Comparing predicted and observed ground motions from UK earthquakes

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SUMMARY:
The selection of appropriate ground motion predictive equations (GMPEs) is one of the major sources of uncertainty in probabilistic seismic hazard assessment (PSHA) and this uncertainty is usually addressed by combining several equations within a logic-tree framework. In the United Kingdom (UK), the uncertainty is large due to the limited number of ground motion records that can provide knowledge on the nature of the ground motions, in particular from M>5.0 earthquake events that are more relevant to the hazard. This data limitation has necessitated the use in the UK of GMPEs derived based on earthquake records from stable continental regions as well as active crustal regions from elsewhere in the world. This paper presents the application of methodology to systematically compare ground motions recorded during recent UK earthquakes with published GMPEs to inform the selection of GMPEs for use in PSHA for important facilities (such as nuclear facilities) in the UK.

Keywords: United Kingdom, ground motion prediction equations, uncertainty, nuclear

1. INTRODUCTION

The UK is within the stable continental region (SCR) of North and Northwest Europe (Johnston et al., 1994). It has generally been assumed that ground motions in SCRs are different from those from plate boundaries and zones of active deformation primarily in terms of frequency content and rates of attenuation with distance. However, it is also understood that there is considerable variation in attenuation characteristics within different SCRs. While the UK has been classified as a SCR the transportability of GMPEs for SCRs from a region such as Eastern North America to the UK has not been investigated in detail. There is uncertainty in the extent to which SCRs are similar in terms of source and propagation properties, as discussed by Bommer et al. (2011). Allen and Atkinson (2007) indicated broad similarities in ground motions from ENA and Australia, whereas studies by Free (1996) and Bakun and Garr (2002) showed differences in intensity and weak-motion data from the SCR regions of ENA, India, Africa, Australia, and Northwest Europe.

2. UK EARTHQUAKE DATA

Most of the existing UK ground-motion data come from M<4.0 events, although three moderate-size events in the UK have been recorded by the BGS network over the last decade, the 22 September 2002 Dudley (M_W=4.2), the 28 April 2007 Folkestone (M_W=4.0) and the 27 February 2008 Market Rasen (M_W=4.5) earthquakes, from which a total of 39 instrumental recordings are available. These data have been supplemented by a further 8 records from events prior to 2002. These records have been processed in a consistent manner and associated information on the causative earthquakes, source-to-site distance metrics and local site conditions at the recording stations has been compiled. The source parameters of the events have been taken from Baptie et al. (2005), Sargeant and Ottemöller (2009) and Ottemöller and Sargeant (2010). Overall, the dataset consists of 47 recordings from 8 earthquakes recorded in the UK from 1996 to 2008. A summary of the earthquakes whose records are used in this study is given in Table 1 and the distribution of the dataset in magnitude-distance space is presented in Figure 1. They show that the data come from events $4.0 \leq M_W \leq 4.5$ events that have been recorded at distances greater than 80 km and hence the majority of the motions recorded are of very low amplitude. The largest PGA listed in Table 1 (i.e. 102 cm/s^2) was recorded during the Folkestone earthquake at TF01 station, about 3 km from the epicentre. Because of the low amplitude of the UK ground motions, units of cm/s^2 have been used.

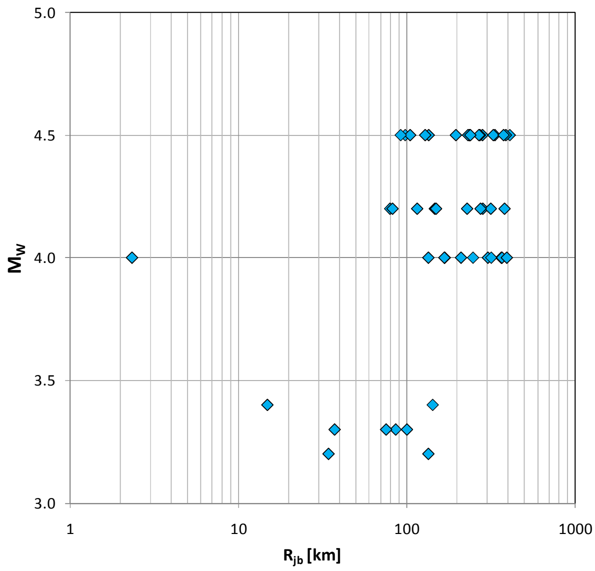

Figure 1. Magnitude-distance distribution of the UK data.

Table 1. Summary of the UK earthquakes whose data have been used to evaluate pre-selected GMPEs

Earthquake Name	Date	Lat [°N]	Lon [°N]	H [km]	M_L	M_W	# of records	R_{jb} range [km]	PGA range geometric mean [cm/s^2]
Penzance	10/11/1996	50.00	-5.58	8.3	3.8	3.2	1	35	3.59
Arran	04/03/1999	55.40	-2.54	19	4.0	3.2	1	135	0.43
Sennybridge	25/10/1999	51.97	-3.57	14.1	3.6	3.3	1	38	2.57
Warwick	23/09/2000	52.28	-1.61	11.4	4.2	3.3	3	76-101	0.51-1.94
Melton	28/10/2001	52.85	-0.86	11.6	4.1	3.4	2	19-144	1-18
Dudley	22/09/2002	52.23	-2.16	14	5.2	4.2	11	80-384	0.01-10
Folkestone	28/04/2007	50.97	1.38	5.0	4.3	4.0	11	2.5-396	0.02-102
Market Rasen	27/02/2008	53.40	0.33	18.5	5.2	4.5	18	93-412	0.1-19

3. GROUND MOTION PREDICTION EQUATIONS

Past ground motion seismic hazard studies for the UK have used GMPEs for intraplate and stable continental regions (Dahle et al., 1990; 1991, Toro et al., 1997) and as well as GMPEs for active crustal regions, including European equations (Ambraseys and Bommer, 1991; Ambraseys et al., 1996; Akkar and Bommer, 2007 and Bommer et al., 2007). In addition, a number of equations have been derived specifically for application in UK seismic hazard studies, including studies specifically for nuclear facilities (PML 1982, 1985 and 1988). Principia Mechanica Ltd (PML) derived empirical GMPEs using a specially selected database of ground-motions recorded worldwide, but mainly from active tectonic regions. The PML GMPEs include a PGA equation derived in 1982, which was later updated and extended in 1985 and equations to derive hazard spectra in 1988. Although the PML equations have been extensively used in seismic hazard assessments for nuclear facilities in the UK, these equations were developed more than 20 years ago using limited databases from active tectonic regimes. Furthermore, there have been considerable advances in ground-motion prediction since their development and studies by Lubkowski et al. (2004) and Bommer et al. (2011) have suggested that the PML GMPEs are no longer the most appropriate GMPEs for use in the UK.

Robust and adequately constrained GMPEs specific to the region of interest should be preferred in seismic hazard studies; however, the paucity of ground-motion data from the UK constitutes a fundamental limitation when empirically developing robust GMPEs. An alternative method, which has been widely used for the development of GMPEs in regions of low seismicity such as Eastern North America (ENA), is the stochastic method. Rietbrock et al. (2011) have recently derived GMPEs for the UK using stochastic simulations, based on source and attenuation parameters for the UK determined by Edwards et al. (2008) using data from earthquakes with magnitude $2 \leq M_W \leq 4$. This approach has also limitations because source parameters of larger earthquakes can systematically differ from those of smaller events. The Rietbrock et al. (2011) equations are understood to have been derived using 126,000 simulated ground-motion values from earthquake events with magnitudes M_W between 3 and 7 at distances ranging from 1 to 300 km.

The extent to which existing published GMPEs are appropriate for UK conditions requires investigation prior to their incorporation into a PSHA. This selection task requires particular attention during a study for a nuclear facility for which the inclusion and exclusion of GMPEs from the PSHA requires robust documentation. The methodology adopted to systematically compare ground motions recorded during recent UK earthquakes with published GMPEs to inform the selection of GMPEs for use in PSHA for nuclear facilities in the UK is described in the following sections. A sub-set of the selected GMPEs are summarised in Table 2.

4. QUALITATIVE COMPARISON OF GMPES AND UK DATA

A sub-set of the selected GMPEs have been compared with the selected UK earthquake data in Figure 2 and Figure 3 for illustrative purposes. Figure 2 shows a comparison between the PGA values recorded during the 2008 Market Rasen (M_W =4.5) earthquake and the median predictions (±2 sigma values) from the selected GMPEs for shallow-crustal and stable continental region earthquakes, as listed in Table 2. Figure 2 indicates that the Atkinson and Boore (2006) equations (adjusted to the Market Rasen's estimated stress drop of ~350 bars and magnitude-dependent stress), appear to fit the PGA data reasonably well. The Boore and Atkinson (2008) and the Akkar and Bommer (2010) equations appear to underestimate the data, but the distance scaling of the former appears to be adequate. This may suggest that if this event's magnitude were higher the Boore and Atkinson (2008) equation would have an excellent fit; however, this scenario will produce 0.2-0.3 g in the near source region which is inconsistent with the negligible damage observed in the epicentral region. This highlights the limitations of the sample data.

Figure 3 shows a comparison between PGA values recorded during the Folkestone (M_W =4.0) and Dudley (M_W =4.2) earthquakes and the same GMPEs shown in Figure 2. The Atkinson and Boore (2006) equation adjusted to these events' estimated stress drop of ~30 bars provides a reasonable fit to the data. The magnitude-dependent stress drop version of this equation over predicts the data at R_{rup} 200 to 400 km. The Boore and Atkinson (2008) equations provide a better fit to the data and appear to fit the data over a broad range of distance R_{jb}. Similarly the Akkar and Bommer (2010) and Bommer et al. (2007) equations fit the data reasonably well. Similar comparison can be made for a full range of ground motion spectral ordinates and other related parameters as required to inform decision making.

It is emphasized that these simple comparisons are to be treated with caution but a couple of preliminary observations can be made. Firstly, that inter-event ground motion variability is reasonably high perhaps due to differences in source parameters. Secondly, it is difficult to make judgements of goodness of fit by visual comparisons with a small sample of events. Thirdly, it is not possible to assume that a GMPE from a perceived similar tectonic environment provides the best fit to the observations.

Table 2. GMPEs selected in this study

Equation	Tectonic Regime	Region	N_R	C	Y	T_{max}	R	[M_w]	[R]	SoF	Site
Rietbrock et al. (2011)	Stable continental regions*	United Kingdom	12600 Simulated	GM	PGA, PSA, PGV	5.0	R_{jb}	3-7	1-300	-	HR
Boore and Atkinson (2008)	Shallow crustal	Worldwide (mainly California)	1574	GM_{RotI50}	PGA, PSA, PGV	10	R_{jb}	5-8	0-200	N,R, S,U	V_{S30}
Boore and Atkinson (2008, 2011)	Shallow crustal	Worldwide (mainly California)	Adjust. for smaller Mag.	GM_{RotI50}	PGA, PSA, PGV	10	R_{jb}	3.5-8	0-200	N,R, S,U	V_{S30}
Akkar and Bommer (2010)	Shallow crustal	Europe and Middle East	532	GM	PGA, PSA, PGV	3	R_{jb}	5-7.6	0-100	N,R,S	RK, ST, SF
Bommer et al. (2007)	Shallow crustal	Europe and Middle East	532+465 (M<5 data)	GM	PGA, PSA	0.5	R_{jb}	3-7.6	0-100	N,R,S	RK, ST, SF
Atkinson and Boore (2006) for 140 stress	Stable continental	Eastern North America (ENA)	34800 simulated records	GM	PGA, PSA, PGV	5	R_{rup}	4-8	1-1000	-	HR, RK and V_{S30}
Atkinson and Boore (2006) for other stress	Stable continental	Eastern North America (ENA)	Adjust for other stress	GM	PGA, PSA, PGV	5	R_{rup}	4-8	1-1000	-	HR, RK and V_{S30}
AB2006 as modified by Atkinson and Boore (2011)	Stable continental	Eastern North America (ENA)	Adjust for other stress	GM	PGA, PSA, PGV	5	R_{rup}	3.5-8	1-1000	-	HR, RK and V_{S30}
Pezeshk et al. (2011)	Stable continental	Eastern North America (ENA)	Hybrid empirical +simulations	GM_{RotI50}	PGA, PSA	10	R_{rup}	5-8	1-1000	-	HR

Notes: *Stable continental region following the Johnston et al., (1994) classification; N_R: Number of records in dataset; C: horizontal component definition: GM_{RotI50} = geometric mean determined from the 50th percentile values of the geometric means computed for all non redundant rotation angles (see Boore et al. (2006) for details), GM = geometric mean; T_{max}: longest response period considered in seconds; Magnitude definition: M_w = moment magnitude; Source-to-site distance definition: R_{jb} = closest distance to the surface projection of the rupture plane, R_{rup} = closest distance to rupture plane; [M]: magnitude range; [R]: distance range; SoF: Style-of-faulting considered in equation: N = normal, R = reverse, S = Strike-slip, U = Undefined, - = not included in the equation; Site: site conditions modeled: V_{S30} = direct input of average shear wave velocity values over the top 30 m (range in brackets show V_{S30} values limits), RK = Rock (V_{S30} >750 m/s), ST = stiff soil (360<V_{S30} ≥750 m/s), SF= soft soil (V_{S30} <360 m/s), HR = hard rock (V_{S30} >2000 m/s), RK = rock (V_{S30}~760 m/s).

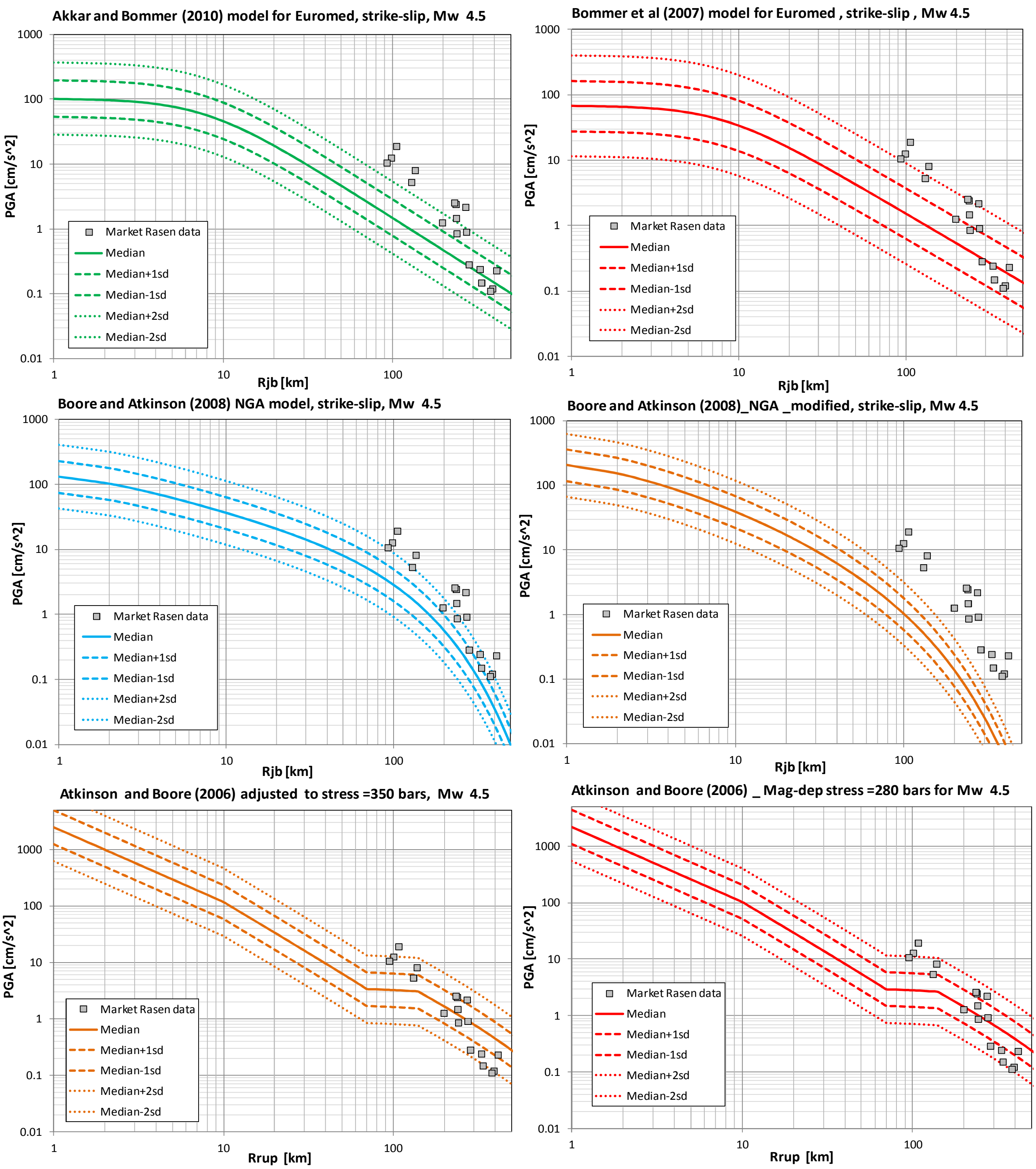

Figure 2. Comparison of data recorded during the Market Rasen (M_W =4.5) earthquake with median PGA values at rock predicted by the GMPEs by Akkar and Bommer (2010) and Bommer et al. (2007) for shallow crustal European and Middle East events, Boore and Atkinson (2008) NGA and Boore and Atkinson (2008 / 2011) modified for shallow crustal events and Atkinson and Boore (2006) for stable continental ENA events.

5. QUANTITATIVE COMPARISON OF GMPES AND UK DATA

A quantitative evaluation of the performance of the selected GMPEs is preferred as it provides a more robust and evidence based methodology to inform decision making with regard to the input to the

PSHA. To further quantify the level of agreement between the observations and predictions, a number of statistical measures of the goodness-of-fit of an equation to a set of data are calculated, following the approach proposed by Scherbaum et al. (2004). These goodness-of-fit measures include the mean, median and standard deviation of the total normalised equation residuals (noted here as Mean [Z_T], Med [Z_T], Std [Z_T], respectively) as well as a the median value of the likelihood parameter (Med [L_H]), specifically developed by Scherbaum et al. (2004) for the purpose of evaluating GMPEs.

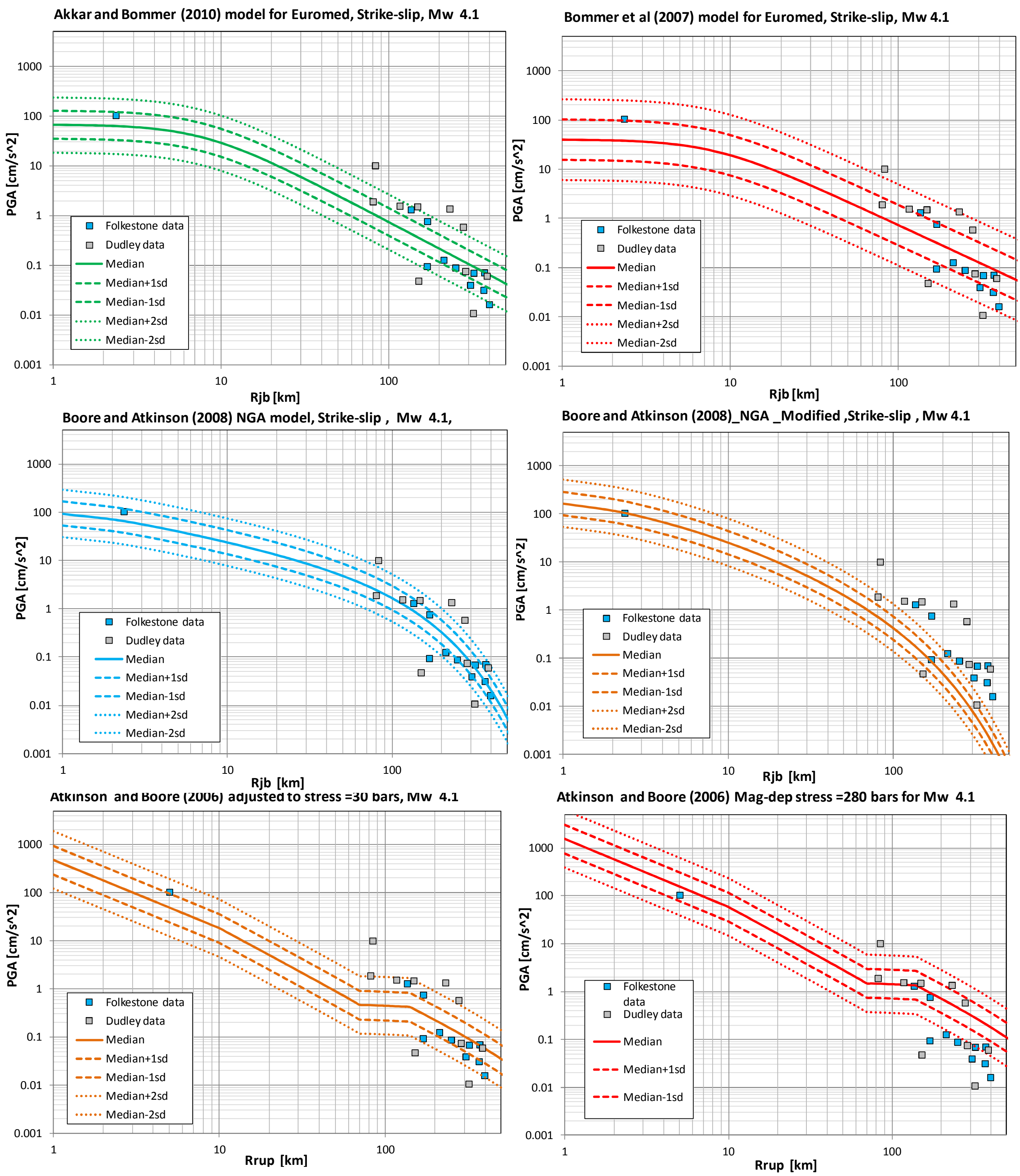

Figure 3. Comparison of data recorded during the Folkestone (M_W=4.1) earthquake with median PGA values at rock predicted by the GMPEs by Akkar and Bommer (2010) and Bommer et al. (2007) for shallow crustal European and Middle East events, Boore and Atkinson (2008) NGA and Boore and Atkinson (2008 / 2011) modified for shallow crustal events and Atkinson and Boore (2006) for stable continental ENA events.

The normalised model residuals can be calculated as:

$$Z_{T,ij} = \frac{\log(gm_{obs,ij}) - \log(gm_{mod,ij})}{\sigma_T} \quad (1)$$

Where Z_T is the total normalised residual for the j^{th} recording from the i^{th} event, $gm_{obs,ij}$ and $gm_{mod,ij}$ are the observed and predicted motions corresponding to this record and σ_T is the total standard deviation of the equation. In this way Z_T represents the distance of the data from the logarithmic mean, measured in units of sigma. To calculate $gm_{mod,ij}$ for the pre-selected GMPEs, all the predictor variables included in each equation must be available. The Atkinson and Boore (2006) and Boore and Atkinson (2008) equations use the V_{S30} value as predictor variable. To calculate predictions for the records in the UK dataset above described, a value of 760 m/s was assigned to sites described as rock (or depth to bedrock of less than 2m) and 520 m/s to sites on weathered rock (i.e. chalk) with depth to bedrock of less than 15 m. Generic site classes were also assigned following the Akkar and Bommer (2010) and Bommer et al. (2007) scheme. Predictions from hard rock equations were adjusted to generic rock, as previously discussed. The likelihood parameter is calculated as:

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

Where Z is the total normalised residual and *Erf* is the error function. The LH parameter reaches its maximum value of 1when the observation coincides with the mean value of the equation (at |Z|=0). For samples drawn from a normal distribution with unit standard deviation, the values of LH are evenly distributed between 0 and 1 and the median value is about 0.5 (see Scherbaum et al. 2004, for a proof of this). Ideally the normalised residuals should be normally distributed with zero mean and unit standard deviation. Hence central tendency measures (Mean [Z_T], Med [Z_T]) close to zero indicate that the equation is unbiased and a standard deviation of the residuals (Std [Z_T]) close to 1 indicates that the standard deviation of the equation adequately captures that of the observed data. A median value of the likelihood parameter Med [LH]) indicates that the GMPE matches the data in terms of both mean and standard deviation.

Scherbaum et al. (2004) defined four categories (A = high predictive capability, B = intermediate capability, C = low capability and D = unacceptable capability), based on the following target values:

- Rank A (high capability): Mean [Z_T] <0.25, Med [Z_T] <0.25, Std [Z_T] <1.125 and Med [LH]>0.4
- Rank B (intermediate capability): Mean [Z_T] <0.50, Med [Z_T] <0.50, Std [Z_T] <1.250 and Med [LH]>0.3
- Rank C (low capability): Mean [Z_T] <0.75, Med [Z_T] <0.75, Std [Z_T] <1.50 and Med [LH]>0.2
- Rank D (unacceptable capability): all other combinations of parameters.

Figure 4 presents examples of the mean normalised residuals (Mean [Z_T]) and standard deviation of the normalised residuals (Std [Z_T]) for selected equations across a range of spectral periods. Note that the values for PGA have been plotted at 0.01 sec. The thick black lines indicate the limits of the goodness-of-fit measures required to class an equation as Rank C. This figure shows that each of the goodness of fit parameters vary considerably with spectral period for the GMPEs. It is also apparent that GMPEs may demonstrate reasonable goodness of fit within a certain spectral period range and demonstrate a poorer goodness of fit for a separate portion of the spectral period range.

Table 3 provides a summary of the overall ranking of the selected GMPEs over selected spectral period ranges using the Schebaum et al. (2004) scoring system. The Atkinson and Boore (2006) equations for 140 bars stress perform well (Mean [Z_T] values close to zero). But fail to capture the standard deviation of the UK data (Std [Z_T]>1.50). The Akkar and Bommer (2010) equations show a systematic bias, especially at periods of less than 0.1 sec. The Bommer et al. (2007) equations for an extended magnitude range perform well and reasonably predict the standard deviation of the data. The Boore and Atkinson (2008) equations for WNA shows a variable performance across the spectral periods. These equations are associated with under prediction at periods of less than 0.2 sec and with over prediction at larger spectral periods. The modified Boore and Atkinson (2008) equations are largely biased (Mean [Z_T] values as large as 4). The Pezeshk et al. (2011) hybrid equations for ENA tends to over predict the UK data (Mean [Z_T] >0.5) at periods of less than 0.5 sec and fails at capturing the standard deviation of the data (Std [Z_T]>1.50).

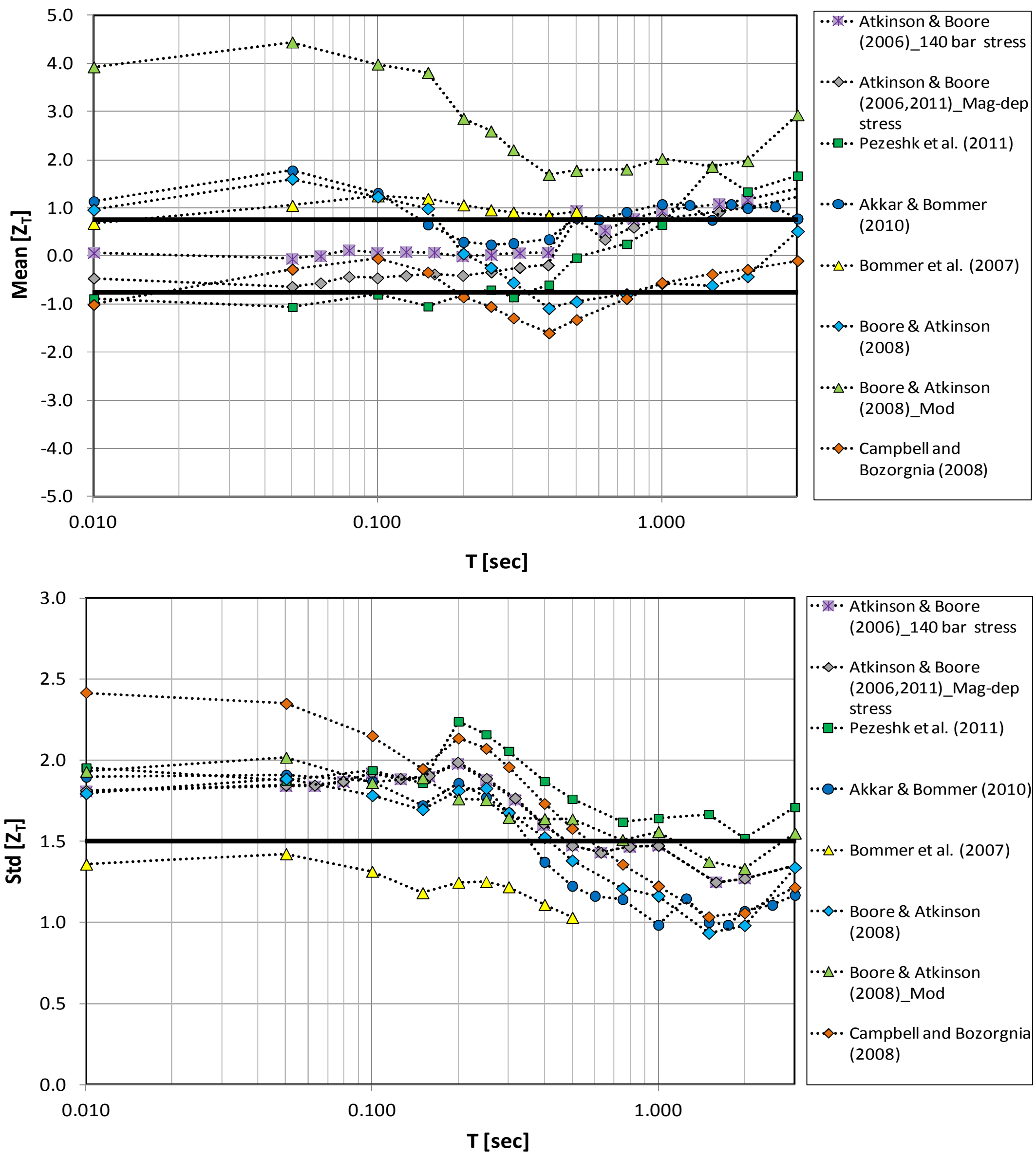

Figure 4. Mean normalised residuals and standard deviation of the normalised residuals (Mean [Z_T] and Std [Z_T], respectively) across the range of spectral periods.

Table 3 indicates that overall the Atkinson and Boore (2006, 2011) equations for ENA are in general better at predicting the median motions from the UK events at high-frequencies (<0.2 sec) and that the shallow-crustal equations of the Akkar and Bommer (2010) and Boore and Atkinson (2008) are better at predicting the median motions at longer periods.

The Rietbrock et al. (2011) study which has been developed specifically for UK conditions was due for publication at the time of reporting and therefore is not presented here.

Table 3. Overall ranking of the selected GMPEs at selected period ranges using the Scherbaum et al. (2004) scoring system

GMPEs	PGA	SA5% 0.05 s	SA5% 0.10 s	SA5% 0.20 s	SA5% 0.50 s	SA5% 1.00 s	SA5% 2.00 s
Atkinson and Boore (2006)_140 bar stress	C	C	C	C	D	D	D
Atkinson and Boore (2006, 2011)_Mag-dep. stress	C	C	C	C	D	D	D
Pezeshk et al. (2011)	D	D	D	D	C	D	D
Akkar and Bommer (2010)	D	D	D	C	C	C	C
Bommer et al. (2007)	D	D	D	D	C	-	-
Boore and Atkinson (2008)	D	D	D	C	C	B	B
Boore and Atkinson (2008, 2011)	D	D	D	D	D	D	D

6. DISCUSSION AND CONCLUSION

The selection of appropriate GMPEs is one of the major sources of uncertainty in PSHA and this uncertainty is usually addressed by combining several GMPEs within a logic-tree framework. In the UK, this uncertainty is large due to the limited number of recorded data that can provide information on the nature of the ground motions, in particular from M>5.0 earthquake events in the near source region, which are more relevant to the hazard. This data limitation and has necessitated the use in the UK of GMPEs derived based on earthquake records from elsewhere in the world. This paper presents methodology to systematically compare ground motions recorded during recent UK earthquakes with published GMPEs to inform the selection of GMPEs for use in PSHA for important facilities (such as nuclear facilities) in the UK.

The ability of the published GMPEs to predict UK earthquake ground motion observations is generally low as demonstrated by a range of statistical measures of the goodness-of-fit. It must be emphasised however that UK dataset is relatively small and with significant inter-event variability, which limits the conclusions that can be drawn from the present analsyis. Furthermore, at some instances the GMPEs have been tested outside their strict range of applicability. Using the Scherbaum et al. (2004) ranking system, the Atkinson and Boore (2006, 2011) equations (for 140 bars stress parameter and magnitude-dependent stress parameter) are associated with the minimum acceptable predictive capability (Rank C) for periods of less than 0.5 sec. However, these equations are assigned an unacceptable predictive capability at periods beyond 0.5 sec. Conversely, the Akkar and Bommer (2010) and Boore and Atkinson (2008) equations are ranked as class D (unacceptable capability) at periods of less than 0.2 sec and as class C and B (intermediate and low capability) at longer periods.

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