Equations for Estimating Horizontal Response Spectra And Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work

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[Abridged Version]

ABSTRACT

In this paper we summarize our recently published work on estimating horizontal response spectra and peak acceleration for shallow earthquakes in western North America. Although none of the sets of coefficients given here for the equations are new, for the convenience of the reader and in keeping with the style of this special issue, we provide tables for estimating random horizontal-component peak acceleration and 5 percent damped pseudo-acceleration response spectra in terms of the natural, rather than common, logarithm of the ground-motion parameter. The equations give ground motion in terms of moment magnitude, distance, and site conditions for strike-slip, reverse-slip, or unspecified faulting mechanisms. Site conditions are represented by the shear velocity averaged over the upper 30 m, and recommended values of average shear velocity are given for typical rock and soil sites and for site categories used in the National Earthquake Hazards Reduction Program's recommended seismic code provisions. In addition, we stipulate more restrictive ranges of magnitude and distance for the use of our equations than in our previous publications. Finally, we provide tables of input parameters that include a few corrections to site classifications and earthquake magnitude (the corrections made a small enough difference in the ground-motion predictions that we chose not to change the coefficients of the prediction equations).

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The results in Boore et al. (1993) were later revised twice. In the first revision (Boore et al., 1994a) the site-effect term was changed from a constant for each site class to a continuous function of shear-wave velocity at the site, averaged to a depth of 30 m. The second revision (Boore et al, 1994b), which was widely distributed but never published, modified the equations to give different ground-motion estimates for strike-slip and reverse-slip earthquakes. The second revision gave equations only for the random horizontal component of motion for peak acceleration and for 5-percent damped oscillator response; the earlier versions (Boore et al, 1993, 1994a) gave equations for both the random horizontal component and the larger horizontal component for peak acceleration and for oscillator response for damping values of 2, 5, 10, and 20 percent.

For conciseness, we refer to Boore et al (1993), Boore et al (1994a), and Boore et al (1994b) as "BTF93," "BTF94a," and "BJF94b," respectively, or as "BJF94ab" or "BJF9394" collectively, as appropriate.

This paper gives a brief description of the equations of B]F93 for peak horizontal acceleration and the random horizontal component for 5 percent. damping, incorporating both revisions (BJF94a, BJF94b). More complete information can be found in the BJF9394 publications. We strongly recommend the use of the BJF94ab equations in preference to those of BJF93 because we believe that the BJF94a revision significantly improves the treatment of site effects. In contrast with BJF9394, we use natural logarithms in this paper and give response values as spectral acceleration in g, for consistency with the other papers in this special issue.

DATA

Ground-Motion Data

The set of data on which the BJF9394 equations are based was chosen from the data used in JB8182 combined with recordings of the 1989 Lorna Prieta, the 1992 Petrolia, and the 1992 Landers earthquakes. Most of the data were collected .by. the California Division of Mines and Geology's Strong-Motion Instrumentation Program and the U.S. Geological "Surveys National Strong-Motion Program. The data set was restricted to shallow earthquakes in western North America with moment magnitude greater than 5.0, shallow earthquakes being defined as those for which the fault rupture lies mainly above a depth of 20 km.

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The regression analysis for response spectra was done on pseudovelocity response, which is computed by multiplying the relative displacement response by the factor $2\pi/T$, where T is the undamped natural period of the oscillator (the pseudovelocity response spectra provided by the U.S. Geological Survey for the 1979 Coyote lake, the 1979 Imperial Valley, and the 1979 Lorna Prieta earthquakes, and perhaps other earthquakes as well, used the damped period, but in the worst case [20 percent damping] this amounts to a difference in response spectra of only 2 percent). In this paper, for consistency with other papers in the issue, the final equations were converted to give pseudoacceleration response in g, where pseudoacceleration response is computed by multiplying the relative displacement response by the factor $(2\pi/T)^2$.

As in JB8182, to avoid bias due to soil-structure interaction, the BJF9394 studies did not use data from structures three stories or higher, from dam abutments, or from the base of bridge columns. In addition, we' included no more than 1 station with the same site condition within a circle of radius 1 km. In such cases, we generally chose the station with the lowest database code number and excluded the others. The radius of 1 km is a somewhat arbitrary choice.

When a strong-motion instrument is triggered by the S wave, the strongest motion may be missed: Unlike in JB8182, the BJF9394 studies made a systematic effort to exclude records from instruments triggered by the S wave (some such records with very emergent S waveforms may have slipped through, but records with emergent S waveforms would capture the peak values of acceleration and spectral response even if they were triggered on 5).
A strong-motion data set will be biased by any circumstance that causes values of ground motion to be excluded because they are low, as happens when the gr9und motion is too weak to trigger the strong-motion instrument, when the ground motion is so weak that an instrument triggers on the S wave, or when records are not digitized because their amplitude is low. To avoid a bias toward larger values, in BJF9394 we imposed a distance cutoff for each earthquake, beyond which we ignored any data available for that earth~ quake. This cutoff should logically be a function of geologic condition and trigger level of the recording instrument. We ignored geologic condition in the determination of cutoff distance, but we have partially considered the effect of trigger level by distinguishing between those stations employing a trigger sensitive to horizontal motion and those that were triggered on the vertical component of motion. Potentially, every earthquake could have two cutoff distances, depending on the type of trigger used in the recorder. In fact, this was only necessary for the 1971 San Fernando earthquake, which occurred during the time of transition between older instruments that trigger on horizontal motion and newer instruments that employ vertical triggers. For peak acceleration, the cutoff distance is equal to the lesser of the distance to the first record triggered by the S wave arid the closest distance to an operational non triggered instrument. For response spectra we chose to presume that amplitude is a factor in deciding which records are digitized, and we set the cutoff distance to the least of three distances: the distance to the first digitized record triggered by the S wave, the distance to the closest non-digitized recording, or the closest distance to an operational non triggered instrument. In Table 1, which gives the cutoff distances, the greater-than sign indicates that the cutoff distance is at an unknown distance greater than that indicated. For the 1992 Landers earthquake the digitizing of the analog records was not complete when we assembled the data set for BJF93 and few records from digital instruments had been released. When additional data from the Landers earthquake are added to the data set the cutoff distance for response spectra for that earthquake will probably increase.

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Predictor Variables

We use moment magnitude as the measure of earthquake size and a distance equal to the closest horizontal distance from the station to a point on the earth's surface that lies directly above the rupture (r*jb*. We estimated the moment magnitudes and the areas of the rupture surface from a literature review of various published studies for each earthquake. Table 2 gives the rake angles for the earthquakes in the data set, using the convention of Aki and Richards (1980) that reverse slip earthquakes have positive rake angles and the absolute value of the rake for left-lateral slip is less than 90 degrees. We define strike-slip earthquakes as those with a rake angle within 30 degrees of horizontal. All of the earthquakes in the data: set are either strike-slip or reverse-slip except for the Daly City earthquake, which appears to be normal-slip (Marsden et al., 1995; Mary Lou Zoback, written communication, 1996). With only one normal-slip earthquake in the data set we do not attempt to include normal-slip earthquakes in our equations for estimating ground motion. Readers interested in estimating ground motion for normal-slip earthquakes should consult Spudich et al. (1997, this issue).

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Figures 5, 6, and 7 compare ground-motion estimates from the equations in this report with JB8182. Pseudovelocity response spectra computed from the parameter values in Table 8 are compared in Figure 5 with spectra given by JB82 for magnitude 6.5 and 7.5 earthquakes, mechanism unspecified, at zero distance at a soil site. Our results at zero distance appear to be relatively stable except in the vicinity of2 sec period. The difference at 2 sec occurs only at small distance. We have no explanation for the difference, except that it must reflect different data. Since the JB82 data set contained few points at small distance, the addition (or subtraction) of data at small distance can make a relatively large change in the estimates.

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Based on the magnitude and distance distribution shown in Figure 1, we stipulate that our equations not be used to predict motions at distances greater than 80 km or magnitudes less than 5.5 or greater than 7.5. These limits are more restrictive than given by BJF9394.

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The third important difference is that we do the regression analysis of response spectra at each period independently. Some analysts do regression analysis on spectral ordinates normalized by peak acceleration and then multiply the results by the value of peak acceleration given by regression analysis of acceleration data. Abrahamson and Silva (this issue) do a multiple-step regression analysis. Peak acceleration is fit in the first step and some of the parameter values are then fixed for subsequent steps in which response values are fit. Our approach requires that the regression coefficients be smoothed over period, but we consider the smoothing to be beneficial rather than detrimental.