In general, it can be appreciated that the European model of Akkar and Bommer (2007a) for spectral ordinates is in closest agreement with the Boore and Atkinson (2007) model and that the agreement between the two models for PGV is remarkably close for the large-magnitude cases. Such an agreement between the PGV predictions was previously highlighted by Akkar and Bommer (2007b) who compared their model with the predictions of the Boore and Atkinson (2007) and Campbell and Bozorgnia (2007) NGA models. Significantly, the points where the European models differ most noticeably from the Boore and Atkinson (2007) model coincide with the points where the Boore and Atkinson (2007) model tends to differ from the other NGA models (c.f., Fig. 2) which suggests that at least as good a match would be obtained using the other NGA models. On the basis of the visual comparison made in Fig. 3 we can tentatively assert that the agreement between the NGA models and the European models is good, particularly for moderate periods. The quality of this agreement should also be judged on the basis of the differences that exist between empirical ground-motion models developed within Europe itself. Bommer (2006) presented comparisons between several empirical ground-motion models that have been developed using data from regions of Europe or individual European countries; these comparisons show a far greater degree of disagreement than the models presented in Fig. 3.

4 Quantitative comparison of the NGA and recent European models

The qualitative comparisons made thus far suggest a reasonable agreement between the NGA models and those developed for Europe, which is consistent with previous findings by Campbell and Bozorgnia (2006). In order to quantify this agreement it is necessary to compare the predictions of the NGA models directly with observed European ground motions. Several options exist for making such comparisons: Scherbaum et al. (2004) describe a number of statistical measures of the goodness-of-fit of a model to a sample of data before presenting a new measure developed specifically for the purpose of comparing ground-motion models. In order to quantify the ability of the NGA models to predict ground motions in Europe, the likelihood-based scoring system of Scherbaum et al. (2004) is adopted. In this method the goodness-of-fit of a model to some observed data is assessed on the basis of a likelihood parameter. This likelihood parameter captures effects associated with the fit of the median values as well as the shape of the underlying distribution of ground-motion residuals. The parameter may be calculated following Scherbaum et al. (2004) and Hintersberger et al. (2007) by Eq. 1:

$$\mathrm{LH}\left(|Z|\right) = \mathrm{Erf}\left(\frac{|Z|}{\sqrt{2}}, \infty\right) = \frac{2}{\sqrt{2\pi}} \int_{|Z|}^{\infty} \exp\left(\frac{-z^2}{2}\right) \mathrm{d}z, \tag{1}$$

where Z represents a normalised model residual and $\mathrm{Erf}(x)$ is the error function evaluated for an argument x. The expression 'model residual' is used here in order to make a distinction between a regression residual that is obtained during a regression procedure and one that is obtained by applying any model to a given dataset and calculating the differences between the observed and estimated values. In all cases in this paper we are dealing with model residuals rather than regression residuals. The process by which the model residuals are determined is to take the dataset used by Akkar and Bommer (2007a,b)—that also shares common metadata with the model of Ambraseys et al. (2005)—and to calculate predictions for all of the records in this dataset. The total model residuals are then calculated using Eq. 2:

$$Z_{\mathrm{T},ij} = \frac{\log\left(gm_{\mathrm{obs},ij}\right) - \log\left(gm_{\mathrm{mod},ij}\right)}{\sigma_{\mathrm{T}}}, \tag{2}$$

where $Z_{\mathrm{T},ij}$ is the total normalised residual for the jth recording from the ith event, $gm_{\mathrm{obs},ij}$ and $gm_{\mathrm{mod},ij}$ are the observed and modelled ground motions corresponding to this record and σ_{T} is the total standard deviation of the model. The base of the logarithms in Eq. 2 depends upon how the standard deviation is specified in the ground-motion models but is always either the natural or common logarithm.

When calculating $gm_{\mathrm{mod},ij}$ for the models of Akkar and Bommer (2007a,b) and Ambraseys et al. (2005) the metadata in the European and Middle Eastern database may be used directly. However, the Boore and Atkinson (2007) model uses the average shear-wave velocity over the upper 30 m as a predictor variable. Approximately half of the records in the European and Middle Eastern database have estimated shear-wave velocities and these are used directly. The remaining records without shear-wave velocities were assigned a value determined from the geometric means of the known shear-wave velocities in each of the three site classes used by the European models. Figure 4 presents the distributions of the normalised residuals and the likelihood values obtained from the European dataset through application of Eqs. 1 and 2 with the models of Akkar and Bommer (2007a), Ambraseys et al. (2005) and Boore and Atkinson (2007). As expected, the model of Akkar and Bommer (2007a) performs best of these three models but one may also appreciate that the performance of all three models is generally very good for the three response periods that are shown.

The performance of the models in Fig. 4 may be assessed by considering both the distributions of the normalised total residuals and the distribution of the likelihood values. In the former case a model is considered to be performing well if the distribution of observed normalised residuals, summarised by the solid black line, agrees well with the standard normal distribution shown by the dashed grey line. An agreement between these two curves indicates that the model is not biased and that the standard deviation of the model appropriately captures the variability in the observed motions. When considering the distribution of the likelihoods, a good performance of a model corresponds to the case where the likelihood values are approximately uniformly distributed (see Scherbaum et al. 2004, for a proof of this). A uniform distribution of likelihood values also indicates that the model is unbiased and that the shape of the residual distribution is consistent with the variance specified in the model.

The distributions shown in Fig. 4 all relate to the total model residuals. However, each of the three models partitions the total variability of the model into two independent components, one corresponding to inter-event variability and the other to intra-event variability. Each of these individual components are modelled by normal distributions and for datasets that are balanced (i.e., with similar numbers of earthquakes from each event) the distribution

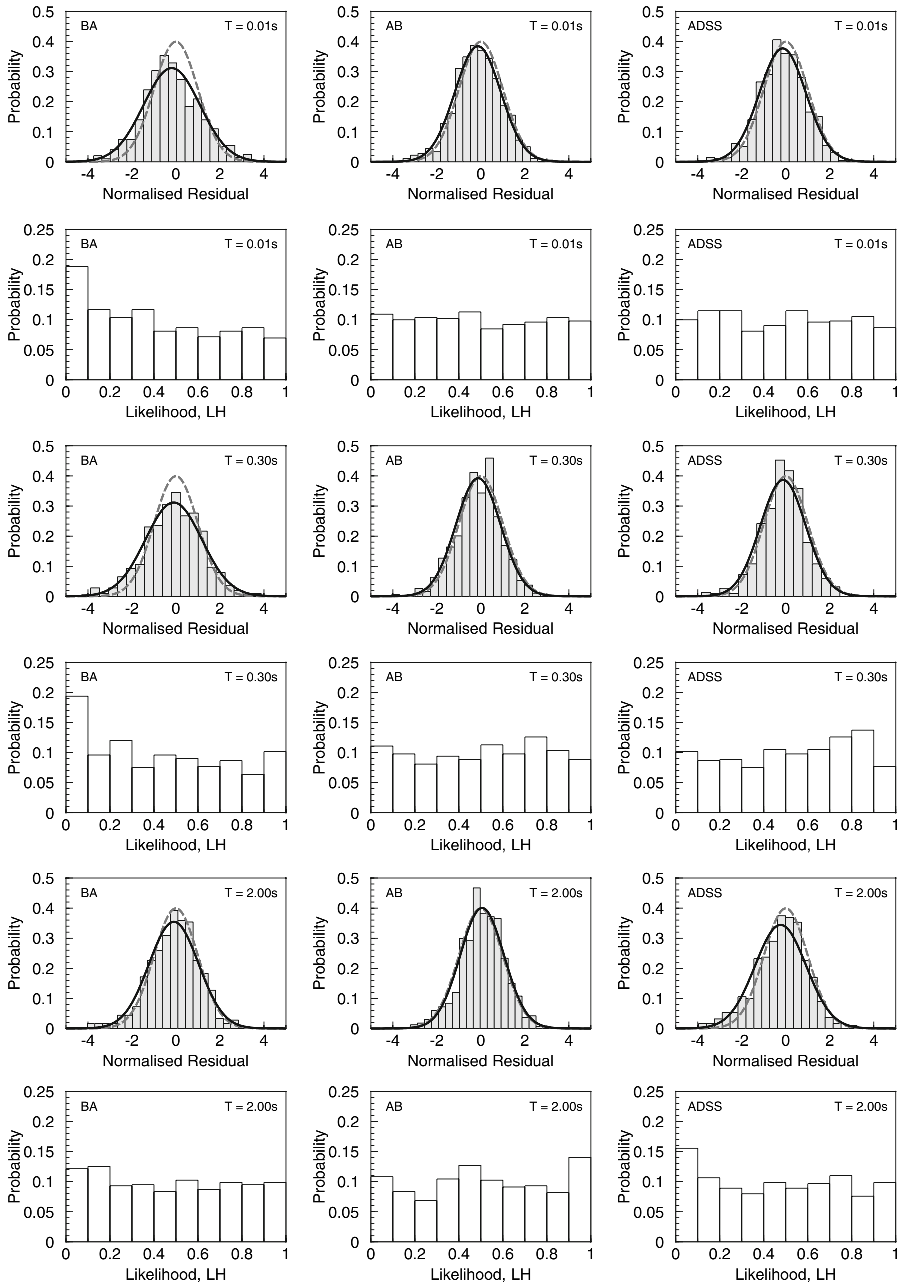

Fig. 4 Histograms of the normalised total model residuals and likelihood values for the three models considered. Columns, from left to right, correspond to Boore and Atkinson (2007) (BA), Akkar and Bommer (2007a) (AB) and Ambraseys et al. (2005) (ADSS). Three response periods of 0.01, 0.30 and 2.00 s are considered. The plots of the normalised total residuals also include the standard normal distribution (*grey dashed line*) and the normal distribution fitted to the residuals (*solid black line*)

of the total residuals will also be close to a normal distribution. However, in the general case, there is no reason why the total residuals should conform to a normal distribution. In the case where certain events provide large numbers of records to the overall dataset, the distribution of total residuals may depart from a normal distribution while the distributions of the inter-event residuals and intra-event residuals remain normally distributed. It is therefore possible that the distributions shown in Fig. 4 may in fact be biased by the relatively well-recorded earthquakes in the European dataset. For this reason, the original proposal of Scherbaum et al. (2004) is modified in this study to allow for the influence of both inter-event and intra-event variance components that are provided in recent ground-motion models. This distinction was not made in the original study, possibly due to the small datasets that were considered. However, in the present work where some well-recorded earthquakes are included in the dataset (such as the 1997 Umbria Marche sequence in central Italy and the 1999 Turkish events) it is important to make this distinction in order to ensure that moment statistics based on residuals are not biased by correlations that exist amongst the residuals. The question thus arises of how one should partition the total residuals into meaningful inter- and intra-event components.

All of the ground-motion models that are considered herein assume that the total residual may be partitioned into a component common to all records from a particular event and a component specific to each record. This partitioning is shown in Eq. 3 in which y_{ij} is the logarithm of the observed ground-motion measure, and $\mu\left(m_i, r_{ij}, \boldsymbol{\theta}_{ij} \middle| \boldsymbol{\beta}\right)$ is the logarithm of the median estimate of the ground-motion given the magnitude, m_i, distance, r_{ij}, various other descriptive parameters relevant to this record, $\boldsymbol{\theta}_{ij}$, and the model parameters, $\boldsymbol{\beta}$. The residual terms are given by $\delta_{\mathrm{E},i}$ for the inter-event residual and $\delta_{\mathrm{A},ij}$ for the intra-event residual:

$$y_{ij} = \mu\left(m_i, r_{ij}, \boldsymbol{\theta}_{ij} \middle| \boldsymbol{\beta}\right) + \delta_{\mathrm{E},i} + \delta_{\mathrm{A},ij} \tag{3}$$

Both the inter-event and intra-event residuals are assumed to be drawn from normal distributions with means of zero and variances of σ_{E}^2 and σ_{A}^2, respectively. Under these conditions of normality the log-likelihood of a set of data given the model parameters, $\ln L\left(\mathbf{y} \middle| \boldsymbol{\beta}, \sigma_{\mathrm{E}}, \sigma_{\mathrm{A}}\right)$, may be calculated using Eq. 4:

$$\ln L\left(\mathbf{y} \middle| \boldsymbol{\beta}, \sigma_{\mathrm{E}}, \sigma_{\mathrm{A}}\right) = \sum_{i}^{N_{\mathrm{EQ}}} \sum_{j}^{n_i} \ln\left[\frac{1}{\sigma_{\mathrm{A}}} \boldsymbol{\phi}\left(\frac{y_{ij} - \mu\left(m_i, r_{ij}, \boldsymbol{\theta}_{ij} \middle| \boldsymbol{\beta}\right) - \delta_{\mathrm{E},i}}{\sigma_{\mathrm{A}}}\right)\right], \tag{4}$$

where $\delta_{\mathrm{E},i}$ may be calculated following Brillinger and Preisler (1985) and Abrahamson and Youngs (1992) from Eq. 5:

$$\delta_{\mathrm{E},i} = \frac{\sigma_{\mathrm{E}}^2 \sum_{j}^{n_i} y_{ij} - \mu\left(m_i, r_{ij}, \boldsymbol{\theta}_{ij} \middle| \boldsymbol{\beta}\right)}{n_i \sigma_{\mathrm{E}}^2 + \sigma_{\mathrm{A}}^2} \tag{5}$$

In Eqs. 4 and 5, N_{EQ} is the total number of earthquakes contributing records to the dataset, with the ith event contributing n_i records, and $\boldsymbol{\phi}(x)$ is the probability density function of the standard normal distribution evaluated for the argument x. The estimator in Eq. 5 is valid regardless of the regression methodology used in the development of the ground-motion model. Even though the variance components may have been obtained using different approaches, in principle they are all supposed to represent the same effect, namely the partitioning of the total variability between the inter-event and the intra-event variability. Once a model has been developed it is always presented in the same way and this presentation meets the conditions of normality required to derive Eq. 5.

The normalised inter-event and intra-event model residuals may be obtained by reformulating Eq. 3 as in Eq. 6. Under this representation, $z_{\mathrm{E},i}$ and $z_{\mathrm{A},ij}$ correspond to the normalised inter-event and intra-event model residuals, respectively.

$$y_{ij} = \mu\left(m_i, r_{ij}, \boldsymbol{\theta}_{ij} \middle| \boldsymbol{\beta}\right) + z_{\mathrm{E},i}\sigma_{\mathrm{E}} + z_{\mathrm{A},ij}\sigma_{\mathrm{A}} \tag{6}$$

Figures 5 and 6 are analogous to Fig. 4 but show the distributions of the normalised inter- and intra-event model residuals and their associated likelihood distributions. In all cases the distributions of the intra-event residuals show an improvement over the total residuals shown in Fig. 4. This confirms the importance of taking the correlation among records from the same event into account. The most interesting aspect of Fig. 5 is that the Boore and Atkinson (2007) model actually appears to perform better than the European models when considering the distributions of the normalised inter-event residuals. In this circumstance, better performance refers to the agreement between the distribution of the normalised model residuals and the standard normal distribution. In Figs. 4–6 these two distributions are shown by the solid black and dashed grey lines, respectively. The quality of the fit between the distributions observed in Fig. 6 for the intra-event residuals is not surprising as Eq. 5 acts to make these distributions as normal as possible by shifting any peculiarities associated with a particular earthquake, such as a consistent under- or over-prediction, into the inter-event residuals. However, the fact that the normalised inter-event residuals still perform so well for the Boore and Atkinson (2007) model by having not only the right distributional shape but also means that are close to zero strongly suggests that this model is doing a good job of modelling the records in the Euro-Mediterranean dataset.

Figures 4–6 only show the distributions of the likelihoods and residuals for three selected response periods. Rather than showing the full distributions for other periods of interest, plots of the relevant summary statistics are presented in Figs. 7 and 8. In Fig. 7 the summary statistics for the total residuals are shown and include the means and medians of both the likelihood values and the normalised model residuals as well as the standard deviations of the normalised model residuals. These are the key summary parameters that were identified by Scherbaum et al. (2004) as being useful for judging the applicability of models to a particular region. Also shown in Fig. 7 is a plot of the correlation coefficient between the observed and predicted ground motions which is another way of quantifying the goodness-of-fit of a given model. In all cases the performance of the models tends to become better as one considers longer response periods.

Figure 8 shows the summary statistics for the inter-event and intra-event cases. The results from the analysis of the intra-event residuals for all considered periods indicates that the Boore and Atkinson (2007) model is generally unbiased with a slight tendency to over-predict the Euro-Mediterranean data. The likelihood values and standard deviations of the normalised residuals also indicate that the Boore and Atkinson (2007) model performs well, particularly for periods beyond approximately 1 s. At short periods the distribution of the normalised residuals for the Boore and Atkinson (2007) model tends to have higher variability than would be expected from a standard normal distribution. This effect is also evident in the mean and median likelihoods where the lowest values correspond to the short period range.

The summary statistics for the inter-event case show similar trends to the intra-event case in terms of the mean normalised residuals with the model of Akkar and Bommer (2007a) performing the best but followed quite closely by the model of Ambraseys et al. (2005). In general, the Ambraseys et al. (2005) model tends to slightly over-predict the ground motions of the Akkar and Bommer (2007a) dataset on a consistent basis. This over-prediction may well be due to their model having a relatively simple linear magnitude dependence. The distributions of the likelihood values for all models in the inter-event case, as inferred from

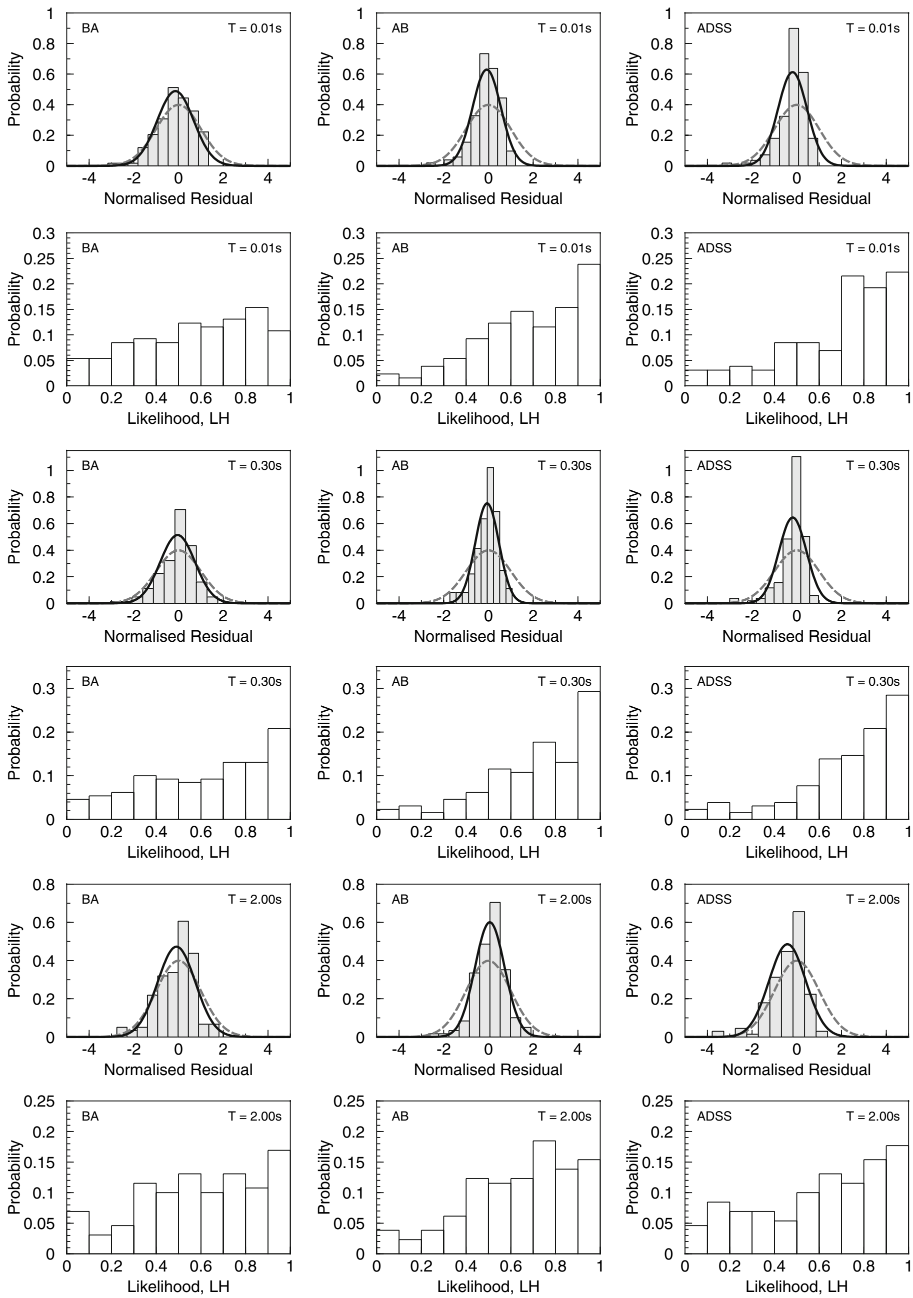

Fig. 5 Histograms of the normalised inter-event model residuals and likelihood values for the three models considered. The columns, from left to right, correspond to Boore and Atkinson (2007) (BA), Akkar and Bommer (2007a) (AB) and Ambraseys et al. (2005) (ADSS). Three response periods of 0.01, 0.30 and 2.00 s are shown. The plots of the normalised inter-event model residuals also include the standard normal distribution (*dashed grey lines*) and the normal distribution fitted to the residuals (*solid black lines*)

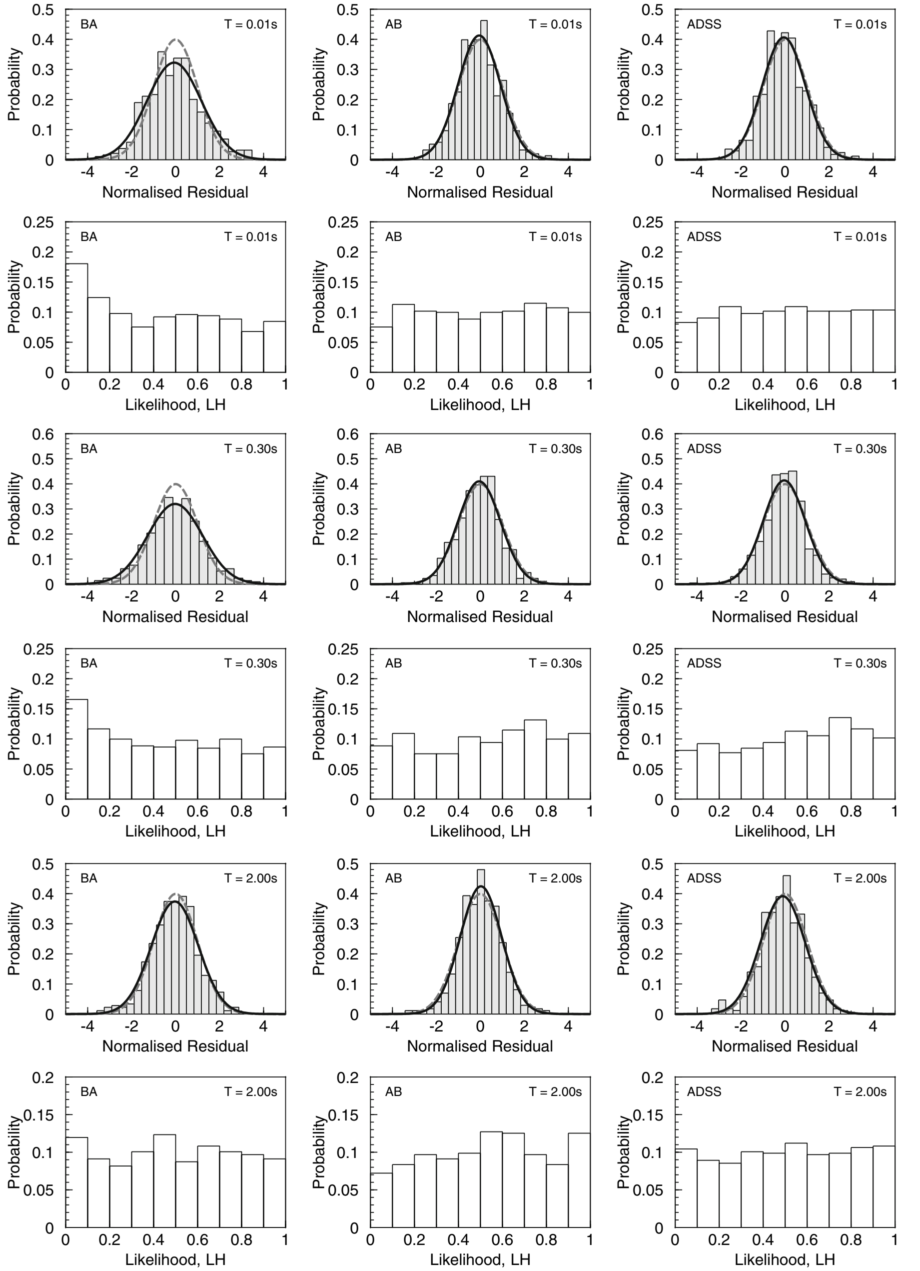

Fig. 6 Histograms of the normalised intra-event model residuals and likelihood values for the three models considered. The columns, from left to right, correspond to Boore and Atkinson (2007) (BA), Akkar and Bommer (2007a) (AB) and Ambraseys et al. (2005) (ADSS). Three response periods of 0.01, 0.30 and 2.00 s are shown. The plots of the normalised intra-event model residuals also include the standard normal distribution (*dashed grey lines*) and the normal distribution fitted to the residuals (*solid black lines*)

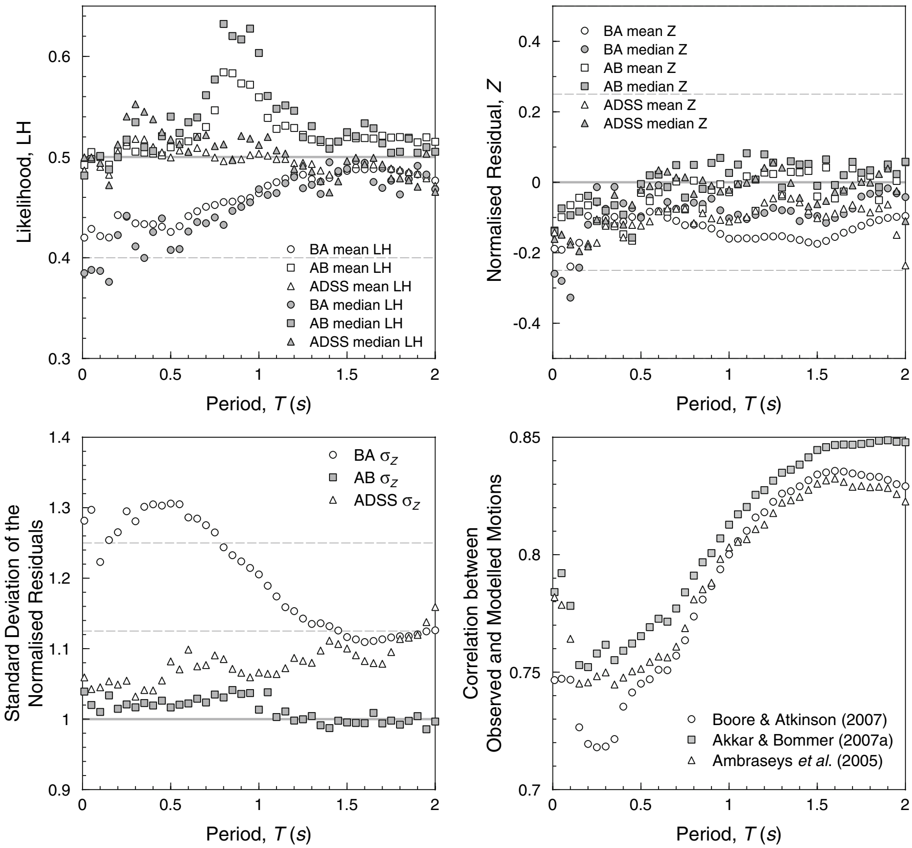

Fig. 7 Summary statistics for the analysis using total normalised model residuals. The dashed grey lines indicate the boundaries between the various classifications of the Scherbaum et al. (2004) model. See Table 2 and the supporting text for the definitions of the boundaries

the median values, are quite significantly skewed towards higher likelihood values. Of the three models, the Boore and Atkinson (2007) model is consistently the closest to the optimal value of 0.5. The reason for the skewed likelihood distributions can be appreciated through inspection of the standard deviations of the normalised inter-event residuals shown in Fig. 8. Here the Boore and Atkinson (2007) models yields standard deviations closest to the optimal value of 1 and further highlights the unusual distributions of inter-event residuals seen previously in Fig. 5 for the models of Akkar and Bommer (2007a) and Ambraseys et al. (2005).

In Table 2 the summary statistics for the total normalised model residuals for all periods considered are presented. In addition the text in the cells of the table is formatted to reflect the performance of the models according to the Scherbaum et al. (2004) classification scheme. As expected, the Akkar and Bommer (2007a) model receives a classification of A for all periods. The Ambraseys et al. (2005) model receives a classification of A for all periods except for two instances of B classifications at periods of 1.95 and 2.00 s. The Boore and Atkinson (2007) model receives classifications of C for periods below 0.8 s, B for periods between 0.8 and 1.5 s, and A at longer periods. A single characteristic tends to prevent the

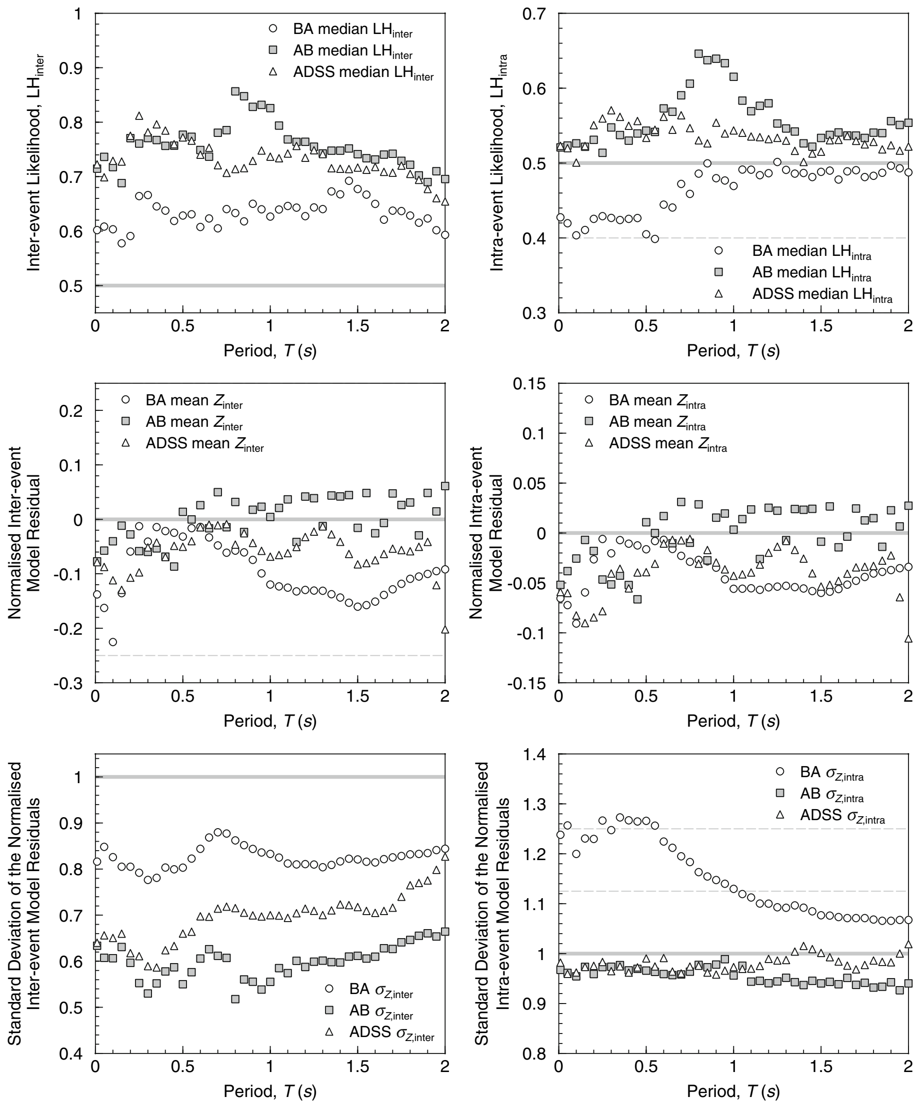

Fig. 8 Summary statistics for the analyses using inter-event and intra-event residuals across all considered periods

Boore and Atkinson (2007) model from receiving a classification of A for most periods: in this case, it is the larger-than-expected standard deviation of normalised residuals that has been noted previously.

Figure 9 suggests that the principal reason why the Boore and Atkinson (2007) model is not classified as A is a result of the standard deviation for this model being significantly lower than those of the European equations. In this figure the means and standard deviations of the total model residuals (not normalised) are presented. The mean values are consistent with those previously observed for the normalised residuals. While the standard deviation presented by Ambraseys et al. (2005) performs relatively well (for the magnitude-dependent

Table 2 Summary statistics for the Scherbaum et al. (2004) classification scheme

Period T (s)	Scherbaum et al. (2004) classification			Boore and Atkinson (2007)				Akkar and Bommer (2007a)				Ambraseys et al. (2005)			
	BA	AB	ADSS	LH_0	Z_0	$E(Z)$	σ_Z	LH_0	Z_0	$E(Z)$	σ_Z	LH_0	Z_0	$E(Z)$	σ_Z
0.00[a]	*C*	**A**	**A**	0.385	**−0.260**	**−0.189**	*1.281*	**0.482**	−0.140	−0.137	**1.039**	**0.500**	−0.161	−0.143	1.059
0.05	*C*	**A**	**A**	0.388	**−0.280**	**−0.192**	*1.297*	**0.498**	**−0.074**	**−0.099**	**1.020**	**0.500**	**−0.149**	**−0.149**	1.043
0.10	B	**A**	**A**	0.387	**−0.328**	**−0.239**	1.223	**0.501**	**−0.094**	**−0.065**	**1.010**	**0.494**	**−0.177**	**−0.167**	1.045
0.15	*C*	**A**	**A**	0.376	**−0.242**	**−0.172**	*1.254*	**0.488**	**−0.084**	**−0.044**	**1.034**	**0.472**	**−0.196**	**−0.196**	1.053
0.20	*C*	**A**	**A**	**0.422**	**−0.121**	**−0.096**	*1.265*	**0.500**	**−0.039**	**−0.066**	**1.015**	**0.512**	**−0.182**	**−0.175**	1.049
0.25	*C*	**A**	**A**	**0.442**	**−0.014**	**−0.057**	*1.295*	**0.517**	**−0.055**	**−0.110**	**1.021**	**0.540**	**−0.106**	**−0.172**	1.054
0.30	*C*	**A**	**A**	**0.411**	**−0.076**	**−0.103**	*1.281*	**0.535**	**−0.081**	**−0.120**	**1.017**	**0.552**	**−0.109**	**−0.124**	1.032
0.35	*C*	**A**	**A**	0.400	**−0.013**	**−0.099**	*1.301*	**0.510**	**−0.066**	**−0.125**	**1.023**	**0.545**	**−0.036**	**−0.117**	1.041
0.40	*C*	**A**	**A**	**0.426**	**−0.060**	**−0.112**	*1.305*	**0.506**	**−0.092**	**−0.148**	**1.019**	**0.538**	**−0.120**	**−0.157**	1.041
0.45	*C*	**A**	**A**	**0.439**	**−0.074**	**−0.099**	*1.303*	**0.521**	**−0.157**	**−0.166**	**1.026**	**0.525**	**−0.064**	**−0.121**	1.055
0.50	*C*	**A**	**A**	**0.408**	**−0.101**	**−0.097**	*1.306*	**0.540**	**−0.006**	**−0.030**	**1.016**	**0.518**	**−0.022**	**−0.124**	1.082
0.55	*C*	**A**	**A**	**0.409**	**−0.043**	**−0.084**	*1.305*	**0.524**	**0.020**	**−0.054**	**1.020**	**0.513**	**−0.011**	**−0.111**	1.070
0.60	*C*	**A**	**A**	**0.426**	**−0.009**	**−0.082**	*1.286*	**0.535**	**0.022**	**−0.028**	**1.022**	**0.505**	**0.034**	**−0.083**	1.099
0.65	*C*	**A**	**A**	**0.435**	**−0.056**	**−0.101**	*1.284*	**0.539**	**−0.014**	**−0.084**	**1.029**	**0.520**	**0.030**	**−0.074**	1.075
0.70	*C*	**A**	**A**	**0.434**	**−0.075**	**−0.110**	*1.275*	**0.561**	**0.048**	**0.002**	**1.024**	**0.522**	**0.013**	**−0.075**	1.077
0.75	*C*	**A**	**A**	**0.440**	**−0.072**	**−0.122**	*1.265*	**0.577**	**−0.044**	**−0.077**	**1.035**	**0.511**	**0.014**	**−0.075**	1.090
0.80	B	**A**	**A**	**0.433**	**−0.058**	**−0.121**	1.244	**0.632**	**0.049**	**0.004**	**1.031**	**0.513**	**−0.034**	**−0.116**	1.085
0.85	B	**A**	**A**	**0.446**	**−0.062**	**−0.123**	1.232	**0.620**	**−0.019**	**−0.076**	**1.041**	**0.497**	**0.006**	**−0.088**	1.071
0.90	B	**A**	**A**	**0.450**	**−0.047**	**−0.131**	1.224	**0.617**	**0.054**	**−0.022**	**1.036**	**0.521**	**−0.010**	**−0.103**	1.066
0.95	B	**A**	**A**	**0.455**	**−0.080**	**−0.147**	1.214	**0.627**	**0.069**	**−0.006**	**1.037**	**0.518**	**−0.027**	**−0.107**	1.059
1.00	B	**A**	**A**	**0.468**	**−0.102**	**−0.161**	1.205	**0.603**	**0.026**	**−0.029**	**1.013**	**0.512**	**−0.021**	**−0.112**	1.066
1.05	B	**A**	**A**	**0.462**	**−0.092**	**−0.160**	1.189	**0.561**	**0.050**	**−0.006**	**1.038**	**0.520**	**−0.005**	**−0.105**	1.064
1.10	B	**A**	**A**	**0.464**	**−0.105**	**−0.159**	1.174	**0.548**	**0.082**	**0.017**	**1.003**	**0.507**	**−0.002**	**−0.098**	1.064
1.15	B	**A**	**A**	**0.474**	**−0.093**	**−0.160**	1.159	**0.551**	**0.007**	**−0.081**	**1.011**	**0.503**	**0.010**	**−0.081**	1.072
1.20	B	**A**	**A**	**0.480**	**−0.087**	**−0.155**	1.153	**0.546**	**0.079**	**0.027**	**0.998**	**0.488**	**0.041**	**−0.058**	1.087
1.25	B	**A**	**A**	**0.469**	**−0.073**	**−0.154**	1.143	**0.520**	**0.056**	**0.023**	**1.000**	**0.491**	**0.056**	**−0.046**	1.083
1.30	B	**A**	**A**	**0.472**	**−0.079**	**−0.153**	1.135	**0.531**	**−0.016**	**−0.040**	**1.004**	**0.486**	**0.041**	**−0.035**	1.080
1.35	B	**A**	**A**	**0.463**	**−0.082**	**−0.159**	1.136	**0.517**	**0.059**	**0.029**	**0.991**	**0.476**	**−0.002**	**−0.046**	1.097
1.40	B	**A**	**A**	**0.495**	**−0.110**	**−0.164**	1.132	**0.508**	**0.050**	**0.028**	**0.987**	**0.465**	**−0.044**	**−0.057**	1.111
1.45	B	**A**	**A**	**0.486**	**−0.093**	**−0.171**	1.126	**0.515**	**0.052**	**0.032**	**0.998**	**0.476**	**−0.069**	**−0.081**	1.107

Table 2 continued

Period T (s)	Scherbaum et al. (2004) classification			Boore and Atkinson (2007)				Akkar and Bommer (2007a)				Ambraseys et al. (2005)			
	BA	AB	ADSS	LH_0	Z_0	$E(Z)$	σ_Z	LH_0	Z_0	$E(Z)$	σ_Z	LH_0	Z_0	$E(Z)$	σ_Z
1.50	**A**	**A**	**A**	**0.488**	**−0.096**	**−0.175**	**1.116**	**0.525**	**−0.010**	**−0.041**	**0.995**	**0.496**	**−0.062**	**−0.102**	1.100
1.55	**A**	**A**	**A**	**0.496**	**−0.116**	**−0.167**	**1.113**	**0.521**	**0.065**	**0.042**	**0.994**	**0.499**	**−0.053**	**−0.097**	1.091
1.60	**A**	**A**	**A**	**0.494**	**−0.101**	**−0.155**	**1.109**	**0.534**	**−0.008**	**−0.046**	**0.994**	**0.493**	**−0.028**	**−0.089**	1.082
1.65	**A**	**A**	**A**	**0.475**	**−0.090**	**−0.144**	**1.111**	**0.529**	**0.020**	**−0.027**	**1.009**	**0.499**	**−0.022**	**−0.075**	1.079
1.70	**A**	**A**	**A**	**0.469**	**−0.075**	**−0.134**	**1.113**	**0.514**	**0.058**	**0.039**	**0.994**	**0.493**	**−0.009**	**−0.064**	1.078
1.75	**A**	**A**	**A**	**0.476**	**−0.041**	**−0.124**	**1.116**	**0.504**	**0.027**	**0.012**	**0.998**	**0.479**	**0.001**	**−0.075**	1.095
1.80	**A**	**A**	**A**	**0.463**	**−0.033**	**−0.114**	**1.117**	**0.505**	**0.034**	**0.018**	**0.992**	**0.479**	**−0.001**	**−0.086**	1.114
1.85	**A**	**A**	**A**	**0.478**	**−0.029**	**−0.108**	**1.118**	**0.518**	**−0.014**	**−0.051**	**0.998**	**0.477**	**0.023**	**−0.074**	1.115
1.90	**A**	**A**	**A**	**0.491**	**−0.018**	**−0.102**	**1.120**	**0.504**	**0.050**	**0.043**	**1.004**	**0.471**	**0.039**	**−0.063**	1.119
1.95	**A**	**A**	B	**0.483**	**−0.032**	**−0.098**	**1.124**	**0.510**	**0.023**	**0.004**	**0.985**	**0.503**	**−0.025**	**−0.149**	**1.138**
2.00	B	**A**	B	**0.468**	**−0.042**	**−0.096**	1.126	**0.505**	**0.058**	**0.057**	**0.997**	**0.465**	**−0.111**	**−0.236**	**1.159**

The following abbreviations are used: BA = Boore and Atkinson (2007), AB = Akkar and Bommer (2007a); ADSS = Ambraseys et al. (2005); LH_0 = median likelihood; Z_0 = median normalised residual; $E(Z)$ = mean of the normalised residuals; and σ_Z = standard deviation of the normalised residuals. The text in the cells is formatted according to their performance with respect to the Scherbaum et al. (2004) classification scheme: entries in bold, normal and italic font correspond to classifications of A, B and C, respectively [a]Peak ground acceleration, PGA

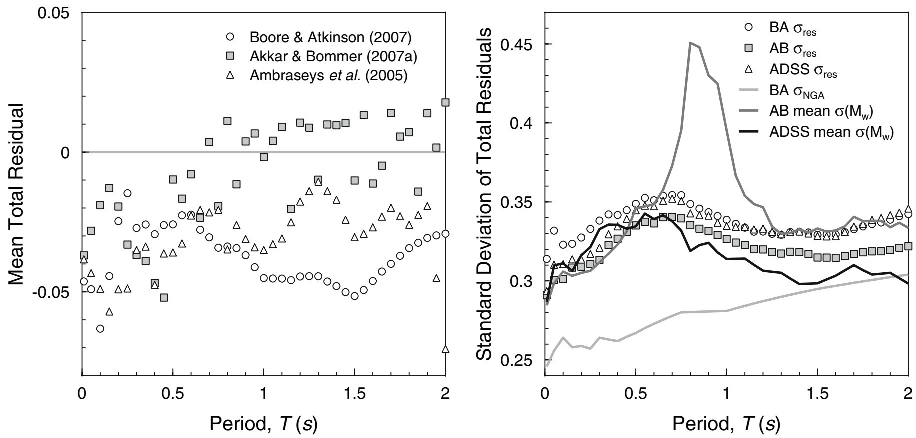

Fig. 9 Summary statistics of the total model residuals (not normalised). The panel on the left shows the means of these residuals across the period range considered while the panel on the right shows the standard deviation of these residuals in addition to the standard deviations specified by the models. For the magnitude-dependent European equations the mean of the standard deviations calculated for this dataset are shown

models the means of the standard deviations determined from the records in the dataset are used), the other models exhibit significant departures. The departure of the Akkar and Bommer (2007a) model is over a small period range just below 1 s while the Boore and Atkinson (2007) model is consistently below the calculated values.

The difference between the standard deviations of the models shown in Fig. 9 initially appears striking and suggests a possible barrier to the application of the NGA models in Europe. Underestimating the variability in ground motions has a significant impact upon the results of probabilistic seismic hazard analyses as has recently been emphasised by Bommer and Abrahamson (2006). One must therefore take care to ensure that any models that are imported into a region not only model the median ground motions adequately but that they also appropriately represent the ground-motion variability. Fortunately, the differences among the models observed in Fig. 9 can largely be explained by differences in the magnitude distributions of the datasets used to develop the models.

Figure 10 presents a comparison of the standard deviations that are specified by the three models. The standard deviations of the Boore and Atkinson (2007) model are homoscedastic but the European models are heteroscedastic with respect to magnitude. In order to compare the European models to that of Boore and Atkinson (2007), single representative magnitude values are used. The solid lines represent the standard deviations calculated by using the mean magnitudes of the datasets used for the development of the European equations. The reason for 'magnitudes' being in plural is that for the inter-event case the mean is taken over the individual earthquake magnitudes while for the intra-event case the mean is taken over the magnitudes associated with all records. These two means provide the most representative estimates of the average inter-event and intra-event standard deviations for these datasets. The total standard deviations are then calculated directly from these two components in the usual manner. The dashed lines correspond to similar standard deviations but with the difference that the mean values are determined for the datasets used to develop the model of Boore and Atkinson (2007). Making the comparison in this way yields very interesting results. The dataset used by Boore and Atkinson (2007) contains roughly three times more records than the European and Middle Eastern dataset with considerably more

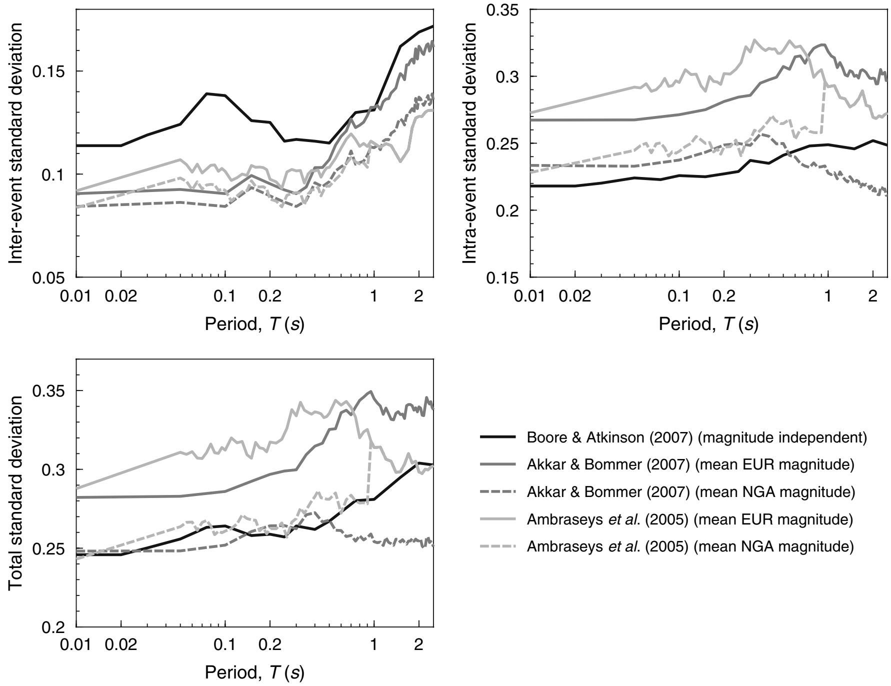

Fig. 10 Comparison of the specified model standard deviations. For the magnitude-dependent European models two generic magnitudes are considered: the mean magnitude used in the development of the European models (EUR) and the mean magnitude used in the development of the Boore and Atkinson NGA model (NGA)

records at larger magnitudes. This distribution dictates that the mean magnitudes for these data are considerably higher than those used by Akkar and Bommer (2007a) and Ambraseys et al. (2005). The most appropriate magnitudes at which to make the comparison with the Boore and Atkinson (2007) model therefore correspond to the dashed lines in Fig. 10. For the intra-event and total standard deviations the use of this mean magnitude brings all of the standard deviations much closer together with the implication that the higher-than-optimal standard deviations of the normalised residuals seen in Figs. 7 and 8 and in Table 2 represent differences in magnitude distributions rather than differences in ground-motion variability between the western US and Europe. This finding also implies that the classification afforded to the Boore and Atkinson (2007) model under the Scherbaum et al. (2004) scheme would be even better if the European dataset contained more records from earthquakes with larger magnitudes.

5 Are Euro-Mediterranean equations applicable to the western US?

The principal focus of this paper has been to test whether or not the NGA relationships may be applied in Europe. We have not made any quantitative tests in the opposite direction to see whether the European relationships are suitable for application in the western US. However, the visual comparison between the Boore and Atkinson (2007) model and the European models in Fig. 3 suggests that the European models would probably perform reasonably well in modelling strong ground-motions in the western US. The primary difference would again appear to be related to the magnitude of the standard deviations of the models from the two regions. It may not be immediately obvious why one would want to apply European-based models in the western US, given that five NGA models have just been developed for this region. However, as discussed by Campbell and Bozorgnia (2007) and mentioned previously, the very close agreement of the NGA models over certain ranges of magnitude and distance may reflect the use of similar datasets rather than low epistemic uncertainty. Campbell and Bozorgnia (2007) advocate the development of separate models for epistemic uncertainty rather than relying purely upon the suite of NGA models to capture this uncertainty. Given that the general scaling with respect to the primary predictor variables of magnitude and distance appears to be very similar among the models developed for Europe and the western US another option for capturing epistemic uncertainty would be to use a suite of ground-motion models including models from both regions. It may well be that separate models for epistemic uncertainty need to be developed (particularly for large-magnitude, near-source motions) as suggested by Campbell and Bozorgnia (2007) but it is likely to be sometime before such a proposal is fully accepted and implemented in common practice. The suggestion of using a combination of models from Europe and the western US therefore presents three significant advantages. The first is that these models are ready to be implemented immediately. The second is that although the NGA database contains a significant number of Euro-Mediterranean earthquakes (albeit that they contribute a disproportionately small number of records), the datasets used for developing models for these two regions are different enough to still provide a reasonable estimate of epistemic uncertainty.

The third advantage relates to the treatment of aleatory variability by the various modellers. Following earlier work by Sadigh (1983), Idriss (1985) and Abrahamson (1988), Youngs et al. (1995) presented a strong argument for the existence of magnitude-dependent heteroscedasticity of strong ground-motion. Many empirical relationships that have been developed for use in both the western US and Europe since publication of the findings of Youngs et al. (1995) have incorporated this dependency. The NGA model of Abrahamson and Silva (2007) retains this feature for the inter-event standard deviation while the models of Campbell and Bozorgnia (2007) and Chiou and Youngs (2006), representing updates of the models of Campbell (1997), Campbell and Bozorgnia (2003) and Sadigh et al. (1997), revert to magnitude-independent variability. Bommer et al. (2007) have recently investigated the influence of magnitude range upon empirical ground-motion models. They found a significant increase in the overall aleatory variability when supplementing the dataset used by Akkar and Bommer (2007a) with additional records from earthquakes with moment magnitudes between M_{w} 3.0 and M_{w} 5.0. A potential explanation for at least some of this observed increase was attributed to relatively poor constraint on the metadata associated with these small-magnitude earthquakes. This sentiment is also expressed by Campbell and Bozorgnia (2007, Sect. 3.1.3, p. 16) who state that "*the previously observed dependence of aleatory variability on magnitude… might largely have been an artifact of the use of poorly recorded events near the upper- and lower-magnitude limits of the data range*". The issue of whether or not aleatory variability should be modelled as being magnitude-dependent or not is unresolved and therefore represents a significant contributor to the overall epistemic uncertainty associated with empirically estimating ground motions. A suite of ground-motion models that encompass current views on this issue may be compiled through combining models developed for Europe and the western US.

The discussion presented herein is also relevant to regions other than the western US where the seismic hazard is influenced by shallow crustal earthquakes. For many such regions there are relatively few empirical ground-motion models and it is therefore common to use relations derived from allogenous data in order to model epistemic uncertainty. Ideally, these allogenous equations are recent equations based upon large datasets that represent the state-of-the-art in ground-motion modelling. However, limited knowledge of some of the predictor variables required for the implementation of these equations may restrict the number of allogenous equations that may be imported in practice. The findings of this study suggesting that there are no significant differences between the predictions of the Euro-Mediterranean models and the NGA models imply that the Euro-Mediterranean models may be a pragmatic choice when selecting models to be imported into these regions.

6 Conclusions

This study has explored to what extent the new ground-motion prediction equations derived within the NGA project could be applied to seismic hazard analyses in Europe and the Middle East. The findings of the study suggest that the Boore and Atkinson (2007) model, which has been shown to be representative of the NGA models in general, provides a very good fit to the strong-motion data from the Euro-Mediterranean region used by Akkar and Bommer (2007a) to derive the most recent European prediction equations. This study therefore supports the conclusion of Campbell and Bozorgnia (2006) that the NGA equations can be applied in Europe.

A significant benefit of using these models for hazard analysis in Europe and the Middle East is to provide constraint on effects that are not currently incorporated into the existing European models of Akkar and Bommer (2007a,b) and Ambraseys et al. (2005). These effects would be important for sites where non-linear soil response was expected and in near-source regions where finite-fault effects are likely to feature. Another very important advantage that the NGA equations present is that they allow the prediction of response spectral ordinates for periods up to 10 s, whereas Ambraseys et al. (2005) are limited to 2.5 s and Akkar and Bommer (2007b) to 4.0 s. One drawback worth noting is that the NGA equations, in common with Ambraseys et al. (2005), only predict spectral ordinates for 5% of critical damping. This can be an important limitation given that the scaling of these ordinates to other target damping levels is dependent on duration (Bommer and Mendis 2005), an effect that is not captured by the application of simple conversion factors such as that proposed in Eurocode 8.

The identification of the ideal model for ground-motion prediction in a particular region is one of the major sources of epistemic uncertainty in seismic hazard analysis, and this leads to the common approach of using several ground-motion models simultaneously, combined within a logic-tree framework. The findings of this study indicate that epistemic uncertainty in ground-motion prediction could be at least partially captured by incorporating one or more of the NGA models into logic-trees for seismic hazard analysis in Europe, and also incorporating recent European equations into hazard analyses in western North America. As the two sets of equations use identical or very similar parameter definitions for the horizontal component of motion, magnitude and style-of-faulting, the inconvenience of applying adjustments for parameter compatibility—and the consequent penalty in increased variability (Scherbaum et al. 2006)—can largely be avoided.

As the results of this study seem to indicate that there are not any systematic differences between ground motions from western North America, on the one hand, and Europe and the Middle East on the other, it is logical to conclude that it would now be beneficial to combine these two datasets. The main challenge that this would present is the uniform evaluation of the metadata parameters used in the NGA models for all the European accelerograms, and there is potentially a major investment of funding and effort required, in particular for the geotechnical characterisation of the recording stations.

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