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ON THE USE OF AFTERSHOCKS WHEN DERIVING GROUND-MOTION PREDICTION EQUATIONS

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ABSTRACT

Strong-motion databanks contain a large and growing proportion of records from aftershocks. Therefore, for the derivation of ground-motion prediction equations (GMPEs) aftershock recordings are a potentially important resource, especially in regions of low to moderate seismicity. Some authors have decided not to use strong-motion data from aftershocks to derive their GMPEs due to concerns over the spectral scaling of aftershock motions or they have included additional terms to model the difference in ground motions between aftershocks and mainshocks. For areas with limited observational datasets these two approaches are unattractive since they oblige the deletion of a large proportion of already limited datasets or they require that additional coefficients be estimated based on few data points. In this study we use data from Europe, the Mediterranean area and the Middle East (EMME) and various statistical techniques to examine the potential issues with using aftershock data when deriving GMPEs. In addition, we examine data from a small-aperture strong-motion array recently installed in Iceland, ICEARRAY, to examine the scaling of aftershock ground motions and their variabilities with respect to magnitude and distance.

We find that aftershock ground motions in EMME are only slightly lower than mainshock motions and that ground-motion variabilities in these two datasets are similar. This suggests that the current general practice of not considering aftershock and mainshock data differently when deriving GMPEs can be maintained. In contrast to a number of recent studies, ICEARRAY ground-motion variability does not show a dependence on magnitude, suggesting that previously observed dependencies could be due to uncertain earthquake locations. In addition, these data show that inter-site variability for PGA, even over ~1.9 km, can be considerable, which suggests a lower bound on the standard deviations associated with GMPEs that is attainable is about 0.15.

Introduction

Models (generally expressed as a simple equation) for the prediction of earthquake

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shaking in terms of strong-motion intensity parameters such as peak ground or response (pseudo) spectral acceleration (PGA or PSA) play a vital role in seismic hazard assessments. These models are derived either directly from ground-motion records (empirical ground-motion prediction equations, GMPEs) or from simulations whose input parameters are constrained by observations. Due to the close link between observations and shaking predicted by such models it is vital the data used to derive these models is not affected by biases and that it is a good representation of the ground motions possible in the region of interest (e.g. western or eastern North America, WNA or ENA). In fact, since seismic hazard assessments [both probabilistic and deterministic (scenario-based) approaches, PSHA and DSHA] are invariably performed to estimate the hazard from mainshocks (i.e. excluding foreshocks and aftershocks) it is necessary that the dataset used to derive GMPEs are representative of *mainshock* ground motions. Analysts for PSHAs, for example, invariably remove aftershocks from the catalogues used to assess Gutenburg-Richter *a* and *b* parameters so that they can assume a Poissonian process and since mainshock hazard is the focus of such assessments. In contrast, the use of aftershock ground motions to derive GMPEs used in these analyses is not often considered to be a problem and aftershock records have rarely been explicitly excluded when deriving such models (Douglas, 2003), which is probably related to a lack of strong-motion data for most parts of the world. However, in a few recent studies for WNA and ENA issues related to the use of aftershock ground motions have been explicitly addressed.

For example, in the PEER Next Generation Attenuation (NGA) project Boore & Atkinson (2008) excluded data from aftershocks since they believed that there could be differences in the spectral scaling of mainshocks and aftershocks, although they note that this reduces the set of available records by about 50%. Similarly, Campbell & Bozorgnia (2008) excluded records from aftershocks when deriving their NGA equations. Two other NGA developer teams: Abrahamson & Silva (2008) and Chiou & Youngs (2008) included aftershock records, which has the benefit of increasing the set of data available to derive their models, but added terms to their equations to account for the observed lower ground motions in aftershocks than in mainshocks. Boore & Atkinson (1989) find evidence, by examining ground motions from the Nahanni (Canada) sequence of earthquakes (generally considered to be representative of ground motions in ENA), that spectral scaling of aftershocks is different than that of mainshocks, although this finding does not seem to have influenced the data used to constrain parameters for their latest GMPEs for ENA (Atkinson & Boore, 2006).

Outside of WNA and ENA (e.g. in Europe) possible problems with using aftershock records when deriving GMPEs have not been widely discussed. Table 1 shows that many of the GMPEs currently in use in Europe have used a significant proportion of aftershock records, which contrasts with GMPEs for California where the proportion of data from aftershocks is usually smaller [note that the majority of the aftershock records used by Abrahamson & Silva (2008) and Chiou & Youngs (2008) are from Chi-Chi (Taiwan) earthquakes]. This is due to: a longer strong-motion recording history in WNA compared to Europe (over seventy years to roughly thirty years) and hence more recorded mainshocks; higher trigger levels in WNA; and the occurrence of long sequences of earthquakes of similar sizes in the Mediterranean region (e.g. the Friuli 1976 and Umbria-Marche 1997-1998 sequences in Italy; the Kozani 1995 sequence in Greece; and the Kocaeli-Duzce 1999 sequence in Turkey). Such sequences contribute a significant proportion of available strong-motion data in these areas, partly because of the installation of temporary networks in their epicentral zones. In WNA, such sequences of earthquakes seem to be less common, with the notable exception of the Mammoth Lakes 1980 and Coalinga 1983 events.

Table 1. Number of total records, number from aftershocks and the percentage of total from aftershocks for various GMPEs (italics means GMPE mainly derived using data from outside WNA). Only the totals used for PGA equations are given.

GMPE	**Total**	**Aftershock total**	**%**
Abrahamson & Silva (2008)	2754	1196	43
Ambraseys et al. (2005)	*595*	*231*	*39*
Berge-Thierry et al. (2003)	*965*	*411*	*43*
Bindi et al. (2009)	*235*	*120*	*51*
Boore & Atkinson (2008)	1574	0	0
Campbell & Bozorgnia (2008)	1561	0	0
Chiou & Youngs (2008)	1950	732	38
Danciu & Tselentis (2007)	*335*	*86*	*26*
Kalkan & Gülkan (2004)	*112*	*0*	*0*
Morasca et al. (2008)	*3090*	*3070*	*99*

There are two main possible problems with aftershock records comprising a significant proportion of the datasets used to derive GMPEs. Firstly, as noted previously, ground motions from aftershocks could be significantly different in terms of amplitudes to those from mainshocks, which could lead to a bias in the shaking predicted by GMPEs derived using many aftershock records and possibly higher aleatory variability (standard deviation, σ) due to the mixture of aftershock and mainshock records. Such bias and associated higher σs could be accounted for by including terms to model the difference between aftershock and mainshock motions (Abrahamson & Silva, 2008; Chiou & Youngs, 2008). Figure 1 shows the ratio between aftershock and mainshock PSAs predicted by these two models for different magnitudes (assuming other parameters are equal). It can be seen that mainshock PSAs are predicted to be up to 40% higher (especially at short periods) than PSAs from aftershocks. This is a similar factor to differences in ground motions due to variations in style of faulting (e.g. Bommer et al., 2003) and, therefore, if this factor is reliable then it should be included in future GMPEs.

The other possible problem with using a significant proportion of records from aftershocks is that ground motions from a series of earthquakes occurring in the same area may be less variable than truly independent mainshocks. Possible reasons for this are: the same fault is rupturing (leading to lower inter-event variability), travel paths will be similar and the same set of stations are recording the shaking (leading to lower intra-event variability). This lower variability could translate into lower σs in the derived GMPEs than are applicable to independent mainshock motions. This potential downward bias in σs from GMPEs dominated by aftershocks does not seem to be observed in reported σs, which are stable between 0.25 and 0.35 (in terms of common logarithms) (e.g. Strasser et al., 2009).

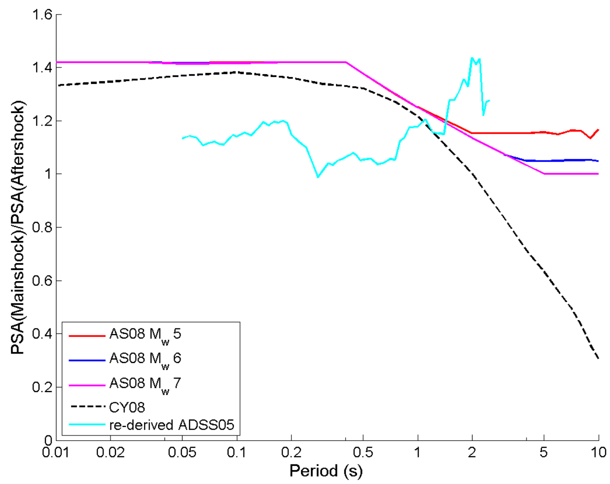

Figure 1. Ratio of mainshock to aftershock PSAs from GMPEs of Abrahamson & Silva (2008, AS08), which predicts a magnitude-dependent ratio, and Chiou & Youngs (2008, CY08), which predicts a magnitude-independent ratio. Also shown is the ratio of mainshock to aftershock SAs from re-derived GMPEs of Ambraseys et al. (2005).

This article presents results obtained using strong-motion data from EMME concerning these two potential problems in combining data from aftershocks and mainshocks together when deriving empirical GMPEs. In addition, data from a small-aperture strong-motion array, ICEARRAY, is examined to investigate the scaling of ground motions from small earthquakes.

Using the data of Ambraseys et al. (2005)

The investigation of the difference in mainshock and aftershock ground motions and their variabilities is complicated by a number of issues. Firstly, according to Båth's law (e.g. Båth, 1979) the magnitude of the largest aftershock is about 1.2 units lower than that of the mainshock and, therefore, comparison of ground motions from aftershocks and mainshocks are complicated by this large difference in magnitude and corresponding difference in amplitudes. Secondly, since aftershocks are generally much smaller than the mainshock (e.g. for a M 6 mainshock the largest aftershock will on average be a M 4.8 event) it can be difficult to obtain consistently reliable metadata on these events. For example, focal mechanisms cannot always be computed for these small events. It is sometimes assumed that aftershocks have the same mechanism as the mainshock but this is not always true (e.g. Bommer et al., 2003). Since ground motions have been shown to be dependent on style of faulting comparisons between mainshock and aftershock motions are made difficult by the potential differences in mechanism. Finally, it has been observed that ground-motion variability seems to increase with decreasing magnitude especially at short periods (e.g. Abrahamson & Silva, 2008; Ambraseys et al., 2005 Campbell & Bozorgnia, 2008; Chiou & Youngs, 2008) and consequently ground motions from aftershocks could show higher variability due to this observation when a lower variability could be expected (see above).

In order to test the effect of using strong-motion data from aftershocks when deriving ground-motion prediction equations the dataset of Ambraseys et al. (2005) in used in the following analysis. Due to a lack of space focus is given here to PGA and spectral acceleration (SA) at 1.0s. This dataset can be thought to be a typical selection of the data available in EMME (and other parts of the world), e.g. it contains a mixture of records from foreshocks, mainshocks, aftershocks and swarms (see Table 1) including both well- and poorly-recorded events. In total, 595 records from 135 earthquakes and 338 different stations in EMME (the majority of data are from Italy, Turkey, Greece and Iceland) were selected by Ambraseys et al. (2005) to derive their equation for PGA. The number of records used by them decreases with period due to the accelerogram processing technique employed and consequently at 1.0s 490 records were used by Ambraseys et al. (2005). To facilitate the comparison between results obtained from different regression analyses performed here, we have re-derived the PGA and SA(1.0s) equations of Ambraseys et al. (2005) assuming homoscedastic variance, i.e. one that is independent of magnitude, unlike Ambraseys et al. (2005) whose model includes a highly magnitude-dependent standard deviation. Otherwise the same functional form was used.

Figure 2 presents residual plots and the computed bias and standard deviations for PGA and SA(1.0s) for aftershock (231 records for PGA and 190 for SA at 1.0s) and mainshock records. It shows that the Ambraseys et al. (2005) dataset does not show a clear difference in mainshock and aftershock ground motions nor their variability since the computed biases and normalized standard deviations from the two subsets are similar and close to null and unity, respectively, as expected. These figures also show that aftershock records dominate for $M_w<6.5$. Due to the difference in the magnitude ranges covered by aftershock and mainshock records we did not perform individual regression on these subsets since the results would be difficult to interpret. However, regression was performed with an additional linear term in the functional form of Ambraseys et al. (2005) equal to b_{11}AS where AS equals 1 for an aftershock record and 0 otherwise (this is similar to the term used by Chiou & Youngs, 2008). The predicted ratio of mainshock to aftershock motions predicted by the developed model are shown in Figure 1, suggesting that EMME aftershock motions are slightly smaller than those from a mainshock but that this factor is less important than predicted by NGA models.

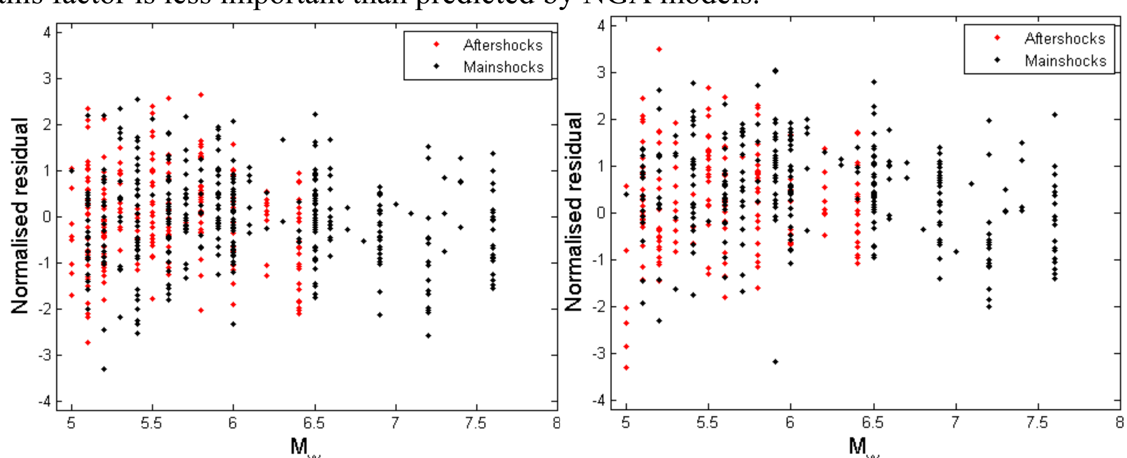

Figure 2. Normalized residuals with respect to M_w for the equations re-derived using the Ambraseys et al. (2005) dataset with the aftershock and mainshock records indicated. Left-hand plot is for PGA (bias for aftershock records: -0.046 with normalized standard deviation 1.02; bias for mainshock records -0.061 with normalized standard deviation 0.98) and right-hand plot is for SA at 1.0s (bias for aftershock records: 0.27 with normalized standard deviation 1.07; bias for mainshock records 0.46 with normalized standard deviation 1.00).

ICEARRAY recordings of the aftershocks of the M_w6.3 Ölfus earthquake in South Iceland

The Earthquake Engineering Research Centre (EERC) at the University of Iceland operates an accelerograph network, the Icelandic Strong-Motion Network (ICESMN). ICESMN has been augmented through the deployment of the Icelandic Strong-Motion Array (ICEARRAY), the first of its kind in Iceland. Such small-aperture, strong-motion arrays are useful for earthquake engineering and engineering seismology. Among other things, their capability to record broad-band ground motion over a wide dynamic range provides the opportunity to investigate the transition of weak to strong motion and the variability of ground motion over short distances.

The array was installed during the latter part of 2007 in the western part of the South Iceland Seismic Zone (SISZ), in the town of Hveragerdi, for the specific purpose of monitoring strong motion, establishing quantitative estimates of strong-motion spatial variability, and investigating earthquake rupture processes and source complexity (Halldórsson and Sigbjörnsson, 2009; Halldórsson et al., 2009). The ICEARRAY consists of 14 triggered stations in an area of ~1.23 km^2 and has an aperture of ~1.9 km and a minimum inter-station distance of ~50 m (Halldórsson et al., 2009). The array is equipped with CUSP-3Clp strong-motion accelerographs manufactured by Canterbury Seismic Instruments Ltd.

At 15:45 UTC on 29 May 2008 an M_w 6.3 earthquake occurred in the western part of the SISZ (Sigbjörnsson *et al.*, 2009). Preliminary results indicate that the first motion originated approximately 6.5 km ESE of Hveragerdi on what aftershocks appear to identify as an almost 10km-long N-S trending fault. However, most aftershocks outlined another almost 20km-long N–S trending fault less than 2 km from the town (Figure 3). During the earthquake the ICEARRAY produced high-quality recordings at 11 stations with each station experiencing strong motion of short duration (4-5 s), large PGA and prominent long-period velocity pulses, both along the strike-normal direction and the strike-parallel direction (Halldórsson and Sigbjörnsson, 2009).

The ICEARRAY produced earthquake records associated with 1083 simultaneous (within 10s) triggers on 2 to 13 stations. The vast majority were simultaneously recorded on more than ten stations (Figure 3). Event location and magnitude calculation algorithms have not yet been implemented for the ICEARRAY and therefore the event parametric information for the aftershocks was obtained from the Icelandic Meteorological Office (IMO). The ICEARRAY events that matched events in IMO's parametric catalogue (300 events, distance calculated to ICEARRAY station IS605) are shown in Figure 4, which indicates the lower bounds in terms of ICEARRAY's sensitivity in terms of magnitude and distance. The variability of PGA across the array for the events considered is shown in Figure 4, where the PGA levels have been sorted and plotted along with their standard deviation (mean value of 0.154 in terms of common logarithms). The variability of high-frequency ground motions across the ICEARRAY appears to be fairly constant for PGAs over roughly two orders of magnitude. Since this variability is mainly coming from variations in local site response over a small area (~1.9 km) with similar site conditions (lava layers) this σ gives a lower bound on the aleatory variabilities of GMPEs derived from these data. As mentioned above most current GMPEs are associated with σs around 0.3 and, therefore, based on these data there does not seem to be much scope to greatly reduce σ.

However, the standard deviation associated with the PGA variability for the mainshock is only 0.08 and, therefore, Figure 4 could be painting an overly pessimistic picture.

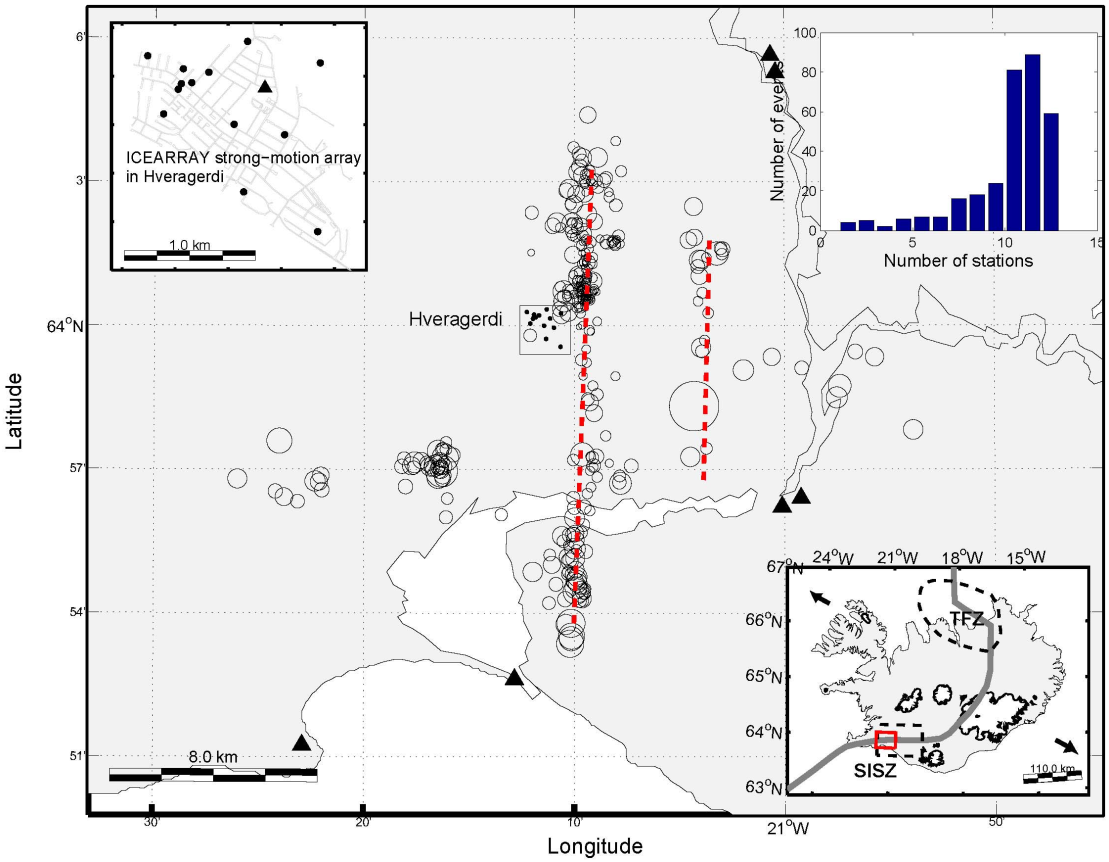

Figure 3. The small map inset at bottom right shows Iceland, an island in the North Atlantic Ocean, in reference to the present-day boundary (gray line) of the Eurasian and North American tectonic plates. Seismic zones are indicated with dashed lines, notably the SISZ. The solid rectangle within the SISZ indicates the macroseismic area of the Ölfus earthquake of 29 May 2008 (shown in the larger map) where the recording sites of the ICESMN are denoted as triangles and those of the ICEARRAY as dots (seen in the small map at top left along with the street layout of Hveragerdi). The ICEARRAY recordings of aftershocks that match the parametric list from the Icelandic Meteorological office are shown in circles, outlining the causative faults (red dashed lines). The diameter of the circles indicates their magnitudes. The histogram indicates the number of events recorded by a given number of ICARRAY stations.

Figure 5 shows the distribution of the mean value of the logarithm of the geometric mean PGA of two horizontal components for each recording station, as a function of distance and magnitude. The attenuation of PGA appears to be proportional to $\sim 1/r^2$ with a σ of 0.3 for M_L 2 to 4 (the lower slope for M_L 1 to 2 is not reliable due to ICEARRAY's incomplete catalogue for small events, see Figure 4). This decay is more rapid than is commonly observed for strong motions, which further shows the need to account for magnitude-dependent decay when deriving GMPEs. The dependency of PGA on M_L appears to be relatively stable at $\sim 0.7 M_L$ as does its variability of roughly 0.2. This variability is lower than is generally observed when using data from small events in other regions. IMO operate a dense network in the SISZ and their hypocentral locations are highly accurate. This further supports the view that a significant proportion of the large σs found when deriving GMPEs for small events is attributable to inaccurate earthquake locations (e.g. Bommer et al., 2007).

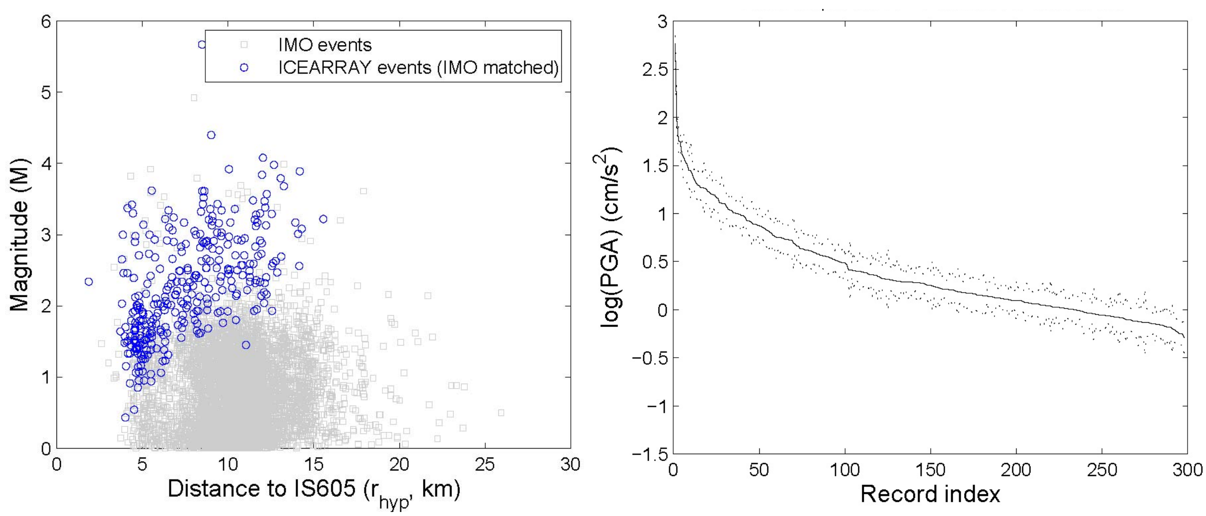

Figure 4. Left: The earthquake catalog published by the IMO (gray) for the year following the main event, along with the matching ICEARRAY records (blue circles). Right: The median geometric mean PGA (solid line) for each event recorded by more than 6 stations of the ICEARRAY, along with the ±σ across the ICEARRAY (dotted lines).

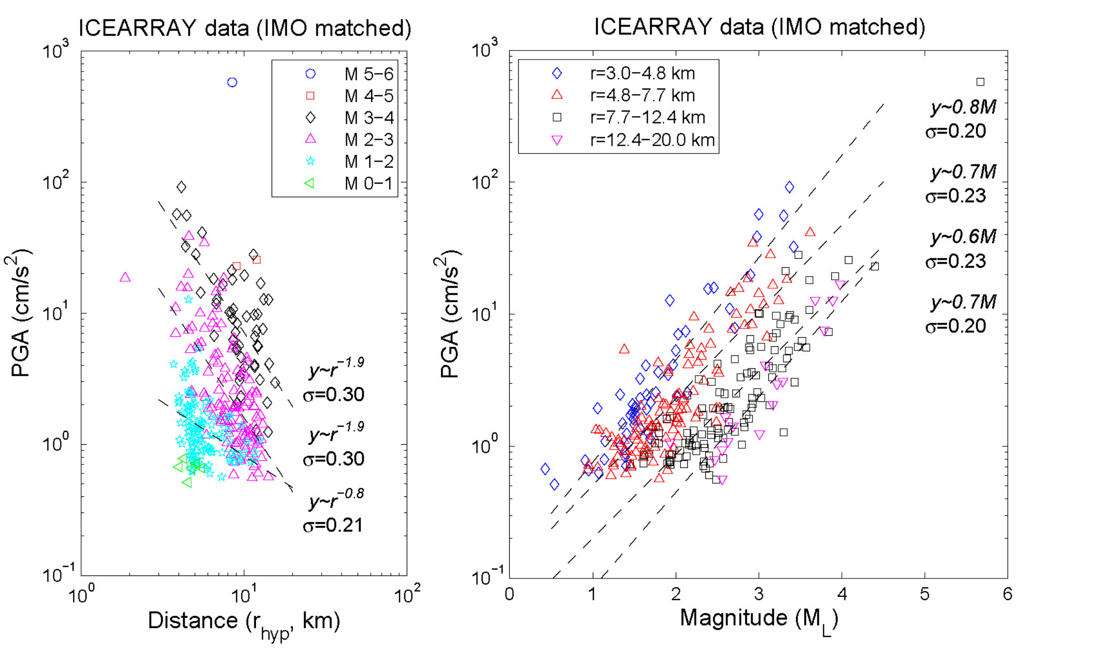

Figure 5. Left: The median PGA across the ICEARRAY plotted vs. hypocentral distance and binned by M_L, along with straight lines fitted through the PGA for three magnitude bins (the dependence on distance and the associated σ is indicated). Right: The same data plotted vs. M_L and grouped by distance-bins through which straight lines are fitted (the dependence on M_L and the associated σ is indicated).

Conclusions

This article examined the question of whether aftershock data can be used to derive GMPEs. Following a brief review of the literature and a demonstration of the importance of this issue, we statistically examined the difference between aftershock and mainshock motions the Ambraseys et al. (2005) dataset. It is found that these data do not demonstrate a clear difference in aftershock and mainshock motions nor their variabilities. This suggests that these data, which contribute more than half of some datasets used to derive GMPEs, can continue to be used without serious implications.

A first look at the ICEARRAY recordings of the aftershocks of the 29 May 2008 Ölfus earthquake in South Iceland is also presented in this study. We find that the variability of the geometric mean PGA values over different ICEARRAY stations for aftershocks during the year after the mainshock appears to be fairly constant for magnitudes ~M_L1-4. The PGAs of the aftershocks attenuate rapidly with hypocentral distance, and scale as ~$0.7M_L$. The inter-site variability is relatively high, which suggests that efforts to significantly reduce σ in GMPEs may soon encounter a physically-based lower bound. Future work is aimed at refining the results utilizing the entire ICEARRAY dataset in the analysis, along with independent calculations of event parameters such as magnitudes and locations, and to include a consideration of other strong-motion parameters.

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References

Abrahamson, N. and W. Silva, 2008. Summary of the Abrahamson & Silva NGA ground-motion relations, *Earthquake Spectra*, 24(1), 67-97.

Ambraseys, N. N., J. Douglas, S. K. Sarma and P. M. Smit, 2005. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration, *Bulletin of Earthquake Engineering*, 3(1), 1-53.

Atkinson, G. M. and D. M. Boore, 2006. Earthquake ground-motion prediction equations for eastern North America, *Bulletin of the Seismological Society of America*, 96(6), 2181-2205.

Båth, M., 1979. *Introduction to Seismology*, Birkhäuser Verlag, Basel, Boston, Stuttgart.

Berge-Thierry, C., F. Cotton, O. Scotti, D.-A. Griot-Pommera and Y. Fukushima, 2003. New empirical response spectral attenuation laws for moderate European earthquakes, *Journal of Earthquake Engineering*, 7(2), 193-222.

Bindi, D., L. Luzi, F. Pacor, F. Sabetta and M. Massa, 2009. Towards a new reference ground motion prediction equation for Italy: update of the Sabetta-Pugliese (1996), *Bulletin of Earthquake Engineering*,7(3), 591-608.

Bommer, J. J., J. Douglas and F. O. Strasser, 2003. Style-of-faulting in ground-motion prediction equations, *Bulletin of Earthquake Engineering*, 1(2), 171-203.

Bommer, J. J., P. J. Stafford, J. E. Alarcón and S. Akkar, 2007. The influence of magnitude range on empirical ground-motion prediction, *Bulletin of the Seismological Society of America*, 97(6):2152–2170.

Boore, D. M. and G. M. Atkinson, 1989. Spectral scaling of the 1985 to 1988 Nahanni, Northwest Territories, earthquakes, *Bulletin of the Seismological Society of America,* 79(6), 1736-1761.

Boore, D. M. and G. M. Atkinson, 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01s and 10.0s, *Earthquake Spectra*, 24(1), 99-138.

Campbell, K. W. and Y. Bozorgnia, 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10s,. *Earthquake Spectra*, 24(1), 139-171.

Chiou, B. S.-J. and R. R. Youngs, 2008. An NGA model for the average horizontal component of peak ground motion and response spectra, *Earthquake Spectra*, 24(1), 173-215.

Danciu, L. and G.-A. Tselentis, 2007. Engineering ground-motion parameters attenuation relationships for Greece, *Bulletin of the Seismological Society of America*, 97(1B), 162-183.

Douglas, J., 2003. Earthquake ground motion estimation using strong-motion records: A review of equations for the estimation of peak ground acceleration and response spectral ordinates, *Earth-Science Reviews* 61 (1-2), 43-104.

Halldorsson, B. and R. Sigbjornsson, 2009. The Mw6.3 Ölfus Earthquake at 15:45 UTC on May 29 2008 in South Iceland: ICEARRAY strong-motion recordings. *Soil Dynamics and Earthquake Engineering*, 29, 1073-1083.

Halldorsson, B., R. Sigbjornsson and J. Schweitzer, 2009. ICEARRAY: the first small-aperture, strong-motion array in Iceland. *Journal of Seismology*, 13(1), 173–178.

Kalkan, E. and P. Gülkan, 2004 Site-dependent spectra derived from ground motion records in Turkey, *Earthquake Spectra*, 20(4), 1111-1138.

Morasca, P., F. Zolezzi, D. Spallarossa, L. Luzi, 2008 Ground motion models for the Molise region (southern Italy), *Soil Dynamics and Earthquake Engineering*, 28(3), 198-211.

Sigbjörnsson, R., J.Th. Snæbjörnsson, S.M. Higgins, B. Halldórsson, S. Ólafsson (2009). A note on the M6.3 earthquake in Iceland on 29 May 2008 at 15:45 UTC. *Bulletin of Earthquake Engineering*, 7(1), 113-126.

Strasser, F. O., N. A. Abrahamson and J. J. Bommer, 2009 Sigma: Issues, insights and challenges, *Seismological Research Letters*, 80(1), 40-56.