Basic Measurement of the strength of earthquakes

Before further discussion of strong motion recordings, it is necessary to describe the size of an earthquake. There are two basic descriptions:

1) Subjected measures (damage-related)

   Intensity (Modified Mercalli) : 진도

2) Objected measures (Instrumental)

   Magnitude : 규모

   Richter magnitude

   Spectrum intensity (Housner)

   Arias Intensity

Subjective measures of EQ strength

Subjective measures of EQ size (intensity) were developed before the advent of modern recording instruments, and are still used today. They attempt to describe the strength of an EQ **in terms of its effects on people, buildings, and landforms**. Numerical scales are established which assign a certain numerical value to different amounts of damage. Clearly, an EQ will have as many different intensity values as there are individuals or affected buildings. **EQs do not have a unique intensity**. It is important to remember that a very strong EQ which affects few people may have a small intensity.

In the western hemisphere, the most widely used intensity scale is that of Mercalli. It was first developed in 1902, and was modified in 1931 by Wood and Neumann to fit California conditions. The **modified Mercalli Intensity Scale (MMI)** assigns Roman numerals from I to XII to increasing amounts of damage.

MODIFIED MERCALLI EARTHQUAKE INTENSITY SCALE

I   Not felt except by a very few under especially favorable circumstances

II   Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III   Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV   During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V   Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI   Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII   Everybody runs outdoors. Damage negligible in buildings of good design and construction: slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII   Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.

IX   Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X   Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI   Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII   Damage total. Practically all works of construction are damaged greatly or destroyed. Waves seen on ground surface. Lines of sight and level are distorted. Objects are thrown into the air.

Isoseismal Map

It must be reiterated that intensity is a subjective measure of the effect of an EQ, rather than a precise engineering measure. The intensity of an EQ does depend on **its strength**, but also on other things: the focal depth, **the focal distance**, the epicentral distance, the distance to the fault surface, **the type and quality of construction**, soil conditions, **the sensitivity of the observers**, and the presence or absence of observers.

No EQ can be described by a single intensity. Observed intensities at different sites are placed on a map at the locations of those sites. Connecting the points of equal intensity, an **isoseismal map** is obtained. The isoseismal lines can be thought of as contour lines for EQ effects. These isoseismal lines are not regular in form. The highest intensities usually occur close to the epicenter. As example of an isoseismal map is shown below.

Isoseismal lines of the Mexico earthquake of 19 May 1962. *After Figueroa (1963).*
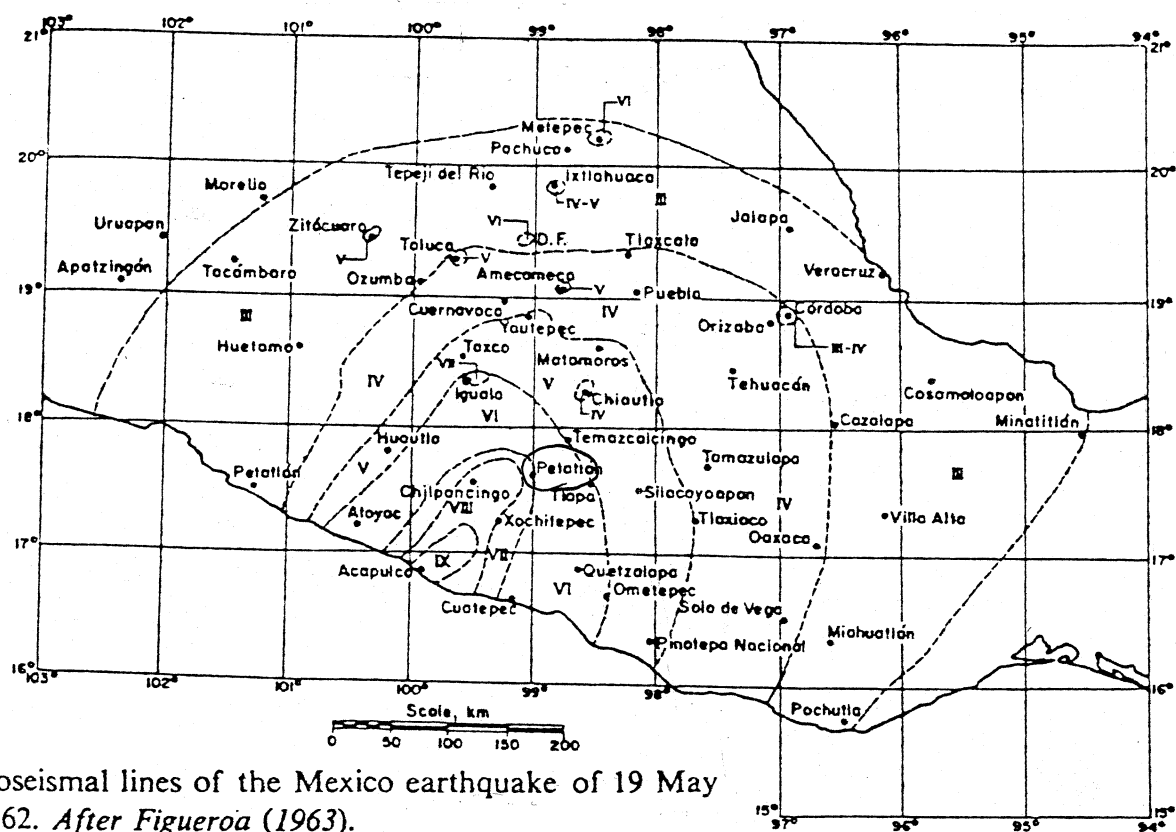
Objective measures (instrumental measures)

Local Magnitude M_L

To avoid the subjectivity associated with intensity measurements, quantitative measurements of EQ strength were developed in the 1930's. One of these, proposed by Richter, was a local magnitude scale, M_L

$$M_L = \log_{10} A$$
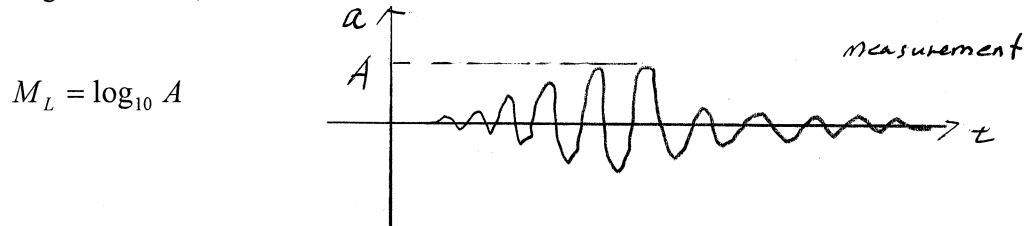
where A is the maximum amplitude, in microns (10^{-3} mm), recorded on a **Wood-Anderson seismograph located at an epicentral distance of 100 KM**. Thus, an EQ with a local magnitude of 6.0 will have 10 times the recorded amplitude an EQ with a local magnitude of 5.0. Evidently, the magnitude scale is open-ended: there is no upper nor lower limit to magnitudes.

The Wood-Anderson seismograph is a sensitive instrument with a fundamental period of that about 0.8 seconds, damping of about 80% of critical, and a magnification of 2500. In an input frequency range of 20-50 Hz, its maximum displacement response is approximately proportional to the ground displacement. Because these instruments are so sensitive, magnitudes are actually estimated from recordings obtained at epicentral distances much greater than 100 km. The epicentral distance is computed from the difference between the P and S wave arrival times, and **Wood-Anderson amplitude at 100 km is calculated using empirical attenuation charts**.

Bullen and Bolt (1985) $M = \log A + 2.56 \log D - 1.67$ (California)

Korea meteorological administration $M = \log A + 1.73 \log D - 0.83$ (Korea)

Problems with local magnitude

However, the local magnitude scale has a problem: Richter did not state which wave to measure (P, S, or Surface). **Different waves have different frequencies** (producing different dynamic amplification from the Wood-Anderson instrument), and **attenuate differently with distance**. To avoid these problems, other magnitudes have been proposed and are being used:

1

Surface wave magnitude M$_S$

Gutenberg defined a magnitude based on the amplitude of **surface waves** from distant EQ. These have periods of about 20 seconds.

Body wave magnitude m$_b$

Because deep-focus EQs cause little surface wave response, their strength would be underestimated by surface wave magnitude measurements. For this reason, a body wave magnitude has been proposed, based on **P wave amplitudes**.

Duration Magnitude M$_D$

None of the above magnitudes accurately distinguish among very small EQs. For this reason, a duration magnitude has been proposed, based on the total duration of an EQ in seconds. It is of interest primarily to **sesmologists rather than EQ engineers**.

In practice today, EQs with **magnitudes greater than about 6 are usually described using surface-wave magnitudes M$_S$;** those with **magnitudes less than 6 are usually described using magnitudes M$_L$** .

Moment magnitude scale M$_W$

All the above magnitudes do not distinguish very well among **very strong EQs**. All very strong EQs have local magnitudes M$_L$ of about 7.0. This phenomenon is sometimes referred to as "magnitude saturation" for long fault rupture length. To avoid this problem, the concept of moment magnitude has been proposed:
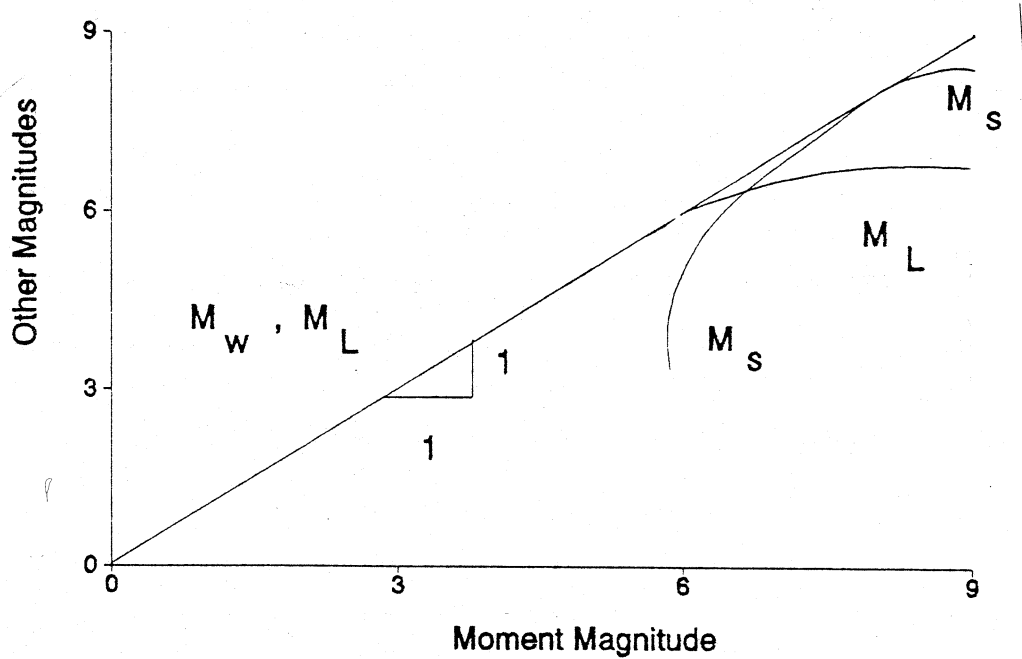
$$M_w = \mu A \bar{u}$$

where $\bar{u}$ = average fault displacement

μ = shear modulus of rock

A = rupture area

Clearly, this has no upper limit. Its parameters cannot be estimated without a large amount of data.

M_D or M_L for magnitudes less than 3

M_L or m_b for magnitudes between 3 and 7

M_s for magnitudes between 5 and 7.5

M_w for magnitudes greater than 7.5

Spectrum Intensity (Housner)

In the 1950's, Housner proposed the following definition for spectrum intensity.

Generally, damage is related to spectrum velocity rather than spectrum acceleration.

$$SI = \int_{0.1s}^{2.5s} PSV(T, \xi = 0.02)dT$$

Aria's Intensity

Intensity based on magnitude of ground acceleration

$$AI = (\pi/2g) \int (a_g)dt$$

3

Fault Area and Magnitude

From the above discussion of moment magnitudes, it can be seen that there is a strong correlation between fault area and magnitude. For classes of EQs in which the basic fault mechanism, the shear modulus, and the depth of the rupture surface are fairly constant (for example, for California strike-slip EQs), good correlation exists between the length of the fault and the magnitude:

$$M_L = a + b \log_{10} L$$

where L = length of fault in km.

Wells and Coppersmith

Strike slip	a= 5.16	b= 1.12
Normal thrust	a= 4.86	b= 1.32
Reverse thrust	a= 5.00	b = 1.22

Rough guidelines are as follows:

M_s, M_L	L, km
5.5	5 – 10
6.5	10 – 20
7.5	60 – 100
8.5	200 - 800

For example, the 1906 San Francisco EQ had an estimated magnitude magnitude of **8.25**, and a fault length of **430 km**. The 1989 Loma Prieta EQ had a magnitude **7.1**, and a rupture length of **35 km**. Most of the energy released by an EQ takes the form of heat and severe inelastic response near the rupture zone. **Only a small fraction of the energy released takes the form of seismic waves.** The ratio of energy released by seismic waves, divided by the total energy released by an EQ, is sometimes referred to as the "**seismic efficiency**" of an EQ. It is typically about 10%.

$M_L < 5.0$ no damage

$5.0 < M_L < 6.0$ damage close to epicenter

$6.0 < M_L < 7.0$ damage over area of 2000 km^2

$7.0 < M_L < 8.0$ damage over area of 10000 km^2

Ground Motion Parameters for EQ Engineering Design

Design ground motions must be specified in terms of parameters describing their strength and other characteristics:

1) Peak ground motion : absolute peak measured
2) Effective peak motion : the peak significantly affecting structures
3) Frequency content : related to Tg
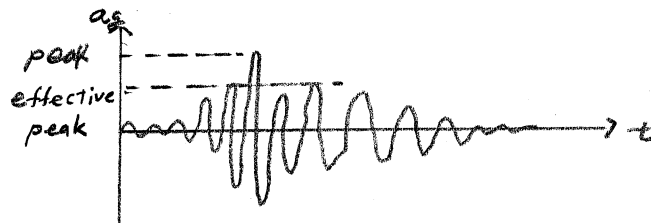4) Duration : related to energy

Peak ground motion

This is the most common parameter. It describes maximum motion at the recording site.

PGA : Peak ground acceleration

PGV : Peak ground velocity

PGD : Peak ground displacement

These are not necessarily peak instrumental values. This is particularly true for PGA. Rather, effective peak motions are used. This somewhat arbitrary concept is intended to eliminate random points that would have little structural effect. **Effective Peak Acceleration (EPA)** is that acceleration which is most closely related to structural response and to damage potential of an EQ. **It differs from and is less than the peak free-field ground acceleration.** It is a function of the size of the loaded area, the frequency content of the excitation (which in turn depends on the closeness to the source of the EQ) and of the weight, embedment, damping characteristics, and stiffness of the structure and its foundation.

For example, in the western U.S., **EPA is estimated by taking an average acceleration ordinate on a tripartite logarithmic spectrum, and dividing that ordinate by a factor of 2.5.** This will be discussed further when we deal with design spectra. Peak instrumental values correlate poorly with observed damage. Effective peak values tend to be repeated in a record, and correlate better with damage. **Effective peak values may differ substantially from peak instrumental values,** particularly for near-source sites. There is little difference for far-source sites.

PGA and PGV are often used. PGD is not used as often because it is more sensitive to processing errors.

6

Frequency Content

Use of effective PGA, PGV, and PGD is a considerable simplification. To include the effects of frequency content, ground motions are often described using response spectrum.

Response Spectrum

The single most common EQ engineering representation of ground motions is in terms of their response spectra., often plotted in tripartite logarithmic coordinates.

Calculation of Pseudo-acceleration
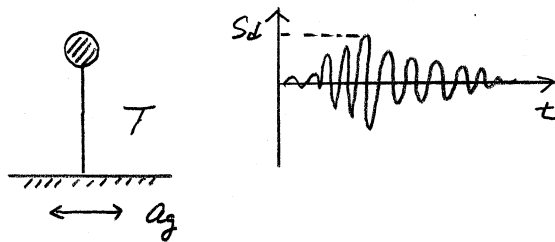
$$S_v = \omega S_d$$

$$S_a = \omega S_v = \omega^2 S_d$$

$$T = \frac{2\pi}{\omega}$$
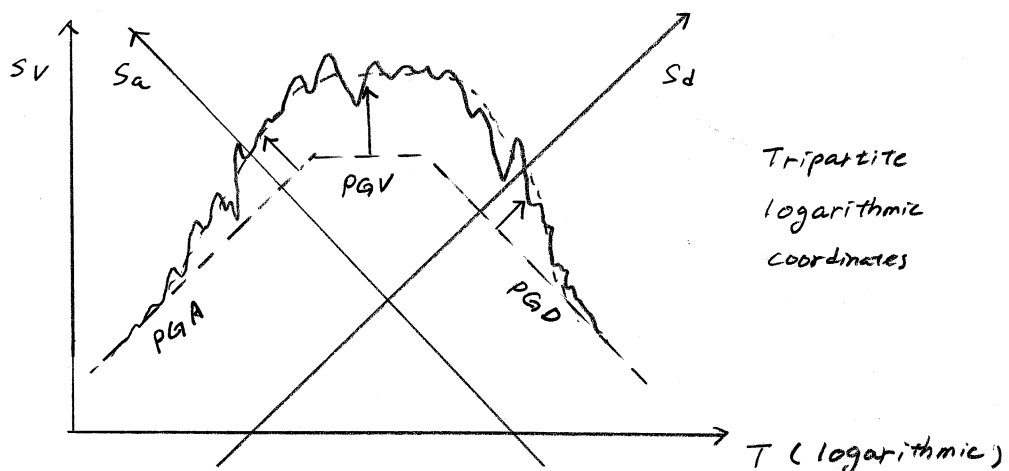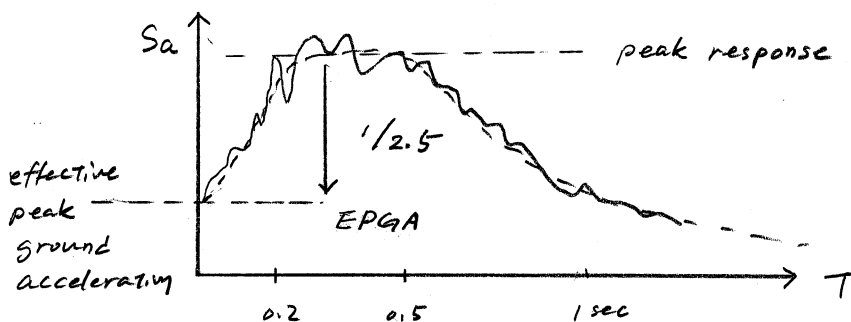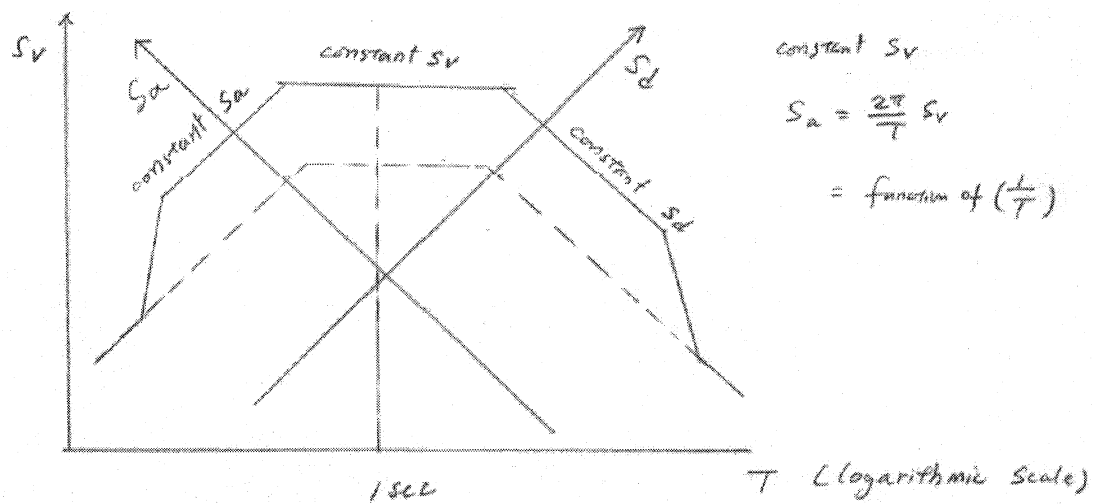
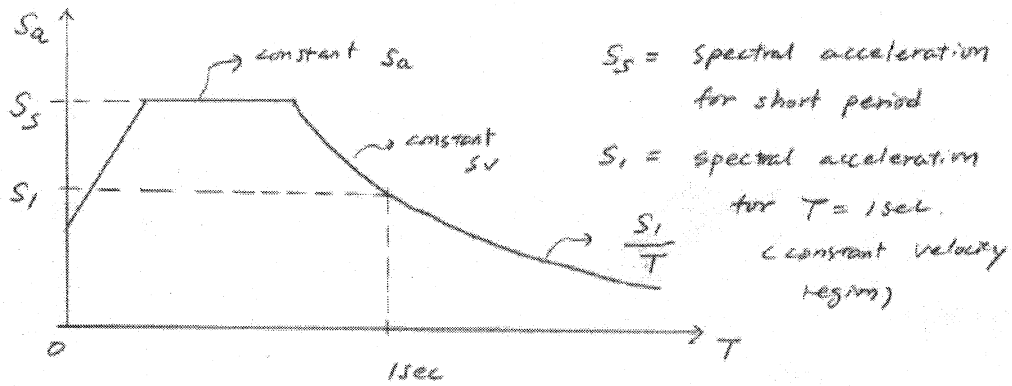Assuming $\quad m\,a + k\,u = 0$

free vibration

$$a = \omega^2 u$$

$$k\,u = f_s = m\,a$$

Pseudo - acceleration

$\neq$ actual acceleration

Tripartite
logarithmic
coordinates

7

S_S = spectral acceleration for short period

S_1 = spectral acceleration for $T = 1$sec.
(constant velocity region)

constant S_v

$$S_a = \frac{2\pi}{T} S_v$$

$$= \text{function of } \left(\frac{1}{T}\right)$$

tripartite log. spectrum

$$Sd = \frac{1}{\omega} S_v \qquad\qquad Sa = \omega S_v$$

$$\log S_v = -\log T + \log Sd + \log 2\pi \qquad \log S_v = y\text{-axis}$$

$$\log S_v = +\log T + \log Sa - \log 2\pi \qquad \log T = x\text{-axis}$$

There is no reliable methodology for specifying a response spectrum directly in terms of EQ parameters (for example, magnitude) and site characteristics (epicentral distance, geology, underlying soil). Therefore, a two-step process is often used for specifying a design response spectrum:

Step I : establish the characteristics of the ground motion (PGA, PGV, PGD). Plot these on a tripartite logarithmic plot.

Step II: Based on that ground motion spectrum, establish a design response spectrum.
1) use average amplification factors : linear elastic design response spectrum (LEDRS with damping), usually 5% damping.
2) consider soil effects : soil factor (amplification factor)
3) consider nonlinear structural response : response modification factor (reduction factor)

However, it should be noted that the concept of effective peak ground acceleration itself is estimated from actual response spectrum of structures.

Duration

The most commonly used definition of duration is the "bracketed duration" the time interval between the first and last acceleration peaks exceeding some threshold value (most commonly 0.05g)

Attenuation

To establish a realistic ground motion spectrum, we need to relate PGA, PGV, and PGD to :
1) EQ source mechanism and region
2) EQ size (magnitude)
3) Distance to site
4) Local site geology and soil conditions
5) Type, condition, and location of recording instrument

We will emphasize the first 3 points. Influence of local site geology and soil conditions will be

covered later.

The study of how ground motions are affected by EQ source mechanism, size, and distance is broadly referred to as attenuation. Specifically, attenuation laws attempt to describe how seismic waves attenuate, or diminish, with increasing focal distance. They are derived from statistical analysis of strong ground motion data sets.

Physical basis for attenuation

Seismic waves generated by a dislocation on a fault propagate in all directions. The wave amplitude decrease with distance because of

1) Geometrical attenuation

$$\text{Amplitude} \quad \propto \frac{1}{R^n}$$
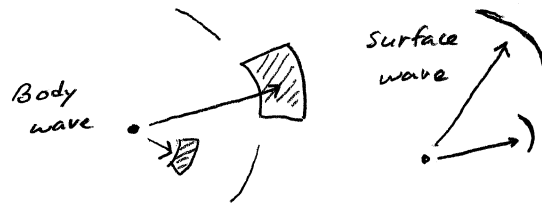
Where n depends on the type of wave. For example, body waves propagate in a hemispherical wave front, whose area increases as a function of R^2. The energy transmitted per unit area of that front decreases as R^{-2}.

In contrast, surface waves propagate on a circular front, whose length increases linearly with R. The energy transmitted per unit length of that front decreases primarily as R^{-1}.

Based on these considerations, it is possible to see in general terms that **surface waves will attenuate much more slowly than body waves.** At large epicentral distances, ground motions will be much richer in dispersive, long-period, surface waves. At short epicentral distance, non-dispersive, short-period waves will predominate.

2) Material energy dissipation (heat, inelastic response):

For example, the amplitude of on S wave is given by

$$A = A_o \left(\frac{1}{\sqrt{R}} \right) \exp\left(\frac{-\omega R}{2QC_s} \right)$$

where R = focal distance

ω = wave frequency

Q = damping coefficient

9

Cs = shear wave velocity

Since attenuation occurs at a constant rate per cycle, **high-frequency waves(such as P and S waves) attenuate more rapidly than low-frequency ones (such as surface waves).** Again, near-source EQs are likely to be rich in high-frequency waves, while far-source EQs will have more low frequencies.

Model for Attenuation Laws

A typical model is : $Y = b_1 f_1(M) f_2(R)$

Earthquake size : $f_1(M) = e^{b_2 M}$

Energy dissipation : $f_2(R) = \left[\dfrac{1}{(R+b_3)^{b_4}} \right] e^{b_5 R}$

In the above expression, Y is a general ground motion parameter (*PGA, PGV, PGD*). The constant b_3 represents saturation of motion close to the source. The constants are determined by statistical analysis of ground motion records.

M is logarithmic scale in amplitude. Thus, **PGA is the function of** e^M

All attenuation laws are functions of distance: epicentral distance; hypocentral (focal) distance; distance to fault. Differences among these distances are important for sites near the focus or the fault.

Sample Attenuation Laws

Many attenuation laws are available. Some of the most common are summarized below.
Units : R (focal distance) in km
PGA (cm/sec2), *PGV* (cm/sec), *PGD* (cm)

Esteva (1977)

$$PGA = \frac{5829 e^{0.8M}}{(R+40)^2}, \quad PGV = \frac{36 e^M}{(R+25)^{1.7}}$$

10

In case of M=6.5, R= 40km PGA = 0.168g ------- close to PGA in Korea.

R=100km PGA = 0.05g

McGuire (1977)

$$PGA = \frac{476e^{0.64M}}{(R+25)^{1.3}}, \quad PGV = \frac{5.64e^{0.923M}}{(R+25)^{1.2}}, \quad PGD = \frac{0.393e^{M}}{(R+25)^{0.885}}$$

Donovan (1973)

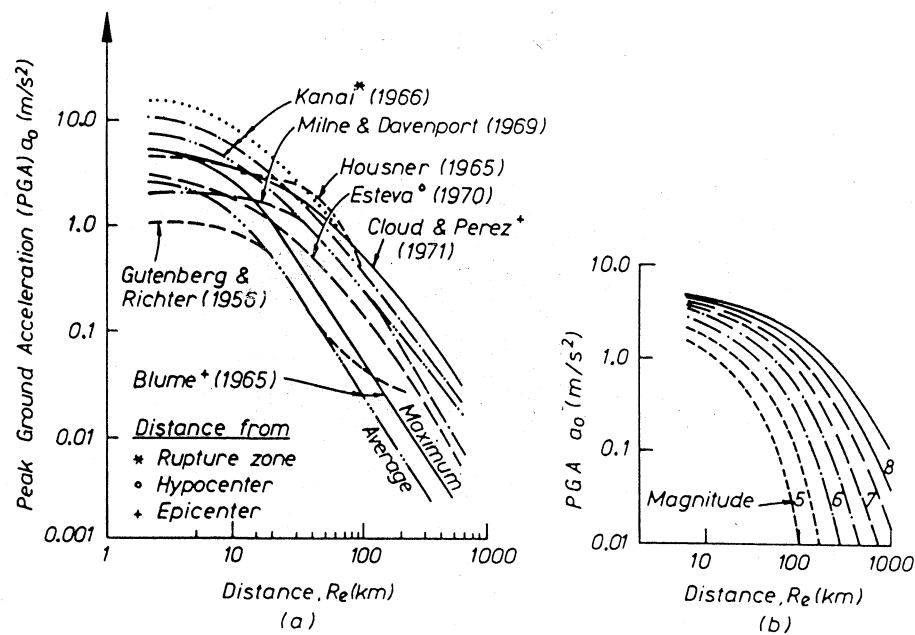$$PGA = \frac{1059e^{0.5M}}{(R+25)^{1.32}}$$

Fig. 2.12 Peak ground acceleration attenuation with epicentral distance: (a) for an M6.5 earthquake; (b) average values for different magnitudes [P52].

11

Table 2-4. Typical Attenuation Relationships

Data Source	Relationship*	Reference
1. San Fernando earthquake February 9, 1971	$\log PGA = 190 / R^{1.83}$	Donovan (2-23)
2. California earthquake	$PGA = y_0 /(1 + (R'/h)^2)$ where $\log y_0 = -(b + 3) + 0.81M - 0.027M^2$ and b is a site factor	Blume (2-26)
3. California and Japanese earthquakes	$PGA = \dfrac{0.0051}{\sqrt{T_G}} 10^{(0.61M - p \log R + 0.167 - 1.83/R)}$ where $P = 1.66 + 3.60/R$ and T_G is the fundamental period of the site	Kanai (2-27)
4. Cloud (1963)	$PGA = 0.0069e^{1.64M} /(1.1e^{1.1M} + R^2)$	Milne and Davenport (2-28)
5. Cloud (1963)	$PGA = 1.254e^{0.8M} /(R + 25)^2$	Esteva (2-29)
6. U.S.C. and G.S.	$\log PGA = (6.5 - 2 \log(R'+80)) / 981$	Cloud and Perez (2-25)
7. 303 Instrumental Values	$PGA = 1.325e^{0.67M} /(R + 25)^{1.6}$	Donovan (2-23)
8. Western U.S. records	$PGA = 0.0193e^{0.8M} /(R^2 + 400)$	Donovan (2-23)
9. U.S., Japan	$PGA = 1.35e^{0.58M} /(R + 25)^{1.52}$	Donovan (2-23)
10. Western U.S. records, USSR, and Iran	$\ln PGA = -3.99 + 1.28M - 1.75 \ln[R = 0.147e^{0.732M}]$ - M is the surface wave magnitude for M greater than or equal to 6, or it is the local magnitude for M less than 6.	Campbell (2-30)
11. Western U.S. records and worldwide	$\log PGA = -1.02 + 0.249M - \log\sqrt{R^2 + 7.3^2} - 0.00255\sqrt{R^2 + 7.3^2}$	Joyner and Boore (2-31)
12. Western U.S. records and worldwide	$\log PGA = 0.49 + 0.23(M - 6) - \log\sqrt{R^2 + 8^2} - 0.0027\sqrt{R^2 + 8^2}$	Joyner and Boore (2-32)
13. Western U.S. records	$\ln PGA = \ln \alpha(M) - \beta(M) \ln(R + 20)$ - M is the surface wave magnitude for M greater than or equal to 6, or it is the local magnitude for smaller M. - R is the closest distance to source for M greater than 6 and hypocentral distance for M smaller than 6. - $\alpha(M)$ and $\beta(M)$ are magnitude-dependent coefficients.	Idriss (2-33)
14. Italian records	$\ln PGA = -1.562 + 0.306M - \log\sqrt{R^2 + 5.8^2} + 0.169S$ - S is 1.0 for soft sites or 0.0 for rock.	Sabetta and Pugliese (2-34)
15. Western U.S. and worldwide (soil sites)	For M less than 6.5, $\ln PGA = -2.611 + 1.1M - 1.75 \ln[R + 0.822e^{0.418M}]$ For M greater than or equal to 6.5, $\ln PGA = -2.611 + 1.1M - 1.75 \ln[R + 0.316e^{0.629M}]$	Sadigh et al. (2-35)
16. Western U.S. and worldwide (rock sites)	For M less than 6.5, $\ln PGA = -1.406 + 1.1M - 2.05 \ln[R + 1.353e^{0.406M}]$ For M greater than or equal to 6.5, $\ln PGA = -1.406 + 1.1M - 2.05 \ln[R + 0.579e^{0.537M}]$	Sadigh et al. (2-35)
17. Worldwide earthquakes	$\ln PGA = -3.512 + 0.904M - 1.328 \ln\sqrt{R^2 + [0.149e^{0.647M}]^2}$ $+ [1.125 - 0.112 \ln R - 0.0957M]F + [0.440 - 0.171 \ln R]S_{sr}$ $+ [0.405 - 0.222 \ln R]S_{hr}$ - $F = 0$ for strike-slip and normal fault earthquakes and 1 for reverse, reverse-oblique, and thrust fault earthquakes. - $S_{sr} = 1$ for soft rock and 0 for hard rock and alluvium - $S_{hr} = 1$ for hard rock and 0 for soft rock and alluvium	Campbell and Bozorgnia (2-36)

18. Western North American earthquakes	$\ln PGA = b + 0.527(M - 6.0) - 0.778 \ln\sqrt{R^2 + (5.570)^2} - 0.371 \ln\dfrac{V_s}{1396}$
	 - where $b = -0.313$ for strike-slip earthquakes
	  $= -0.117$ for reverse-slip earthquakes
	  $= -0.242$ if mechanism is not specified
	 - V_s is the average shear wave velocity of the soil in (m/sec) over the upper 30 meters
	 - The equation can be used for magnitudes of 5.5 to 7.5 and for distances not greater than 80 km
		Boore et al. (2-37)

* Peak ground acceleration PGA in g, source distance R in km, source distance R' in miles, local depth h in miles, and earthquake magnitude M. Refer to the relevant references for exact definitions of source distance and earthquake magnitude.

Campbell and Bozorgnia

Peak horizontal acceleration given as function of fault type, magnitude, soil type, and distance:

$$ln\,PHA(g) = -3.512 + 0.904M_w - 1.328ln[R^2 + (0.149exp0.647M_w)^2]^{1/2}$$

$$+ (1.125 - 0.112lnR - 0.0957M_w)F$$

$$+ (0.44 - 0.171lnR)S_{SR} + (0.405 - 0.222lnR)S_{HR}$$

in which R is the closest distance in km to fault rupture (records as close as 3 km included) and $\sigma_{lnPGA} = 0.55$ for PGA < 0.07g,

= 0.173-0.14Ln(PGA) for 0.07g<PGA<0.21g, and = 0.38 for PGA > 0.21g

Fault Type	F
Strike Slip & Normal	0
Reverse and Thrust	1

Soil Type	S_{SR}	S_{HR}
Hard Rock	0	1
Soft Rock	1	0
Alluvial Sites	0	0

Near-Source Attenuation of Peak Horizontal Acceleration from World-wide Accelerograms, **Proceedings**, 5USNCEE, Chicago, EERI, Oakland 1994.

Boore, Joyner and Fumal

Acceleration amplitude given as function of magnitude, soil condition and distance

$$log\,PHA(\%\ g) = b_1 + b_2(M_w-6) + b_5logR + b_6G_B + b_7G_C$$

for $5.0 \le M_w \le 7.7$ where $R = [d^2 + h^2]^{1/2}$
and d is the closest surface projection of fault to site(in km)

	b_1	b_2	b_5	b_6	b_7	h	$\sigma\,log_{PHA}$
Random	-0.105	0.229	-0.778	0.162	0.251	5.57	0.23
Larger	-0.038	0.216	-0.777	0.158	0.254	5.48	0.21

Soil Class	Shear Wave Velocity in upper 30 m, in m/sec	G_B	G_C
A	≥750	0	0
B	360-750	1	0
C	180-360	0	1

Estimation of Response Spectra and Peak Accelerations from Western North America Earthquakes, Open File Report 93-509, USGS, Reston, VA,1993.

As shown in the figure, all these attenuation relationships have considerable scatter. If they are used to predict PGA, PGV, and PGD for a given site, the relations among those three parameters can often be unrealistic. If little or no seismological data are available for a given sites, the following guidelines may be used.

1) pick PGA (estimate or use attenuation law)
2) estimate corresponding PGV and PGD using standard ratios for different soil types:

PGV/PGA = 122 cm/sec g = 48 in/sec g   for firm soil

$\qquad\qquad$ = 91 cm/sec g = 36 in/sec g   for rock

This difference reflects the fact that EQs on rock are likely to be richer in high frequencies than EQs on soil. For sinusoidal excitation, maximum velocity is maximum acceleration divided by the circular frequency. Therefore, for a given acceleration, the higher the frequency, the lower the velocity.

3) For adequate frequency content of ground motion, use

$$\frac{PGA \cdot PGD}{PGV^2} = 6$$, where units are consistent.

For example, using this procedure, the maximum credible California EQ for firm soil can be estimated:

PGA=0.5g

PGV=122 (cm/sec g) (0.5g) = 61 cm/sec

PGD = (6) $(61)^2$/(0.5x981) = 46 cm

Correlation between Earthquake Parameters and Structural Damage

Observed damage in EQ zones has been found to correlate very poorly with PGA. Correlation is much better with PGV. The following relation, proposed by Neumann, is widely used:

$$MMI_{site} = \frac{\log_{10}(PGV_{site} \cdot 14)}{\log_{10} 2}$$

In other words, $PGV_{site} = \dfrac{2^{MMI}}{14}$

Calculation Example using Measure of Earthquake Strength

The relationships discussed above (attenuation and damage correlation) can be used to obtain a good idea of the characteristics of an EQ based on intensity observations. As an example of this, consider the isoseismal map discussed previously, for the Mexican EQ 19 May 1962. Based on the intensity observations and their corresponding focal distances, the magnitude of the earthquake can be estimated, along with the remaining earthquake parameters:

Based on the isoseismal map, the epicenter is placed at Acapulco. Prior geologic knowledge leads to an estimate of the focal depth as 30 km.

Focal distances to other sites can therefore be calculated as the square root of the sum of the squares of their respective epicentral distances, and the 30 km focal depth.

A sample calculation is given below for one location (Petatlan). That site is at an epicentral distance of about 115 km, corresponding to a focal distance of 120 km. The observed Modified Mecalli Intensity there was VII. Using the above relation between MMI and PGV, the PGV at Petatlan is calculated as

$$PGV_{petatlan} = \frac{2^{MMI}}{14} = 9.14 cm/\sec$$

For this Mexican coastal EQ, the attenuation relationship proposed by Esteva for shallow-focus coastal EQs is appropriate:

$$PGV = \frac{36e^{M}}{(R+25)^{1.7}}$$

Here R and PGV are known, and we can solve for M:

$$M = \ln\frac{PGV \cdot (R+25)^{1.7}}{36} = \ln\frac{9.14 \cdot (120+25)^{1.7}}{36} = 7.1$$

The average calculated magnitude value is 6.9. Using that value, and the same epicentral

distances as before, it is possible to calculate *PGV* values at the site.

Corresponding *PGV* and *PGD* values can in turn be calculated, using the standard ratios discussed above for firm soil. For Petatlan, for example, using the magnitude value of 6.9 and the epicentral distance of 120 km, the expected *PGV* can be calculated as

$$PGV = \frac{36e^M}{(R+25)^{1.7}} = \frac{36e^{6.9}}{(120+25)^{1.7}} = 7.56 \text{ cm/sec}$$

and the corresponding PGA and PGD are given by

$$PGA = \frac{PGV}{122} = 0.06g$$

$$PGD = \frac{6 \cdot (PGV)^2}{PGA}$$

Finally, using the calculated *PGV* values, expected MMI values can be calculated and compared with the original observations. The closeness of the calculated MMI values to the original observations can be used as an index of the internal consistency of this process.

sites	MMI	R(km)	M	Ground motions from average M			MMI	
				PGA(g)	*PGV*(cm/s)	*PGD* (cm)		
Acapulco	IX	30	6.8	0.32	39	29	9.1	IX
Cilpacingo	VIII	90	7.4	0.09	11	8.3	7.3	VII
Petatlan	VII	120	7.1	0.06	7.5	5.6	6.7	VII
Metamoros	V	250	6.8	0.02	2.5	1.9	5.2	V
Puebla	IV	300	6.4	0.02	1.9	1.4	4.7	V

From this example, it can be seen that the relationship discussed here (intensity, magnitude, attenuation) are at least reasonable.