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Using Aftershock data when Deriving Earthquake Ground-motion Prediction Equations

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Introduction

Seismic hazard assessments are invariably performed to estimate the hazard from mainshocks (i.e. excluding foreshocks and aftershocks) hence it is necessary that the dataset used to derive ground-motion prediction equations (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 because 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, except in the recent PEER Next Generation Attenuation (NGA) project. Commonly-used GMPEs in Europe (and elsewhere) have used a significant proportion of aftershock records, which contrasts with GMPEs for California where the proportion of data from aftershocks is usually smaller.

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, sigma) due to the mixture of aftershock and mainshock records. Such bias and associated higher sigmas could be accounted for by including terms to model the difference between aftershock and mainshock motions (Figure 1).

Using a significant proportion of records from aftershocks (a series of earthquakes occurring in the same area) may actually lead to lower sigmas than using 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 sigmas in the derived GMPEs than are applicable for independent mainshock motions. This potential downward bias in sigmas from GMPEs dominated by aftershocks does not seem to be observed in reported sigmas, which are stable between 0.25 and 0.35 (in terms of common logarithms) even if many aftershock records are used.

Using data of Ambraseys et al. (2005)

To test the effect of using strong-motion data from aftershocks when deriving GMPEs the dataset of Ambraseys et al. (2005) is reanalysed. Figure 2 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 sigmas from the two subsets are similar and close to 0 and 1, 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. The predicted ratio of mainshock to aftershock motions predicted by the developed model are shown in Figure 1, suggesting that aftershock motions are slightly smaller than those from a mainshock but that this effect is not significant.

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

ICEARRAY was installed during the latter part of 2007 in the western part of the South Iceland Seismic Zone (SISZ), in the town of Hveragerði. 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. At 15:45 UTC on 29 May 2008 an M_w6.3 earthquake occurred in the western part of the SISZ (Figure 3). 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). The ICEARRAY events that matched events in the Icelandic Meteorological Office's (IMO) parametric catalogue (300 events, distance calculated to ICEARRAY station IS605) are shown in Figure 4.

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) it gives a lower bound on sigma of GMPEs derived from these data. The sigma associated with the PGA variability for the mainshock is only 0.08 and, therefore, Figure 4 could be painting an overly pessimistic picture.

Attenuation of PGA appears to be proportional to ~$1/r^2$ with a sigma of 0.3 for M_L2 to 4 (Figure 5). This decay is more rapid than is commonly observed for larger earthquakes, which again 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 ~0.7M_L as does its sigma of roughly 0.2. This sigma is lower than is generally observed when using data from small events in other regions. IMO operate a dense seismic network in the SISZ and their hypocentral locations and M_L are very accurate. This supports the view that a significant proportion of the large sigmas found when deriving GMPEs for small events is attributable to inaccurate earthquake locations.

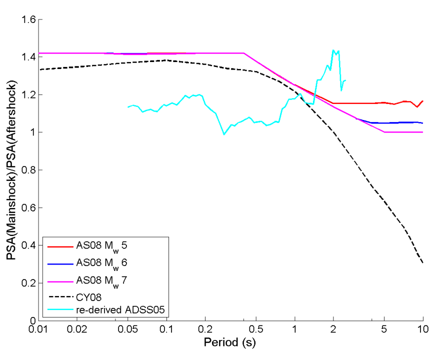

Fig. 1 – Ratio of mainshock to aftershock PSAs from GMPEs of Abrahamson & Silva (2008, AS08), which predicts a magnitude-dependent ratio, and Chiou & Youngs (2008, CY08), which predicts a magnitude-independent ratio. Also shown is the ratio of mainshock to aftershock SAs from re-derived GMPEs of Ambraseys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

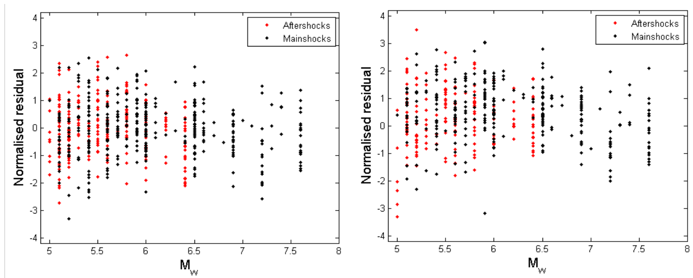

Fig. 2 – Normalized total residuals with respect to M_w for the equations re-derived using the Ambraseys et al. (2005) dataset with the aftershock and mainshock records indicated. Left-hand plot is for PGA (bias for aftershock records: -0.046 with normalized sigma 1.02; bias for mainshock records -0.061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

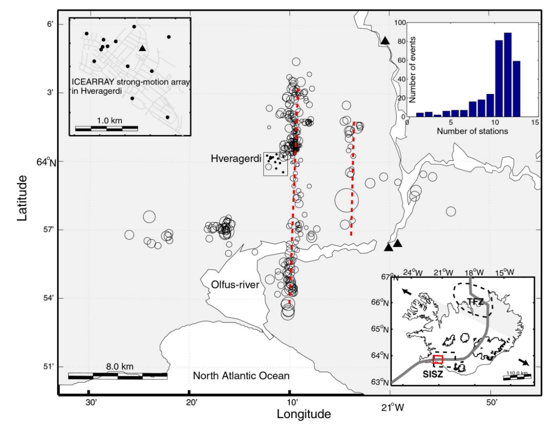

Fig. 3 – The small map inset at bottom right shows Iceland, an island in the North Atlantic Ocean, in reference to the present-day boundary (gray line) of the Eurasian and North American tectonic plates. Seismic zones are indicated with dashed lines, notably the SISZ. The solid rectangle within the SISZ 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.

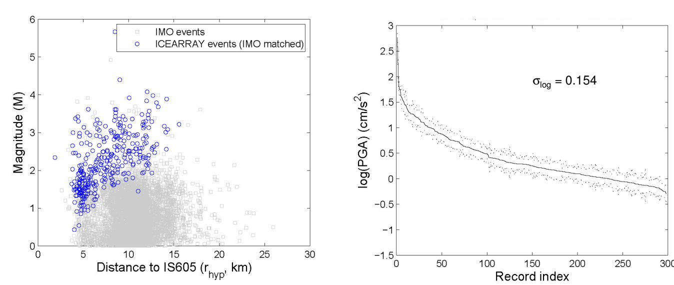

Fig. 4 – Left: The earthquake catalog published by the IMO (gray) for the year following the main event, along with the matching ICEARRAY records (blue circles). Right: The median geometric mean PGA (solid line) for each event recorded by more than 6 stations of the ICEARRAY, along with the ±σ across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

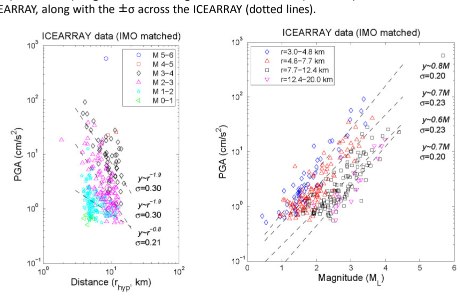

Fig. 5 – Left: The median PGA across the ICEARRAY plotted vs. hypocentral distance and binned by M_L, along with straight lines fitted through the PGA for three magnitude bins (the dependence on distance and the associated σ is indicated). Right: The same data plotted vs. M_L and grouped by distance-bins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

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