STATE-OF-THE-ART FOR ASSESSING EARTHQUAKE HAZARDS IN THE UNITED STATES

Report 26
PARAMETERS FOR SPECIFYING MAGNITUDE-RELATED EARTHQUAKE GROUND MOTIONS

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A set of charts is presented that relate earthquake magnitude and distance from source to peak horizontal acceleration, velocity, and duration for hard and soft sites. The charts are in two groups: one for shallow plate boundary earthquakes with focal depths \( \leq 19 \) km; another for subduction zone earthquakes with focal depths \( \geq 20 \) km.

The motions that are obtainable from these charts are for use where dynamic analyses are contemplated and cyclic loading is required that approximates the effect of earthquakes as they would be felt in the free field at an engineering site.
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The authors are grateful to Mr. Tatsuo Uwabe of the Port and Harbor Research Institute of Yokusuka, Japan, for assistance in the processing of tapes of Japanese data. Mr. Dale Barefoot of GL assisted with assemblage of data and the preparation of the charts. General supervision was by Dr. D. C. Banks, Chief, EGRMD, and Dr. W. F. Marcuson III, Chief, GL.

COL Dwayne G. Lee, CE, was the Commander and Director of WES during the publication of this report. Dr. Robert W. Whalin was Technical Director.
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I: INTRODUCTION

This paper presents curves for use in deriving parameters for peak earthquake ground motions from earthquake magnitude and distance from source. The data are for plate boundaries, however, the curves are applicable for other regions if attenuations are adjusted and if an assumption is made that the stress drops are the same in all areas. Should stress drops increase, as they might with an increase in seismic moment, a further adjustment of these curves, or the use of other curves, would be called for.

The motions that are obtainable from these charts are for use where dynamic analyses are contemplated and time histories are required that approximate the effects of earthquakes as they would be felt in the free field at an engineering site. The motions may be used also for constructing response spectra.
II. THE DATA

General

The data from which this study was developed was published by Krinitzsky and Chang (1987) in the Appendix A of that report. Those data were developed from a selected world-wide set of 987 strong-motion accelerograms. Of those, 679 were for horizontal motions and 308 for vertical. For each accelerogram, the following data were provided:

Epicentral location (latitude and longitude)
Magnitude of earthquake (M)
Intensity of earthquake (Modified Mercalli)
Focal depth (km)
Distance (km) is focal distance for earthquakes of focal depths < 19 km and epicentral distance for focal depths ≥ 20 km (Japan).
Site classification
Horizontal acceleration (cm/sec²), velocity (cm/sec), duration (≥ 0.05 g, sec)
Vertical acceleration (cm/sec²), velocity (cm/sec), duration (≥ 0.05 g, sec)
Horizontal predominant period (sec) as taken from accelerograms
Vertical predominant period (sec) as taken from accelerograms
Type of fault
The data are from source areas that represent the seismically active plate boundaries.

Earthquake Magnitude

The magnitude in this study, designated as M (Richter magnitude), is equivalent to $M_w$ (moment magnitude) for $M$ up to 8.3, to $M_L$ (local magnitude) for $M$ below 5.9, and to $M_S$ (surface-wave magnitude) for $M$ at 5.9 to about 8.0.

Focal Depth

The source areas in the plate boundaries include earthquakes that range from very shallow to deep within the subduction zone. The present authors made a separation between shallow earthquakes and subduction zone earthquakes by using focal depths $<19$ km for shallow plate boundary and $\geq 20$ km for subduction zone. It was noted that these two categories show characteristic differences. Subduction zone events have lower peak accelerations and velocities near their sources but the motions are felt at greater distances. Shallow earthquakes have greater peak motions near the sources but the motions attenuate more rapidly.

Appendix A of this report presents the data for earthquakes with focal depths $<19$ km; Appendix B shows subduction zone earthquakes $\geq 20$ km.

Appendices A and B contain peak values for horizontal acceleration, velocity and duration. These are presented for earthquake magnitude (M) by one-magnitude spreads that overlap by one-half magnitude ($M=5.0$ to 5.9, $M=5.5$ to 6.4, $M=6.0$ to 6.9, etc.). These plots were used to generate curves at half-magnitude increments ($M=5.5$, $M=6.0$, $M=6.5$, etc.).

Site Classification

Sites were classified as follows:
1 = rock  
2 = Stiff soil  
3 = Deep cohesionless soil (>16 m)  
4 = Soft to medium stiff clay (>16 m) 

\{ \begin{align} 
H & = \text{Hard} \\
S & = \text{Soft} 
\end{align} \}

The boundary between hard and soft was established by Krinitzsky and Chang (1987), using field evidence, at a shear wave velocity of 400 m/sec and at blow counts (N) of the Standard Penetration Test numbering 60.

Designation of a soft site requires a minimum thickness of 16 m in this study. The minimum of 16 m is that which is used by the Port and Harbor Research Institute in Yokusuka, Japan, many of whose accelerograms are used in this report. Campbell (1981) noted that soil sites, where soil is 5 to 10 m thick, need to be excluded. Accelerations on rock were 26% higher than those recorded on such thin soils. However, when the thin soil sites were excluded, the differences in acceleration on soil and rock were not found to be statistically significant. Joyner and Boore (1981) classified as a rock site those locations where soils were less than 4 to 5 m thick. They judged that resonant frequencies of such thin soil layers would be greater than 10Hz, thereby beyond the range of frequencies that compose the dominant part of the accelerograms.

**Distance from Source**

The distance from source in this report is epicentral distance for the Japanese data and focal distance for all other data. The selection of epicentral distance for Japanese data was taken as a practical means for representing deep subduction zone earthquakes on charts for which locations of faults are distant and imprecise.

Others, such as Campbell (1981) and Joyner and Boore (1981), have taken the distance to be the closest distance to a projection to the surface of the fault plane along which the earthquake occurred. The assumption has to be
that the stress drop and the peak motions will occur with equal strength along the length of the fault rupture, something that is unlikely. Moreover, for most of the data, the fault traces are not reliably determinable.

Peak Motions

When the San Fernando, California, earthquake of 9 February 1971 produced a record at Pacoima Dam with the, until then, unheard-of horizontal acceleration of 1.25 g, there was a rush to repudiate the record. The instrument was on a ridge at the abutment of the dam and the high acceleration was attributed to a topographic effect. Campbell (1981) and Joyner and Boore (1981) would not use the record. Seed and Idriss (1983) revised the record down to 0.80 g. Those decisions were arguable from the beginning.

Morrill and others (1971) noted that the Kagel Canyon Fire Station, situated in a canyon bottom only 8 mi from the epicenter suffered some extraordinary motions though there were no accelerations measured. A 20-ton fire truck, in gear, with the brakes set, moved about 6 to 8 ft forward and backward and 2 to 3 ft sideways, with no visible skid marks. Marks were found made by the right rear tire on the door at 3 ft above the floor. A small frame building in Kagel Canyon was lifted off its foundation, turned slightly and set down again. Rocks were lifted off the ground. These evidences imply vertical accelerations of more than 1 g. Unknown are the horizontal accelerations but there is the possibility that they could be equally large. Since then, there has been a horizontal acceleration measured at 1.3 g during the Morgan Hill, California, earthquake of 24 April 1984 (California Division of Mines and Geology, 1984).

Brune (1984) made a foam rubber model of the Pacoima site. He introduced vibrations into the model from different paths and examined the effects at the Pacoima site. Though the Pacoima record was recorded on a ridge, the ridge is
situated well within a canyon. Brune's modelling indicates that the Pacoima site represents the equivalent of an unaffected free field and that the Pacoima record is a legitimate record to use.

Elsewhere, there are effects of directivity focusing by which large motions as at Morgan Hill can be accounted for (see Bolt, 1983). There is still a paucity of data but the indications are that the few high peak values that have been observed cannot be dismissed without the possibility that the interpretations will be affected dangerously.

**Effects of Structures**

Where there were no other data, motions were used from first floors and basements of small or low structures (under 3 stories). Observations made in the free field and in adjacent lower parts of low buildings in Mexico during the 1985 earthquake show negligible differences, accelerations in cm/sec² of 32, 33, 34 and 35 for free field on rock and 28, 34, 35 and 39 for first floors in buildings on rock (see Krinitzsky, 1985, table 3). Basement records may be identical to first floors, if a structure is monolithic, or they may provide lesser values, so they would not contribute to conservatism in the results: they would have either no effect or an opposite effect. Yet, there is such an enormous spread in the data for earthquake ground motions, one to two orders of magnitude as is seen in the appendices to this report, and they derive from such an enormous range of influences, so that vetting the data for structural effects, other than what is indicated, was not judged to be worthwhile.

**Effects of Recording Instruments**

In considering Japanese data, there is some question concerning the relation of values recorded by the SMAC instruments in use in Japan and recordings by other instruments elsewhere. The SMAC instruments record comparably to
other instruments up to about 10Hz. Higher than 10Hz, the SMAC instruments show reduced sensitivity to peak values. For the subduction zone records (≥20 km focal depth) that were used in this study, values greater than 10Hz were not significant parts of the records. Thus the subduction zone curves produced from the Japanese data should be suitable for direct comparison with curves from other data. For the shallower earthquakes (focal depth ≤19 km), where the higher frequency components of motion may be significant, the records used in this report do not include Japanese data.

Calculations

As noted above, for focal depths ≤19 km, no Japanese data were used; 389 accelerograms for horizontal motions were used. For the subduction zone, ≥20 km focal depth, 195 accelerograms for horizontal motions were used. All were Japanese.

Using the data plots described for Appendices A and B, calculations were made for mean, mean + σ and mean + 2σ for each half-magnitude interval. These calculations were done for the points within either one box or two or three boxes. The boundaries of these boxes are shown on the data plots. The boundaries were selected to encompass those areas where the spread of data was best developed. The positions of the calculated values were then used as guides for shaping appropriate attenuation curves. These curves were prepared initially for the magnitude level for which there was the most data, notably M = 6.5. In this way, initial shapes were given to the curves. From this beginning, additional curves were shaped to accommodate the data presented for smaller and larger magnitudes. The resulting curves at each half-magnitude interval for mean, mean + σ, and mean + 2σ, for each of the components of motion are presented in Appendices A and B.
It will be noted in Appendix A, focal depth $\leq 19$ km, that data for hard sites and soft sites were combined for the accelerations. In Appendix B, focal depth $\geq 20$ km, the hard and soft sites were combined for the accelerations and durations. Hard and soft values were combined where the spreads in the data overlapped and the differences between hard and soft were judged to be within the range of error which was taken to be less than one standard deviation.

**Representativeness of the Data**

Researchers have tried various stratagems to try to improve the representativeness of the data. Joyner and Boore (1981) assumed that a distance in which an instrument was operational but not triggered was the limit of an earthquake. No triggered values beyond that limit were used for that earthquake. Similarly, they tried to avoid preferential selection of high amplitude records by noting the smallest distance for such a record and excluding all data of like amplitude recorded at equal or greater distances for such an event.

To assume that the furthest limit of an earthquake is where an operational recording unit was not triggered, though other units may have been triggered beyond that distance, does not take into account the enormous spread in motions that occur everywhere and that in the periphery of an earthquake-affected area can range from zero to measurable values.

Preferential selection of high amplitude records could be a statistical problem if there were an appreciable amount of such data. For any one set of circumstances, such as a given magnitude and distance from source, there is overwhelmingly an absence of data rather than a surfeit of high amplitude records. Reference to Appendices A and B of this report shows that everywhere the spread in the data is statistically uneven. The way the problem is handled in this report is to take all of the data at hand and to bracket it.
this report, boxes were selected purposely to include the biggest spreads in
the data without excluding any values.
III. MAGNITUDE-BASED EARTHQUAKE GROUND MOTIONS

The data in Appendices A and B were developed into families of curves for earthquake magnitudes, motions and focal distances from sources.

Equations

Following are the equations for the mean values of the curves:

(1) **Plate Boundary, focal depth ≤19 km:**

\[
\begin{align*}
\log A & = 1.23 + 0.385 M - \log r - 0.00255 r \\
\log A & = 1.41 + 0.385 M - \log r - 0.00255 r \\
\log V & = -0.67 + 0.489 M - \log r - 0.00256 r \\
\log V & = -0.32 + 0.489 M - \log r - 0.00256 r \\
\log D & = -2.36 + 0.43 M + 0.30 \log (r/10) \\
\log D & = -2.06 + 0.43 M + 0.60 \log (r/10)
\end{align*}
\]

where \( r \) is focal distance in kilometers.

(2) **Plate boundary, subduction zone, focal depth ≥20 km:**

\[
\begin{align*}
\log A & = 2.08 + 0.35 M - \log (r^2 + 100^2)^{1/2} - 0.0025 r \\
\log A & = 2.32 + 0.35 M - \log (r^2 + 100^2)^{1/2} - 0.0025 r \\
\log V & = 0.63 + 0.38 M - \log (r^2 + 100^2)^{1/2} - 0.0025 r \\
\log V & = 0.87 + 0.38 M - \log (r^2 + 100^2)^{1/2} - 0.0025 r \\
\log D & = -2.36 + 0.43 M + 0.30 \log (r/10) \\
\log D & = -2.06 + 0.43 M + 0.60 \log (r/10)
\end{align*}
\]

where \( r \) is epicentral distance in kilometers.
### Charts

Figure numbers for charts in the series for plate boundary, focal depth \( \leq 19 \text{ km} \), are as follows:

<table>
<thead>
<tr>
<th>HOR ACCEL (ALL SITES)</th>
<th>HOR VEL (HARD SITE)</th>
<th>HOR DUR (HARD SITE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Mean + ( \sigma )</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Mean + 2( \sigma )</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>(Soft Site)</td>
<td>(Soft Site)</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Mean + ( \sigma )</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Mean + 2( \sigma )</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure numbers for charts in the series for plate boundary, subduction zone, focal depth \( \geq 20 \text{ km} \), are:

<table>
<thead>
<tr>
<th>HOR ACCEL (ALL SITES)</th>
<th>HOR VEL (HARD SITE)</th>
<th>HOR DUR (HARD SITE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Mean + ( \sigma )</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Mean + 2( \sigma )</td>
<td>22</td>
<td>23</td>
</tr>
<tr>
<td>(Soft Site)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Mean + ( \sigma )</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Mean + 2( \sigma )</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Acceleration, mean, all sites, ≤ 19 km focal depth
Figure 2. Velocity, mean, hard site, ≤ 19 km focal depth
Figure 3. Duration, mean, hard site, ≤ 19 km focal depth
Figure 4. Acceleration, mean + σ, all sites, ≤ 19 km focal depth
Figure 5. Velocity, mean + σ, hard site, ≤ 19 km focal depth
Figure 6. Duration, mean + σ, hard site, ≤19 km focal depth
Figure 7. Acceleration, mean + 2σ, all sites, ≤ 19 km focal depth
Figure 8. Velocity, mean + 2σ, hard site, ≤ 19 km focal depth
Figure 9. Duration, mean + 2σ, hard site, ≤ 19 km focal depth
Figure 10. Velocity, mean, soft site, ≤ 19 km focal depth
Figure 11. Duration, mean, soft site, ≤ 19 km focal depth
Figure 12. Velocity, mean + σ, soft site, ≤ 19 km focal depth
Figure 13. Duration, mean + σ, soft site, ≤ 19 km focal depth
Figure 14. Velocity, mean + 2σ, soft site, ≤ 19 km focal depth
Figure 15. Duration, mean + 2σ, soft site, ≤19 km focal depth
Figure 16. Acceleration, mean, all sites, subduction zone
Figure 17. Velocity, mean, hard site, subduction zone
Figure 18. Duration, mean, all sites, subduction zone
Figure 19. Acceleration, mean + $\sigma$, all sites, subduction zone
Figure 20. Velocity, mean + σ, hard site, subduction zone
Figure 21. Duration, mean + σ, all sites, subduction zone.
Figure 22. Acceleration, mean + 2σ, all sites, subduction zone
Figure 23. Velocity, mean + 2σ, hard site, subduction zone
Figure 24. Duration, mean + 2σ, all sites, subduction zone
Figure 25. Velocity, mean, soft site, subduction zone
Figure 26. Velocity, mean + σ, soft site, subduction zone
Figure 27. Velocity, mean + 2σ, soft site, subduction zone
The relation of selected curves from the charts developed in this study to comparable curves from earlier studies are shown in figures 28 and 29. Figure 28 relates mean values at $M = 6.5$ for horizontal acceleration, in cm/sec$^2$, for Joyner and Boore (1981), Campbell (1981), and Seed and Idriss (1983) with this study. Figure 29 relates subduction zone curves for horizontal acceleration, cm/sec$^2$, by Iai and Tsuchida (1980), Jacob and Mori (1984), Kawashima et al. (1984) and this study.

Joyner and Boore (1981)

Joyner and Boore (1981) developed charts for acceleration and velocity for mean and mean $\pm \sigma$ using data from western United States, mostly from California, but with values from St. Elias and Sitka in Alaska and Managua, Nicaragua. Their values are from the shallow plate boundary earthquakes, not more than 20 km in focal depth. They selected an $M$ value that is based on seismic moment. Where seismic moment data were not available, they took $M_L$ to be the equivalent of moment magnitude. The largest $M_L$ value was 6.2 for Managua. Assuming that large structures, three stories or more, would bias the motions at their bases, they excluded those values. They also excluded data from abutments of dams such as the Pacoima record. They developed distances to source using the distance of closest projection from a fault rupture. They assumed that distances where instruments were operational but not triggered were the limits of an earthquake. No triggered values beyond that limit were used for that earthquake. They tried to avoid preferential selection of high amplitude records by noting the smallest distance for such a record and excluded all other such records of the same amplitude at equal or greater distances. Soil was not designated where thicknesses were 5 m or less. Their
selection of data was partly equal to what was done in this study and was partly less conservative to an unknown degree.

A resulting comparison between Joyner and Boore and this study for the mean curve for $M = 6.5$ is shown in figure 28. The curve in this study goes only to 10 km from a source. It is assumed that from 10 km to a source the values cannot be specified more accurately. Radiation occurs from the fault at depth and rupture propagation, with focusing of waves, comes into play so that the site to source distance is not a fixed quantity at 10 km, at which the Joyner and Boore acceleration is 25 percent less than in this study. At greater distances, the Joyner and Boore values are moderately lower than for this study reflecting some of the lessened conservatism noted in their handling of the data. For $M$ greater than 6.5, they have smaller accelerations and for $M$ less than 6.5 they have larger accelerations compared to the values given in this study. Joyner and Boore's velocity curves for hard rocks are identical to those in this study. For soft rock, their values are smaller.

Campbell (1981)

Campbell (1981) examined accelerations within 50 km of their sources. His $M$ represents moment magnitude and Richter magnitude as used in this study. He selected the closest distances to projections of fault sources. He excluded soft soil deposits and he excluded the Pacoima record. These decisions are reductions in conservatism.

At a distance of 10 km, Campbell's mean horizontal acceleration is almost half the value in this study and about a fourth lower than Joyner and Boore. The latter difference was noted by Campbell and attributed to data selection and analysis techniques.
Joyner and Boore used the larger of the two horizontal components. Campbell used the arithmetic mean of the two horizontal components. Consequently, Campbell's values are about 10 percent lower. The data used in this study included the two horizontal components as separate data points.

Campbell's curves show increasingly greater accelerations for larger magnitudes of earthquakes at the 10 km distance, but at shorter distances the motions are very similar to each other for magnitudes that range from 6.5 to 8.0. Campbell's assumption is that the same accelerations are produced by all magnitudes of earthquakes near a source. His conception does not allow for the effects of focusing of waves and he has excluded the high accelerations that have been recorded. As a consequence, his results lack conservatism.

Seed and Idriss (1983)

Comparisons with the Seed and Idriss (1983) curve for acceleration in Figure 28 shows a close approximation to the comparable curve for this study. However, they allow higher peak motions nearer the source than are allowed in this study. The peak motions are nearly unchanged in the Seed and Idriss family of curves from \( M = 6.0 \) to \( M = 8.5 \). In preparing their curves, Seed and Idriss reevaluated the Pacoima record and reduced it from 1.25 g to about 0.80 g. As stated earlier, these decisions are arguable. Their effect is to provide near-source values that may be unconservative.

The Subduction Zone

In Figure 28, the subduction zone curve developed in this study for focal depths \( \geq 20 \) km shows a characteristic shape that differs from the shallower events by having lower peak values near the source and higher values at greater distances from the source.

Figure 29 shows comparisons with a selected group of curves that are for subduction zone sources using Japanese data as was done in this study. These
Figure 28. Comparison of mean curves, $M = 6.5$, produced in this study with earlier curves for shallow plate boundaries.
Figure 29. Comparison of subduction zone curves for mean values, $M = 6.0$, from this study and earlier sources.
are curves by Iai and Tsushida (1980), Kawashima and others (1984) and Jacob and Mori (1984). All of these curves contain higher accelerations close to a source than does the comparable curve generated in this study. The difference appears to result from their inclusion of earthquakes that are shallower in focal depth than the 20 km taken as a limit in this study.
V: INFLUENCE OF FAULT MECHANISMS

Campbell (1981) noted that reverse faults provided accelerations that were 28 percent higher than those for other fault types. But he cautioned that if three records were removed, those from Lima, Gazli and Tabas, the disparity dropped to 17 percent.

McGarr (1984) studied ground motion parameters and fault mechanisms for 66 records all of which were for situations close to the earthquake sources. Focal depths ranged from 0.1 to 18 km. McGarr noted that focal depth and stress drop have first order effects on earthquake ground motions. He compared normal faults with reverse and strike-slip faults. He indicated that normal faults produced motions with a factor of 3 less for accelerations and 2 less for velocities. However, he cautioned that his data were chosen to examine source processes and that caution was needed in extrapolating his results to other field situations. Particularly the attenuation of high frequency motions might significantly alter the relationships.

In strong contrast to McGarr's results, Scholz and others (1986), working with 29 intraplate records from earthquakes in western United States observed no significant difference in motions generated by normal, reverse and strike-slip fault movements.

An attempt was made to examine the data gathered in this report for effects of fault mechanism. The faults were separated into two groups: extensional and compressional. These two groups were necessary as very few faults were clearly normal faults. They were normal with a significant strike-slip component. The two were combined and treated as extensional.

The examinations that were made in this study are shown in Appendix C. Each half-magnitude level was looked at separately. Only the earthquakes with
focal depths ≤ 19 km were considered. Accelerations were observed for combined hard-and-soft sites, velocities for hard sites and soft sites, and durations for hard and soft sites. In each of these categories, the data were taken within the boxes shown in Appendix A.

Where there was more than one box for a given magnitude, the numeration of the boxes as they appear in Appendix A is given (1, 2 or 3). Also noted in the plates of Appendix C are the numbers of data points.

The combined data in each box was averaged to form a base value. Then these data were separated into extensional and compressional values. Each was averaged. Then the percentage difference of each from the combined average was noted and was plotted on the plates of Appendix C. The variance ranges from a few percentage points to some high values (185 percent) where there are few and erratic data. On the whole, the variance is from a few percentage points to under 20 percent. Interestingly, the relatively higher motions are in every case for extensional faults.

The above relationships are the opposite of what was observed by Campbell (1981) and McGarr (1984). Obviously, it is a matter of what data are used. The cause, at this stage, can only be speculated upon. It is possible that the controlling factor for the values in this study lies in the closeness of fault breakage to the ground surface and the lateral extent of such breakage. Extensional faults may be more characteristic in this way than thrust faults. Meanwhile, the spread in the data is not consistent enough to warrant corrections of adjustment for fault mechanism.
VI: USE OF THE CHARTS

Specifying Earthquake Ground Motions for Magnitude and Distance at Plate Boundaries

A flow chart for developing magnitude-related motions in plate boundary areas is shown in Figure 30.

The procedure begins with an examination of all geological and seismological information relevant to defining earthquake sources, i.e., capable faults, earthquake source zones or both.

A decision has to be made: has the largest earthquake occurred or not? If it has, then one can designate that earthquake to be the maximum credible earthquake. If it has not, then one must estimate such an earthquake. The estimation can be made from fault dimensions. Lacking evidences from faulting, it can be made from a combination of earthquake history and judgement.

Another decision must be made: are the earthquakes relatively shallow, focal depths \( \leq 19 \text{ km} \), or relatively deep, \( \geq 20 \text{ km} \)? The latter may be subduction zone earthquakes. In the United States, a subduction zone occurs along the coasts of northernmost California, Oregon and Washington, and along the coast of Alaska.

Where subduction zone earthquake motions are indicated, two earthquakes are needed: one for focal depths of \( \leq 19 \text{ km} \) and the other for the subduction zone, \( \geq 20 \text{ km} \).

The American subduction zone dips under the North American Plate. The dip of the subduction zone can be obtained from plots in a vertical plane of recorded earthquakes. The dip varies regionally. However, without
information on dip, the subduction zone in North America can be treated as having a dip of 45 degrees.

There is no subduction zone along the coast of central and southern California, only transform faults many of which break the surface. The plate boundary charts with focal depths ≤ 19 km are applicable to this area. These charts also may be used generally for western United States and Alaska.

To obtain acceleration and velocity from the charts, the shortest distance from site to fault or zone should be used. For duration, the distance at which to enter the chart is the distance from the site to the farthest interpreted point of fault breakage or an equivalent distance.

The charts provide parameters of acceleration, velocity and duration for hard and soft sites. These are then used to scale analogous time histories or to create synthetic time histories. The accelerograms may then be used to generate response spectra. Alternatively, one may enter existing response spectra. To enter response spectra, the parameters for shaping an accelerogram must be reduced appropriately (see Vanmarcke, 1979).

Specifying Earthquake Ground Motions for Magnitude and Distance in Intraplate Areas

For almost all of the intraplate area of North America, there are very few strong motion records and none for earthquakes greater than $m_b = 5.2$. Thus motions for the intraplate must be largely interpreted in order for magnitude and distance to be used as criteria.

Following are some considerations:

1. Near field motions from plate boundary areas can be used for the near field in intraplate areas. Within the near field, geometric spreading of the
earthquake waves is the principal cause of attenuation and is the same in both areas. Limits of the near field (see Krinitzsky and Chang, 1977) can be taken to be:

<table>
<thead>
<tr>
<th>M</th>
<th>Distance from Source, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>5</td>
</tr>
<tr>
<td>5.5</td>
<td>15</td>
</tr>
<tr>
<td>6.0</td>
<td>25</td>
</tr>
<tr>
<td>6.5</td>
<td>35</td>
</tr>
<tr>
<td>7.0</td>
<td>40</td>
</tr>
<tr>
<td>7.5</td>
<td>45</td>
</tr>
</tbody>
</table>

2. In the far field, the intraplate attenuations are distinctly different from those of the plate boundary. The plate boundary charts for focal depths ≤19 km can be used for the intraplate areas when they are adjusted for attenuations and possibly for stress drops. Motions in the intraplate area are believed to result from shorter fault lengths and from higher stress drops. Shorter fault lengths would imply reduced focusing effects, thus lower peak motions and shorter durations, while the greater stress drops would imply relatively higher peak motions for the shorter segments of faults. There is no evidence on which to assign dimensions for any of those effects. An ad hoc approach is to use the plate boundary values as they are, but with the indicated adjustments for attenuation.

3. Local attenuations have been worked out and peak motions have been interpreted to produce intraplate charts. Nuttli and Herrmann (1984) applied spectral scaling techniques to observatory seismographic data to set up relations between peak ground motions and attenuations of \( m_b \) values that are valid for the far field. They compared these with MM intensity attenuations in
central United States and found agreement. On this basis, they developed charts of motions for magnitude and distance in central United States. The problem is a lack of data for earthquakes greater than $m_b = 5.2$ in the far field and a lack of data for hard or rock sites. However, the Nuttli and Herrmann charts are particularly useful for their attenuations and for their values for small to moderate earthquakes on soil. They are speculative for large earthquakes. Nuttli and Herrmann did not provide charts for durations.

A procedure for specifying motions based on earthquake magnitude and distance from source is given in the flow chart in Figure 31.

One begins by obtaining all relevant information that will assist in defining the earthquake sources. A judgement has to be made to decide if the largest earthquake has occurred. If it has, that earthquake becomes the maximum credible earthquake. If not, then an estimation has to be made in order to assign a maximum credible earthquake.

Next, one must decide if the maximum credible earthquake is near field or far field.

For the near field, one may use the intraplate charts of Nuttli and Herrmann (1984). Their charts are especially good for small to moderate earthquakes of $m_b \leq 6.5$, on soil, and for shallow focal depths. The plate boundary charts in this study, for focal depths $\leq 19$ km, also may be used for the near field.

For the far field, intraplate charts may be used to obtain motions for small to moderate earthquakes and may be used with reservation for larger earthquakes. The plate boundary charts in this study can be used, again with reservation, if they are modified to reflect the attenuations that are appropriate for the intraplate area.
Both the near field and far field sources of earthquake ground motions can then be used for obtaining analogous accelerograms, for generating synthetic accelerograms, or for entering response spectra.
EXAMINE GEOLOGY, GEOPHYSICS, SEISMIC HISTORY

DEFINE EQK. SOURCES:
(1) CAPABLE FAULTS
(2) EQK. SOURCE ZONES

JUDGEMENT:
HAS THE LARGEST EQK. OCCURRED?

YES

ASSIGN MAXIMUM CREDIBLE EQK.

SHALLOW: \( \leq 19 \) KM

USE PLATE BOUNDARY, NON-SUBDUCTION ZONE, CHARTS

OBTAIN PEAK ACCELERATION, VELOCITY, DURATION FOR HARD OR SOFT SITES.

SELECT ANALOGOUS ACCELEROGRAMS, SYNTHESIZE ACCELEROGRAMS OR ENTER RESPONSE SPECTRA

NO

ESTIMATE THE MAXIMUM EQK.
(1) CAPABLE FAULT: RELATE EQK. TO FAULT DIMENSIONS
(2) EQK. HISTORY: INTERPRET MAXIMUM EQK. FROM INTENSITY REPORTS, MICROEQK. DATA, 3-DIMENSIONAL HYPOCENTER DISTRIBUTION, RECURRENCE RATES, ETC.

DEEP:
SUBDUCTION ZONE EQK. \( \geq 20 \) KM
NORTHWEST U.S., ALASKA

USE SUBDUCTION ZONE CHARTS

Figure 30. Magnitude-related motions for earthquakes in plate boundary areas
EXAMINE GEOLOGY, GEOPHYSICS, SEISMIC HISTORY

DEFINE EQK. SOURCES:
(1) CAPABLE FAULTS
(2) EQK. SOURCE ZONES

JUDGEMENT:
HAS THE LARGEST EQK. OCCURRED?

YES

ASSIGN MAXIMUM CREDIBLE EQK.

NO

ESTIMATE THE MAXIMUM EQK:
(1) CAPABLE FAULT: RELATE EQK. TO FAULT DIMENSIONS
(2) EQK. HISTORY: INTERPRET MAXIMUM EQK. FROM INTENSITY REPORTS, MICROEQK. DATA, 3-DIMENSIONAL HYPOCENTER DISTRIBUTION, RECURRENCE RATES, ETC.

NEAR FIELD OR FAR FIELD?

NEAR FIELD

FOR PEAK ACCELERATION, VELOCITY, DURATION; FOR HARD AND SOFT SITES; USE
(1) INTRAPLATE CHARTS
(2) PLATE BOUNDARY (NON-SUBDUCTION ZONE) CHARTS

SELECT ANALOGOUS ACCELEROGRAMS, SYNTHESIZE ACCELEROGRAMS OR ENTER RESPONSE SPECTRA

FAR FIELD

FOR PEAK ACCELERATION, VELOCITY, DURATION; FOR HARD AND SOFT SITES; USE
(1) INTRAPLATE CHARTS
(2) PLATE BOUNDARY (NON-SUBDUCTION ZONE) CHARTS WHEN ADJUSTED FOR INTRAPLATE ATTENUATIONS

Figure 31. Magnitude-related motions for earthquakes in intraplate areas.
A set of charts were developed that relate earthquake magnitude and distance from source to peak horizontal acceleration, velocity and duration for hard and soft sites. The charts are in two groups: one for shallow plate boundary earthquakes with focal depths ≤19 km; another for subduction zone earthquakes with focal depths ≥20 km. Curves are presented for mean values, mean + σ and mean + 2σ.

An analysis was made of relative motions for extensional versus compressional faults. The extensional faults show the highest peak motions probably because rupture propagation comes closer to the ground surface than is the case for compressional faults.

The parameters for motions obtainable from the above charts are proposed as a means for generating measures of cyclical loading, suitable for use in dynamic analyses, that approximate the effect of earthquake shaking as it would be felt in the free field at an engineering site.
REFERENCES


APPENDIX A: PLATE BOUNDARY CHARTS,
FOCAL DEPTH < 19 KM

1. M = 5.0 to 5.9: All Sites: Acceleration, M = 5.5
2. M = 5.5 to 6.4: All Sites: Acceleration, M = 6.0
3. M = 6.0 to 6.9: All Sites: Acceleration, M = 6.5
4. M = 6.5 to 7.4: All Sites: Acceleration, M = 7.0
5. M = 5.0 to 5.9: Hard Site, Soft Site: Velocity, M = 5.5
6. M = 5.5 to 6.4: Hard Site, Soft Site: Velocity, M = 6.0
7. M = 6.0 to 6.9: Hard Site, Soft Site: Velocity, M = 6.5
8. M = 6.5 to 7.4: Hard Site, Soft Site: Velocity, M = 7.0
9. M = 5.0 to 5.9: Hard Site, Soft Site: Duration, M = 5.5
10. M = 5.5 to 6.4: Hard Site, Soft Site: Duration, M = 6.0
11. M = 6.0 to 6.9: Hard Site, Soft Site: Duration, M = 6.5
12. M = 6.5 to 7.4: Hard Site, Soft Site: Duration, M = 7.0

Note: Data points are designated for "hard" and "soft" sites. Calculations were made for "all" sites, meaning "hard" and "soft" sites combined, or for "hard" and for "soft" sites separately. The data points in each box were used to perform the calculations shown for the box. The range in values are for one M unit (Example: M = 5.0 to 5.9); the curves are for the appropriate mid-magnitude (M = 5.5). All of the curves are calculable by the equations in the report.
Figure A1. $M = 5.0$ to $5.9$: All Sites: Acceleration, $M = 5.5$
Figure A2. $M = 5.5$ to 6.4: All Sites: Acceleration, $M = 6.0$
Figure A3. $M = 6.0$ to 6.9: All Sites: Acceleration, $M = 6.5$
Figure A4. $M = 6.5$ to 7.4: All Sites: Acceleration, $M = 7.0$
Figure A5. M = 5.0 to 5.9: Hard Site, Soft Site: Velocity, M = 5.5
Figure A6. $M = 5.5$ to 6.4: Hard Site, Soft Site: Velocity, $M = 6.0$
Figure A7. M = 6.0 to 6.9: Hard Site, Soft Site: Velocity, M = 6.5
Figure A8. $M = 6.5$ to $7.4$: Hard Site, Soft Site: Velocity, $M = 7.0$
Figure A9. M = 5.0 to 5.9: Hard Site, Soft Site: Duration, M = 5.5
Figure A10. M = 5.5 to 6.4: Hard Site, Soft Site: Duration, M = 6.0
Figure All. M = 6.0 to 6.9: Hard Site, Soft Site. Duration, M = 6.5
Figure A12. $M = 6.5$ to $7.4$: Hard Site, Soft Site: Duration, $M = 7.0$
APPENDIX B: PLATE BOUNDARY CHARTS, SUBDUCTION ZONE,  
FOCAL DEPTH ≥20 KM

1. M = 5.0 to 5.9: All Sites: Acceleration, M = 5.5
2. M = 5.5 to 6.4: All Sites: Acceleration, M = 6.0
3. M = 6.0 to 6.9: All Sites: Acceleration, M = 6.5
4. M = 6.5 to 7.4: All Sites: Acceleration, M = 7.0
5. M = 7.0 to 7.9: All Sites: Acceleration, M = 7.5
6. M = 7.5 + : All Sites: Acceleration
7. M = 5.0 to 5.9: Hard Site, Soft Site: Velocity, M = 5.5
8. M = 5.5 to 6.4: Hard Site, Soft Site: Velocity, M = 6.0
9. M = 6.0 to 6.9: Hard Site, Soft Site: Velocity, M = 6.5
10. M = 6.5 to 7.4: Hard Site, Soft Site: Velocity, M = 7.0
11. M = 7.0 to 7.9: Hard Site, Soft Site: Velocity, M = 7.5
12. M = 7.5 + : Hard Site, Soft Site: Velocity
13. M = 5.0 to 5.9: All Sites: Duration, M = 5.5
14. M = 5.5 to 6.4: All Sites: Duration, M = 6.0
15. M = 6.0 to 6.9: All Sites: Duration, M = 6.5
16. M = 6.5 to 7.4: All Sites: Duration, M = 7.0
17. M = 7.0 to 7.9: All Sites: Duration, M = 7.5
18. M = 7.5 + : All Sites: Duration
Figure B1. M = 5.0 to 5.9: All Sites: Acceleration, M = 5.5
Figure B2. M = 5.5 to 6.4: All Sites: Acceleration, M = 6.0
Figure B3. $M = 6.0$ to $6.9$: All Sites: Acceleration, $M = 6.5$
Figure B4. M = 6.5 to 7.4: All Sites: Acceleration, M = 7.0
Figure B5. $M = 7.0$ to $7.9$: All Sites: Acceleration, $M = 7.5$
Figure B6. $M = 7.5 +$ : All Sites: Acceleration
Figure B7. M = 5.0 to 5.9: Hard Site, Soft Site: Velocity, M = 5.5
Figure B8. $M = 5.5$ to 6.4: Hard Site, Soft Site: Velocity, $M = 6.0$
Figure B9. \( M = 6.0 \) to 6.9: Hard Site, Soft Site: Velocity, \( M = 6.5 \)
Figure B10. M = 6.5 to 7.4: Hard Site, Soft Site: Velocity, M = 7.0
Figure B11. M = 7.0 to 7.9: Hard Site, Soft Site: Velocity, M = 7.5
Figure B12. $M = 7.5 +$ : Hard Site, Soft Site: Velocity
Figure B13. M = 5.0 to 5.9: All Sites: Duration, M = 5.5
Figure B14. $M = 5.5$ to $6.4$: All Sites: Duration, $M = 6.0$
Figure B15. $M = 6.0$ to 6.9: All Sites: Duration, $M = 6.5$
Figure B16. M = 6.5 to 7.4: All Sites: Duration, M = 7.0
Figure B17. M = 7.0 to 7.9: All Sites: Duration, M = 7.5
Figure B18. M = 7.5 + : All Sites: Duration
APPENDIX C: COMPARISON OF PEAK MOTIONS FROM EXTENSIONAL FAULTS AND COMPRESSIONAL FAULTS.

1. Acceleration, Hard and Soft Sites
2. Velocity, Hard Site
3. Velocity, Soft Site
4. Duration, Hard Site
5. Duration, Soft Site
Figure C1. Acceleration, Hard and Soft Sites

LEGEND

\(\triangle\) EXTENSIONAL FAULTS

○ COMPRESSIONAL FAULTS

1, 2, 3 DATA SET

(20) NUMBER OF DATA UNITS
Figure C2. Velocity, Hard Site
Figure C3. Velocity, Soft Site
Figure C4. Duration, Hard Site
Figure C5. Duration, Soft Site