Bounds on the distribution of amplitudes in ground motion prediction models

Jeff Fisher[1], Paul Somerville[1], John Zhao[2] and Jian Zhang[2]

[1] Risk Frontiers
[2] GNS Science

Abstract

In current ground motion models, the uncertainty in predicted ground motion is modelled with a lognormal distribution. One consequence of this is that predicted ground motions do not have an upper limit. In reality, there probably exist physical conditions that limit the ground motion. Use of unbounded models in probabilistic seismic hazard analysis leads to ground motion estimates that may be unrealistically large, especially at the low annual probabilities considered for important structures, such as dams or nuclear reactors. Due to the limited size of earlier strong motion data sets, statistical analysis of the distribution of earthquake ground motion amplitudes was unable to provide a clear point at which to truncate the lognormal distribution.

Recently, very large data sets of strong motion recordings have become available, making statistical analysis more viable. We have analysed very large strong motion data sets from the K-net and Kik-net strong motion networks in Japan. Preliminary analyses by us and other investigators using normal probability plots show departures from lognormal behaviour at about 2.5 standard deviations above the median. Our basic approach is to calculate residuals of the recorded data from the ground motion model developed for Japan by Zhao et al. (2006) using the K-net and Kik-net data. These residuals are then used to construct normal probability plots, and the significance of departures of the residuals from lognormal distributions is quantified. The significance of departures is assessed in light of earthquake source, wave propagation, and site response effects that may be present in the data but not taken into account in the ground motion model of Zhao et al. (2006) that form the basis for measurement of residuals.

Introduction

Due to the limited size of strong motion data sets, statistical analysis of the distribution of earthquake ground motion amplitudes has, to date, been unable to provide a clear indication that the distribution has an upper limit. Recently, very large data sets of strong motion recordings have become available, making statistical analysis more viable (Bommer et al., 2004). The three crustal earthquake data sets analyzed by these authors using normal probability plots all show departures from lognormal behaviour at about 2 standard deviations above the median, tending toward shorter upper tails. However, the Japanese K-net data sets that were analyzed contain ground motion values almost 5 standard deviations above the median. We anticipate that these very high values may be due to data errors or to extreme site effects.

Data analysis

Strasser and Bommer (2005) analysed the intra-event variability of ground motion amplitudes in sets of K-net recordings of individual crustal earthquakes in Japan using K-net data. They noted data quality issues in the strong motion recordings, but did not attempt to correct them. They used site corrections derived from extrapolation of shallow shear wave velocity measurements to 20 metre depth, but found them not to have a large impact on their measurements of ground motion variability. They concluded that the distribution of ground motion amplitudes is consistent with the lognormal distribution up to the 2.5 sigma level.

The methods used by Zhao et al. (2006 a,b) in deriving their ground motion model may provide a more reliable basis for the evaluation of ground motion variability, because of the approaches taken for strong motion data processing and the classification of recording sites. In Zhao et al. (2006 a,b), strong motion recordings from Japanese earthquakes recorded on strong motion stations of the K-net and Kik-net networks were gathered and processed using a high-pass filter to eliminate the long period ground motions with frequency less than the corner frequency of the filter determined for each record. Among the total of 4518 Japanese records from 249 earthquakes, 1285 are from crustal events, 1508 are from interface events and 1725 are from slab events.

The magnitude and source distance distribution for earthquakes with focal depths of up to 162 km is shown in Figure 1(a) for the Japanese strong-motion data set used by Zhao et al. (2006). In order to eliminate the bias that could be introduced by untriggered instruments, data for the modelling were selected from a much larger data set by exclusion of data at distances larger than a specified value for a given magnitude. For subduction slab events, the maximum source distance was set to 300km. Earthquake locations, especially focal depths, determined by JMA were not consistent with those determined by other seismological organizations, and so the relocated ISC locations and depths were used. The moment magnitudes from the Harvard catalogue were used unless moment magnitude from a special study was available. In addition to the crustal earthquake category analysed by Strasser and Bommer (2005), our analysis includes subduction interface earthquakes and intra-slab earthquakes, which have larger magnitudes and much larger numbers of recordings than the crustal earthquakes. Our analysis also looks at the full variability in the ground shaking, both the intra-event variability and the inter-event variability.

The standard deviations used are those of the Zhao et al. (2006) models, which are independent of magnitude. For subduction and slab events, these standard deviations are much lower than those of the widely used subduction zone model of Youngs et al. (1997), especially for periods longer than 0.2 seconds. This is an important feature of the Zhao et al. (2006) model, because in probabilistic seismic hazard analysis, the variability of ground motion about the median value is often just as important as the median value itself.

Since many of the K-net stations have shear wave velocities that extend to depths of only 10 and some to 20 meters, Zhao et al. (2006) devised an alternative method for categorising their site conditions, based on response spectral ratios of horizontal to vertical ground motions. They used H/V ratios for records from K-net sites having adequate shear-wave velocity measurements to establish a site classification index using the mean spectral ratios over a wide range of spectral period, to assign sites to the long-established Japanese classes (Molas and Yamazaki 1995) that correlate approximately with the US NEHRP classes as indicated in Table 1. Using the index, they were able to classify both K-net stations with soil layers thicker than 20m and other strong-motion stations in Japan. The peak period of the H/V spectral ratio was also used to identify soft soil sites.

Results

Our basic approach is to calculate residuals of the recorded data from the ground motion model of Zhao et al. (2006) using the site classifications developed by Zhao et al. (2006). The significance of departures of the residuals from lognormal distributions has been quantified. These significance of departures will be assessed in light of earthquake source, wave propagation, and site response effects that may be present in the data but not taken into account in the ground motion models of Zhao et al. (2006 a, b) that form the basis for measurement of residuals.

Figure 2 shows the distribution of the residuals after they have been normalised. It is apparent that the lognormal distribution fits the bulk of the data very well. However, this relationship is well established and it is the tail ends of the distribution that is of interest, particularly the upper tail, although the lower tail is also important. What happens in the tail is best described with a normal plot, as shown in Figure 3. In this figure, a lognormal probability distribution is indicated by a straight diagonal line. The change of the slope of the data points for residuals between 2 and 2.5 log units above the median indicates departure from the lognormal distribution through a shortening of the tail of the distribution, consistent with the idea that physical bounds do indeed limit the upper tail of the distribution. However, there are still two points that lie outside this limit, indicating that more extreme values are possible. These outliers pose a significant problem. If they are legitimate recordings, i.e. not caused by data or recording errors, then any truncation point should lie outside these values.

We examined the two records with the largest positive deviations from the median value to see if there was anything unusual about them. We found that each has a single isolated spike in acceleration whose amplitude is considerably higher than the next highest peak. The fact that one of the sites produced this spike in just one earthquake and not in ten others suggests that the site response is dependent on the azimuth and/or incidence angle of the incoming ground motion, possibly due to departures from flat lying ground structure near the site. The other station has only one record so we are unable to determine whether it characteristically has such a spike.

We also examined the spectral acceleration curves of each of these records to determine if there is a single period that is extremely high or if this is consistent across all periods. They both had an extremely elevated peak between 0 seconds and 0.3 seconds and after this they died away very rapidly. At longer periods, 1 and 3 seconds, the residuals for both recordings had dropped back to between 0.9 and 1.6. While these numbers are still higher than those predicted by the attenuation relations, they are well within the bounds of the proposed truncation point of 2.4. As such we felt that these data points were not sufficiently problematic to warrant extending the truncation point so as to include them, since it is the longer spectral periods that are most important for a typical seismic hazard analysis.

Conclusions

Current ground motion prediction models assume an unbounded lognormal distribution of random variability in ground motion level. In reality, there probably exist physical conditions that limit the ground motion distribution. Use of unbounded models in probabilistic seismic hazard analysis leads to ground motion estimates that may be unrealistically large, especially at low annual probabilities. The probabilistic seismic hazard map of Australia uses ground motion models that are assumed to be truncated at three standard deviations above the median value. Given that the standard deviation in the attenuation model is of the order of 0.7 log units for most spectral periods, it is likely that truncating 2.1 log units above the mean is probably slightly underestimating the uncertainty. The current study indicates that a more appropriate cutoff point would be 2.0 – 2.5 log units beyond the median. Truncating the distribution in this fashion would serve to reduce the hazard at long return periods.

References

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

Bommer, J.J., Abrahamson, N.A., Strasser, F.O., Pecker, A., Bard, P.Y., Bungun, H., Cotton, F., Fäh, D., Sabetta, F., Scherbaum, F. and Studer, J., 2004. The challenge of determining upper limits on earthquake ground motions, Seism. Res. Lett., 75: 82-95.

Chang, T.Y., Cotton, F. and Angelier, J., 2001. Seismic attenuation and peak ground acceleration in Taiwan, Bull Seism. Soc Am, 91: 1229-1246.

Lussou, P., Fukushima, Y., Bard, P.Y. and Cotton, F., 2001. Seismic design regulation codes: contribution of Knet data to site effect evaluation, Journal of Earthquake Engineering, 5(1): 13-33.
Molas, G.L. and Yamazaki, F. (1995), Attenuation of earthquake ground motion in Japan including deep focus events, Bulletin of the Seismological Society of America, Vol. 85, No. 5, pp. 1343-1358
Strasser, F.O., and J.J. Bommer (2005). Analysis of intra-event ground-motion residuals from K-NET and KiK-NET data. Research Report No. 05-003-SM, Imperial College, London, U.K.
Youngs, R.R., Chiou, S.-J., Silva, W.J. and Humphrey, J.R. (1997), Strong ground motion attenuation relationships for subduction zone earthquakes, Seismological Research Letters, Vol. 68, pp. 94-127
Zhao, J.X., J. Zhang, A. Asano, Y. Ohno, T. Oouchi, T. Takahashi, H. Ogawa, K. Irikura, H.K. Thio, P.G. Somerville, Yasuhiro Fukushima, and Yoshimitsu Fukushima. (2006a). Attenuation relations of strong ground motion in Japan using site classification based on predominant period. Bull. Seism. Soc. Am., 96, 898-913.
Zhao, J.X., Irikura, K., Zhang, J., Fukushima, Y., Somerville, P.G., Asano, A., Ohno, Y., Oouchi, T., Takahashi, t. and Ogawa, H. (2006b). An empirical site classification method for strong motion stations in Japan using H/V response spectrum ratio. Bull. Seism. Soc. Am., 96, 914-925.

Table 1. Site class definitions used by Zhao et al. (2004; 2005) and the approximately corresponding NEHRP site classes (BSSC 2000)

Site class	Description	Natural period	V_{30} calculated from site period	NEHRP site classes
SC I	Rock	T < 0.2s	V_{30} > 600	A+B
SC II	Hard soil	0.2 = T < 0.4s	300 < V_{30} = 600	C
SC III	Medium soil	0.4 = T < 0.6s	200 < V_{30} = 300	D
SC IV	Soft soil	T ≥ 0.6s	V_{30} ≤ 200	E+F

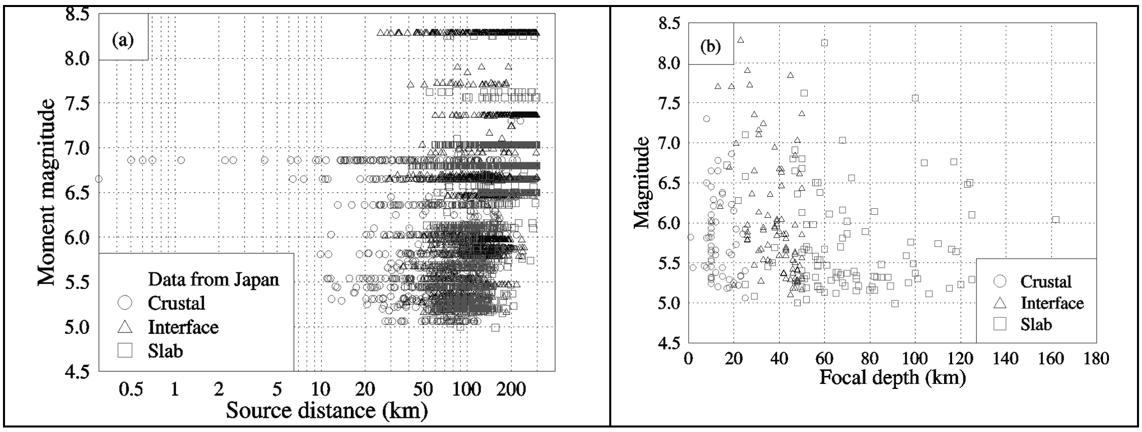

Figure 1 Magnitude-distance distribution for (a) data from Japan; and (b) magnitude-focal depth distribution of Japanese data. Source: Zhao et al. (2006)a.

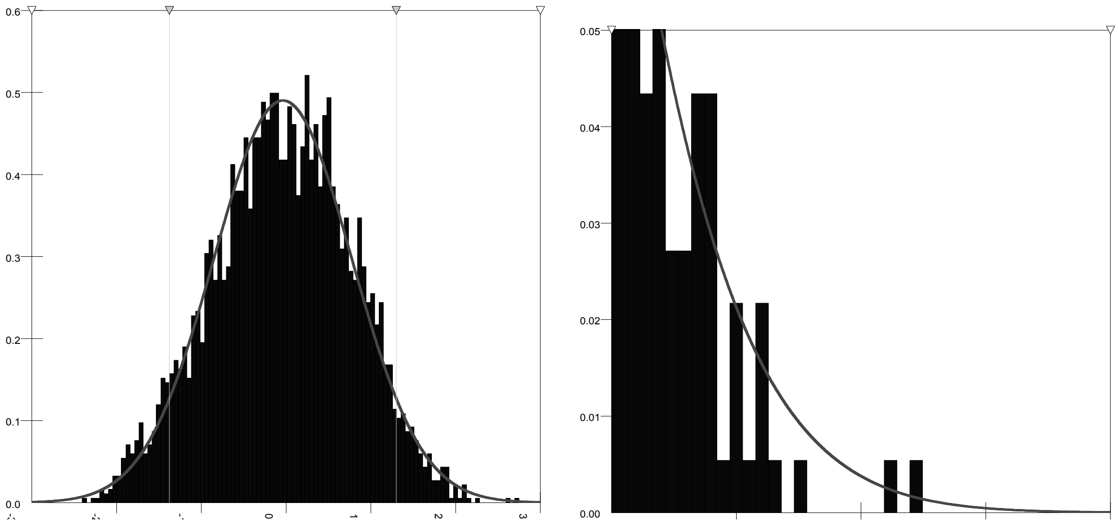

Figure 2 a. Full distributions of the residuals. b. The upper tail of the distribution.

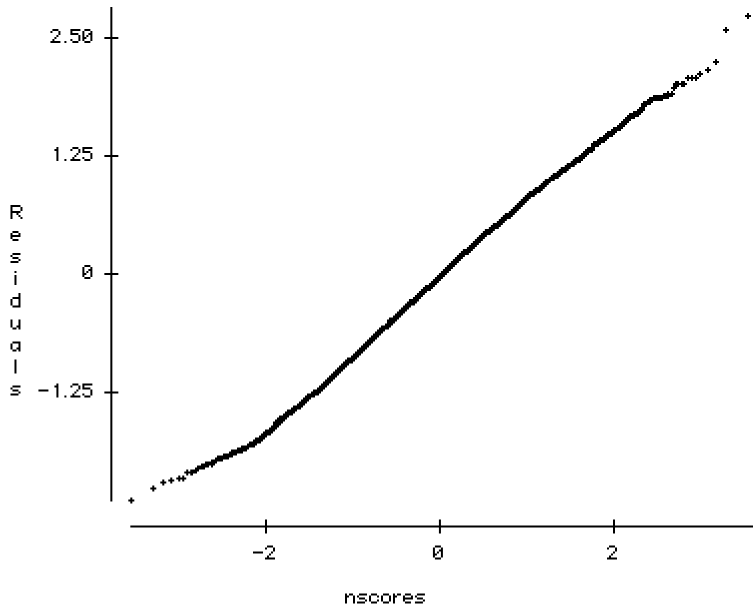

Figure 3 Normal probability plot of the ground motion residuals against their n-scores.