A NOTE ON THE USE OF STRONG-MOTION DATA FROM SMALL MAGNITUDE EARTHQUAKES FOR EMPIRICAL GROUND MOTION ESTIMATION

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Abstract

A common practice in the derivation of equations for the prediction of strong ground motions is to supplement the still sparse data from large damaging earthquakes with data from smaller earthquakes, which is much more abundant. In this paper, it is shown that even though strong-motion records from small magnitude earthquakes are often affected by recording problems, such as low A/D convertor resolution, they often can yield accurate response spectral accelerations (SAs). The paper then highlights some possible problems with the practice of combining strong-motion data from small and large magnitude earthquakes. These possible problems include: the difficulty of obtaining estimates of the independent parameters (magnitude, distance and faulting mechanism); more rapid decay of ground motions from small earthquakes compared to ground motions from large earthquakes; higher dependence of ground motions on magnitude for small earthquakes compared to large earthquakes; and larger variability in ground motions from small earthquakes compared to large earthquakes.

Introduction

Due to a limited amount of strong-motion data from damaging moderate and large earthquakes, it is common practice to supplement sets of records used for the derivation of equations for strong ground motion estimation with data from earthquakes of small magnitude. The assumption made is that this data can be used to help constrain the derived equations and that consequently the coefficients of the obtained equations will be more robust. In this paper, a number of aspects related to the use of data from small magnitude earthquakes for the derivation of empirical equations for the estimation of ground motions are discussed.

In low seismicity areas, such as north-west Europe, large earthquakes happen infrequently and consequently data from small and moderate earthquakes has to be used for assessing the possible ground motions because strong-motion records from large earthquakes do not exist.

Data from small and moderate magnitude ($M_w \leq 6$) earthquakes is more abundant than data from large earthquakes, which are more likely to cause engineeringly-significant ground motions, because small earthquakes occur more frequently than large earthquakes. Gutenberg-Richter relations (i.e. $\log N = a - bM$ where N is the number of earthquakes with magnitude greater than M) for many parts of the world have a b value of about 1 (Frohlich & Davis, 1993) and hence earthquakes of one magnitude unit lower occur about ten times more frequently. After large earthquakes, temporary strong-motion stations are sometimes installed in the epicentral area (e.g. Çelebi *et al.*, 2001) and consequently many small aftershocks are recorded. However, because ground motions from smaller magnitude earthquakes are of generally lower amplitudes than motions from larger magnitude earthquakes strong-motion instruments are less likely to be triggered by small earthquakes than by large earthquakes, especially since, as is shown below, ground motions from small earthquakes decay more rapidly than those from large earthquakes. Also strong-motion records from small earthquakes are less likely to be imported into strong-motion archives than those from larger earthquakes because of their low engineering significance. Therefore the distribution of strong-motion records with respect to magnitude does not simply reflect the Gutenberg-Richter relation for the area in question.

Quality of strong-motion records from small magnitude earthquakes

Since ground motions from small magnitude earthquakes are of generally lower amplitudes they are more likely to be affected by problems such as low A/D convertor resolution. Figure 1 shows an example of a strong-motion record affected by this problem. This problem means that records from such earthquakes can appear to be of low quality.

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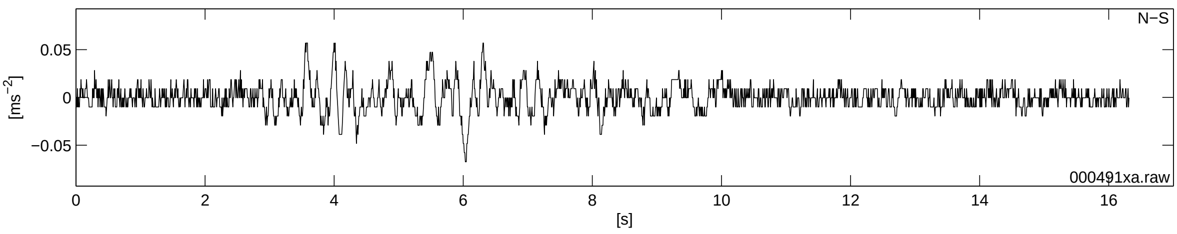

Figure 1: Uncorrected horizontal acceleration time-history from Vanadzor of a Javakheti Highland earthquake ($M_W = 5.4$, $d = 91\,\mathrm{km}$) showing the effect of low A/D convertor resolution.

To assess the effect of low A/D convertor resolution 421 high-quality strong-motion records from digital instruments with high bit ranges were selected. These records were passed through numerical A/D convertors with different bit ranges (8, 10 and 12 bits) and amplitude ranges ($0.5\,\mathrm{g}$ and $1\,\mathrm{g}$). SAs, at natural periods of 0.2, 0.5 and $1\,\mathrm{s}$ for 5% critical damping ratio, from these simulated records were then compared with those from the original record to assess the effect of the instruments' low bit ranges. Figure 2 shows the ratio of SA from the simulated records from an instrument with a 12 bit range and $0.5\,\mathrm{g}$ amplitude range to SA from the original record against the peak ground acceleration (PGA) of the original record. It shows that when there are a sufficiently high number of different acceleration levels present (about 20) SA from the record affected by low A/D convertor resolution is close to that from the original (high-quality) record.

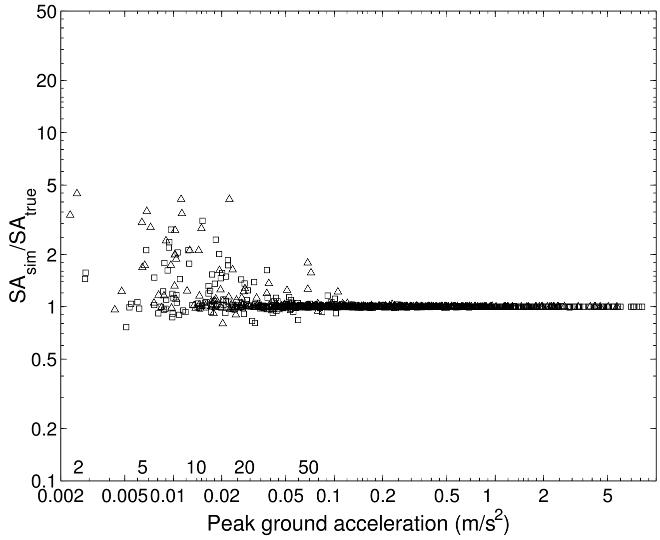

Figure 2: Ratio of SA for 5% damping and natural period $0.5\,\mathrm{s}$, for time-histories from a simulated instrument with a 12 bit range and $0.5\,\mathrm{g}$ amplitude range to the SA calculated from the original time-histories, against the PGA of the original time-history. Also given on the figure is the number of acceleration levels present in the time-histories from the simulated instruments. Squares are for horizontal components and triangles are for vertical components.

It is found that for periods of main engineering interest ($0.2 \leq T \leq 1.0\,\mathrm{s}$) about 20 acceleration levels are sufficient to yield good estimates of SA, however, outside of this period range the low A/D convertor resolution can significantly effect SA estimates unless more than 50 acceleration levels are present in the acceleration time-history. This study is described in more detail in Douglas (2003). Therefore strong-motion records from small magnitude earthquakes can often be used for the derivation of ground motion estimation equations even if they appear to be of low quality.

Independent parameters

To derive equation for the estimation of strong ground motions each record used must have a reliable estimate for each of the independent parameters present in the equation. These independent parameters always include magnitude and distance, usually a local site classification and sometimes a faulting mechanism classification. The possible problems with obtaining reliable estimates for these parameters for data from small earthquakes is briefly discussed in this section.

Reported locations, particularly focal depths, for small earthquakes are likely to be less accurate than estimated locations of large earthquakes because small earthquakes are not usually studied in detail because of their low significance for hazard analysis and partly because of the lack of high-quality data to obtain accurate locations. Therefore the associated source-to-site distances of strong-motion records from small earthquakes are likely to be more uncertain than those from larger earthquakes.

Moment magnitude, M_w, (Kanamori, 1977) is routinely derived by Harvard CMT (Harvard Seismology, 2003) and other groups for earthquakes with $M_w \geq 5.5$. Similarly surface-wave magnitude, M_s, is routinely derived for earthquakes with $M_s \geq 4.5$ by the International Seismological Centre (International Seismological Centre, 2002) and other groups. Therefore these two magnitude scales can be used for characterising the size of moderate and large earthquakes. For small magnitude earthquakes, often only local magnitudes (M_L) provided by the operators of the local networks are available. If data from small and large earthquakes is combined, M_L estimates should be converted to the magnitude scale used for characterising the large earthquakes, either M_w or M_s. This conversion can be impossible because of the lack of appropriate conversion formulae. It also introduces extra uncertainty into the magnitude estimates because the conversion formulae are associated with a large scatter (e.g. Ambraseys & Bommer, 1990).

Recently equations have been derived for ground motion estimation that have included the effect of faulting mechanism (style-of-faulting) on ground motion amplitudes (e.g. Aptikaev & Kopnichev, 1980; Crouse & McGuire, 1996; Abrahamson & Silva, 1997; Boore *et al.*, 1997; Sadigh *et al.*, 1997; Campbell & Bozorgnia, 2003). SAs have been found to be a factor of up to 1.8 times higher from reverse faulting earthquakes compared to strike-slip faulting earthquakes although there are large differences between the estimated ratio of reverse to strike-slip ground motions in different studies (e.g. Strasser *et al.*, 2003, Fig. 2).

For most moderate and large ($M_w \geq 5.5$) earthquakes focal mechanisms are published by Harvard CMT (Harvard Seismology, 2003), which can be used to classify the earthquakes used into style-of-faulting classes (see Strasser *et al.* (2003) for a discussion of these classification methods). Focal mechanisms for aftershocks are sometimes published based on data from local networks. However, published focal mechanisms do not exist for most small ($M_w < 5$) earthquakes and consequently, if used, the earthquakes must be classified using other methods. For example, the faulting mechanism of aftershocks is often assumed to be the same as that for the mainshock. For some earthquakes, however, this is not always true. For example, Ouyed *et al.* (1983) compute well-constrained focal mechanisms for 81 aftershocks of the thrust faulting 10/10/1980 El Asnam (Algeria) earthquake using an array of 28 portable seismic stations. They find that aftershocks mainly displayed thrust mechanisms but a significant proportion showed strike-slip mechanisms and two aftershocks even had normal faulting. Lyon-Caen *et al.* (1988) compute focal mechanisms of 133 aftershocks of the normal faulting 13/9/1986 Kalamata earthquake using records from 16 temporary stations. They find that although most aftershocks displayed normal mechanisms, some showed strike-slip faulting and some aftershocks in the footwall had reverse mechanisms. Consequently, if records from aftershocks with no published focal mechanisms, but which are assumed to have the same mechanism as the main shock, are used, this can increase the uncertainty in the computation of style-of-faulting coefficients.

Attenuation

It is commonly assumed that ground motions from different sized earthquakes decay at the same rate when deriving ground motion estimation equations (e.g. Ambraseys *et al.*, 1996; Boore *et al.*, 1997). Often the geometrical decay is assumed to be $1/r$ (e.g. Joyner & Boore, 1981; Ambraseys & Bommer, 1991; Zonno & Montaldo, 2002) and deviations from this in the far-field are modelled as anelastic attenuation through the multiplication by an additional term with the form $\exp(kr)$ where k is a constant.

Figure 3 shows the decay of PGA with distance for three well-recorded small and moderate magnitude earthquakes and a comparison with -1 and -2 decay rates[2]. This figure shows that the observed decay for these earthquakes is more rapid than $1/r$ and for one earthquake it is more rapid than $1/r^2$. This compares with the decay rate of -0.922 derived by Ambraseys *et al.* (1996), using data from earthquakes with $4.0 \leq M_s \leq 7.9$.

[2] In this paper the exponent of the distance r is called the decay rate.

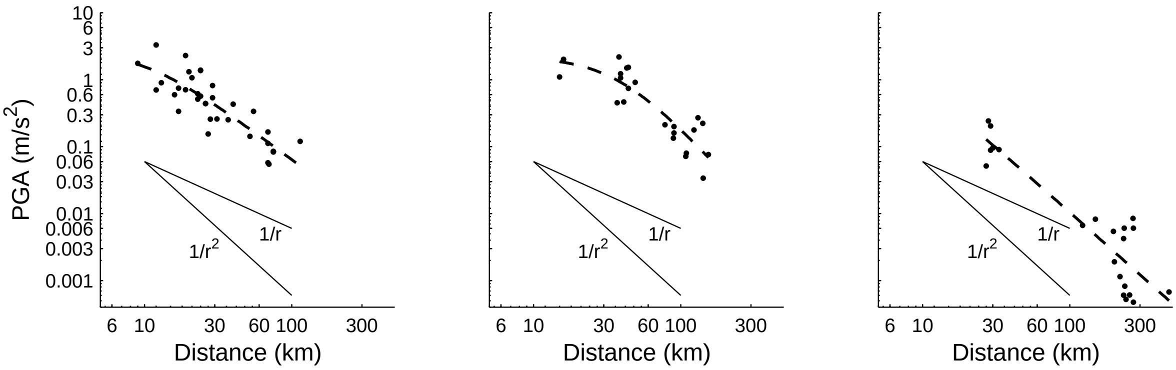

Figure 3: Decay of PGA with epicentral distance for three small and moderate magnitude well-recorded earthquakes and the best-fit decay curve of the form $\log y = a_1 + a_2 \log \sqrt{d^2 + a_3^2}$. The left-hand graph is for the 14/10/1997 15:23 Umbria-Marche aftershock ($M_w = 5.6$) ($a_2 = -1.63$, $a_3 = 9.99$, 35 records), the central graph is for the 29/09/1999 00:13 Kocaeli aftershock ($M_w = 5.2$) ($a_2 = -2.41$, $a_3 = 37.4$, 22 records) and the right-hand graph is for the 25/02/2001 18:34 Nice earthquake ($M_w = 4.5$) ($a_2 = -1.96$, $a_3 = 6.70$, 21 records).

More rapid than $1/r$ decay of PGA for small magnitude earthquakes is not a new finding and has been observed in numerous studies. Early ground motion prediction equations show a decay of approximately $1/r^2$ (Trifunac & Brady, 1976). Boore & Page (1972) find that ground motions from five moderate earthquakes (Parkfield 1966, San Fernando 1971 and three shocks of the Matsushiro 1966 swarm) show decay rates of between -1.4 and -1.8 beyond 5 to $20\,\mathrm{km}$. Sen (1990) finds that the decay of horizontal PGA for small earthquakes ($2.2 \leq M_L \leq 3.5$) in the Whittier Narrows area is $r^{-1.928}$. Costa *et al.* (1998) find that the decay of horizontal PGA for small earthquakes ($1.3 \leq M_D \leq 4.3$) in the Friuli region is $r^{-1.693}$ and the decay of vertical PGA is $r^{-1.908}$. In their study of strong ground motions from normal faulting earthquakes Westaway & Smith (1989) find that for earthquakes with $M < 5$ horizontal PGA attenuates rapidly with distance at distances greater than about $10\,\mathrm{km}$ with a decay rate approximately equal to -2. They suggest this may be due to the effect of anelasticity on the relatively high frequency content of the signal radiated by small earthquake sources with corner frequencies above $10\,\mathrm{Hz}$.

Possible causes for geometrical decay rates lower than -1 are discussed by Frankel *et al.* (1990, pp. 17455–17456). They compute synthetic SH seismograms for a typical eastern North American crust and find a decay rate of -1.5 for hypocentral distances between 15 and $90\,\mathrm{km}$. They note that this steep decay is caused by the reflection of the upgoing direct S wave off the underside of the layer interfaces above the source. As hypocentral distance increases, the upgoing ray impinges at a more shallow angle on the interfaces, reflecting increasing amounts of energy downwards and reducing the energy transmitted to the surface. For crustal structures without interfaces above the source they find $1/r$ decay.

More rapid decay for ground motions from small magnitude earthquakes means that the area likely to be subjected to damaging ground motions around these earthquakes is smaller than would be expected from extrapolation from larger earthquakes.

Since the decay rate of ground motions from small earthquakes is higher than that from larger earthquakes care is needed when combining data from different-sized earthquakes if a magnitude-independent decay rate is assumed. Assuming a magnitude-independent decay rate could lead to biased predictions at large distances for both small and large magnitudes (overprediction for small earthquakes and underprediction for large magnitudes) and will lead to higher standard deviations than a functional form that allowed different decay rates for different-sized earthquakes.

Scaling of ground motions with magnitude

Most equations for the estimation of ground motions assume a linear dependence between the magnitude and the logarithm of ground motion amplitude (e.g. PGA or SA) although some recent equations (e.g. Boore *et al.*, 1997; Campbell & Bozorgnia, 2003) allow for nonlinear scaling between the logarithm of ground motion and magnitude. Figure 4 compares the computed dependence between PGA and magnitude for six different equations that have used data from different magnitude ranges and have assumed a linear dependence between magnitude and the logarithm of PGA. It shows that PGA seems to scale differently at different magnitudes; for small magnitudes the dependence with M is significantly greater than at larger magnitudes.

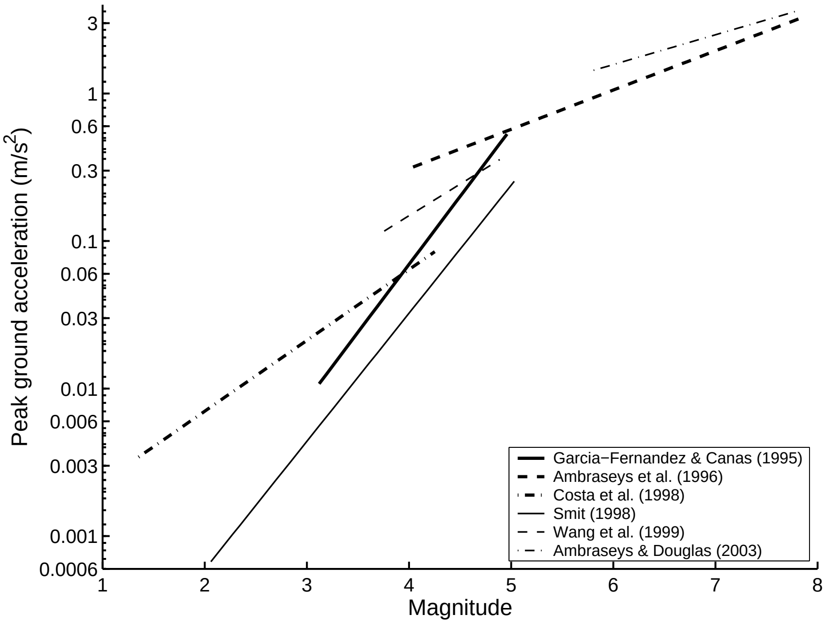

Figure 4: Comparison of the scaling of PGA with magnitude for a source-to-site distance of $15\,\mathrm{km}$ from six equations which have used data from different magnitude ranges. No conversion between magnitude scales was attempted and consequently some of the differences between the scalings of PGA with magnitude could be caused by the lack of a common magnitude scale. Predictions from the equations of Ambraseys *et al.* (1996) and Ambraseys & Douglas (2003) are for rock sites; other equations are independent of site conditions.

It is important that this effect is investigated and incorporated into equations that use data from small magnitude earthquakes if they are to be used for the prediction of ground motions from large earthquake because otherwise ground motions could be significantly overpredicted. This can be seen if the lines shown on Figure 4 are extrapolated outside their range of applicability.

Scatter

It has been suggested that ground motions from small magnitude earthquakes are more variable than those from large magnitude earthquakes (e.g. Youngs *et al.*, 1995). To investigate this suggestion Douglas & Smit (2001) used a large set of 1484 strong-motion records and placed the records into intervals (bins) of $0.2M_s \times 2\,\mathrm{km}$ in which it was assumed that the ground motions are similar. This enables the actual variability in strong ground motions to be assessed independently of the functional form or regression technique used for the derivation of the ground motion estimation equation. It also allows for a number of statistical tests to be performed on the binned data. When unweighted regression analysis is performed it is assumed that the variance is constant with respect to the dependent and independent variables. If an investigation of the residuals with respect to magnitude reveals that the scatter is dependent on magnitude the regression analysis should be repeated using weights to remove this dependence.

Within each magnitude-distance interval the mean, η, and unbiased standard deviation, σ, of the ground motion (PGA and SA) was calculated using the maximum-likelihood method (Spudich *et al.*, 1999, p. 1170). Figure 5 shows the coefficient of variation, $V = 100\sigma/\eta$, against M_s for PGA. If V was independent of M_s then this graph should show no trend with increasing magnitude. A linear equation $V = \alpha + \beta\eta$ was fitted to the graph and is also shown. In the caption α, β, their 95% confidence intervals, standard deviation, the computed and critical t value for $\beta = 0$ for 5% significance level and the degrees of freedom are given. The fitted line coefficients show that there is a decrease in error with increasing M_s and the t test shows that the hypothesis that the error is independent of M_s can be rejected at the 5% significance level.

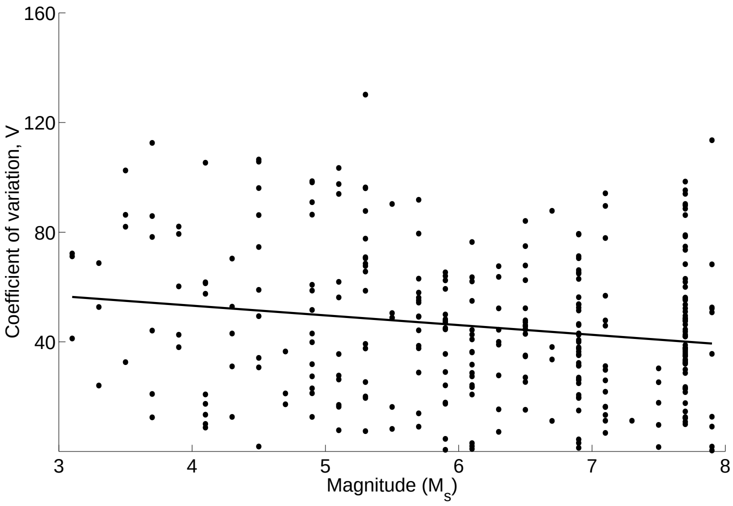

Figure 5: Coefficient of variation, V, against M_s for horizontal PGA. The coefficients of the fitted line ($V = \alpha + \beta M_s$) are $\alpha = 67.34 \pm 14.35$, $\beta = -3.54 \pm 2.27$, $\sigma = 26.08$. The critical t for 306 degrees of freedom is 1.97 and the computed t is 3.07.

The finding that the scatter in ground motions is higher for small magnitude earthquakes is important because it implies that if data from such earthquakes are used, the standard deviations of the derived ground motion estimation equations is likely to be higher than the true standard deviation of ground motions of engineering significance. This could lead to an overestimation of the seismic hazard.

Conclusions

In this paper a number of problems that should be considered when using data from small and moderate magnitude earthquakes for empirical regressions are discussed.

It is shown that although data from such earthquakes are more affected by recording problems than data from larger earthquakes the records can often be used within a limited period range as long as certain criteria are met.

For the derivation of ground motion estimation equations that include the effect of faulting mechanism records from aftershocks without published focal mechanisms but that are classified based on the observed focal mechanism of the mainshock could be incorrectly classified. This would lead to less reliable regression coefficients. Therefore it is suggested that only records from earthquakes with actual published focal mechanisms are used for the derivation of equations that incorporate coefficients to model the effect of style-of-faulting on ground motions.

The decay of ground motions from small earthquakes has been shown to be more rapid than that from large earthquakes and also much more rapid than the commonly assumed $1/r$. Therefore a functional form that allows for a magnitude-dependent decay rate should be used.

Ground motions from small earthquakes display a higher dependence on magnitude than those from large earthquakes showing the need for a quadratic or other nonlinear magnitude term in equations for the estimation of ground motions. However, these functional forms can only be used when there is sufficient data at all magnitude ranges because otherwise the derived coefficients could be non-physical.

Ground motions from small and moderate earthquakes seems to be associated with higher scatter than motions from large earthquakes. This means that a weighting scheme should be applied to the ground motions, with weights inversely proportional to the magnitude-dependent variance, when using them for the derivation of ground motion estimation equations. Also the standard deviations associated with equations derived using data from small magnitude earthquakes are probably too high when used for the prediction of ground motions from larger magnitude earthquakes.

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