APPENDIX D
GROUND MOTION BACKGROUND DATA

D-1. Earthquake Source and Earthquake Size Definition

a. A Simple Earthquake Source Model. The actual release of earthquake energy along a fault plane in the crust of the earth is a very complex phenomenon. All the physical processes that occur just before, during and after a seismic event are still not completely understood, and considerable research is going on to better describe this phenomenon. However, for engineering purposes, the above complex phenomenon is idealized, and Figure D-1(a) gives the resulting simplified model representation of the earthquake source. In this model, an earthquake is caused by the sudden release of energy accumulated during tectonic processes. The energy is released via faulting (rupture) of rock along a plane (the fault plane). Part of the energy is converted into elastic energy carried by seismic waves and thus the shaking that is felt during earthquakes.

b. Earthquake Location. Even though a substantial volume of the earth's crust is involved in the energy release, it is generally assumed that the faulting initiates at a discrete point (the hypocenter or focus) and then spreads over a larger area (Figure D-1(a)). The term epicenter is used to denote the point on the earth's surface directly above the hypocenter. In recent times (since the installation of seismographs), the locations of the hypocenter are determined by means of instruments. Before the advent of instrumentation, the epicenter was located by means of finding the region of most intense shaking. Quite often, the field epicenter (region of intense shaking) and the instrumentally located epicenter do not coincide.

c. Types of Faulting. Figure D-2 shows the three basic types of faulting. They are defined by the sense of relative displacement between the two adjoining blocks along the fault plane. In a normal fault, the upper block slides downward relative to the lower block. In a reverse fault, the upper block rides up. In a strike-slip fault, one block moves horizontally past the other. Any faulting may be described as a combination of these three basic types of faulting.

d. Types of Seismic Waves. Seismic waves generated by an earthquake source are of three main types: P, S, and surface waves (Figure D-1(b)). The P wave has the fastest travel speed and its particle motion involves compression and expansion of the rock. The S waves travel more slowly than P waves, arrive after the P waves, and exhibit particle motion transverse to the direction in which they travel. Both P and S waves move through the body of the earth and are thus called body waves. Body waves are followed by surface waves that travel along the earth's surface and have motion that is restricted to near the earth's surface.

e. Earthquake Size.

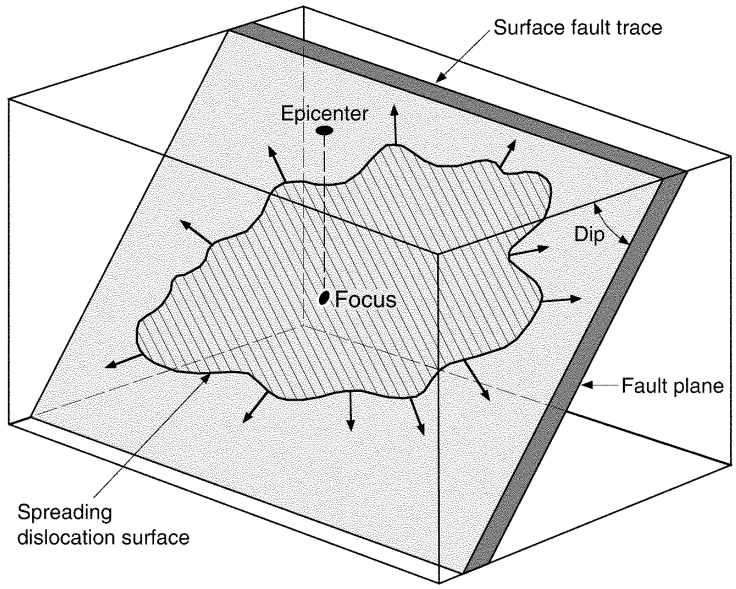
(1) Magnitude. Among the various quantitative measures of earthquake size, magnitude is undoubtedly the most successful and widely used. The basic concept of magnitude is to compare sizes of earthquakes in a relative manner. In his definition of magnitude, Richter (Richter, 1958) rates an earthquake relative to a standard size earthquake by comparing their maximum amplitudes recorded by the same type of seismometer at the same distance to the epicenter,

$$M = \log \left[\frac{A(\Delta)}{A_o(\Delta)} \right] \qquad \text{(D-1)}$$

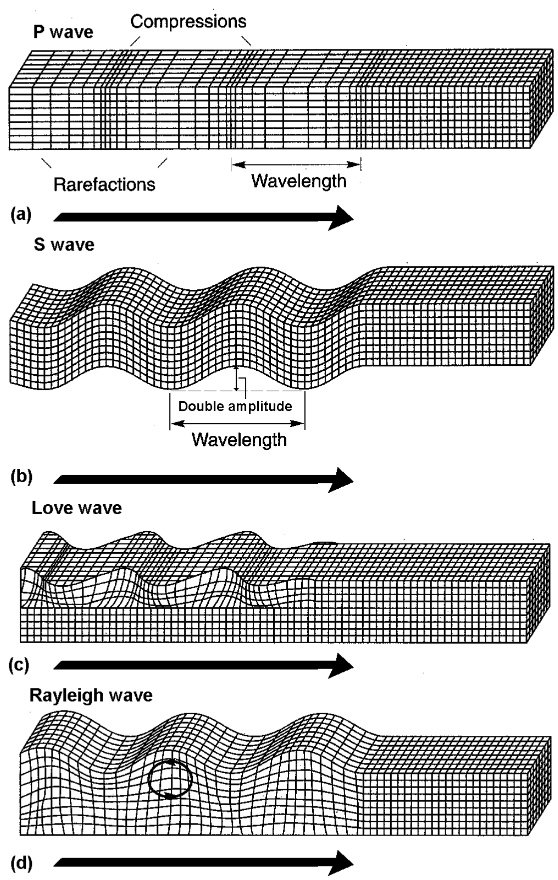
where) is the distance from observation location to the epicenter (epicentral distance), *A* and *A*@denote the recorded maximum amplitudes of an earthquake and the standard size earthquake, respectively. The standard size earthquake is defined as to have *A*@= 1 :m (10^{-6} meter or 3.3×10^{-6} feet) recorded by a Wood-Anderson seismometer at) = 100 km (62 miles). Tables were constructed empirically to reduce from 100 km (62 miles) to any distance. A graphical representation of the table is given in Figure D-3. Since the scale is logarithmic, an increase of one step on the magnitude scale increases the amplitude scale by a factor of 10 (see Figure D-3). Richter magnitude scale was originally defined for local earthquakes in southern California; the definition has been adopted and expanded to become applicable to other regions using different type of instruments. Richter magnitude is only used for shallow local () < 600 km or 375 miles) earthquakes, hence it is also called the local magnitude (M_L). Body-wave magnitude (m_b) and surface-wave magnitude (M_s) have been introduced to measure the size of distant earthquakes () > 600 km or 375 miles). Surface-wave magnitude M_s is usually based on the amplitude of 20 seconds period surface waves recorded at distances of thousands of kilometers, where seismograms are dominated by surface waves. Body wave magnitude is based on the maximum amplitude of 1 second period P-waves.

(2) Seismic moment. As more is known about the earthquake source mechanism and about the size of earthquake events, it is becoming increasingly clear that the

existing magnitude scales are inadequate to describe the overall size or the energy content of earthquake events. To



a) Earthquake rupture propagation



b) Types of seismic waves

Figure D-1 Earthquake source model and types of seismic waves (from Bolt, 1993).

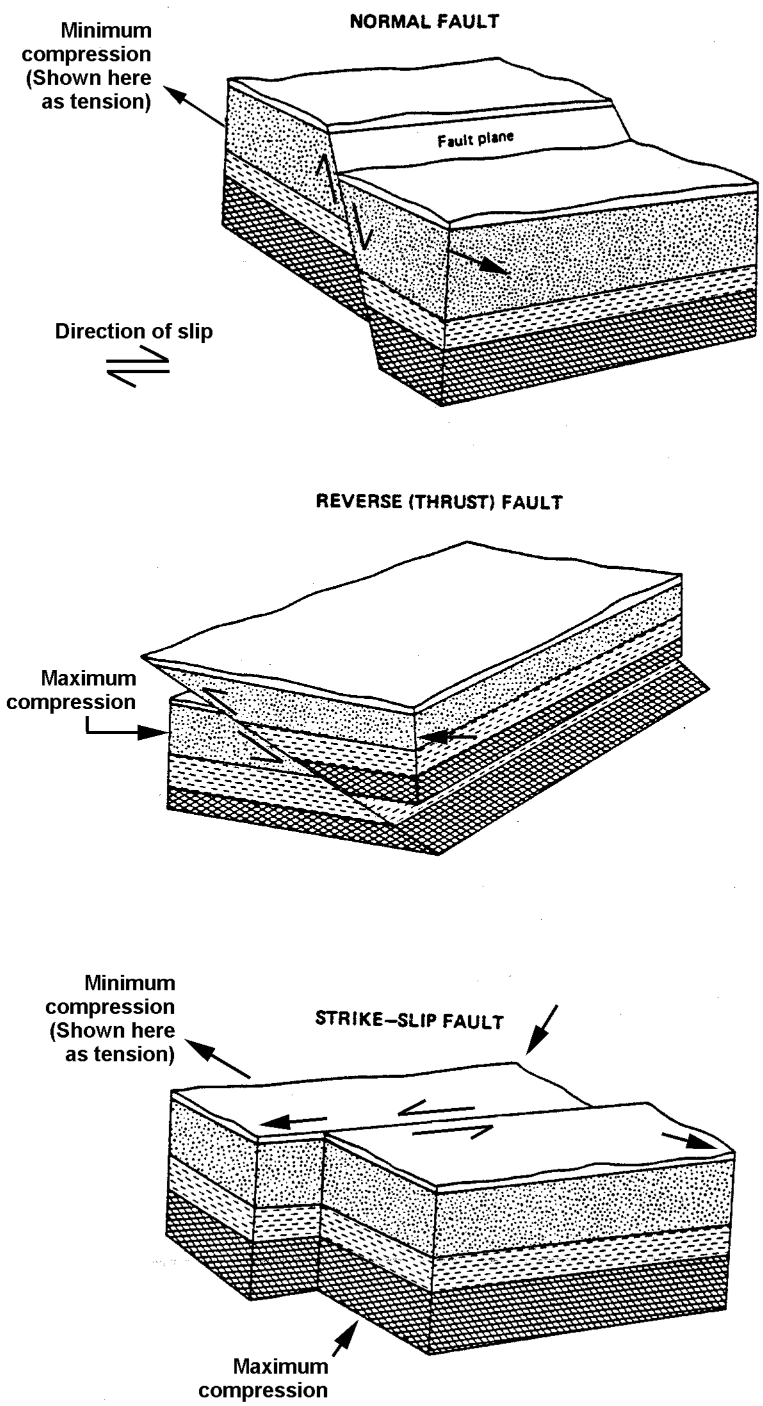
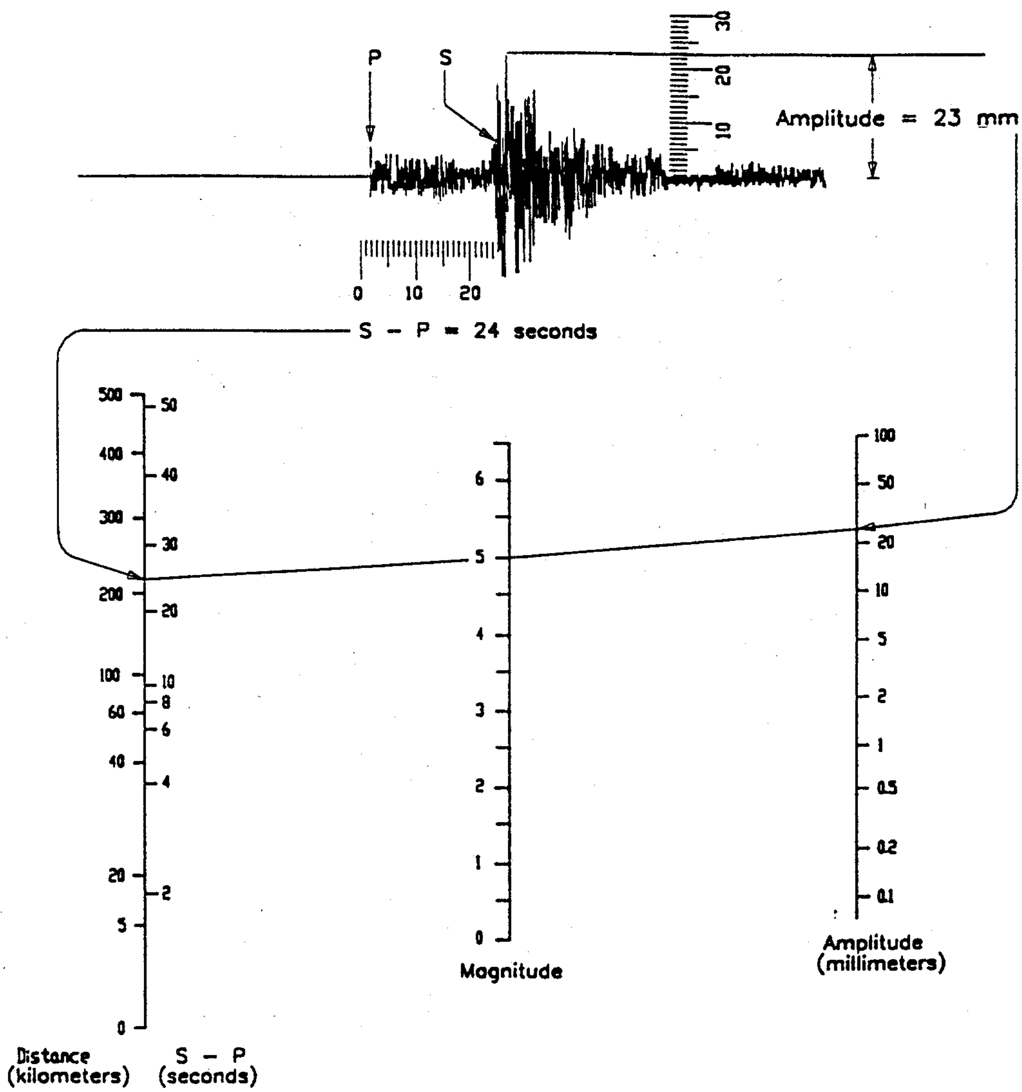


Figure D-2 Types of fault slip.



Procedure for calculating the local magnitude, M_L

1. Measure the distance to the focus using the time interval between the S and the P waves (S − P = 24 seconds).
2. Measure the height of the maximum wave motion on the seismogram (23 millimeters).
3. Place a straight edge between appropriate points on the distance (left) and amplitude (right) scales to obtain magnitude M_L = 5.0.

1 km = 0.62 miles; 1 mm = 0.04 inches

Figure D-3 The Richter Scale (after Bolt, 1988).

overcome this deficiency, seismologists have introduced a "physical" parameter called seismic moment, $M_@$, to describe the size of an earthquake. This parameter is directly related to the size of the fault rupture area, the average slip on the fault, and the property in shear of the ruptured zone (recall that the magnitude scale is a relative scale). $M_@$ is defined as:

$$M_o = G \; A \; S \qquad \text{(D-2)}$$

where

G = average shear modulus over the rupture zone
A = fault rupture area
S = average slip on the fault during the earthquake.

(3) Moment magnitude. In order to relate seismic moment to the existing magnitude scales, a moment magnitude (M_w) has been introduced. In the M_L range of 3 to 6, M_w corresponds to M_L. M_w is related to seismic moment $M_@$ by the following relationship (Hanks and Kanamori, 1979).

$$M_w = \frac{2}{3} Log M_o - 10.7 \qquad \text{(D-3)}$$

where M_o is in units of dyne-cm.

Comparative values of the moment magnitudes and seismic moments of some well-known earthquakes are given in Table D-1.

(4) Intensity measures. Another means of describing the size of an earthquake at a given location is the intensity scale. The two intensity scales used in the United States are the Rossi-Forel Scale (RF Scale) and the Modified Mercalli Scale (MM Scale).

(a) The Modified Mercalli scale is the most common. A simplified version of this scale is given in Table D-2. The RF scale, which was developed in the late 19th century, was used in this century until 1930. Since then, use of the MM scale has become more common. It is important to note that the above scales are subjectively assigned by investigators after observing and reviewing the earthquake effects in a given region. The assignment of proper intensity value therefore requires a careful analysis of the affected region. Unless the guidelines for assigning intensities are properly and correctly followed, there could be an error in the assigned value.

(b) Empirical relationships are available in the literature to relate the magnitude of an earthquake and the intensity in the epicentral area. The following illustrate such relationships.

(Gutenberg and Richter, 1956)

$$M_L = 1 + \frac{2}{3} I_o \qquad \text{(D-4)}$$

(Krinitzky and Chang, 1975)

$$M_L = 2.1 + \frac{1}{2} I_o \qquad \text{(D-5)}$$

(Chinnery and Rogers, 1973) for Northeastern United States,

$$M_L = 2.1 + 0.6 I_o \qquad \text{(D-6)}$$

where

M_L = Richter magnitude or local magnitude
$I_@$ = Modified Mercalli intensity in the epicentral area

(c) All such relationships, including those derived for specific sites where specific data are available, are extremely approximate and the scatter of data about the predicted lines is large. Note that much of the scatter is due to the necessity of empirically converting site intensity data to the equivalent $I_@$ value in the epicentral area, so as to normalize the site distance attenuation effects. Figure D-4 (Krinitzky and Chang, 1975) shows the relationships given by Equations D-4 and D-5 along with earthquake data.

D-2. Ground Motion Recordings and Ground Motion Characteristics

a. Characteristics in the Time Domain. With the introduction of modern strong motion instruments, the actual ground motion at a given location is often derived from instrumentally recorded motions. The most commonly used instruments for engineering purposes are strong motion accelerographs. These instruments record the acceleration time history of ground motion at a site, called an accelerogram. Figure D-5(a) shows a typical accelerogram. By proper analysis of a recorded accelerogram to account for instrument distortion and base line correction, the resulting corrected acceleration record can be used by engineers. This corrected acceleration record can yield ground velocity and ground displacement by appropriate integration (Figure D-5(a)).

(1) A number of parameters may be used to characterize strong ground motion in the time domain.

Table D-1 Moment Magnitude, M_w, and Seismic Moment, M_o of some well-known earthquakes.

Earthquake	M_w	M_o (dyne-cm)
1960 Chile Earthquake	9.6	2.5×10^{30}
1964 Alaska Earthquake	9.2	7.5×10^{29}
1906 San Francisco, CA Earthquake	7.9	9.3×10^{27}
1971 San Fernando, CA Earthquake	6.6	1.0×10^{26}
1976 Tangshan, China Earthquake	7.5	1.8×10^{27}
1989 Loma Prieta, CA Earthquake	6.9	2.7×10^{26}
1992 Cape Medocino, CA Earthquake	7.0	4.2×10^{26}
1994 Northridge, CA Earthquake	6.7	1.3×10^{26}
1995 Kobe, Japan Earthquake	6.9	2.5×10^{26}

1 dyne-cm = 7.4×10^{-8} foot-lbs

Table D-2 Modified Mercalli Intensity Scale.

Mercalli's improved intensity scale (1902) served as the basis for the scale advanced by Wood and Neumann (1931), known as the modified Mercalli scale and commonly abbreviated MM. The modified version is described below with some improvements by Richter (1958).

To eliminate many verbal repetitions in the original scale, the following convention has been adopted. Each effect is named at that level of intensity at which it first appears frequently and characteristically. Each effect may be found less strongly or more often at the next higher grade. A few effects are named at two successive levels to indicate a more gradual increase.

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering.

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

Modified Mercalli Intensity Scale of 1931 (Abridged and Rewritten by C.F. Richter)

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by person at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken visibly, or heard to rustle.

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, also unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bell rings. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frames structure, if not bolted, shifted off foundation. Frame racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas, sand and mud ejected, earthquake fountains, sand craters.

Table D-2 Modified Mercalli Intensity Scale.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large Landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Undergournd pipelines completely out of service.

XII Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

(Reprinted from "*Elementary Seismology*", C.F. Richter, 1958, with permission from W.H. Freeman and Company.)

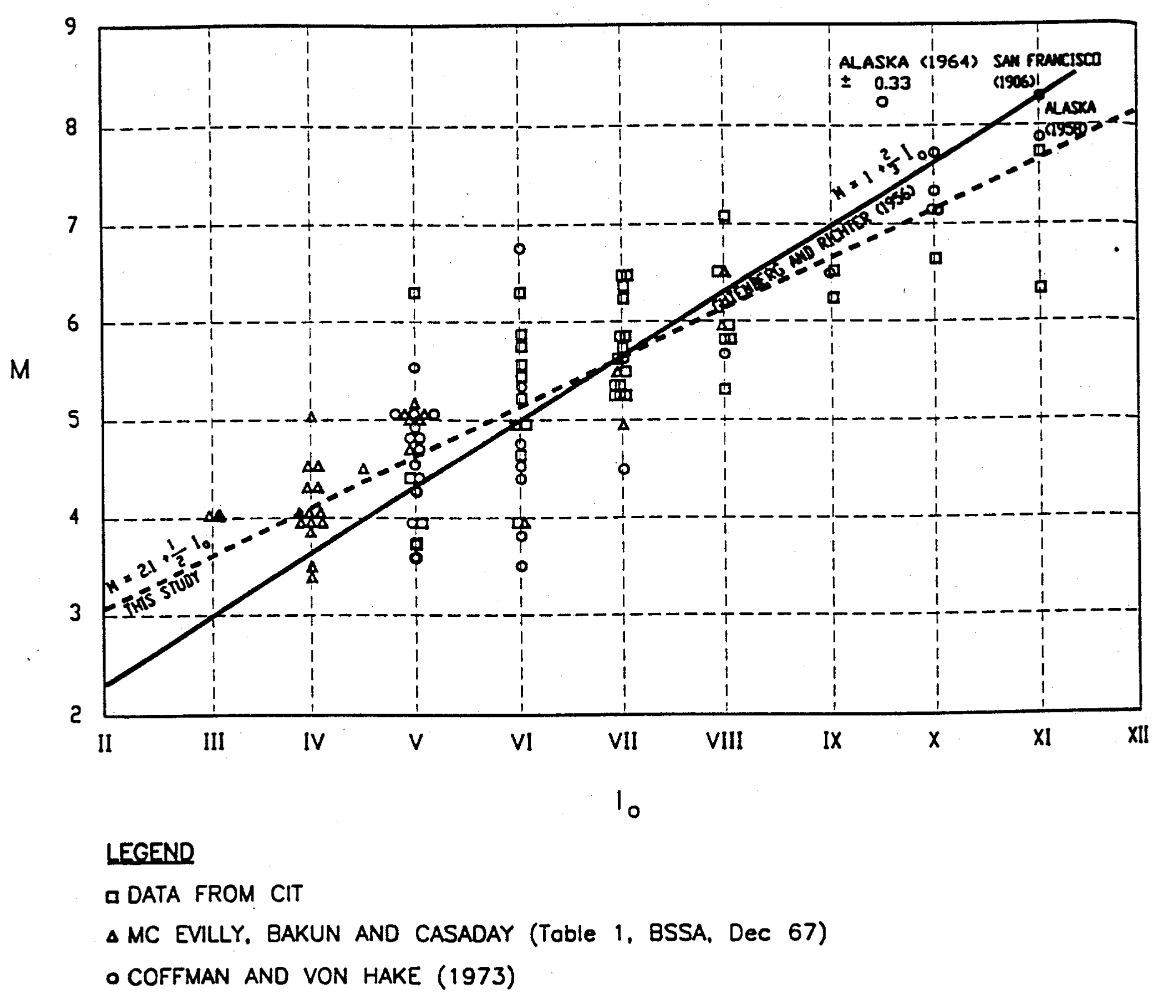
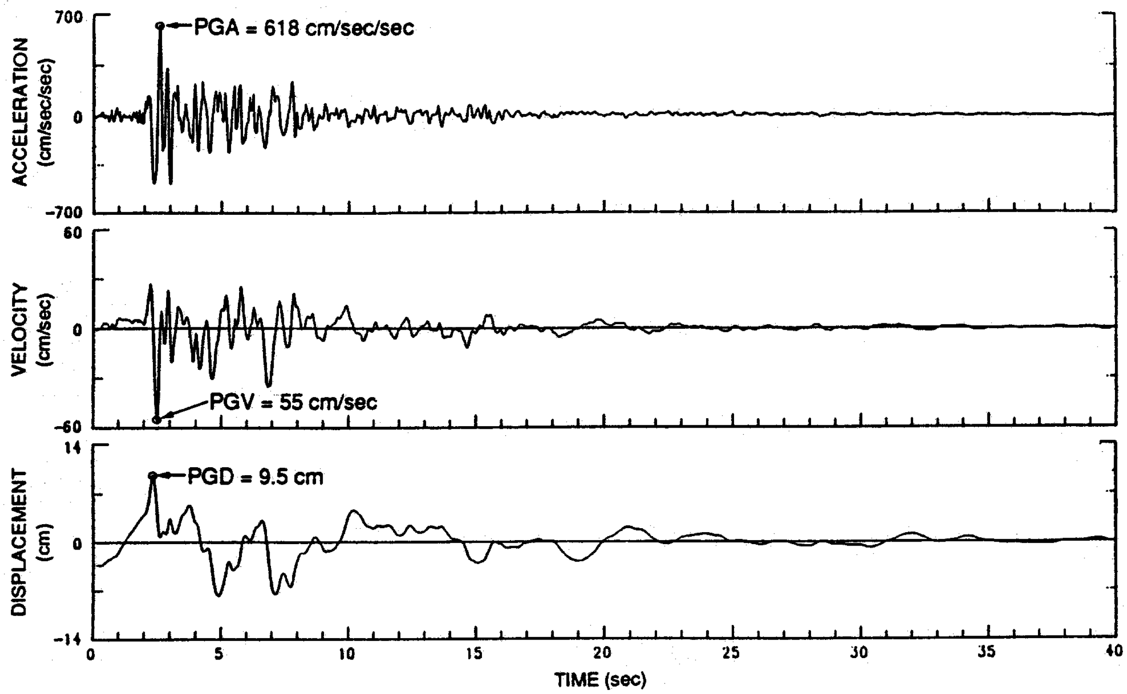
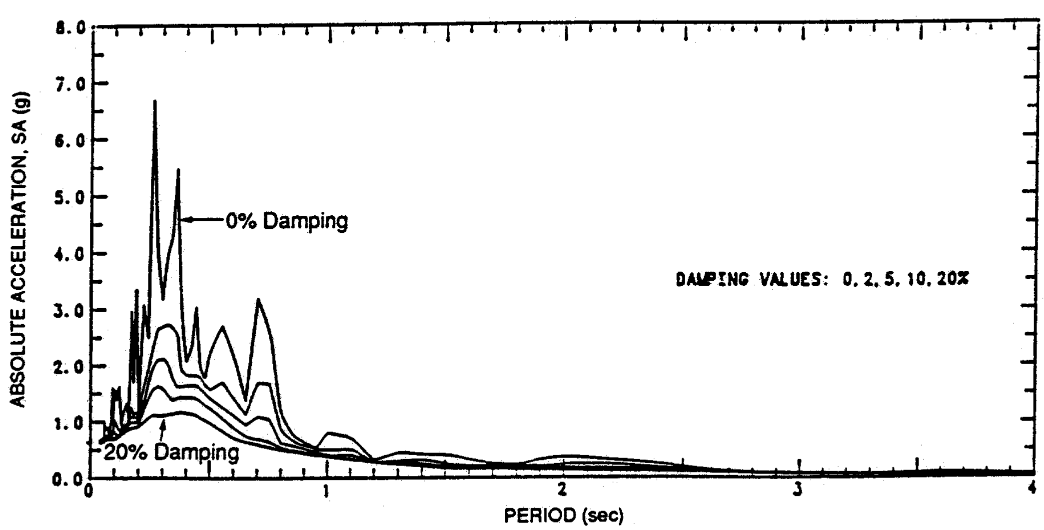


Figure D-4 Relation between earthquake magnitude and epicentral intensity in the western United States (after Krinitzky and Chang, 1975).



a) Acceleration, velocity, and displacement time histories.



b) Acceleration response spectra.

1 cm = 0.4 inches

Figure D-5 Corralitos ground motion recording, component 0E, October 17, 1989, Loma Prieta, California earthquake (after California Division of Mines and Geology, 1989).

These include peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and strong motion duration. It should be noted that these ground motion parameters provide only gross descriptions of the recorded ground motions. The PGA value, normally expressed as a fraction of the earth's gravity (note that one gravity unit, or 1g, is equal to 980.7 cm/sec^2 or 32.2 ft/sec^2), has been the key parameter in the past characterizing the level of ground shaking for engineering purposes; while duration has been used to characterize the time duration of significant shaking during earthquakes. Different definitions of strong motion duration have been used. Bolt (1973) defined a bracketed duration as the lapsed time between the first and last acceleration greater than a given level (0.05 g and 0.10 g as used by Bolt (1973)). Trifunac and Brady (1975) and Dobry et al. (1978) defined significant duration as the time needed for the integral of $(x^2(t))^2$, where $x^2(t)$ is the ground acceleration at time t, to build up between 5 and 95 percent of its total value for the accelerogram. The integral of $(x^2(t))^2$ is a measure of the energy of an accelerogram (Arias, 1969). There are empirical relationships between duration and earthquake magnitude (e.g., Bolt, 1973; Dobry et al., 1978).

(2) In general, the recorded ground motion consists of the three main types of seismic waves described in paragraph D-1d.. Experience indicates that each accelerogram has a variable degree of detail. For example, at distances close to the earthquake fault, the onset of the main S waves is often associated with a longer-period pulse related to the fault slip (see Figure D-6). It is important to take this into consideration when designing structures near an active fault.

b. Response Spectrum. Seismic ground motion may be characterized as the superposition of a set of harmonic motions having a fairly broad range of frequencies. This characterization of the ground motion (called the Fourier spectrum) is often used by seismologists and is different from the response spectrum discussed here. Structures subjected to the input ground motion tend to amplify the harmonics near their own natural frequencies and filter or attenuate the others. The resulting structural response therefore depends upon the frequency content of the harmonics in the ground motion and their relation to the dynamic frequency characteristics of the structure. This paragraph provides the definitions and discussions of the response spectrum representation of this inter-relationship between ground motion input and structural response.

(1) Single degree-of-freedom system response. Figure D-7 shows the system and the definition for seismic input and response.

(a) Response to arbitrary ground motion input *x(t)*. For any given ground acceleration $x^2(t)$, the relative displacement response *u(t)* is

$$u(t) = -\frac{1}{w_D} \int_o^t x''(t)\; e^{-wb(t-t)}\; \sin[w_D(t-t)]\; dt \quad \text{(D-7)}$$

where $w_D = w\,(1-b^2)^{1/2}$ is the damped natural frequency of the single-degree-of-freedom system and b is the damping ratio. For the case of zero damping, this equation simplifies to

$$u(t) = -\frac{1}{w} \int_o^t x''(t)\; \sin[w\,(t-t)]\; dt \qquad \text{(D-8)}$$

where w is the undamped natural frequency of the system. Relative velocity and acceleration responses are given by the time derivatives $u'(t)$ and $u''(t)$, respectively.

(b) Response to sinusoidal input. If the ground acceleration $x''(t)$ were to be a single unit amplitude sinusoid at frequency Ω, $x''(t) = sin\Omega t$, then the corresponding response is given by $u(t) = H(T)\, sin[\Omega t + N]$, where N is a phase angle and

$$H(w) = \frac{1}{\left[\left(1-(\Omega/w)^2\right)^2 + \left(2b\ \ \Omega/w\right)^2\right]^{1/2}} \qquad \text{(D-9)}$$

is the system's frequency-response function which either amplifies or attenuates the response according to the frequency ratio Ω/w, and the damping ratio b, see Figure D-8. This function is most useful in the explanation of how predominant harmonics in ground motion can amplify the ordinates of the response spectrum.

(2) Response spectra. For a given ground acceleration $x^2(t)$ such as shown in Figure D-5(a), and given damping ratio, the absolute maximum values found from the complete time history solution of equation D-7 provide the response spectrum values at the system frequency w, or period, $T=2\pi/w$. A response spectrum is traditionally presented as a curve connecting the maximum response values for a set of prescribed frequency or period values, such as shown in Figure D-5(b). The different response spectra quantities are defined as:

$$SD = [\ u(t)\ ]_{max} = \text{Relative Displacement Response}$$

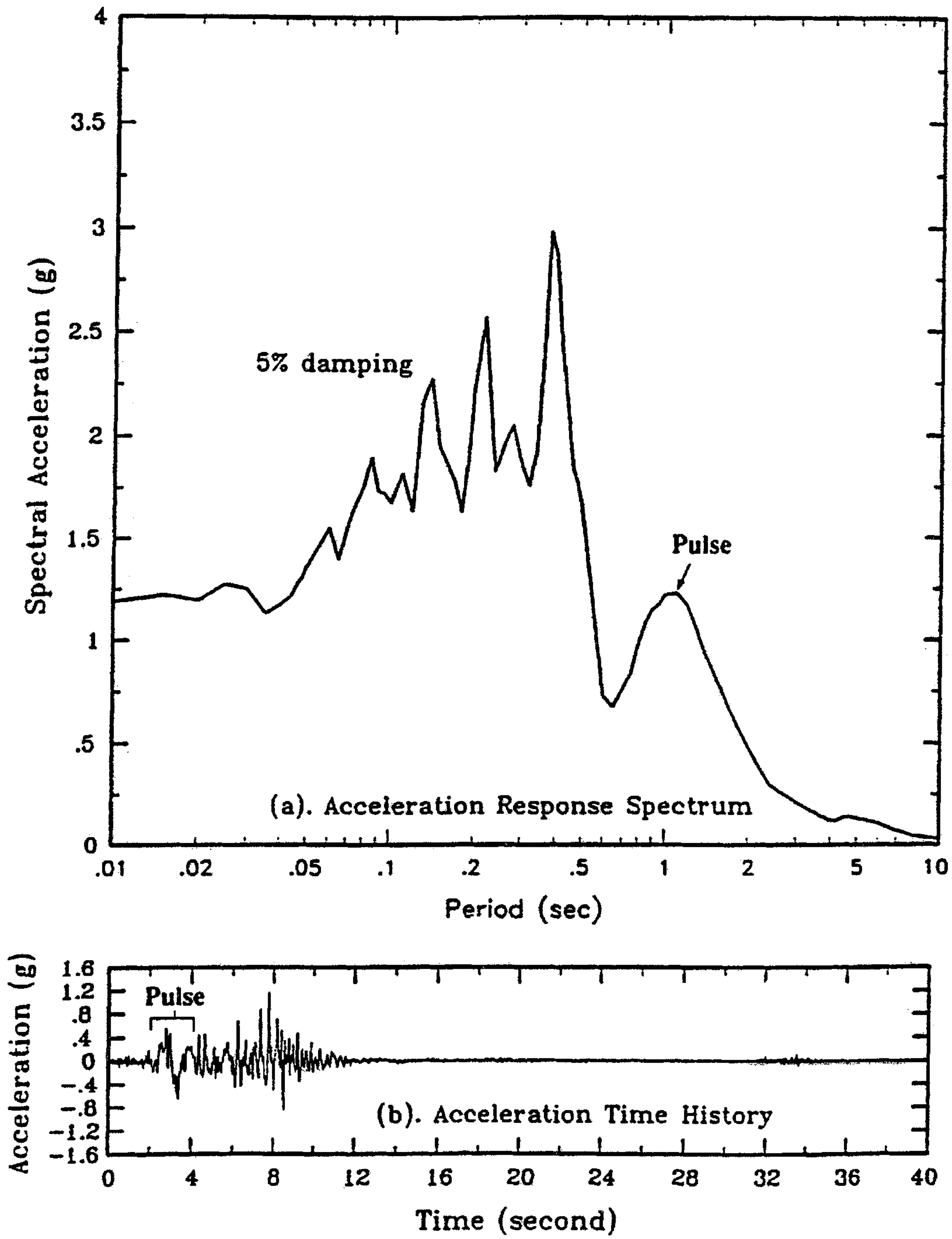
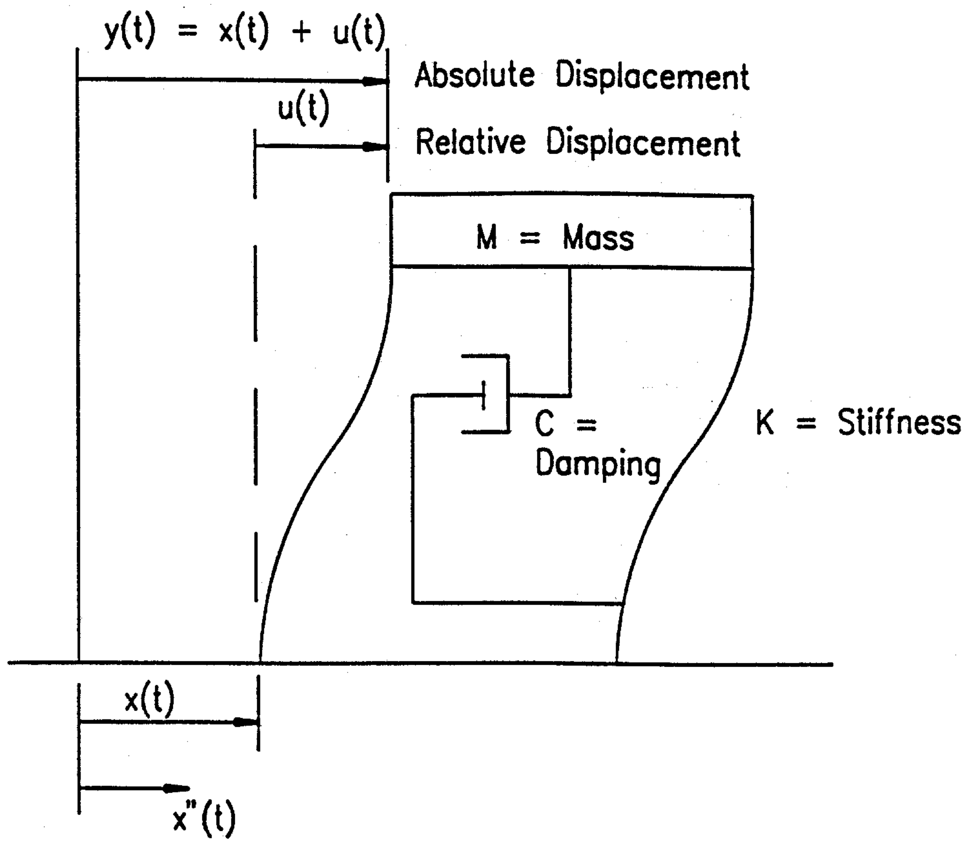


Figure D-6 Pacoima dam recording (S14W component) obtained 3 km (1.9 miles) from the causative fault during the 1971 San Fernando, California earthquake.



<u>System Properties</u>

$\omega = \sqrt{K/M}$ = undamped natural frequency

$\beta = \dfrac{C}{2M\omega}$ = fraction of critical damping

$\omega_D = \omega\sqrt{1-\beta^2}$ = damped natural frequency

<u>Ground Motion</u>

$x(t)$ = displacement

$x'(t) = \dfrac{dx}{dt}$ = velocity

$x''(t) = \dfrac{d^2x}{dt^2}$ = acceleration

Figure D-7 Single degree of freedom system.

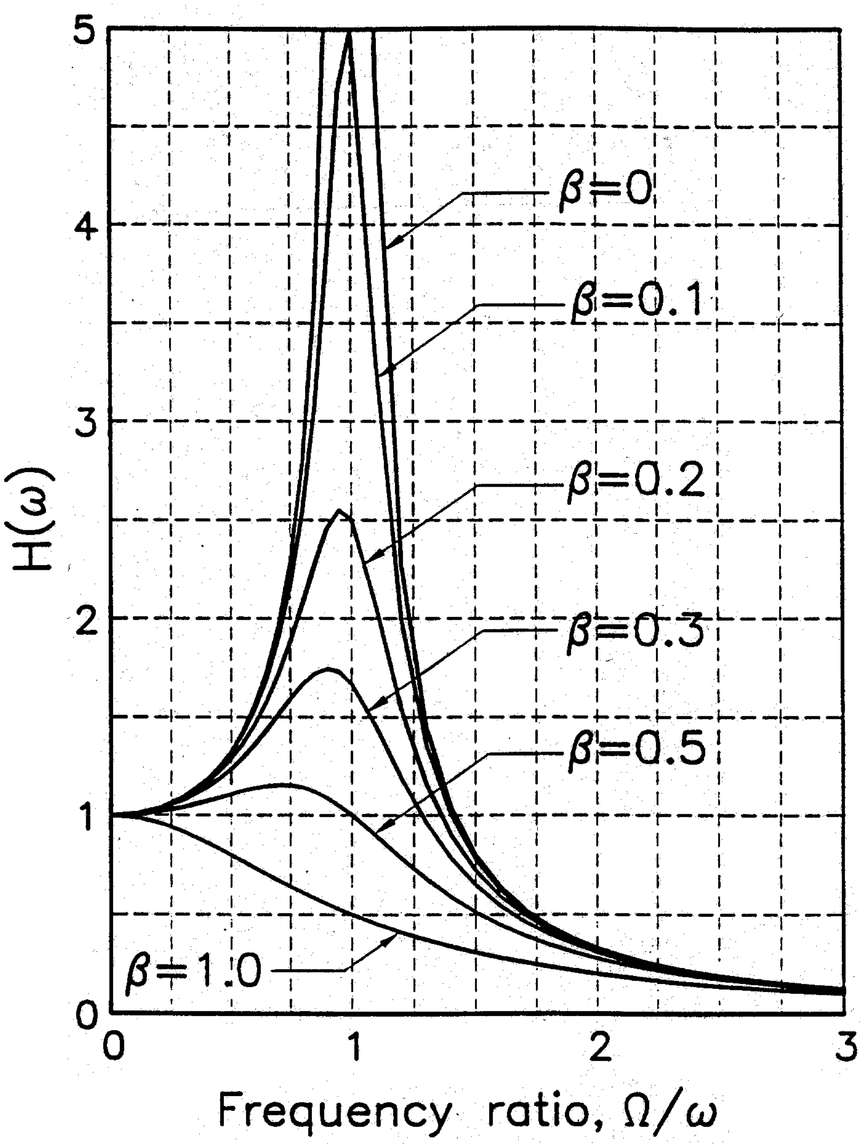


Figure D-8 Maximum dynamic load factor for sinusoidal load.

$SV = [\ u'(t)\ ]_{max}$ = Relative Velocity Response

$SA = [\ y''(t)\ ]_{max} = [\ u''(t) + x''(t)]_{max}$ =
Absolute Acceleration Response

Then using the close approximation of $w = w_D$ for b £ 0.1, the more commonly employed versions for engineering purposes are:

$S_v = w \cdot SD$ = Pseudo-Relative-Velocity Response

(D-10)

$S_a = w^2 \cdot SD$ = Pseudo-Acceleration Response

(D-11)

For the common structural damping ratios, and the earthquake type of input motion, there is essential equality for the real and pseudo values,

$$S_v \cong SV \qquad \text{(D-12)}$$

$$S_a \cong SA \qquad \text{(D-13)}$$

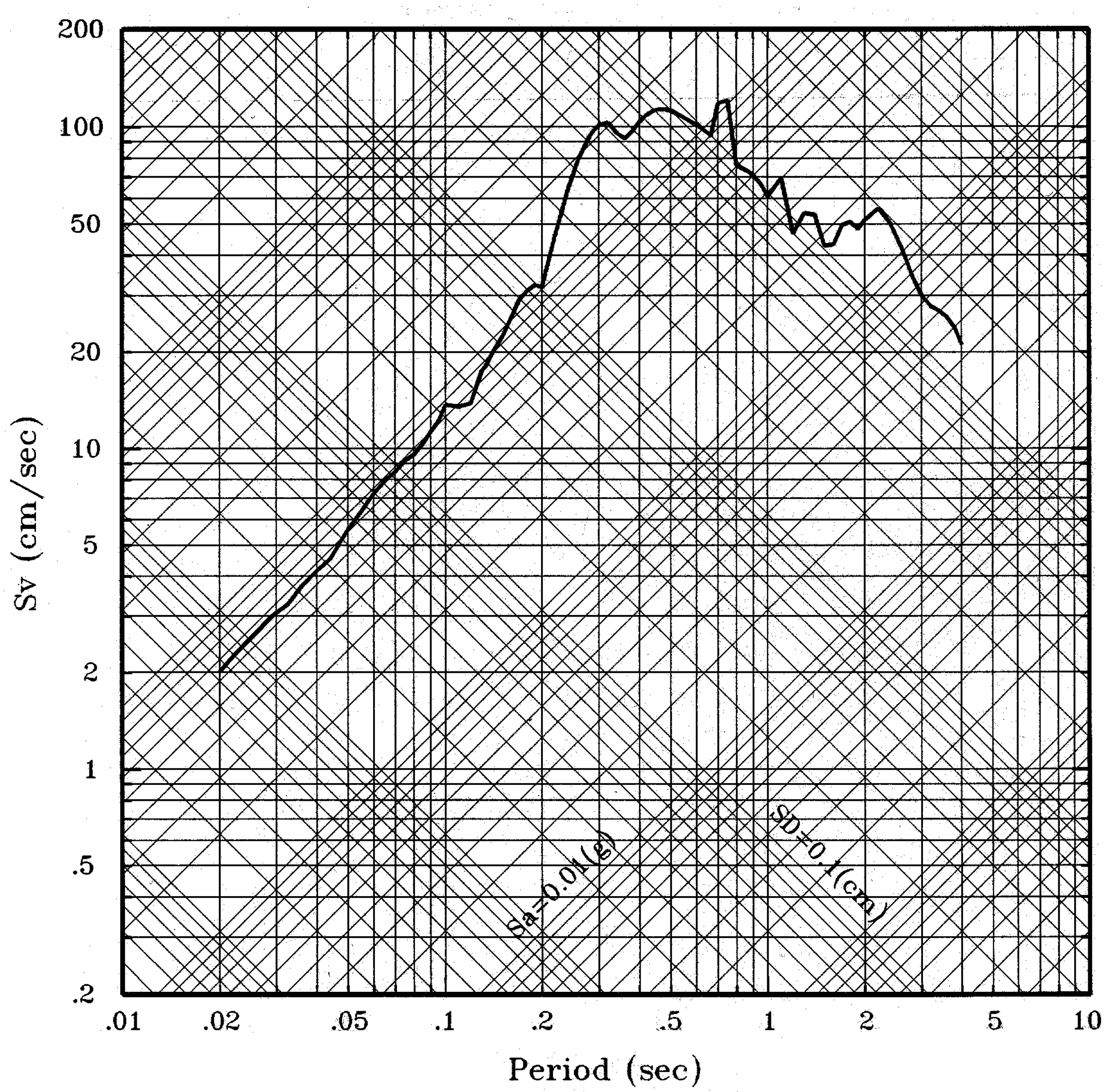
Of course, for long period structures, the velocity equality breaks down since S_v approaches zero, while SV approaches peak ground velocity (PGV). The relationships between SD and S_a can be justified by the following physical behavior of the vibrating system. At maximum relative displacement SD, the velocity is zero, and maximum spring force equals maximum inertia force,

$K \cdot SD = m \cdot S_a$,

where K is stiffness and *m* is mass, giving

$$S_a = K/m \cdot SD = w^2 \cdot SD \qquad \text{(D-14)}$$

Detailed discussions on response spectra and their computation from accelerograms are given in Ebeling 1992, Chopra 1981, Clough and Penzien 1993, and Newmark and Rosenblueth 1971. An example of a typical acceleration response spectrum is shown in Figure D-5(b). Also, because of the relation $S_a = w\, S_v = w^2$ SD, it is possible to represent spectra on tripartite log paper (Figure D-9).



1 cm = 0.4 inches

Figure D-9 Tripartite plot of the response spectrum from the Corralitos recording, component 0E, of the 1989 Loma Prieta, California Earthquake.