Ground motion and probabilistic hazard

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Abstract

It might be thought that an empirical ground motion prediction model has only to describe the variations in the input data set as accurately as possible in order to be useful, with the proviso that the data set is reasonably extensive and well-selected. If the model is to be used in probabilistic seismic hazard assessment, however, the model will probably be subject to extrapolation beyond the parameter space within which it was constructed, especially for hazard at low annual probabilities. In this case, features of the model, especially its functional form, may turn out to have unexpected and undesirable implications. The end result can be conclusions about the hazard that are clearly not in accordance with commonsense. In this study, two test cases are used to examine the application of some recent ground motion models to probabilistic hazard studies. Problems are found that suggest that, although a ground motion model may be a correct representation of its data set, the effects of the functional form applied can be such that it becomes doubtful whether the model should be used for probabilistic hazard purposes.

Keywords

Strong ground motion, attenuation, seismic hazard, magnitude, distance

Introduction

It is conventional, in papers on strong ground motion that present new models, that after giving the results as a table of coefficients, the new model will also be presented as a series of ground motion curves for two or three magnitudes, showing attenuation of PGA or some other parameter with distance. These curves will often be compared to similar curves from other well-used models in the literature. Spectral shapes for selected magnitude-distances will also be presented and compared. However, two models that appear similar when compared in this way may actually behave rather differently when applied in seismic hazard studies, and this is not usually discussed in the ground motion model paper, though it may be demonstrated in other papers dealing with hazard studies (Lombardi et al 2005, Cramer 2006 for two recent examples). Modelling of strong ground motion is not something undertaken as an intellectual exercise, and the dominant use of such models is in probabilistic seismic hazard analysis (PSHA), so an appreciation of the impact of any model on hazard estimates is important.

In this short paper, the ground motion model of Ambraseys et al (2005) is principally examined, in terms of its effects on hazard calculations. This model, when compared to its predecessor Ambraseys et al (1996), provides a good illustration of how two models that appear similar at first, may not be. From reading the discussion in Ambraseys et al (2005), one would think that the new model is similar to the old (in terms of median ground motions), but as will be shown, it behaves very differently in hazard studies. The recent literature on strong ground motion models is extensive, and it is not the intention of this paper to present a wide review. However, comparisons are also made with two other recent models. More examples could be adduced, but the purpose of this paper is to draw attention to some basic points.

Models, data and hazard

Any empirical ground motion model is constructed from a strong motion database, and takes the form of an equation and accompanying coefficients that represent the variations in data as a function of magnitude, distance, and sometimes other parameters such as fault mechanism or site conditions (Douglas 2003). The coefficients are determined by regression and thus the model should provide the best representation of variation in ground motion parameters as shown by the effects of the earthquakes in the database used. It would therefore seem that the quality of any model rests chiefly on the quality of the underlying database in terms of representing a wide number of cases within the potential magnitude-distance spectrum (and appropriate to some specified tectonic setting), and that it is unequivocal that, on the basis of the data used, the values predicted by the model for any given magnitude-distance combination will be the best estimate that can be obtained (taking into account also the aleatory uncertainty, which is an integral part of modern models).

In cases of deterministic or semi-deterministic hazard, where one starts with the parameters of a design earthquake and needs only to compute the expected ground motion and perhaps some upper percentile of the uncertainty, this is a straightforward procedure. (Except, of course, for the choice of which percentile, which is arbitrary – Bommer and Scherbaum 2005, Abrahamson 2006). In PSHA, matters are not so simple, because the PSHA process samples the extremes of all possible outcomes in order to arrive at a hazard estimate, often for quite low annual probabilities. This involves using the ground motion model in a way that effectively extrapolates beyond the original database, and how the model behaves in such a context depends to a large degree on the shape of the model as given by the functional form of the basic equation. This can have unexpected consequences, as will now be demonstrated.

ADSS05

The ground motion model by Ambraseys et al (2005), which will hereafter be referred to as ADSS05, is the latest of a series of models beginning with Ambraseys and Bommer (1991) and including Ambraseys (1995) and Ambraseys et al (1996). All of these use data from Europe and southwest Asia, and have been extensively used, not just in Europe. The publication of ADSS05, using an improved and updated database, should therefore render the previous models in the series obsolete. The range of validity of the model is stated as being for shallow crustal earthquakes of Mw ≥ 5 and at distances less than 100 km. The largest earthquake actually present in the database is 7.6 Mw.

The basic functional form used is

$$\log y = a_1 + a_2\, Mw + (a_3 + a_4\, Mw) \log \sqrt{(d^2 + a_5^2)} \qquad (1)$$

To this is added a series of variables representing faulting and site conditions. In this equation, d is Joyner-Boore distance (distance to the surface projection of the rupture) and the a_5 term is the pseudo-depth parameter often written as h_0. Values of the various coefficients are given for 62 spectral periods from zero (PGA) to 2.5 s. Uncertainty is given both for σ_1 (intra-earthquake variability) and σ_2 (inter-earthquake variability), and both these generally take the form

$$\sigma = s1 + s2\, Mw \qquad (2)$$

where s2 is negative, and the overall sigma value decreases with increasing Mw.

For the purposes of illustration, two fictional cases will now be considered. The first is a high-hazard case where a site is close to (distance about 5 km) a single active vertical strike-slip fault capable of large earthquakes. The second is a low-hazard case typical of NW Europe, where the site is situated in a zone of diffuse seismicity and even moderately large earthquakes are rare. Comparisons will be made with the Ambraseys et al (1996) model, which uses Ms rather than Mw as the magnitude scale. Conversions were applied according to the formula given in Ambraseys (1995). In all the comparisons in this paper, it is possible that the values obtained with the Ambraseys et al (1996) model are influenced by this conversion, which tends to give progressively lower Ms values compared to Mw for magnitudes below 6 Mw.

Demonstration – high hazard case

Dealing first with the high hazard case, Figure 1 shows two sets of standard probabilistic hazard curves, for (a) PGA and (b) 2.0 s spectral acceleration (5% damping). In each case, the hazard has been computed using three different values for maximum magnitude: 6.0, 7.0 and 8.0 Mw. The last value is perhaps slightly out of the range of the original database, but it is not explicitly excluded by the authors, and one cannot assess hazard for, say, Turkey, without being able to include the possibility of 8.0 Mw events. (Recall also that if Mmax = 7.0 Mw, all events 7.1-7.9 are excluded.)

Figure 1 (a) and (b) present a remarkable contrast. In Figure 1 (a) the three curves are hardly differentiated, while in Figure 1 (b) they diverge hugely. In the case of Figure 1 (b), it is to be expected that long period hazard should be controlled by large earthquakes, but is it realistic to suppose that the hazard amplitude trebles if the maximum magnitude is increased from 7 to 8 Mw?

Figure 1 (a) is completely unexpected. What it says is that for very low annual probabilities, the expected ground motion is unaffected by maximum magnitude. It is completely immaterial whether the fault can produce a magnitude 8.0 Mw earthquake or just a magnitude 6.0. The hazard amplitudes are entirely controlled by earthquakes less than 6.0 Mw. This runs completely counter to commonsense.

If one examines the workings of the hazard assessment (or disaggregation - Musson 1999), the reason becomes clear. The inverse correlation between aleatory uncertainty and magnitude, combined with the higher occurrence rate for smaller earthquakes, outweighs the rate at which potential ground motion increases with magnitude. Thus, very high ground motions within the PSHA calculations are almost exclusively from small earthquakes with high scatter.

This has an interesting side effect. Normally, restricting the number of standard deviations of scatter to three sigma has very little effect on the hazard results. With ADSS05, the impact is much greater, as is shown in Figure 2, which should be compared to Figure 1 (a). Since the hazard is so completely dependent on the scatter, applying a limit causes the hazard curves to become relatively quickly asymptotic to a maximum value.

Figure 3 (a) and (b) repeat the calculations for Figure 1, but substituting the Ambraseys et al (1996) ground motion model (ASB96 hereafter). In Figure 3 (a) the pattern is completely different, and accords with what one expects to see.

Obviously, the authors of ADSS05 represented the magnitude-dependence in the uncertainty in the way they did because it corresponds to what was found in the empirical data with which they were working, and there is no suggestion that the model is incorrect in its representation of the input data. The dataset (595 records) is still relatively small when measured against the complete magnitude-distance-uncertainty spectrum, and the pattern found in ADSS05, when extrapolated to low probability levels, yields effects that are unlikely to be realistic. Also, Campbell and Borzognia (2007) have suggested that an apparent increase of sigma with decreasing magnitude simply reflects poorer metadata for smaller events.

In the case of longer period motions, the reason for the much higher divergence of curves in Figure 1 (b) compared to 3 (b) is not to do with the scatter, but simply due to the fact that ADSS05 predicts rather high SAs at very long periods and for high magnitudes, partly due to the convolution of magnitude with the distance term in equation (1), and partly due to the lack of a quadratic magnitude term. For 2 s SA, the predicted values rise very sharply with increasing magnitude above 7 Mw, and magnitude 8 Mw events (admittedly outside the range of the input data) have predicted SAs in excess of 1 g at close range, before scatter has even been taken into account.

Demonstration – low hazard case

In this second example, the issue to be considered is not the maximum magnitude for PSHA, but the minimum (or lower-bound) magnitude. The seismicity model contains a single zone containing 21,500 sq km, with seismicity such that the annual probability of an earthquake of 4.0 Mw anywhere in the zone is 0.045, and the *b* value is close to 1.0. Maximum magnitude is 6.5 Mw. This is therefore a case where the hazard should be low by any standards.

Hazard was computed using both 4.0 and 5.0 as minimum magnitude. For the former case, this is extending ADSS05 outside its limits of validity. However, 4.0 Mw is often used as a minimum in cases of studies not for engineered construction (Benjamin 1989), so if ADSS05 is adopted for use in PSHA, it is likely that analysts will be obliged to make this extrapolation to lower magnitudes. The effect is shown in Figure 4. The comparative results using ASB96 are shown in Figure 5.

Minimum magnitude is a necessary element in PSHA, but its effects are frequently pernicious. Since it is an arbitrary value related to what is considered to be “engineering significance”, it is undesirable if this value has an overly large influence on the results of a study – if one can manipulate results by varying a single subjective parameter, the study loses objective credibility. Because the magnitude-dependent sigma in ADSS05 boosts the possibility of small earthquakes generating high ground motions, it means that hazard results become very sensitive to changes in the minimum magnitude value used, as seen in Figure 4. In Figure 5, minimum magnitude has much less impact, and in fact, at very low annual probabilities it has no effect at all, since the contribution of the smallest earthquakes drops away, and the two curves merge. In contrast, in Figure 4 there is no sign of the curves converging.

One should note also the high hazard values in Figure 4. Considering that this is a low seismicity area, with an earthquake > 4 Mw every 20 years, it seems remarkable that the hazard with annual probability of 0.0001 should be as high as 0.38 g. This can be put down to extension of the model beyond its validity, but in this case it should be noted that the model responds particularly badly to such an extrapolation.

The problem is ameliorated but not eliminated by capping the ADSS05 sigma values at the values derived for 5 Mw, following a suggestion by Douglas (*pers. comm.*). This has the effect of reducing the PGA amplitudes in Figure 4 by about 15%.

Discussion

It should be understood that no criticism of the authors of ADSS05 is intended here; it is not disputed that they followed correct procedures in the selection of data and in analysis. The discussion here applies to the use of ADSS05 in PSHA studies as a direct model of ground motion in terms of magnitude and distance, and especially for low annual probabilities. There are other applications of the model for which the objections raised here do not apply.

One can think of all potential outcomes of an earthquake as being represented by a three dimensional space in which the axes are magnitude, distance, and degree of scatter in the ground motion from the most probable value (often represented by the letter ε). In ground motion studies, usually the dataset imperfectly samples even the two-dimensional space represented by the magnitude and distance. The full three-parameter space is even less well sampled, particularly with regard to the uppermost layer of high scatter. However, in PSHA, the full three-dimensional space is always fully used.

As a result, one can argue that for PSHA purposes, it is insufficient for a model to describe purely the input data. Thought needs to be given to what the implications are with regard to the complete three-dimensional space from which hazard estimates will be determined. Thus, whether or not it turns out to be the case, within a given data set, that scatter in values is greater for smaller magnitude events (and this is not an isolated observation – see, for instance, Youngs et al 1995, Sadigh et al 1997), the implications of this in PSHA (at least for annual probabilities less than around 0.003) are unwelcome and contrary to commonsense.

Comparison can be made with some more recent studies, especially the Next Generation Attenuation (NGA) project (Power et al 2006, 2008). In the exercises that follow, priority is given to comparing PGA hazard in the high-hazard case; similar comparisons could be made for hazard at other spectral values.

The NGA studies benefited from a larger database than ADSS (3,551 records compared to 595) with a better, though still incomplete, sampling of the entire magnitude-distance domain (Power et al 2008, Chiou et al 2008, Stafford et al 2008). Secondly, the studies were characterised by much more elaborate functional forms than hitherto; Campbell and Borzognia (2007, 2008), for instance, uses a tripartite magnitude scaling, which allows for a more sensitive treatment of the way in which ground motion varies with magnitude.

An important recent study by Bommer et al (2007), following on from Akkar and Bommer (2007), took a similar data set to that of ADSS05, but with the inclusion of smaller events down to 3.5 Mw. Their results show that ground motions from weak events are grossly over-predicted by any ground motion model computed from data >5 Mw (Figure 4 of this paper is thus shown to be completely unrealistic, as might be supposed). They conclude that not only are ground motion models invalid when extrapolated below the lower bound of their input data, models are also unreliable *near* the lower bound. By implication, the same may occur at the upper bound, though this is harder to test.

Bommer et al (2007) also found no evidence for regional variations of attenuation within Europe (see also the discussion in Stafford et al 2008). The conclusion to be drawn is that, for purposes of hazard assessment, priority should be given to models (a) based on the largest possible datasets with the most complete sampling of the magnitude-distance domain, (b) with advanced functional forms capable of dealing with non-linear scaling within the magnitude-distance domain. (One should perhaps write: magnitude-distance-epsilon domain). These considerations are likely to be more important than the use of local data. This has implications for the selection of appropriate models for use in PSHA in the future.

By way of comparison, Figures 6 and 7 show curves for the two cases using ADSS05, Ambraseys et al. (1996), Bommer et al (2007), and, as a representative of the NGA models, Campbell and Bozorgnia (2007). Minimum magnitude is 5 Mw and maximum magnitude is 7 Mw in Figure 6, and PGA is plotted. In Figure 7, minimum magnitude is 4 Mw, maximum magnitude is 6.5 Mw, and sigma is capped where appropriate at the value for 5 Mw. There is a reasonable consensus between the different models in Figure 6 (unlike Figure 7, where ADSS05 is a strong outlier).

Even these figures do not tell the whole story. From Figure 6 one might conclude that the ADSS05 and Campbell and Bozorgnia (2007) models gave similar results. However, testing the effect of varying maximum magnitude using Campbell and Bozorgnia (2007) gives results similar to Figure 3a, not Figure 1a. (The difference is that changing Mmax from 7.0 to 8.0 makes less difference than changing it from 6.0 to 7.0, reflecting non-linearity in ground motion scaling as a function of magnitude.)

Testing the effect of maximum magnitude with Bommer et al (2007) is complicated by the fact that the authors give two versions of the model, one with magnitude-dependent sigma (termed “heteroscedastic” by the authors) and one without (“homoscedastic”). In the latter case the sigma values are higher. With magnitude-dependent sigma, the result is similar to Figure 1a but less extreme; the curves for Mmax=7.0 and Mmax=8.0 almost overplot, but that for Mmax=6.0 does not. Using the fixed sigma values gives a separation of curves similar to that found with Campbell and Bozorgnia (2007), but with markedly high values overall (Figure 8).

This is symptomatic of a deeper problem. The scatter in a given empirical model reflects a number of different things. Leaving aside factors that can be modelled relatively easily, such as style of faulting, in a given database, the records for the combination of any given magnitude and distance may vary due to: differences in region, differences in path within a region, directionality effects, rupture complexity effects and path complexity effects. The first two of these are a function of mixing data from different sources, the others reflect inherent unpredictability. Combining these is essentially mixing some epistemic uncertainty into the aleatory variability, which is what Brune (1999) refers to as the “ergodic assumption”. In addition, imperfect meta-data increases the observed scatter. It was suggested at least as early as Musson et al (1997), that since the application of ground-motion sigma in PSHA is intended to account for true aleatory variability, it can be appropriate to reduce the published sigma by an arbitrary amount to try and remove some of the added uncertainty from epistemic contamination. Of course, the problem here is that it assumes that the median ground motion predictions from the model are exactly appropriate for the paths relevant to hazard at one’s site. In other words, although the aleatory variability is inflated due to the convolution of some epistemic uncertainty, applying an arbitrarily lower sigma value simply removes this element of epistemic uncertainty entirely.

However, the metadata issue is somewhat different. If it were the case that all, or a large amount, of the increased scatter observed at low magnitudes were due to meta-data problems (for instance, it is suggested by Musson and Sargeant 2007, that Joyner-Boore distance is inappropriate for small-magnitude earthquakes), then the scatter observed for large-magnitude events should be indicative of what would be obtained for smaller events given better metadata. In which case, there would be justification for taking the magnitude range that yields the smallest sigma values (subject to sufficient data) and taking the resulting sigma as appropriate for use over the entire magnitude range, with the justification that doing this eliminates the contribution from poorer metadata at lower magnitudes. If the higher sigma for lower magnitudes is only due to worse metadata, then this procedure would seem to be justified in a way that arbitrarily reducing the sigma is not, in that the reduction of sigma is achieved by removing only noise in the data, not true uncertainty, either aleatory or (convolved) epistemic.

Figure 8 is instructive, because the results of a PSHA study are supposed to be in some way a “true” statement about the real world. The two sets of curves in Figure 8 are very different, and can’t both be true. It is somewhat distressing that this very large change in results is obtained simply by a decision on the part of the analyst to choose Tables 2 and 3 from Bommer et al (2007) or Tables 4 and 5, which is not a decision that corresponds to any testable hypothesis, but is purely a methodological choice. One can put the question in this way: do we believe, as seismologists or engineers, that it makes a difference to the hazard (in terms of PGA), whether a site is subject to magnitude 5 to 6 earthquakes only, or whether it is subject to magnitudes up to 7 or even up to magnitude 8? If the answer is yes, then any model that produces results like Figure 1a should not be used for PSHA. If the answer is no, then any model that produces results like Figure 3a should not be used for PSHA (and one might also add that PGA is even worse as a measure of strong ground motion than reputed). Both can’t be correct. This is a simple and rather fundamental question about earthquake hazard.

From the reasoning already given, I would tentatively propose that both sets of curves in Figure 8 are incorrect as statements about the probability of strong ground motion at site. One set is influenced by noisy metadata into exaggerating the hazard from low-magnitude events; the other exports this noise over the whole magnitude spectrum, resulting in an overall increase in hazard values. It can further be speculated that a good part of this noise is due to the use of Joyner-Boore distance, which may be inappropriate for events with small ruptures that do not approach the surface. It is noticeable that Campbell and Bozorgnia (2007), which did not find magnitude-dependent scatter, also uses rupture distance, not Joyner-Boore distance. Ambraseys et al (2005) also use Joyner-Boore distance.

It is conjectured, therefore, that the scatter in the data around magnitude 6 Mw is a representative value of the true scatter once noise from the metadata has been subtracted. For Bommer et al (2007), this gives an overall sigma value of 0.23 for PGA, compared to a value of 0.35 in Table 5 of that paper. The comparable value for Ambraseys et al (2005) is 0.29. The effect of this is shown in Figure 9. The curves labelled BSAA should be compared in particular with the “b” curves in Figure 8. In fact, the BSAA curves in Figure 9 are remarkably consistent with those in Figure 3a.

Finally, in Figure 10 the Bommer et al (2007) curves from Figure 9, with sigma fixed at the 6.0 Mw value, are compared with the equivalent curves from Campbell and Bozorgnia (2007). There is remarkable agreement, the main difference being that Campbell and Bozorgnia (2007) predict higher PGA values when maximum magnitude is 7.0 Mw.

Conclusions

Ground motion models for use in PSHA should be chosen with care. It is not sufficient that a model should represent the input data, even if the input data is of good quality. The form of the model used may have implications when extrapolated in low probability hazard analysis. Merely comparing median ground motion curves for a given magnitude can be misleading. Priority should be given to models that are sensitive to all parts of the magnitude-distance domain, and that can take into account that simple linear scaling within this domain is unrealistic.

Particular reservations apply to the modelling of aleatory uncertainty in ground motion using a magnitude-dependent approach. Whether or not this is found in the input data, when applied in PSHA it leads to the conclusion that maximum magnitude is an irrelevant parameter, and that hazard is the same no matter what is the largest event a site is exposed to. This cannot be realistic. Ground motion models that lead to unrealistic conclusions should not be used. It is suggested that, if an apparent correlation between scatter and magnitude is, in fact, due to poorer metadata for smaller events (especially as regards distance), then the observed scatter for higher magnitudes (around 6 Mw) is probably representative of the true uncertainty for the whole magnitude range.

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Figure Captions

Note: All figures are plotted to the same scale to aid comparison.

Figure 1

(a) Hazard curves for a high hazard site, showing effect of changing maximum magnitude. Ground motion model is ADSS05, parameter is PGA.

(b) Hazard curves for a high hazard site, showing effect of changing maximum magnitude. Ground motion model is ADSS05, parameter is 2 s SA, 5% damping.

Figure 2

Hazard curves for a high hazard site, showing effect of changing maximum magnitude. Ground motion model is ADSS05, parameter is PGA. A limit to the aleatory scatter of three sigma is applied.

Figure 3

(a) Hazard curves for a high hazard site, showing effect of changing maximum magnitude. Ground motion model is ASB96, parameter is PGA.

(b) Hazard curves for a high hazard site, showing effect of changing maximum magnitude. Ground motion model is ASB96, parameter is 2 s SA, 5% damping.

Figure 4

Hazard curves for a low hazard site, showing effect of changing minimum magnitude. Ground motion model is ADSS05, parameter is PGA.

Figure 5

Hazard curves for a low hazard site, showing effect of changing minimum magnitude. Ground motion model is ASB96, parameter is PGA.

Figure 6

Hazard curves for a high hazard site, comparing the ground motion models of Ambraseys et al (2005), Ambraseys et al (1996), Bommer et al (2007) and Campbell and Bozorgnia (2007). Mmax is 7.0, Mmin is 5.0, parameter is PGA.

Figure 7

Hazard curves for a low hazard site, comparing the ground motion models of Ambraseys et al (2005), Ambraseys et al (1996), Bommer et al (2007) and Campbell and Bozorgnia (2007). Mmax is 6.5, Mmin is 4.0, parameter is PGA.

Figure 8

Hazard curves for a high hazard site, showing effect of changing maximum magnitude. Ground motion model is Bommer et al (2007), parameter is PGA. The “a” series of curves is the heteroscedastic model, the “b” series the homoscedastic model, i.e. sigma either is (a) or isn’t (b) correlated with magnitude.

Figure 9

Hazard curves for a high hazard site, showing effect of changing maximum magnitude, comparing the ground motion models of Bommer et al (2007) and Ambraseys et al (2005); parameter is PGA. Sigma is fixed at the value for 6.0 Mw in both cases.

Figure 10

Hazard curves for a high hazard site, showing effect of changing maximum magnitude, comparing the ground motion models of Bommer et al (2007) and Campbell and Bozorgnia (2007); Sigma is fixed at the value for 6.0 Mw for Bommer et al (2007) as in Figure 9.

Figures

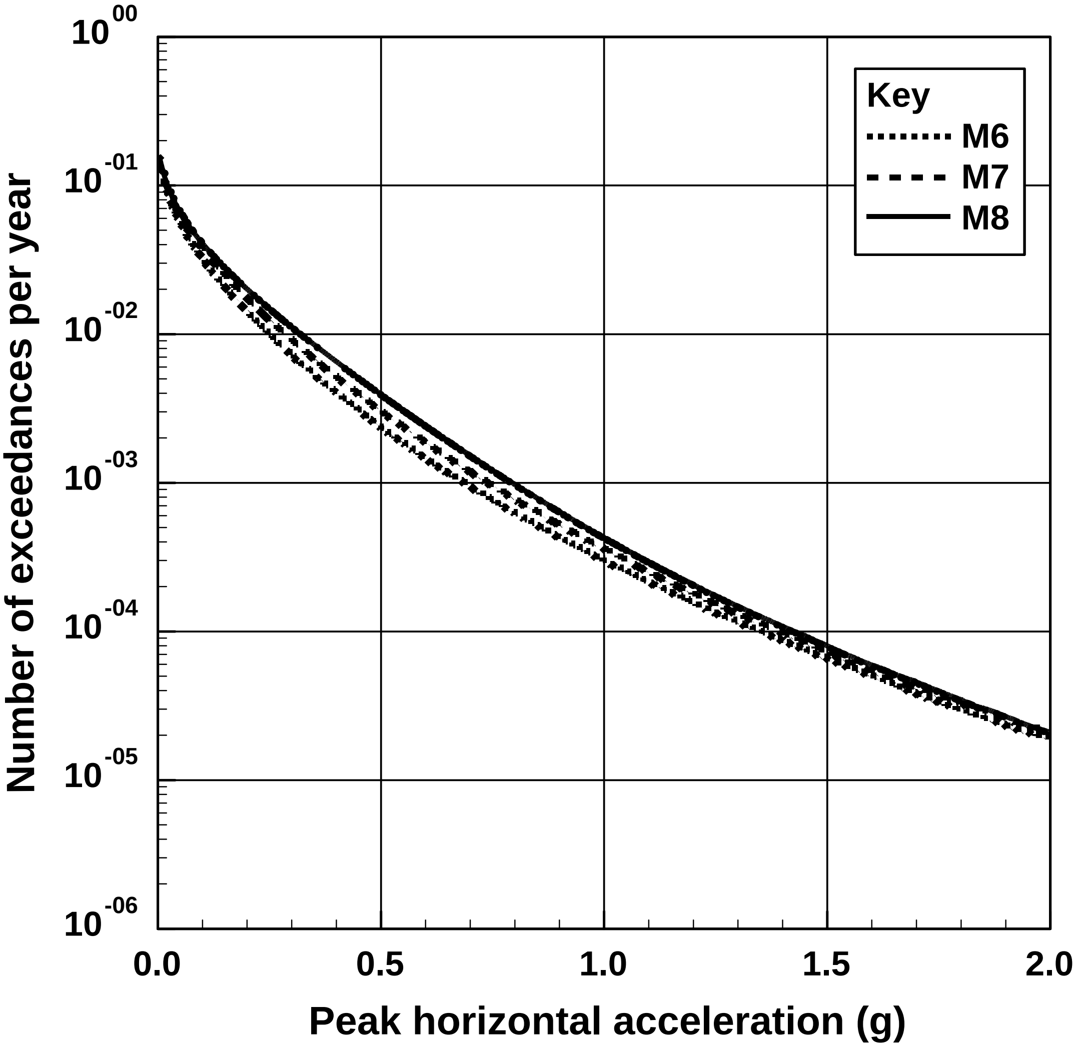


Figure 1 (a)

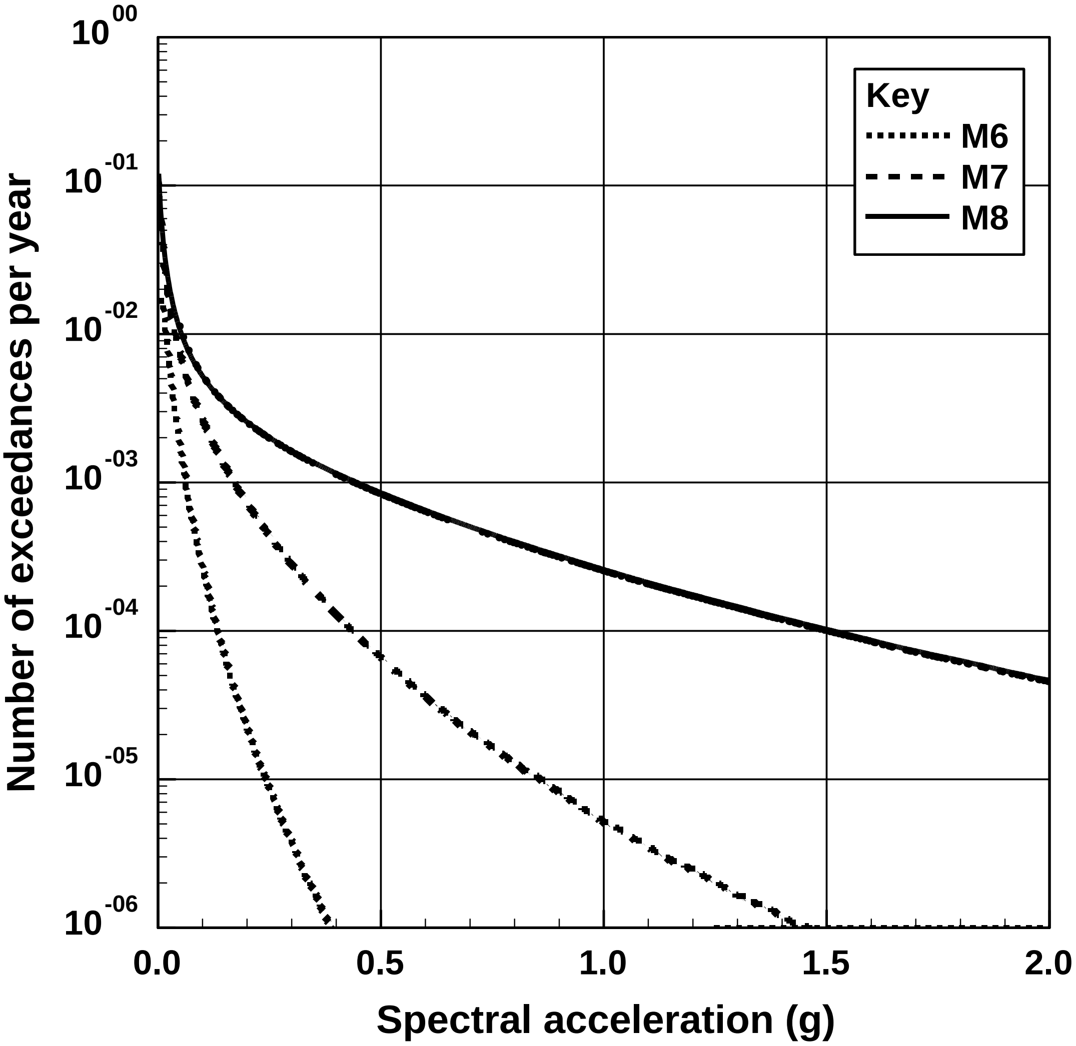

10^00
10^-01
10^-02
10^-03
10^-04
10^-05
10^-06
Number of exceedances per year
0.0
0.5
1.0
1.5
2.0
Spectral acceleration (g)
Key
M6
M7
M8

Figure 1 (b)

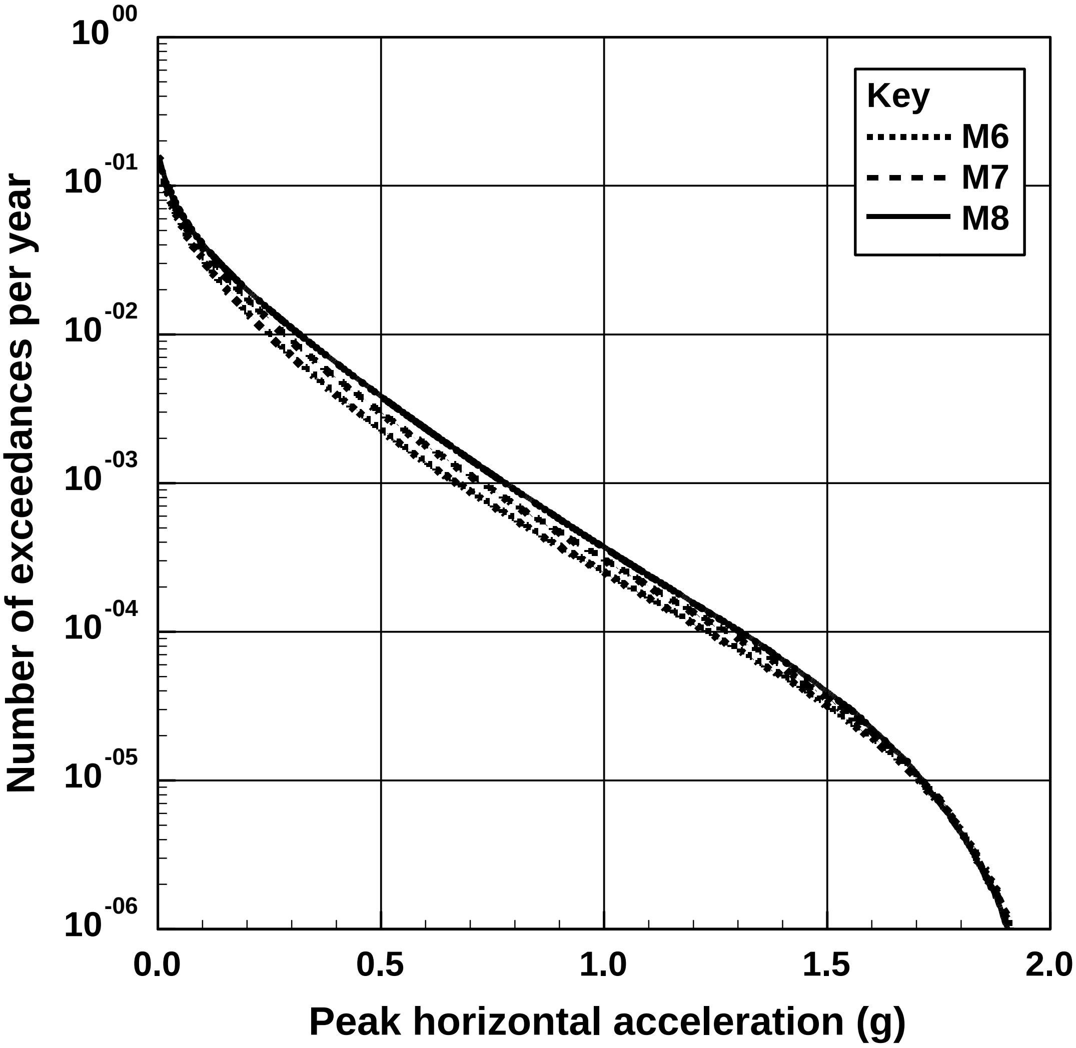
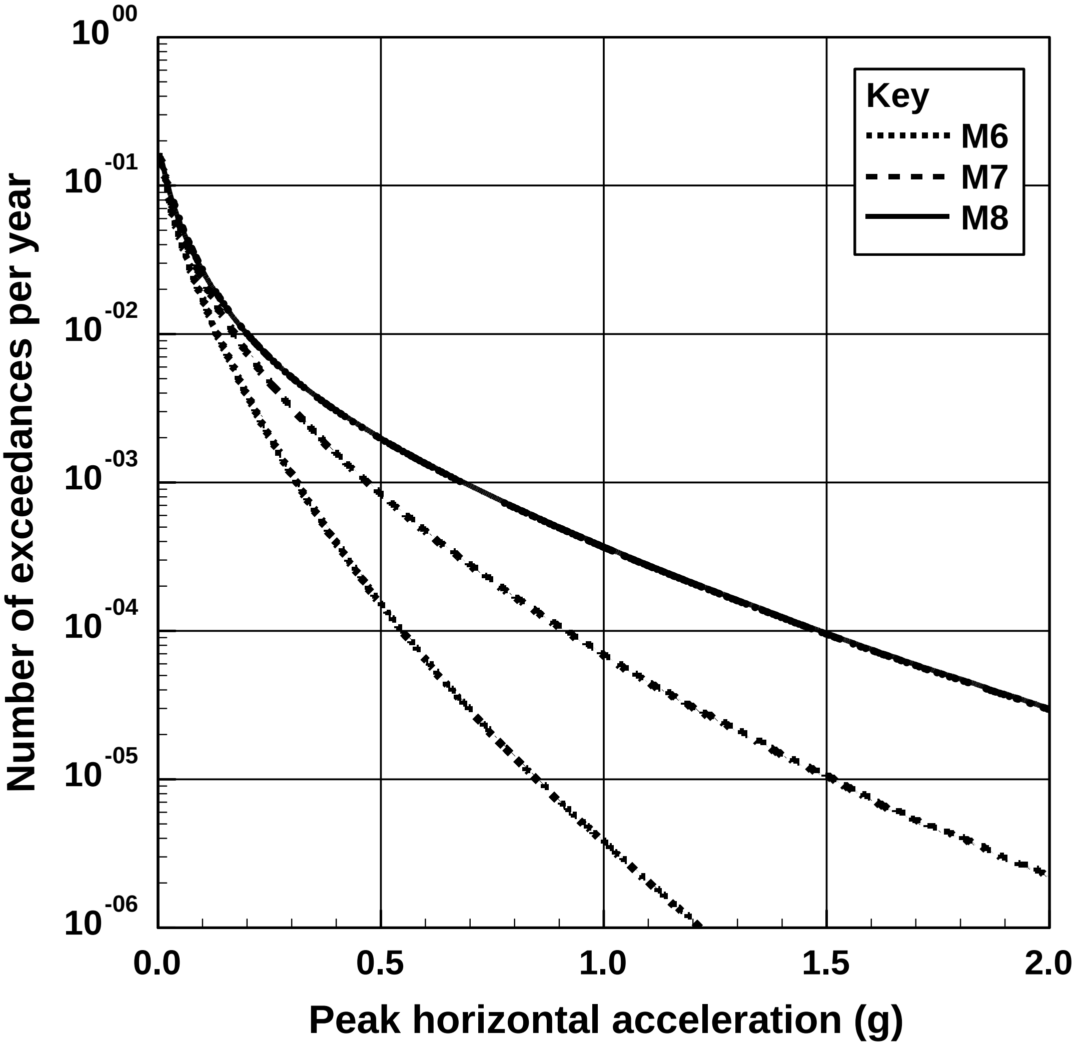

Key
M6
M7
M8
Number of exceedances per year
10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)

Figure 2



Key
M6
M7
M8
10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
Number of exceedances per year
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)

Figure 3 (a)

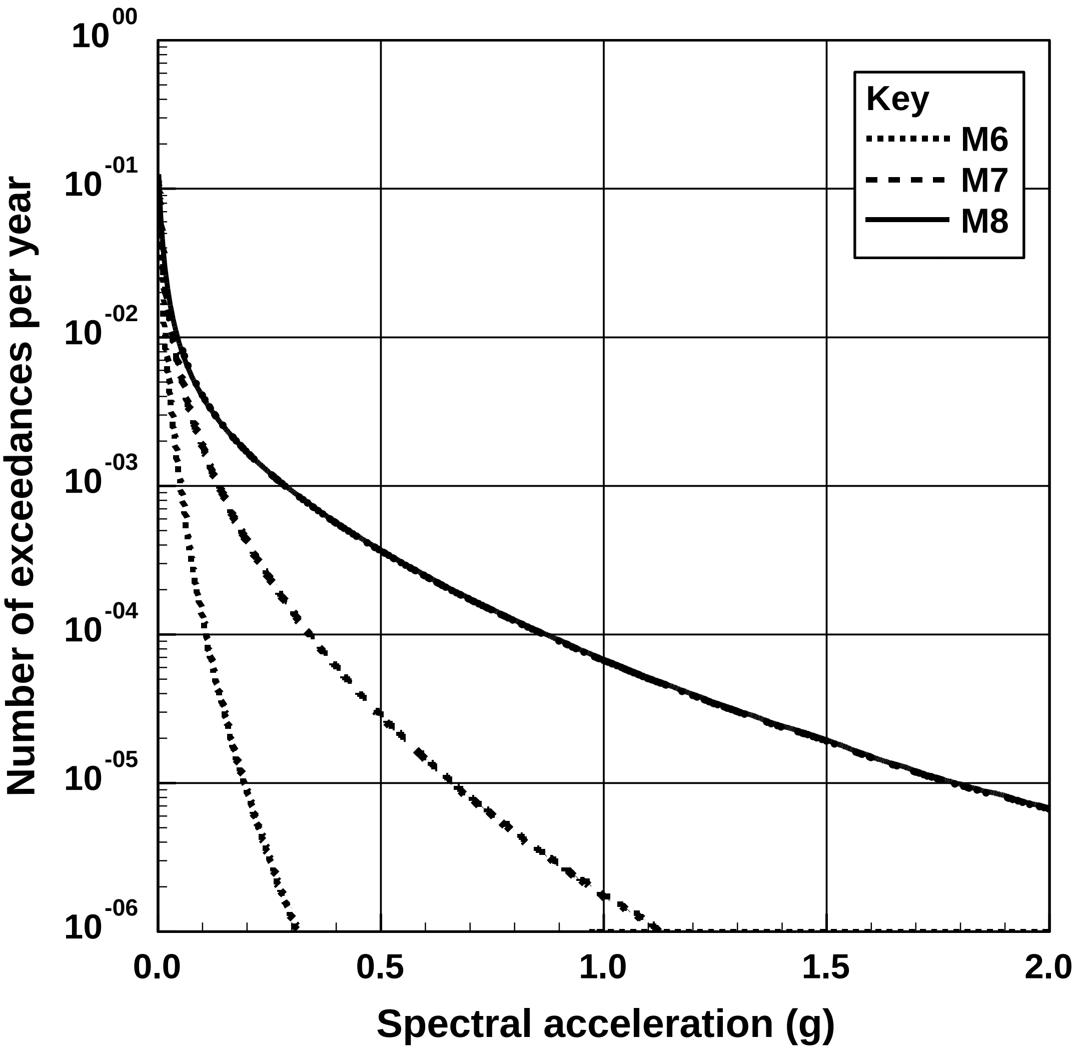

Key
M6
M7
M8
10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
Number of exceedances per year
0.0
0.5
1.0
1.5
2.0
Spectral acceleration (g)

Figure 3 (b)

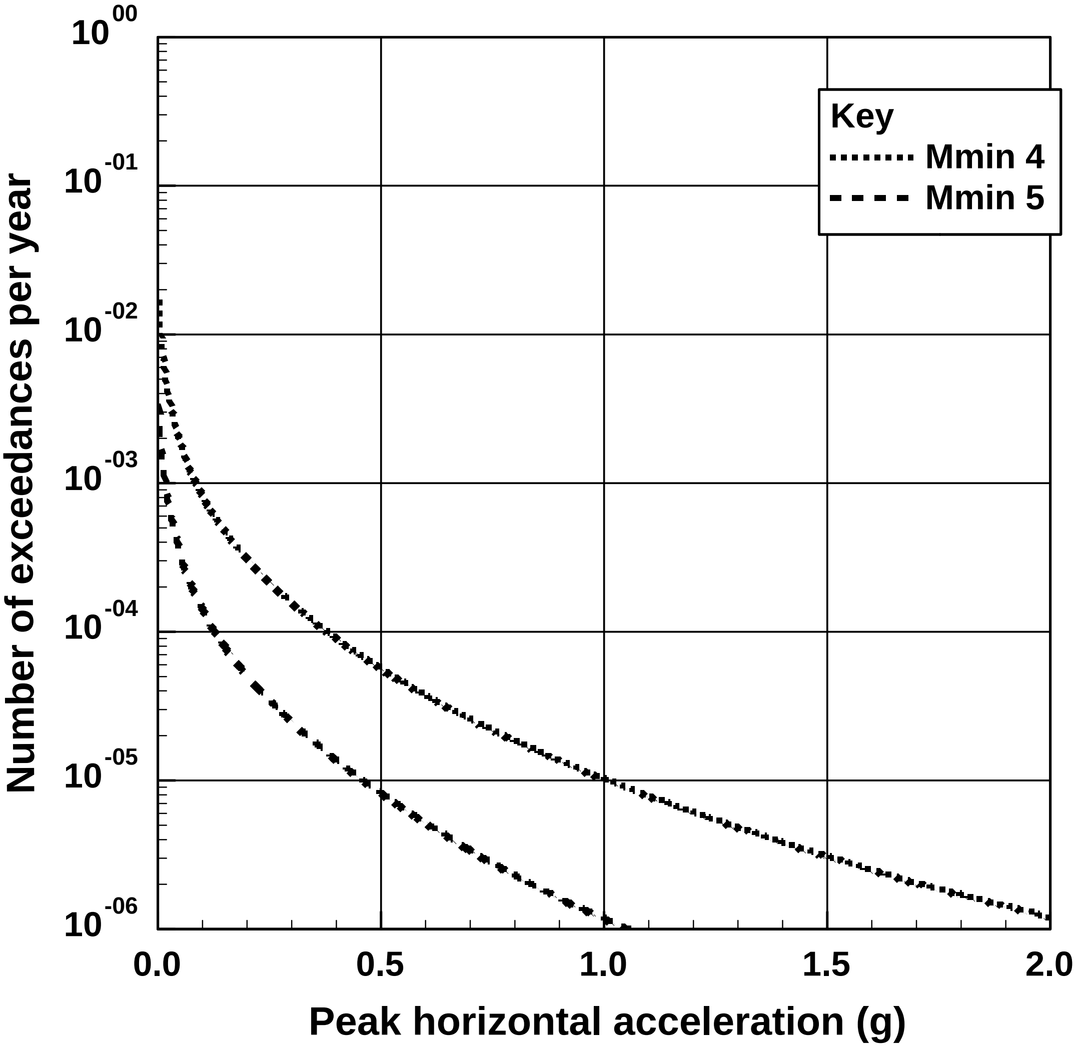
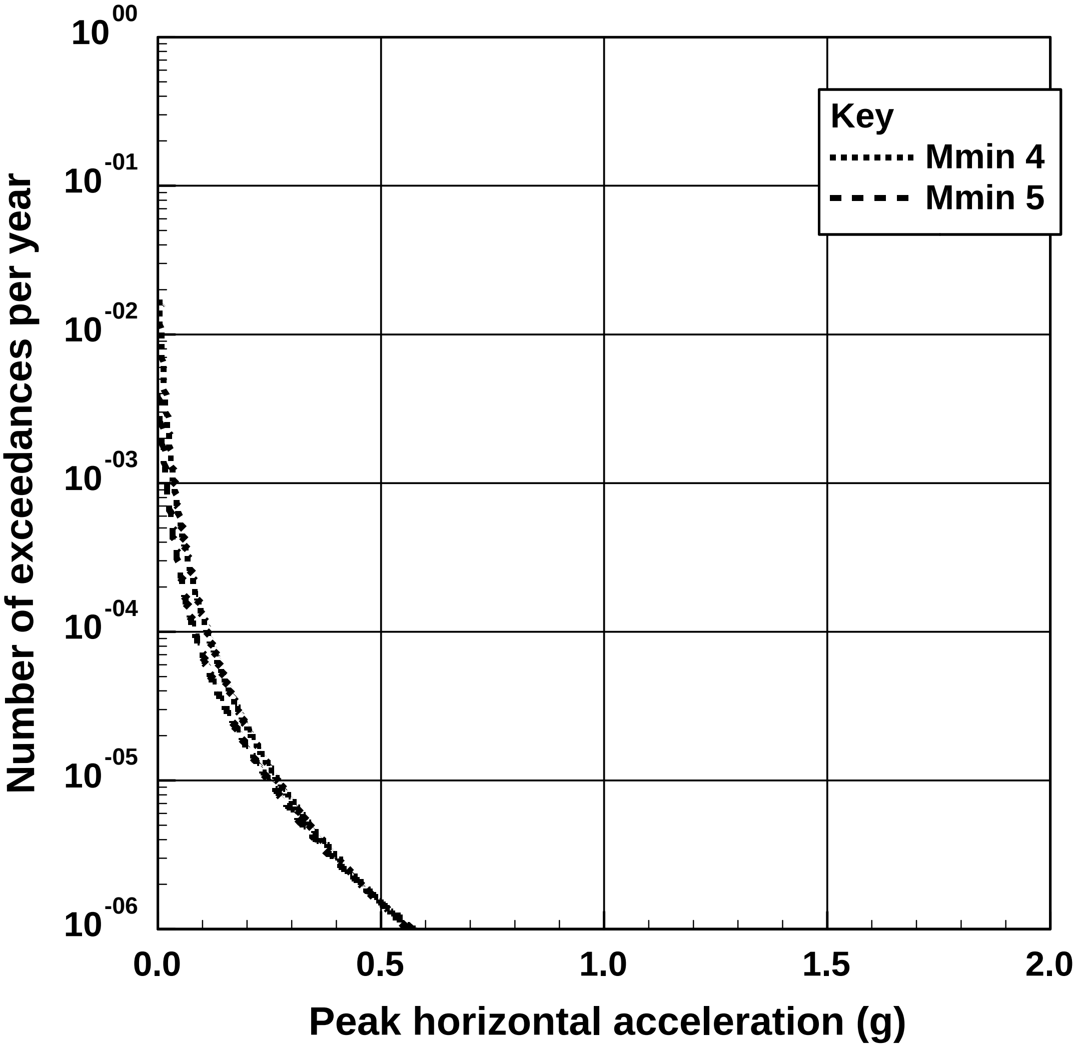

10^00
10^-01
10^-02
10^-03
10^-04
10^-05
10^-06
Number of exceedances per year
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)
Key
Mmin 4
Mmin 5

Figure 4



10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
Number of exceedances per year
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)
Key
Mmin 4
Mmin 5

Figure 5

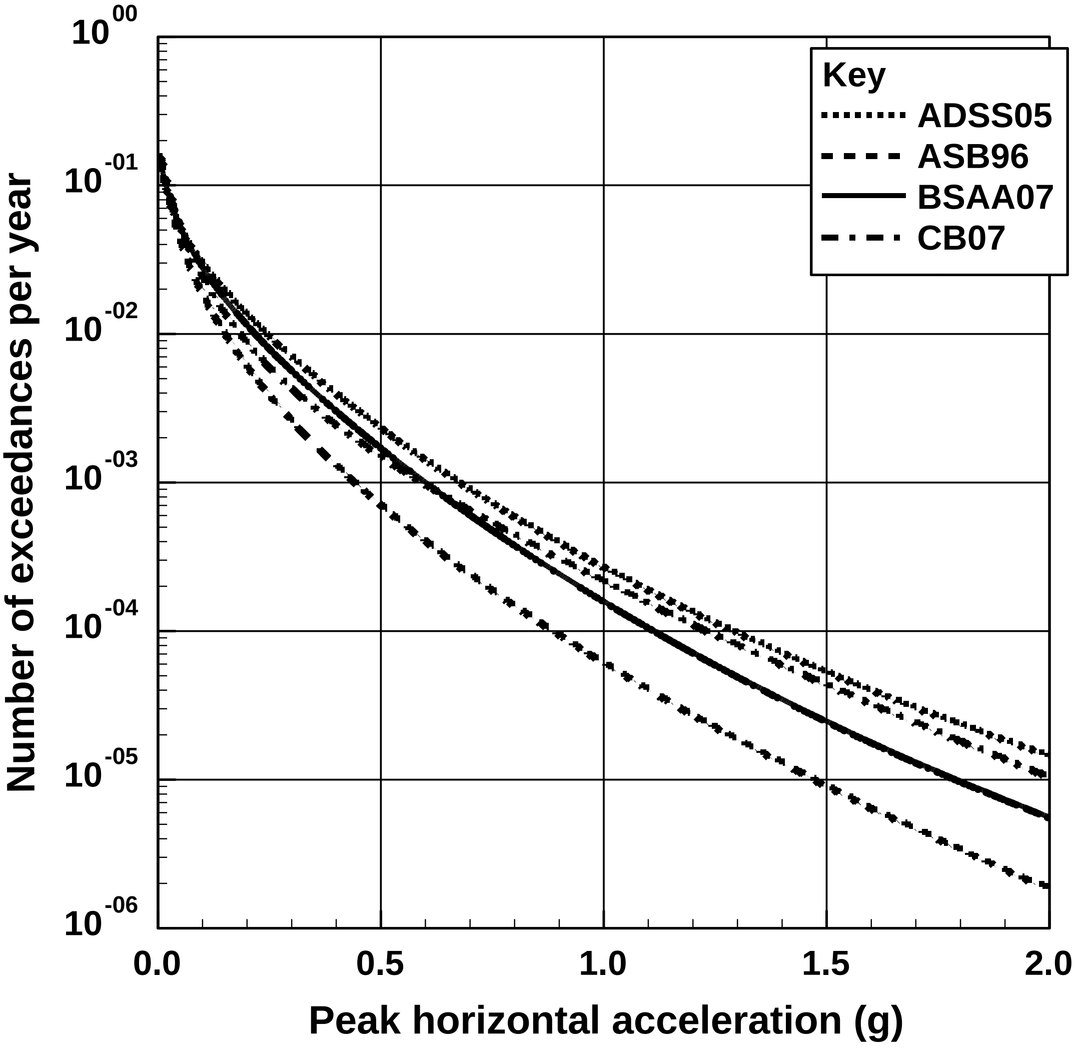
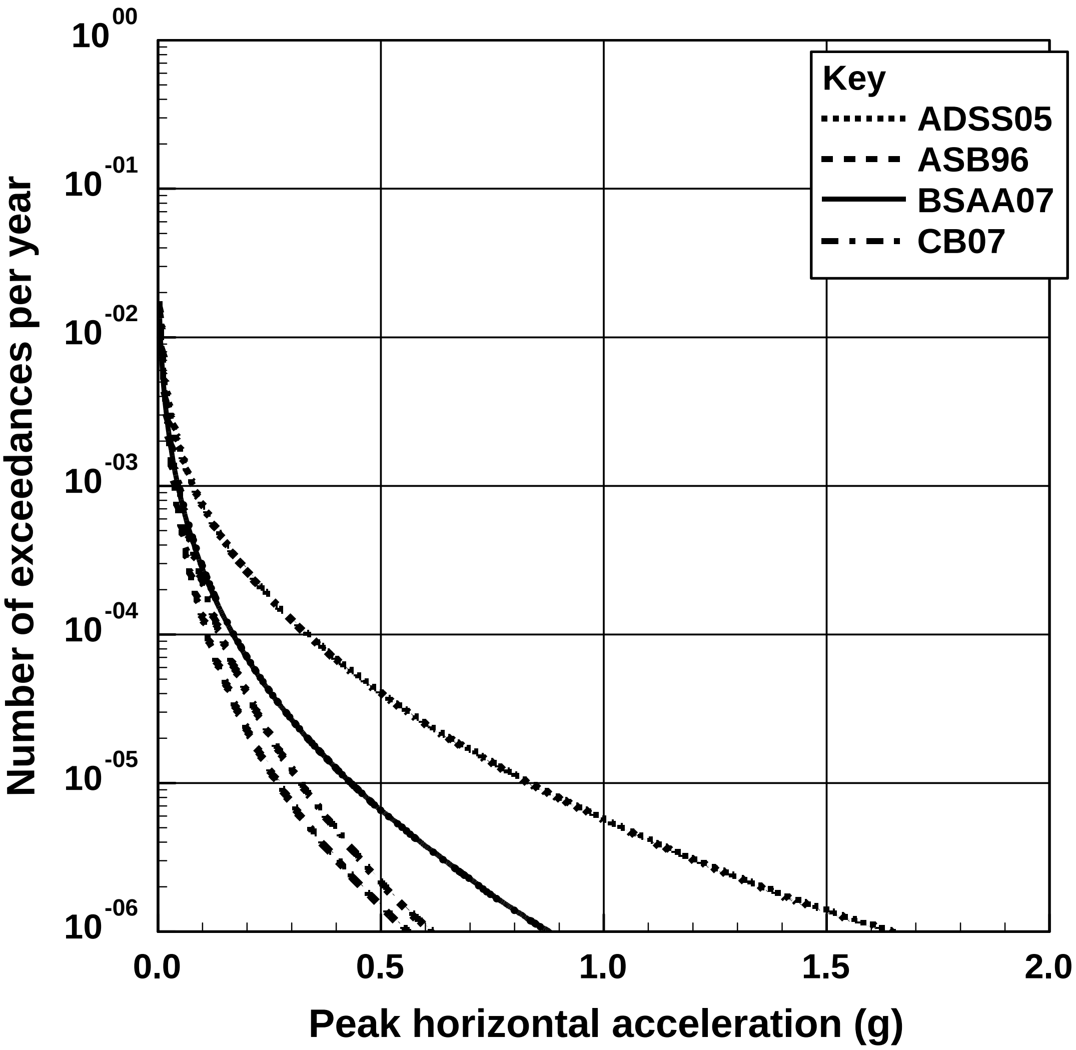

Key
ADSS05
ASB96
BSAA07
CB07
Number of exceedances per year
10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)

Figure 6



Number of exceedances per year
10^00
10^-01
10^-02
10^-03
10^-04
10^-05
10^-06
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)
Key
ADSS05
ASB96
BSAA07
CB07

Figure 7

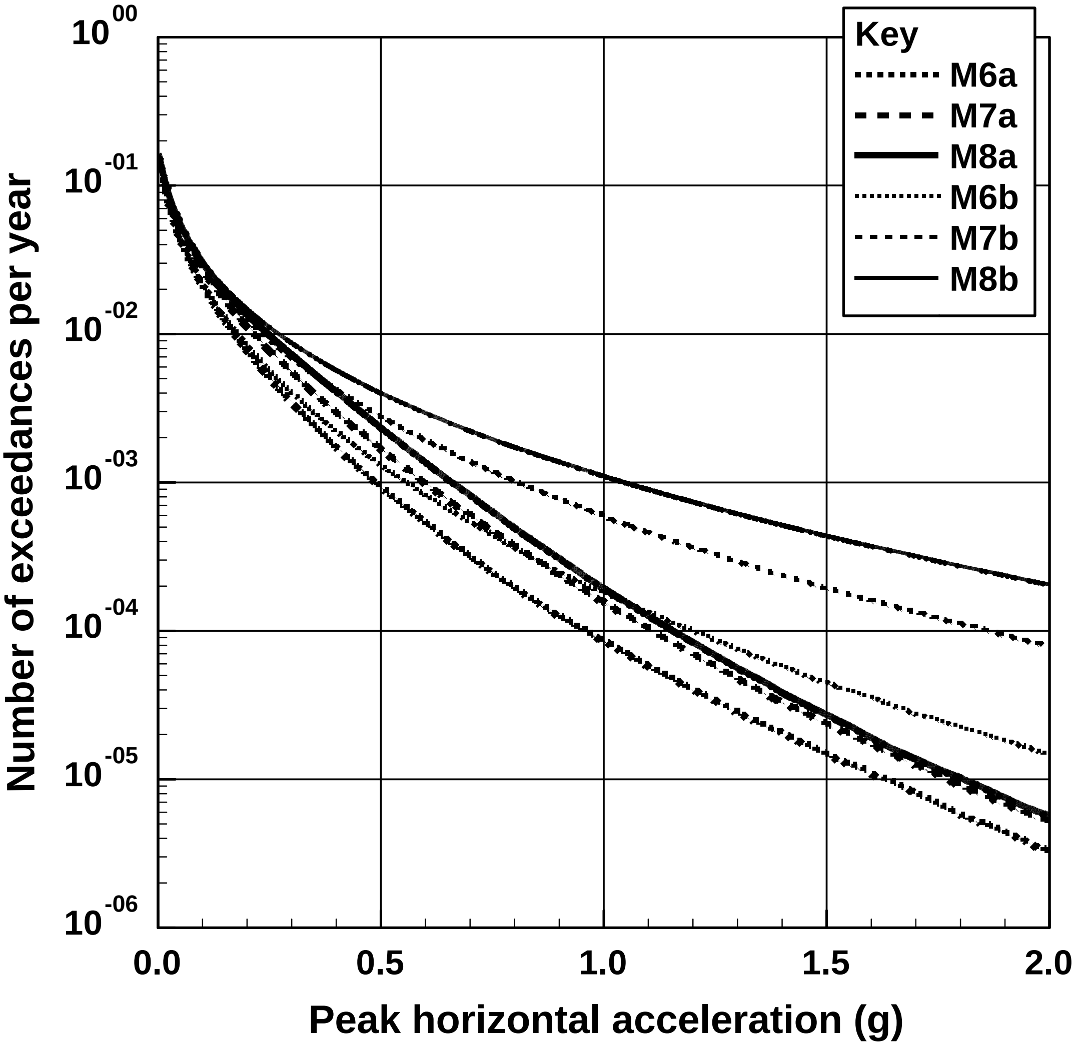

Key
M6a
M7a
M8a
M6b
M7b
M8b
10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
Number of exceedances per year
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)

Figure 8

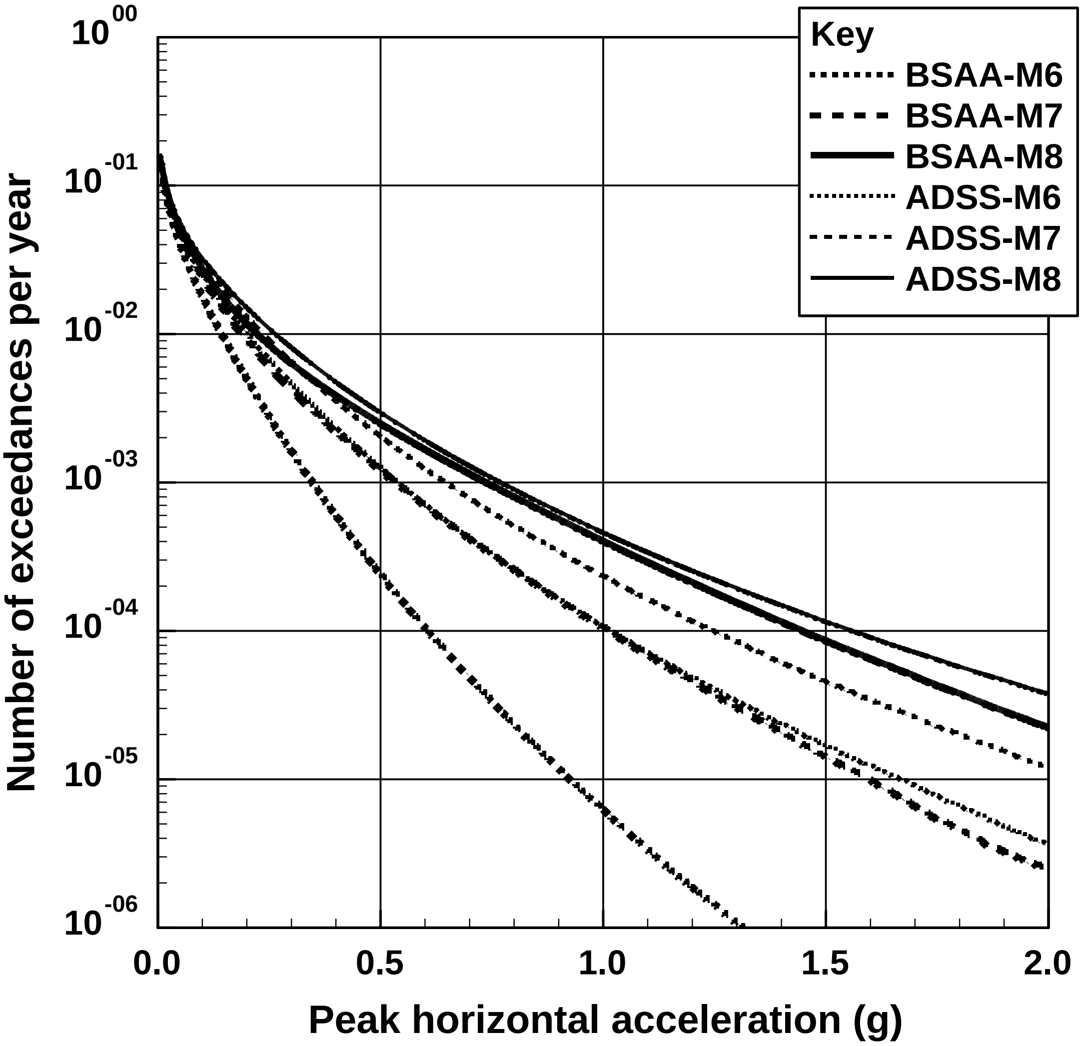

Key
BSAA-M6
BSAA-M7
BSAA-M8
ADSS-M6
ADSS-M7
ADSS-M8
10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
0.0
0.5
1.0
1.5
2.0
Number of exceedances per year
Peak horizontal acceleration (g)

Figure 9

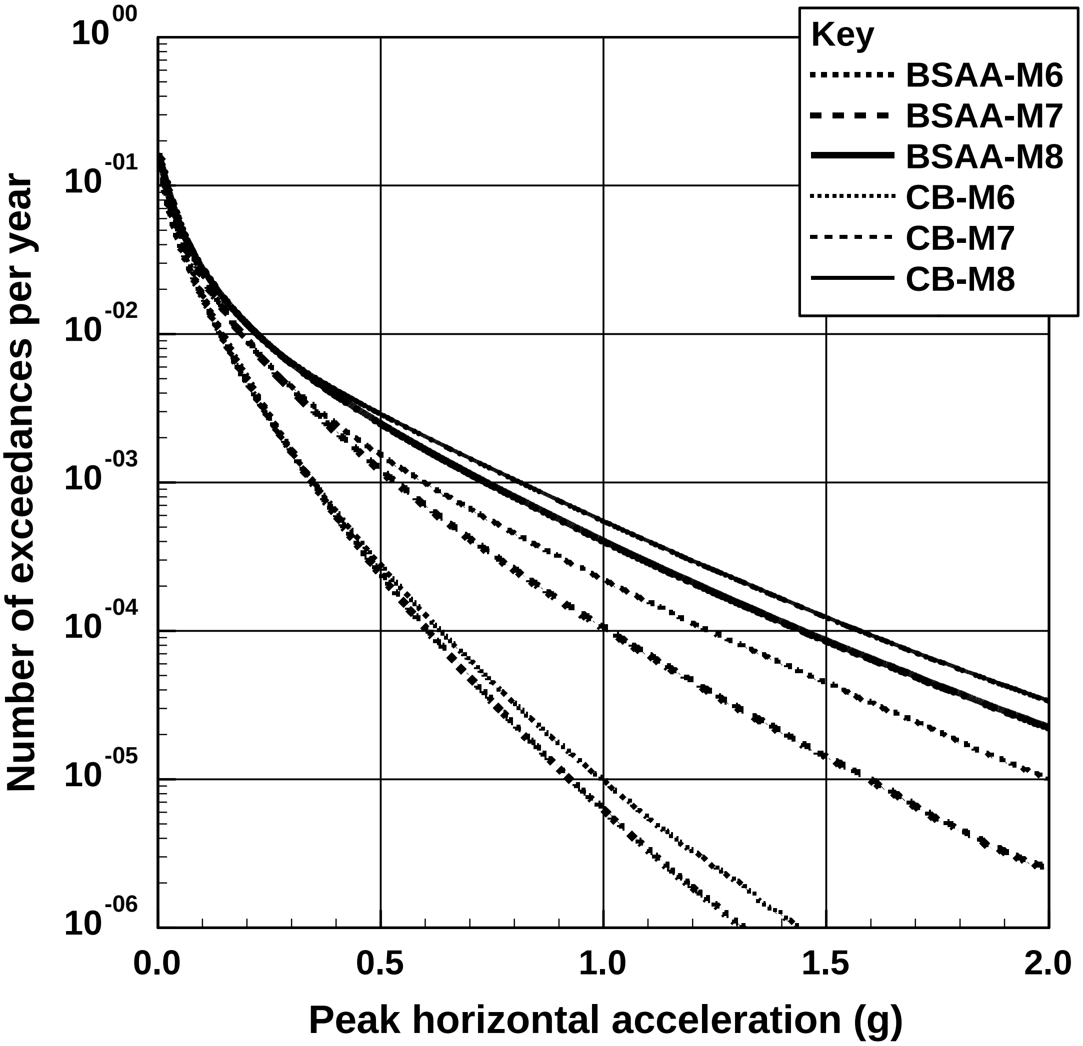

Key
BSAA-M6
BSAA-M7
BSAA-M8
CB-M6
CB-M7
CB-M8
Number of exceedances per year
10^{00}
10^{-01}
10^{-02}
10^{-03}
10^{-04}
10^{-05}
10^{-06}
0.0
0.5
1.0
1.5
2.0
Peak horizontal acceleration (g)

Figure 10