An Overview of the Largest Amplitudes in Recorded Ground Motions

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SUMMARY:
The amplitudes of the strongest observed ground motions are useful to evaluate the results of seismic hazard analysis. The author has previously compiled a set of 255 records intended to include as many as possible of the strongest openly-available strong ground motions. In that compilation, the largest 100 accelerograms had vector pga over about 750 cm/s^2, and the largest 100 velocities had vector pgv over about 75 cm/s. This paper extends the earlier results to response spectra, and identifies PSA response spectra with approximately the same occurrence rates. This paper also extends the original compilation with the addition of more recent data and a few previously overlooked records. The extended compilation includes 409 records, including 71 with pga over 1 g and 41 with pgv over 1 m/s.

Keywords: strong motion, engineering seismology, extreme ground motion, seismic hazard analysis

1. INTRODUCTION

Anderson (2008, 2010) compiled 255 strong motion records (from 82 earthquakes) for which either peak acceleration on one component exceeded 500 cm/s2 or peak velocity on one component exceeded 50 cm/s. Anderson referred to such accelerograms as “exceptional”, using the word exceptional with the same meaning as when one says it was “an exceptionally rainy month”. This collection of records will be referred to as the “2010 compilation”.

There are several motivations to compile the strongest records into one place. First, the results provide a context by which to evaluate the strong motion records from any earthquake. Second, the strongest records can be examined in order to understand those conditions that are associated with the highest levels of shaking. Contributing factors that can be considered include tectonic and geological setting, focal mechanism, fault-station geometry including rupture kinematics, stress drop on the fault as a whole and on asperities, and site conditions. Third, if there are upper bounds to the peak acceleration or peak velocity caused by tectonic earthquakes, the results will provide constraints on those bounds.

Another motivation for Anderson (2008, 2010) was to compare these results with the predictions of probabilistic seismic hazard analysis (PSHA) for the most critical facilities, such as large dams and nuclear power plants. PSHA results at very low probabilities (e.g. less than 10^{-4} per year) are quite sensitive to the aleatory uncertainty in ground motion prediction equations (e.g. Sabetta et al, 2005; Bommer and Abrahamson, 2006). Key examples come from seismic hazard analyses for nuclear facilities at Yucca Mountain, Nevada (Stepp, 2001) and in Switzerland (Abrahamson et al, 2002). At exceedance rates of 10^{-6}, 10^{-7}, and 10^{-8} per year, the Yucca Mountain study computed peak accelerations of 2.9 g, 5.8 g, and 11 g, and peak velocities of 3.0 m/s, 6.5 m/s, and 14 m/s (Stepp, 2001; Hanks et al, 2005, 2006; Wong et al, 2006). Evidence bearing on whether these results are reasonable may come from reexamination of how uncertainty is treated (e.g. Anderson and Brune,

1999) or from survival of precarious rocks (e.g. Brune, 1996, 1999). Knowledge of the largest motions that have been observed to date is also needed to inform an evaluation of these computations.

Anderson (2010) reported on the occurrence of peak acceleration and peak velocity, but not the values of others of the many parameters that are frequently used to measure the strength of ground motions. This paper extends the prior results to response spectra. This paper also adds 154 accelerograms, predominantly from the 2011 Tohoku, Japan, earthquake and aftershocks. A project to incorporate as many as possible of the recent openly-available accelerograms is underway, and this expansion of the compilation is the result of progress towards those project goals.

2. CHARACTERISTICS OF THE COMPILED DATA SET

At the time of this writing, the 2010 compilation has been expanded to 409 accelerograms (110 earthquakes). The most recent event occurred in Japan in March, 2012. However, 2008-2011 data from other countries has not yet been included systematically. This set of records will be referred to as the "2012a compilation". Figure 1 shows the locations of all earthquakes in the 2012a compilation. The map shows that the distribution of sources is global, but also that data from Japan and California are the most prevalent. Figure 2 shows locations of Japanese earthquakes, and Figure 3 shows locations of California earthquakes that are included in this study.

Figure 4 shows some statistical characteristics of the 2012a compilation. This figure shows several expected characteristics of the data. The rate of data collection has increased with improved instrumentation, but is also influenced by clusters of earthquakes. Below M~6.5, where the most data is available to establish a trend, the empirical upper bound on peak accelerations are showing only a weak magnitude dependence, as expected from, e.g., Hanks and McGuire (1981). The distribution of peak velocity below M~6.5 appears to be bounded by an increasing upper bound. From Figure 4 there are 71 records with a_{max} , measured as the magnitude of a three-component vector, that are larger than 1 g, and 41 records with v_{max} larger than 1 m/s.

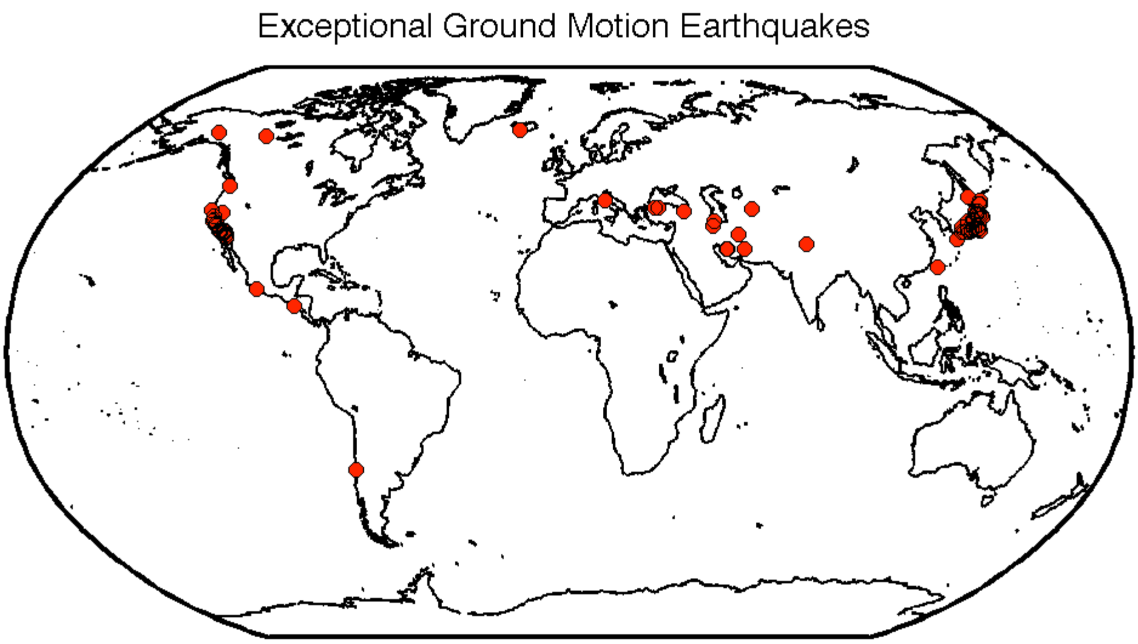

Figure 1. Epicenters of earthquakes causing openly available accelerograms with exceptional ground motions and reported in this study.

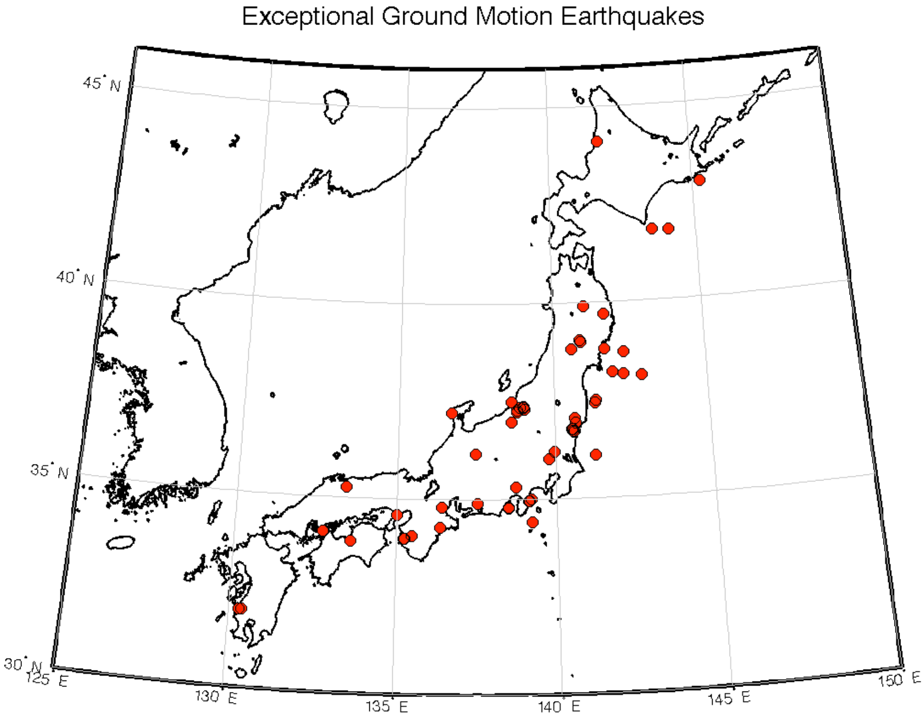

Figure 2. Epicenters of Japanese earthquakes causing exceptional ground motions reported in this study.

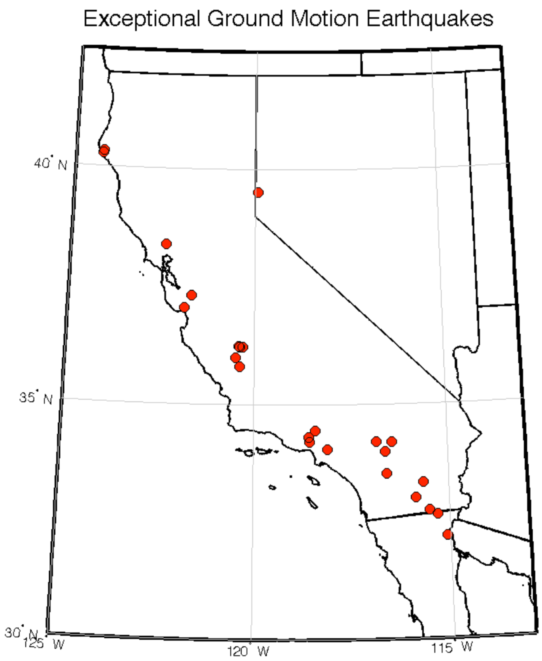

Figure 3. Epicenters of California and Nevada earthquakes causing exceptional ground motions reported in this study.

All records have been high-pass filtered with a corner frequency of 0.05 Hz or higher. Response spectra have been calculated for 280 periods from 0.01 s to 100 s. To be specific, the calculations determine the displacement response (Sd) with damping parameter h=5%. For this paper, however, the spectral values shown are $PSA=(2\pi/T_n)^2Sd(T_n)$. There is legitimate concern that the long periods are contaminated by instrument or processing noise on many of the records. Note however that the long period asymptote of the response spectrum is asymptotic to the peak ground displacement. Thus provided the integration to displacement is stable, the filtering will tend to cause the long periods of the spectrum to be underestimated, rather than overestimated. For that reason, this paper proceeds to present the full calculated period range even though the long period asymptotes, being dependent on the filter parameters, are more uncertain than are the short period estimates.

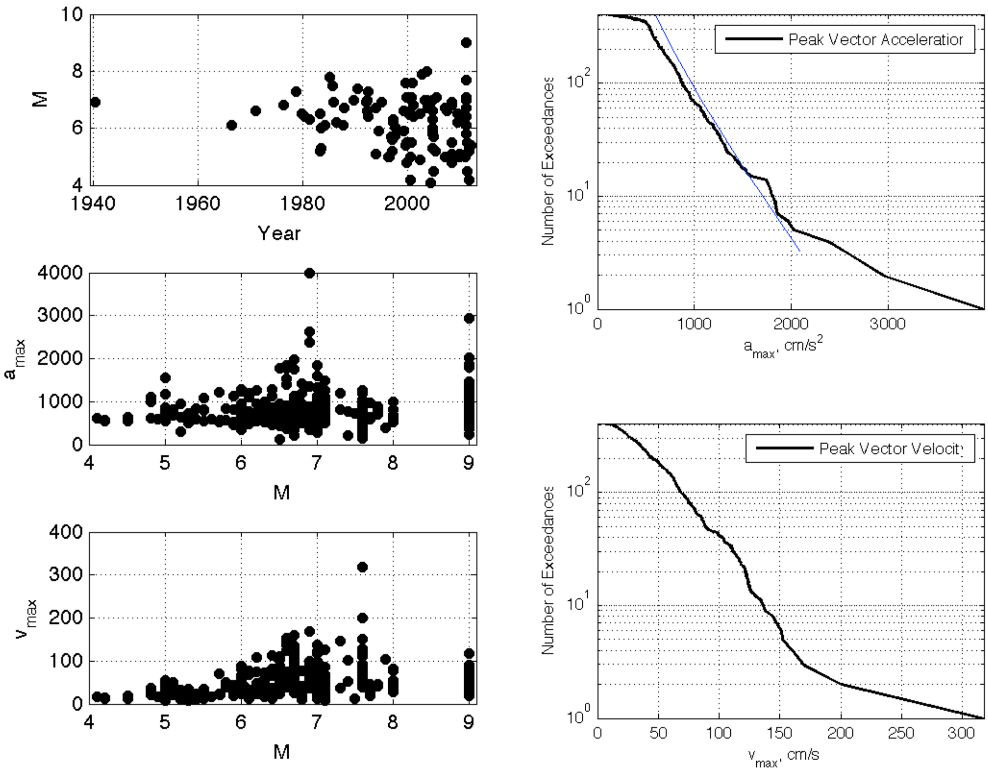

Figure 4. Characteristics of the 409 accelerograms in the 2012a compilation of exceptional ground motions. Left column, magnitude vs occurrence time, peak acceleration vs magnitude, and peak velocity vs magnitude. Right column, number of records exceeding the peak acceleration (top) or peak velocity (bottom) on the abscissa. The blue line compared with the exceedance rate for peak acceleration is the hazard curve for San Bernardino, California, prepared by the US Geological Survey (Petersen et al., 2008), scaled as discussed in the text.

3. RESPONSE SPECTRA OF EXCEPTIONAL GROUND MOTIONS

Figures 5 and 6 show the distribution of the maximum values of the response spectra, in the 2012a compilation, at 16 selected periods. The distribution is created by compiling the value of PSA at the selected period from all accelerograms in the database. The values shown are the larger horizontal component value at each period, without rotation. To generate these figures, the values are sorted from strongest to smallest. The strongest is assigned the rank of 1, the second is assigned the rank of 2, and so on. Thus the rank gives the number of records in the compilation with PSA equaling or exceeding the value corresponding to that record. Figure 5 shows these ranks for periods T_n between 0.01 s and 0.5 s. Figure 6 shows the ranks for selected periods from 1.0 s and 100 s.

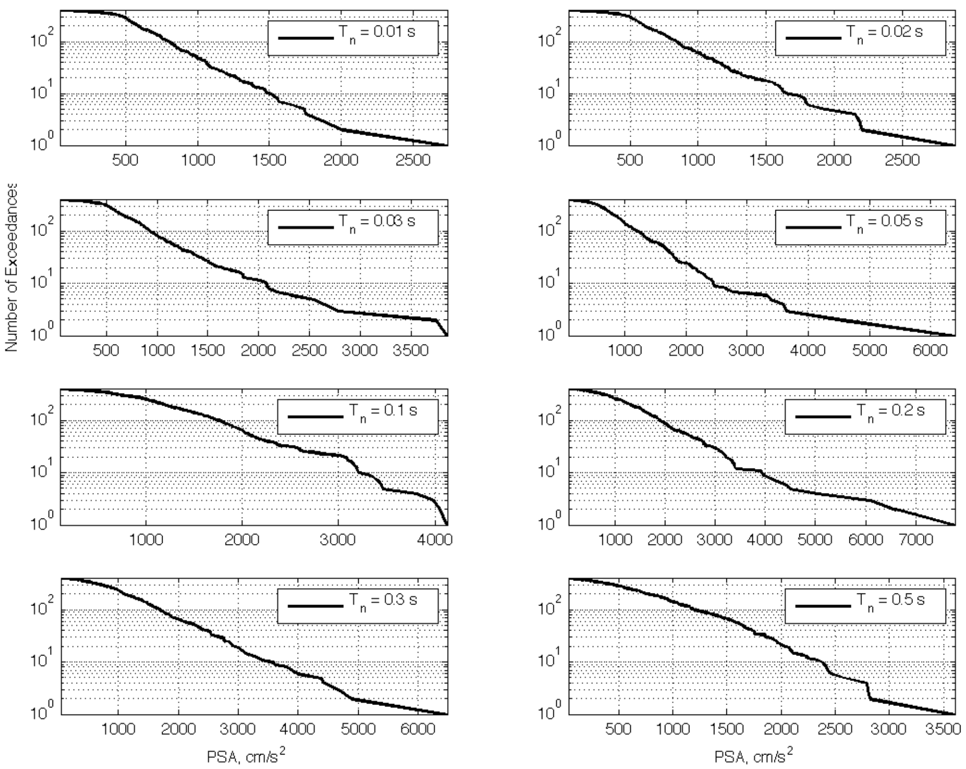

Figure 5. Distribution of the maximum values of PSA response spectra for 409 accelerograms in the 2012a compilation, for oscillator periods T_n between 0.01 s and 0.5 s.

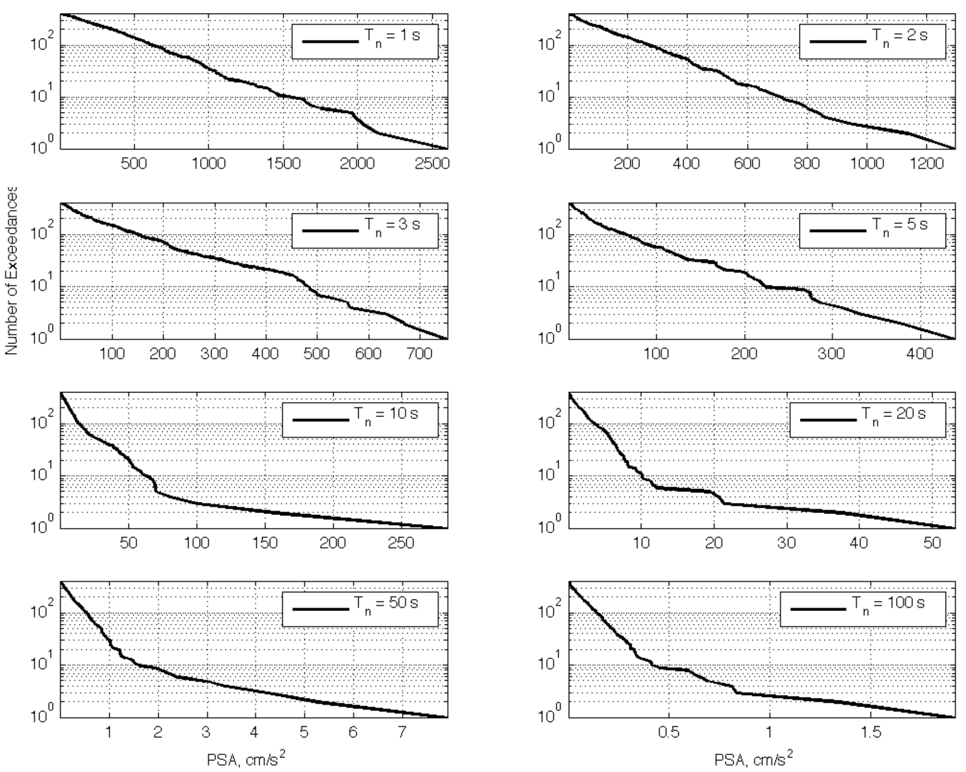

Figure 6. Distribution of the maximum values of PSA response spectra for 409 accelerograms in the 2012a compilation, for oscillator periods T_n between 1.0 s and 100 s. Note that the long periods, which are proportional to the peak displacement on the record, are affected by filter parameters.

There is, of course, no physical reason to expect that these curves should follow any particular well-behaved mathematical shape. An effort to predict the shape would involve some weighted average of the hazard curves determined by probabilistic seismic hazard analysis at each of the strong motion sites that is represented. Figures 5 and 6 are plotted with a logarithmic y-axis primarily because this makes the most readable graph. This arbitrary choice of axes does suggest a test for a particular distribution, however. A linear relationship on these axes indicates that the number of accelerograms exceeding the value of PSA on the abscissa is decreasing exponentially with increasing amplitude. In fact, the figures suggest that the linear relationship works reasonably well for periods T_n<=5.0 s. For T_n >=10 s, the distributions show a distinct bend, or might be described as concave upwards. The net effect is that there are more points at these periods with large amplitudes than might be expected from an exponential fit to the curves at smaller amplitudes. If one must fit a curve to these long-period distributions, a power law might have smaller residuals.

Based on curves like those in Figures 4, 5, and 6, it is possible to extend the definition of exceptional ground motions to the response spectral domain. Anderson (2010) labeled as "exceptional" those records with a vector peak acceleration exceeding 750 cm/s^2 and vector peak velocity exceeding 75 cm/s. Those amplitudes occurred about 100 times in the 2011 compilation. Thus an approximately equivalent relationship for response spectra, meaning a selection of ground motions with approximately the same occurrence rate in the strong motion database, can be associated with the values of SA at any period that have been exceeded 100 times in the same data set.

However, it is perhaps slightly more meaningful to consider amplitudes exceeded about 150 times in that original data set. The reason is that Anderson (2010) estimated that the 2010 compilation incorporated the highest records from about 150,000 instrument years of observations. That estimate was admittedly very approximate, but to the extent that it is reasonable, the top 150 records would represent the level of ground motion occurring with the rate of $\sim 10^{-3}$ per instrument-year in the compilation. Similarly, the top 15 records would represent the level of ground motion occurring with the rate of 10^{-4} per instrument-year in the compilation. Since round numbers like these rates are perhaps slightly more intuitive, if not more meaningful, this paper suggests the amplitudes obtained with this criterion as the threshold of "exceptional" ground motions.

Figure 7 shows the PSA response spectra of all 409 accelerograms used in this study. In addition, it shows the values of PSA_{150} and PSA_{15}, and the current empirical upper bound for all 280 periods considered. The current empirical upper bound is clearly caused by a contribution from many earthquakes. In fact, 22 different seismograms contribute to the current empirical upper bound at some period.

Table 1 lists "PSA[10^{-3} per instrument-year]" and "PSA[10^{-4} per instrument-year]" values determined following the above description. The actual values of PSA exceeded exactly 150 times, have been rounded and smoothed in Table 1, as more than two significant figures would have no meaning. Table 1 also shows the results of the same exercise, seeking PSA exceeded about 15 times in the 2010 compilation. Finally, Table 1 gives the current empirical upper bound of all observations in the 2012a compilation.

If one were to try to predict the numbers of exceedances in Figures 4, 5, and 6, the procedure would probably involve a weighted average of the exceedance rate curve obtained from a probabilistic seismic hazard analysis for each of the sites contributing a strong motion record. Considering that most of these records are obtained from active tectonic regions, Figure 4 shows as an experiment the exceedance rate curve for San Bernardino, California, which near the San Andreas and San Jacinto faults in southern California. Since the 2008 compilation is estimated to represent 150,000 instrument-years, the San Bernardino curve is multiplied by 150,000, to give an estimate of the numbers of records expected to be obtained as a function of the peak acceleration. In fact, this approach to estimating the numbers of peak accelerations gives a reasonable approximation of the number of observations.

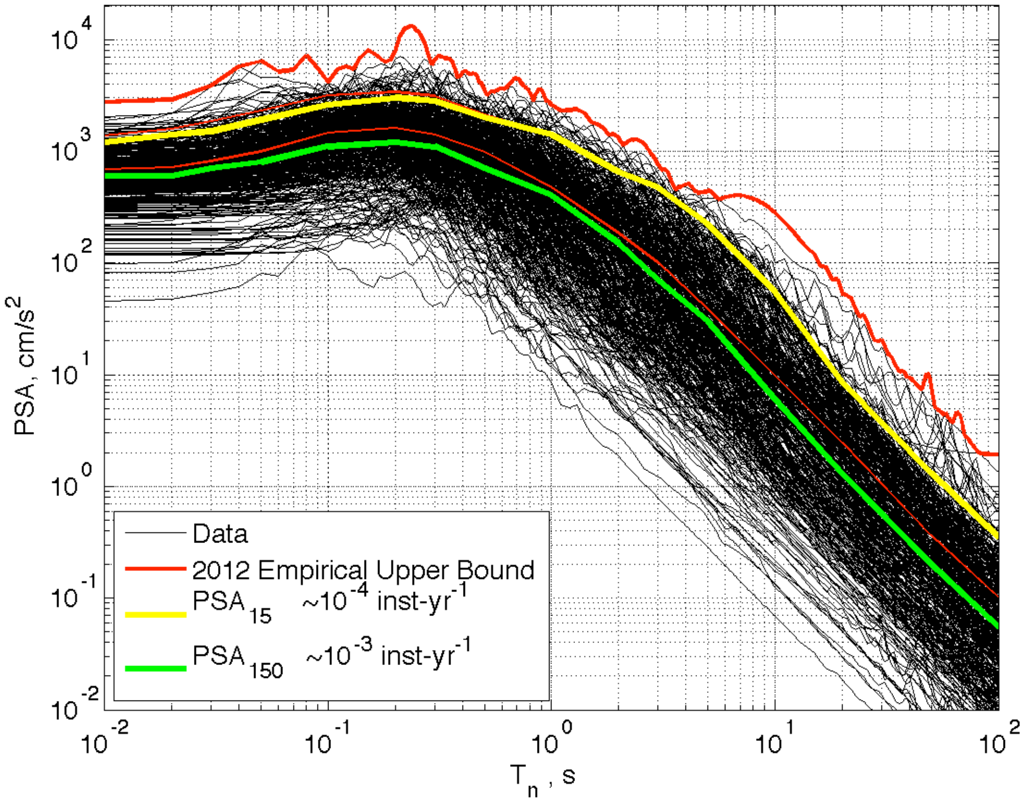

Figure 7. PSA response spectra, with 5% damping, corresponding to all 409 records in the current compilation. Note that the long period asymptotes, which are proportional to the peak displacement on the record, are affected by filter parameters.

Table 1. Values of PSA, in units of cm/s^2 , with estimated exceedance[1] rates per instrument year of $\sim 10^{-3}$ and $\sim 10^{-4}$, respectively, and the current empirical upper bound of PSA.

T_n	$\sim 10^{-3}$ inst-yr^{--1}	$\sim 10^{-4}$ inst-yr^{--1}	PSA
0.01	600	1200	2740.1
0.02	600	1400	2887.7
0.03	700	1500	3855.1
0.05	800	1900	6376.8
0.1	1100	2600	4129.1
0.2	1200	3000	7778.4
0.3	1100	2800	6484.4
0.5	700	2000	3604.3
1	400	1500	2601.7
2	150	650	1293.5
3	70	470	752.42
5	30	220	438.76
10	6	55	283.29
20	1.3	8.5	53.064
50	0.2	1.3	7.9261
100	0.055	0.35	1.9153

Note 1: As discussed in the text the 2010 compilation represents an estimated 150,000 instrument-years of strong motion recording. Thus accelerations (rounded) that are exceeded approximately 150 times and approximately 15 times in the 2010 compilation imply exceedance rates per instrument year of $\sim 10^{-3}$ and $\sim 10^{-4}$, respectively.

4. COMMENTS ON THESE EXCEPTIONAL MOTIONS

Prior to adding the data from Tohoku, the number of records with peak accelerations greater than 1g was similar to the number with peak velocity greater than 1 m/s. However, the data from the Tohoku region changed that relationship significantly. The cause is a rather prevalent site condition with a strong, high-frequency resonant peak (e.g. Kawase and Matsuo, 2004; Kawase, 2006; Assimaki et al, 2008). A narrow peak at high frequencies may contribute strongly to peak acceleration, but much less to the peak velocity. Another notable feature of the added data is the accelerograms from the April 11, 2011 normal faulting earthquakes in Tohoku (M_W=6.7), apparently triggered by the magnitude 9.0 main shock. Normal faulting has been sparsely represented in the 2010 compilation.

5. CONCLUSIONS

The 2012a compilation of 409 strong response spectra shown in Figure 7 is not complete, although the records yet to be included are not expected to significantly modify the results presented here. However, it must be expected that the current empirical upper bound on the response spectrum will be exceeded in future earthquakes, just as it was by records from the Tohoku earthquake, by shaking from a fault that is generally no closer than ~50 km from the stations. It is just a matter of time until very large crustal earthquakes will be recorded at much shorter distances to the fault, and on site conditions that strongly amplify the ground motions.

The large increase in the number of records in 2011 is due to the well-recorded Tohoku earthquake. Obviously, earthquake clusters of such large magnitude are very rare. Thus the numbers of exceptional records added in this update, with over 100 records added in 2011, is highly anomalous. The rate of new data collection established in preceding years, with only a few exceptional records per year, is not expected to increase without major increases of strong motion instrumentation.

The causes of many of these exceptional records are not yet investigated. Still, it is clear that strong site response is a very important factor for a large fraction of the records. This high variability in site response results in many different earthquakes contributing to the empirical upper bound, and to the spectral amplitudes ranking 15 or 150 in this collection. The empirical upper bound and amplitudes at rank 15 and 150 are estimated here to correspond to exceedance rates of under 10^{-5}, 10^{-4} and 10^{-3} per year, respectively. The variability of the site response has been largely smoothed by the many contributions to the compilation.

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