Strong Earthquake Ground Motion and Engineering Design

by William B. Joyner and David M. Boore

Introduction

Designing structures to resist earthquake ground motion is an important engineering challenge. Essential to meeting that challenge is the ability to estimate the level of ground motion in future earthquakes. The seismic zone map in the 1988 edition of the Uniform Building Code is based on ground-motion estimates. The design of important structures structures such as nuclear-power facilities, dams, and high-rise buildings uses estimates of ground motion made for specific construction sites. In what follows we will first tell how ground motion is recorded and what data is available and then discuss how ground-motion estimates are made.

Strong-Motion Data

Special instruments are required to measure strong motion, that is, ground motion at potentially damaging levels. Figure 1 shows the most common of such instruments. The motion of the ground in two horizontal and one vertical direction is recorded by light beams acting on photographic film. Older instruments used photographic paper instead of film. The newest instruments make digital recordings on magnetic-tape cassettes or in solid-state memory units. Digital recording has important advantages, but, because of cost, it will probably be many years before the film-recording instruments are replaced. Strong-motion instruments are turned on by the earthquake ground motion itself. They are unattended and are protected from weather and vandalism by a shelter such as the one shown in Figure 2. An example of the records made by these instruments is given by Figure 3, which shows the record made at Pacoima Dam in the San Fernando earthquake of 1971. This record was obtained a few miles from the site of the Olive View hospital, which was severely damaged in the earthquake, as shown in Figure 4. The hospital was later torn down and replaced.

The business of strong-motion recording requires an extraordinary degree of patience and diligence. Instruments may be deployed for decades before an earthquake occurs that is strong enough and near enough to make a record. Under such circumstances special efforts are required to insure that a high percentage of instruments is operational when an earthquake does occur. The U.S. national strong-motion recording program was begun in the 1930's and has produced the largest share of the available data, at least until recently. At present the national program, which is operated by the U.S. Geological Survey in cooperation with other federal, state and local agencies, has about 600 three-component instruments deployed to measure ground motion. In addition, instrumentation has been placed in structures for monitoring their response to earthquake motion. Figure 5 shows the location of instruments belonging to the national program. The State of California established its own program in 1972, funded by a small fee levied on building permits. This funding mechanism is

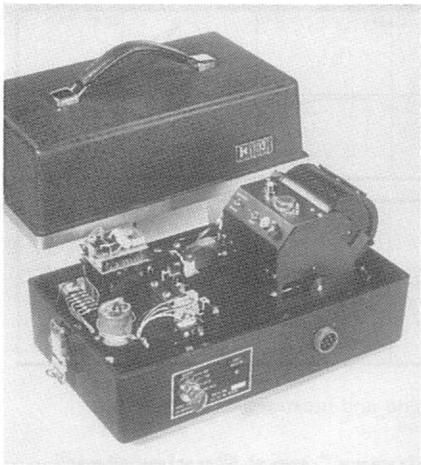

Fig. 1. Typical strong-motion recording instrument, which records three components of ground motion on photographic film. (Photo from Kinemetrics).

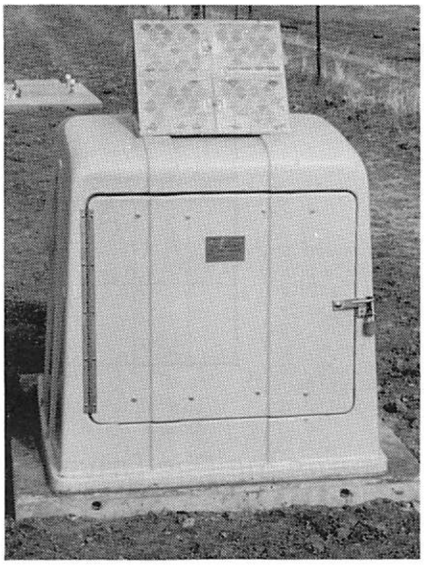

Fig 2. Typical shelter for strong-motion instrument.

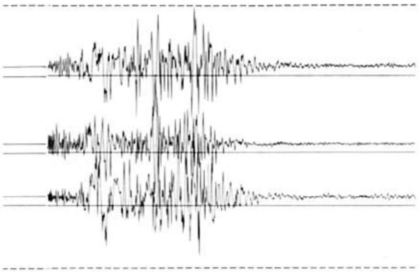

Fig. 3. Strong-motion record made at Pacoima Dam in the 1971 San Fernando, California, earthquake. The middle trace shows the vertical component and the top and bottom traces show the horizontal components. The largest excursion represents an acceleration slightly greater than 1 g; the record shows the motion for 22 sec after the initial motion.

especially advantageous because it provides the continuity so important to strong-motion recording. The California program now maintains about 350 three-component instruments to measure ground motion, in addition to instrumentation in structures. Other instrumentation is operated by universities and government and private organizations throughout the world.

Different Measures of Ground Motion

A number of different quantities, calculated from records such as the one shown in Figure 3, may be used for purposes of seismic design. Peak acceleration is the most commonly used; other quantities used are peak velocity and response spectral values. The response spectrum is defined as the maximum responses, to a given motion, of a set of single-degree-of-freedom oscillators (for example, mass-spring systems) having different natural periods and damping. The response spectral values are useful in structural design because they take account of the frequency of the structure. The response spectrum can be thought of as the maximum responses, to a given motion, of a set of simple mathematical models of structures.

Peak horizontal acceleration may be used in simplified procedures for evaluating liquefaction potential and in pseudostatic studies of slope stability. Peak acceleration has also been commonly used in the past as a scaling parameter to scale a normalized spectral shape and obtain response spectra for analysis of structural response. This is an unsound procedure. It would be valid in general only if the shape of response spectra were independent of earthquake magnitude, source distance, and recording-site conditions. A number of studies (McGuire, 1974; Mohraz, 1976; Trifunac and Anderson, 1978; Joyner and Boore, 1982), however, have shown that the shape of response spectra is strongly dependent on magnitude and site conditions. At periods greater than about 0.3 sec, large errors can result from the practice of scaling fixed spectral shape by peak acceleration. These errors can be partially avoided by Newmark and Hall's (1982) method, in which the short-period part of the spectrum is proportional to peak acceleration, the intermediate portion (about 0.3 to 2.0 sec) to peak velocity, and the long-period portion to peak displacement. Our work (Joyner and Boore, 1982), however, shows that the proportionality factor between velocity and intermediate period response varies significantly with magnitude and site conditions and that the shape of the response spectrum varies significantly with distance. We prefer to estimate response spectra directly, by regression of individual spectral ordinates for a suite of periods. One point deserves emphasis: the search for a single parameter to characterize ground motion is doomed to failure. Because the shape of the spectrum changes with magnitude and site conditions, a single parameter that represents ground motion well at one period must necessarily fail to do so at others.

Empirical Estimates of Ground Motion

Empirical estimates of ground motion are based on analysis of strong-motion recordings. It is not feasible to restrict the analysis to records obtained in the vicinity of the site of interest. There are simply too few recordings available. Because large earthquakes are relatively rare events and the funding for strong-motion instrumentation is limited, the number of available records is small, particularly for large magnitudes and small source distances, just the conditions most critical for earthquake-resistant design. The best that can be done is to take data from a large region (e.g. western North America), see how ground motion is influenced by factors such as magnitude, distance, and site conditions and somehow arrive at estimates appropriate to the site of interest, in that region, for the different earthquakes that may affect it.

A number of different relationships for estimating ground motion have been developed by fitting mathematical equations or graphical curves to the existing strong-motion data set. A comprehensive review of relationships developed before the 1979 Imperial Valley, California, earthquake was given by Idriss (1979). The 1979 Imperial Valley earthquake marked a major change in the strong-motion data base by providing many more near source data points than had been available previously. More recent reviews have been written by us (Boore and Joyner, 1982; Joyner and Boore, 1988) and Campbell (1985).

In developing relationships for estimating ground motion three main factors are considered, earthquake magnitude, source distance, and local geologic site conditions. Some authors also include type of faulting. There are other factors that influence ground motion but it is not clear that incorporation of additional factors would improve the estimates. Because the relationships are developed by fitting the recorded ground-motion data set, the ground-motion estimates and the estimates of variability will implicitly reflect these additional factors. Strong-motion instruments are deployed in a quasi-random fashion in seismic regions in the hope that the records will be representative of the ground motion that structures will experience.

We (Joyner and Boore, 1982, 1988) have developed the following equations for estimating horizontal ground motion from shallow earthquakes in western North America:

$$\begin{aligned} &\log y = a + b(\mathrm{M}\text{-}6) + c(\mathrm{M}\text{-}6)^2 + d \log r + kr + s \\ &5.0 \leq \mathrm{M} \leq 7.7 \qquad\qquad (1) \\ &r = (\mathrm{r}^2{}_0 + h^2)^{1/2} \end{aligned}$$

where y is the ground-motion quantity to be estimated, M is the moment magnitude of the earthquake, r_0 is the shortest distance (km) from the site of interest to the vertical projection of the earthquake fault rupture on the surface of the earthquake, and s is the site-effect coefficient. Values of $a,b,c,d,k,h,$ and s

Period (sec)	a	b	c	h	d	k	s	V_{S0}	e	$\sigma_{\log y}$
Pseudoacceleration response (g)										
0.1	0.97	0.25	-0.06	11.3	-1.0	-0.0073	-0.02			0.28
0.15	1.03	.30	- .08	10.8	-1.0	- .0067	- .02			.28
0.2	0.97	.35	- .09	9.6	-1.0	- .0063	- .01			.28
0.3	0.80	.42	- .11	6.9	-1.0	- .0058	.04	590	-0.28	.28
0.4	0.64	.47	- .13	5.7	-1.0	- .0054	.10	830	- .33	.31
0.5	0.52	.52	- .14	5.1	-1.0	- .0051	.14	1020	- .38	.33
0.75	0.27	.60	- .16	4.8	-1.0	- .0045	.23	1410	- .46	.33
1.0	0.09	.67	- .17	4.7	-1.0	- .0039	.27	1580	- .51	.33
1.5	-0.18	.74	- .19	4.7	-1.0	- .0026	.31	1620	- .59	.33
2.0	-0.37	.79	- .20	4.7	-1.0	- .0015	.32	1620	- .64	.33
3.0	-0.65	.85	- .22	4.7	-0.98	.0	.32	1550	- .72	.33
4.0	-0.84	0.88	-0.24	4.7	-0.95	0.0	0.29	1450	-0.78	0.33
Peak acceleration (g)										
	0.43	0.23	0.0	8.0	-1.0	-0.0027	0.0			0.28
Peak velocity (cm/sec)										
	2.09	0.49	0.0	4.0	-1.0	-0.0026	0.17	1190	-0.45	0.33

Table 1. Coefficients in the Equations of Joyner and Boore (1988) for the Randomly Oriented Horizontal Component of Ground Motion

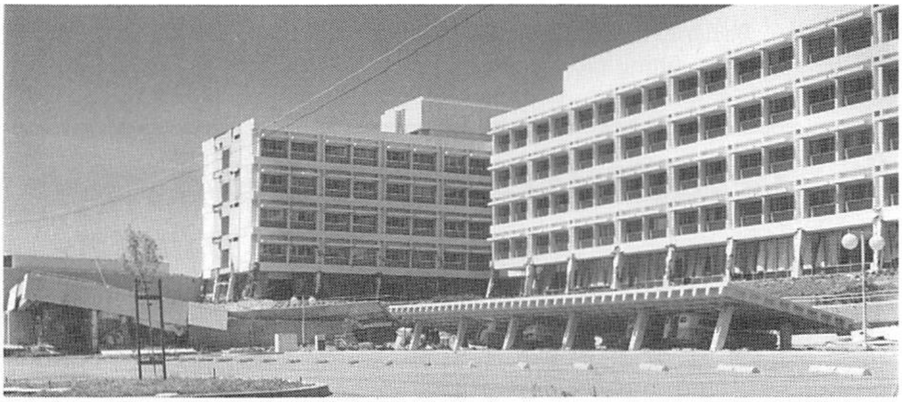

Fig. 4. The Olive View Hospital, damaged in the San Fernando earthquake and later demolished. The Hospital was located within a few miles of the site where the record shown in Figure 3 was made. Note the shattered first-floor columns and the displacement of the upper stories. (Photo by Robert E. Wallace, U.S. Geological Survey).

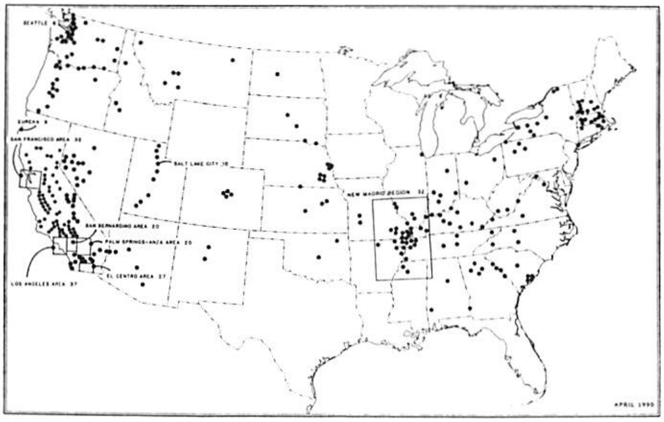

Fig. 5. Map showing locations of strong-motion instruments operated by the U.S. Geological Survey in cooperation with other agencies.

for soil sites (sites with 5 m or more of soil), determined by fitting the strong-motion data set, are given in Table 1 for estimating quantities corresponding to the randomly oriented horizontal component. For rock sites $s = 0$. For response spectral values the coefficients given in Table 1 correspond to pseudo-acceleration response at 5 percent damping. (Pseudoacceleration response is simply displacement response multiplied by $(2\pi/T^2)$, where T is period in sec.)

The moment magnitude M is used in equation (1) because it corresponds to a well defined physical property of the earthquake source. It is defined in terms of the seismic moment $M\phi$, which is the product of three factors, the area of the rupture surface, the average slip, and the modulus of rigidity in the source zone. Moment magnitude is thus a measure of the size of an earthquake in a very specific sense. The equation for computing moment magnitude is

$$\mathrm{M} = \frac{2}{3} \log M\phi - 10.7$$

where the units of $M\phi$ are dyne-cm (Hanks and Kanamori, 1979). The magnitudes most commonly cited in earthquake engineering are the Richter local magnitude M_{L} and the surface-wave magnitude M_s. M_{L} is determined from the trace amplitude on a record made by a particular kind of seismograph, the Wood-Anderson seismograph, located within a few hundred km of the earthquake. M_s is determined from the ground motion associated with surface waves of 20 sec period recorded anywhere in the world. For earthquakes in California with M_{L} less than about 6.5 the commonly cited magnitude is M_{L}. For earthquakes worldwide with M_s greater than about 6.5 the commonly cited magnitude is M_s. Generally speaking, below a moment magnitude of about 8.0, moment magnitudes are approximately the same as the commonly cited magnitudes.

If shear-wave velocity data are available for the site of interest, the following expression (Joyner and Fumal, 1984) should be used to determine the site coefficient:

$$s = e \log \left(\frac{Vs}{Vsf}\right) \qquad (2)$$

where V_s is the site shear-wave velocity

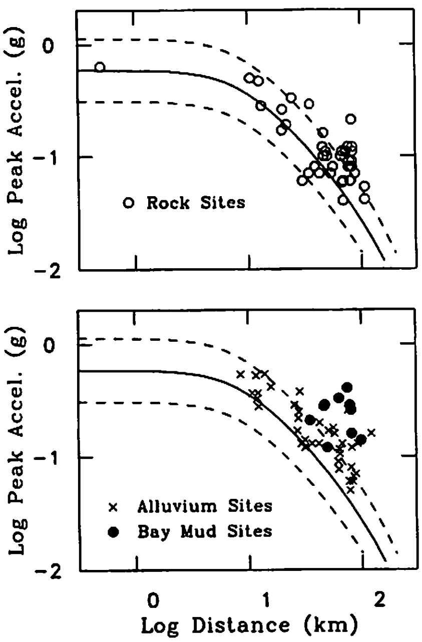

Fig. 6. The larger of two horizontal components of peak acceleration recorded in the 1989 Loma Prieta, California, earthquake compared with estimates from our equations (Joyner and Boore, 1982, 1988). The median estimate is shown by the solid line and the estimates at plus and minus one standard deviation are shown by the dashed lines. Distance is the closest distance to the vertical projection of the fault rupture on the surface of the earth.

averaged to a depth of one-quarter wavelength at the period of interest and e and $V_S\phi$ are given in Table 1.

As previously stated, equation (1) applies to shallow earthquakes, that is, earthquakes for which the fault rupture lies mainly above a depth of 20 km. Most earthquakes in the "lower 48" states of the U.S. are shallow by that definition. Subduction earthquakes, which are common in Alaska and which have been postulated for the Pacific Northwest of the U.S., may be deeper and different relationships should be used to estimate ground motion from such earthquakes.

All ground-motion estimates are subject to large errors. Table 1 gives estimates of $^{\sigma}$ log y, the standard error of an individual prediction of log y using equation (1). The values listed correspond to errors of about a factor of 2 above and below the median estimate.

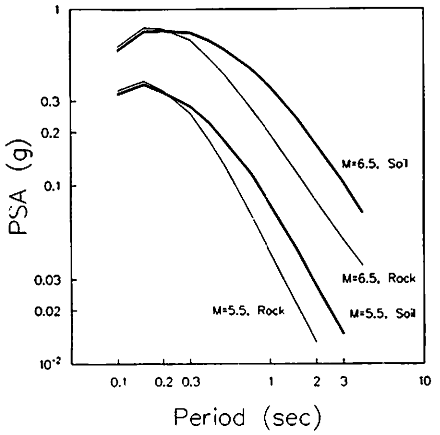

Fig. 7. Estimated pseudoacceleration spectra of shallow earthquakes for 5 percent damping at soil sites (heavy lines) and rock sites (light lines) for 10 km distance and moment magnitude 5.5 and 6.5. Spectra correspond to the randomly oriented horizontal component and were computed from equation (1) using the coefficients in Table 1. Distance is as defined in Figure 6.

Some other investigators give lower values, but generally no less than factors of about 1.5 above and below the median estimate.

Figure 6 shows a comparison between curves of peak horizontal acceleration from equation (1) for moment magnitude 6.9 and data from the 1989 Loma Prieta, California, earthquake, which had a moment magnitude of 6.9. No data more recent than 1981 were used in determining the curves, which show the median estimate and the estimates at plus and minus one standard deviation. What is plotted in Figure 6 represents the larger of two horizontal components, and the curves are 15 percent higher than would be obtained using the coefficients given in Table 1. A table of coefficient values for the larger of two horizontal components is given elsewhere (Joyner and Boore, 1988).

The curves in Figure 6 apply to both rock and soil sites. The recorded data are plotted with different symbols for the different site categories, rock, alluvium, and bay mud. The values for the three categories are factors of 1.6, 1.8, and 4.5 higher than the curves, which were derived from a data set that included rock and alluvium sites but not bay mud sites. The larger values for rock and alluvium may represent ordinary earthquake-to-earthquake variability, but the values for bay mud clearly represent an amplification due to bay mud, which is characterized by soft clays with shear-wave velocities less than 100 m/sec. Similar amplification accompanied by severe building damage and collapse occurred on very soft clay deposits in Mexico City in the 1985 Michoacan earthquake. Analysis of the Loma Prieta data is still underway. Ultimately the analysis will lead to a much better understanding of the effect of local geology on earthquake ground motion.

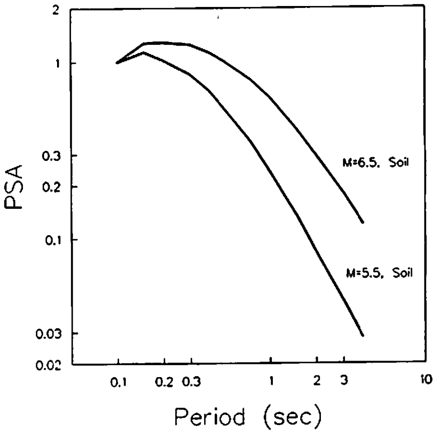

Fig. 8. Spectra from Figure 7 at soil sites normalized to the value at 0.1 sec to show the difference in shape for different magnitude.

An example of the use of equation (1) in estimating response spectra is shown in Figure 7, which gives the pseudoacceleration response spectra at 5 percent damping for the randomly oriented horizontal component at 10 km distance (rf) for moment magnitude 5.5 and 6.5 at rock and soil sites. Figure 7 illustrates the point made earlier that the shape of response spectra depends strongly on magnitude and site conditions. To show the dependence on magnitude more clearly the soil spectra are replotted in Figure 8, normalized to the value at 0.1 sec. The spread of the curves at longer periods indicates the errors that would result from scaling fixed spectral shapes.

Theoretical Estimates of Ground Motion

In many regions, such as eastern North America, too few strong-motion data are available for making empirical estimates. Why not estimate ground motion theoretically? The theory of seismic wave propagation is sufficiently well developed so that ground motion could be calculated *if* all the necessary information were available. The catch is that the needed information is not available, and, in our view, probably will not be within the foreseeable future. The fault rupture that is the source of ground motion may be 10 km or more beneath the surface of the earth. It would be necessary to know the properties of all the material along the propagation path between the fault at depth and the site on the surface where the ground-motion estimate was wanted. The amount of slip on the fault would have to be known, and, more important, how that slip varied from point to point on the fault. A new approach has been developed recently, however, that makes theoretical estimates of earthquake ground motion possible. It combines simple approximations to wave-propagation effects with a statistical description of the variability of slip on the fault. Estimates made with this approach agree very well with the recorded ground-motion data that is available, and the approach makes possible what, in our view, are the first realistic theoretical estimates in regions for which there are few data. A discussion of the approach and its application to estimating ground motion at rock sites in eastern North America is given to Atkinson and Boore (1990).

References

Atkinson, G.M. and D.M. Boore (1990). Recent trends in ground motion and spectral response relations for North America, *Earthquake Spectra* **6**, 15-35.

Boore, D.M. and W.B. Joyner (1982). The empirical prediction of ground motion, *Bull. Seism. Soc. Am.* **72**, S43-S60.

Campbell, K.W. (1985). Stong motion attenuation relations: a ten-year perspective, *Earthquake Spectra* **1**, 759-804.

Hanks, T.C. and H. Kanamori (1979). A moment magnitude scale, *J. Geophys. Res.* **84**, 2348-2350.

Idriss, I.M. (1979). Characteristics of earthquake ground motions, in *Earthquake Engineering and Soil Dynamics, Proc. Am. Soc. Civil Eng. Geotech. Eng. Div. Specialty Conf.*, June 19-21, 1978, Pasadena, California, **3**, 1151-1265.

Joyner, W.B. and D.M. Boore (1982). Prediction of earthquake response spectra, *Proc. 51st Ann. Convention Structural Eng. Assoc. of Cal.*, also *U.S. Geol. Surv. Open-File Rept. 82-977, 16p*

Joyner, W.B. and T.E. Fumal (1984). Use of measured shear-wave velocity for predicting geologic site effects on strong ground motion, *Proc. Eighth World Conf, on Earthquake Eng. (San Francisco)* **2**, *777-783.*

Joyner, W.B. and D.M. Boore (1988). Measurement, characterization, and prediction of strong ground motion, in *Earthquake Engineering and Soil Dynamics II, Proc. Am. Soc. Civil Eng. Geotech. Eng. Div. Specialty Conf.*, June 27-30, 1988, Park City, Utah, 43-102.

McGuire, R.K. (1974). Seismic structural response risk analysis, incorporating peak response regressions on earthquake magnitude and distance, *Research Report R74-51*, Dept. Civil Eng., Mass. Inst. of Tech., Cambridge, Mass., 371 p.

Mohraz, B. (1976). A study of earthquake response spectra for different geological conditions, *Bull. Seism. Soc. Am.* **66**, 915-935.

Newmark, N.M. and W.J. Hall (1982). *Earthquake Spectra and Design*, Earthquake Engineering Research Institute Monograph, 103 p.

Trifunac, M.D. and J.G. Anderson (1978). Preliminary empirical models for scaling pseudo relative velocity spectra, appendix A in *Methods for Prediction of Strong Earthquake Ground Motion, U.S. Nuclear Regulatory Commission Report NUREG/CR-0689*, A1-A90.

William B. Joyner and David M. Boore
U.S. Geological Survey
345 Middlefield Road MS 977
Menlo Park, California 94025