Credits: 3 + 0

Spring 2021 Semester

Performance-based Seismic Design of Structures

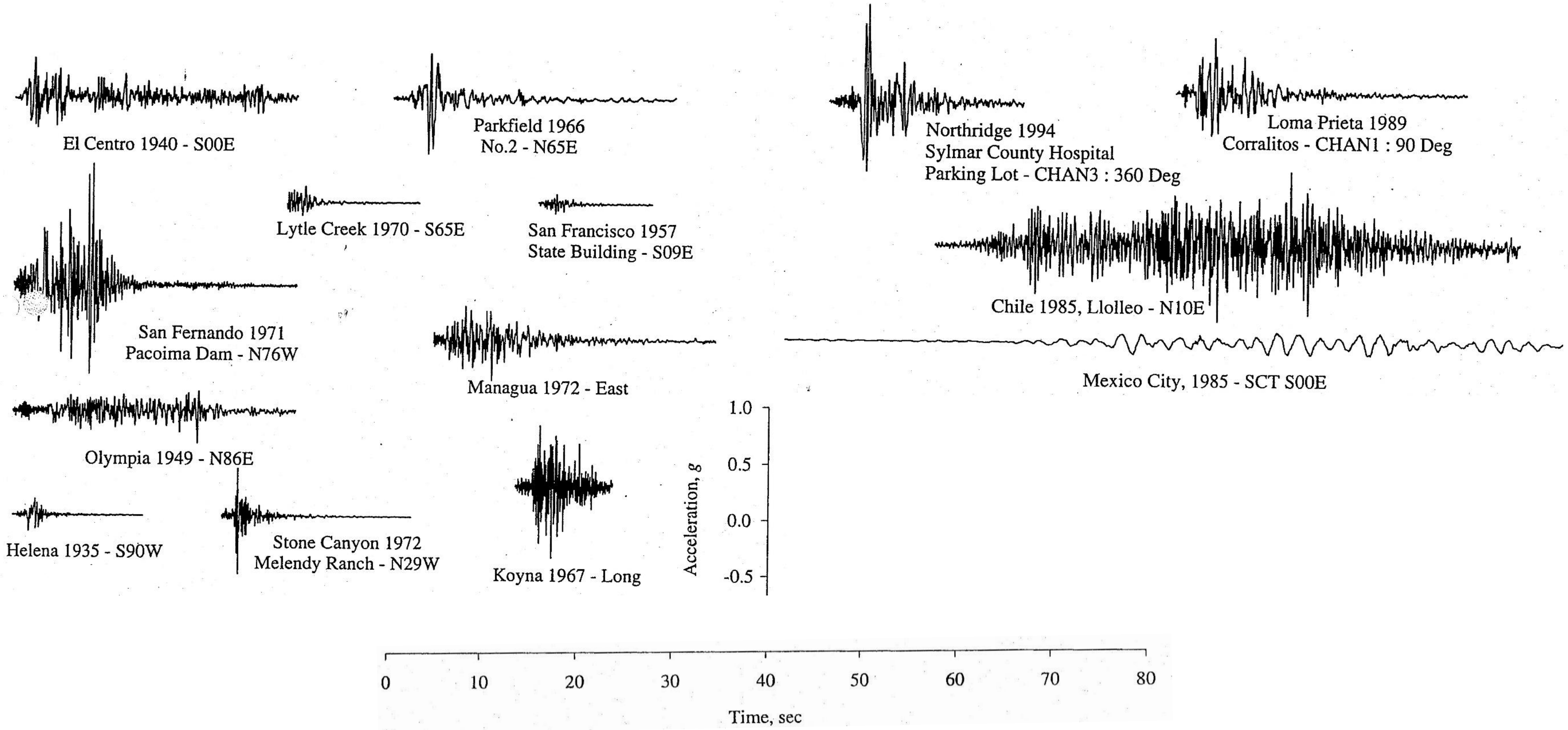
Fawad A. Najam, PE, PhD.

Assistant Professor (Structural Engineering)
Department of Structural Engineering
NUST Institute of Civil Engineering (NICE)
National University of Sciences and Technology (NUST)
H-12 Islamabad, Pakistan
Cell: 92-334-5192533, Email: fawad@nice.nust.edu.pk

Ground Motion Parameters

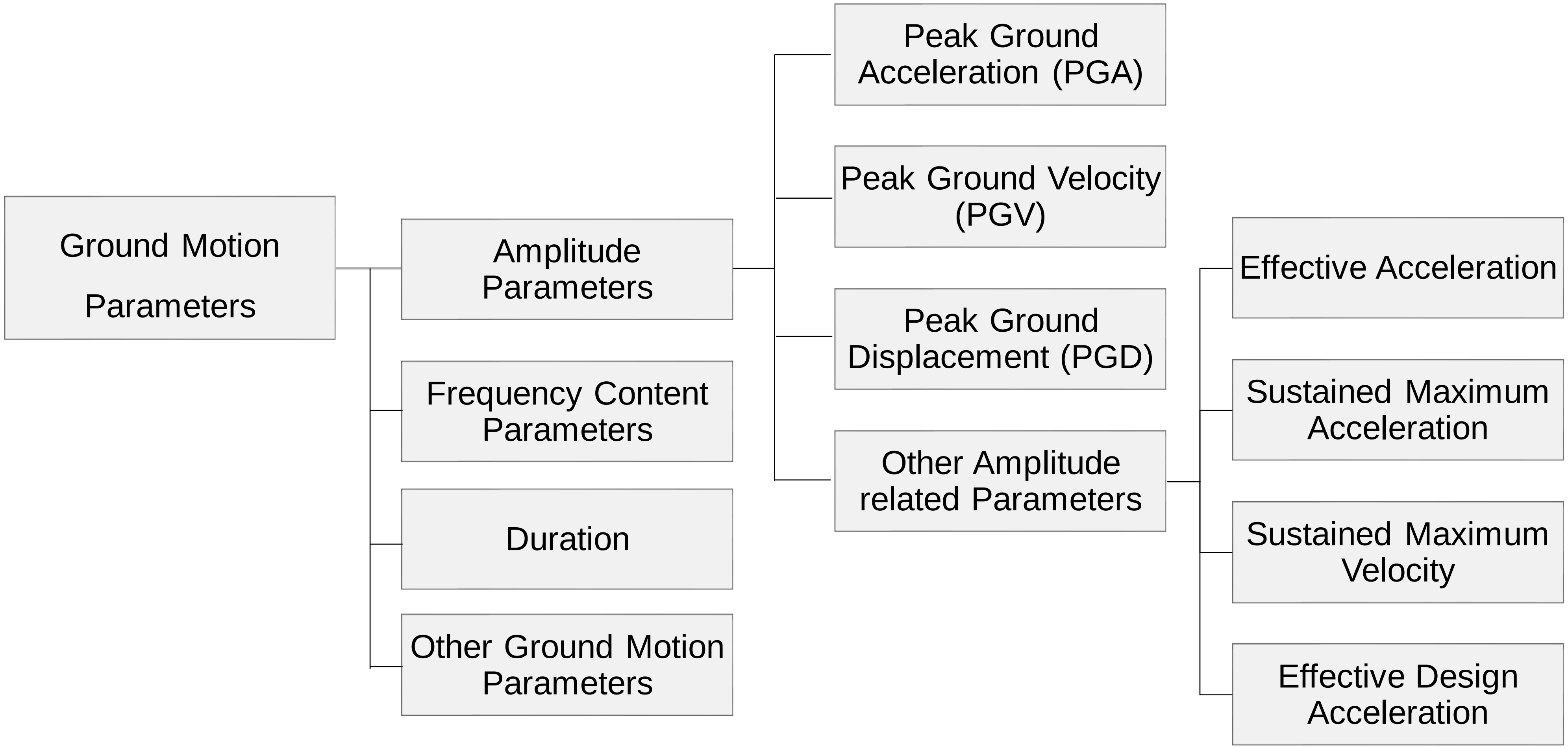
This section is mainly based on Section 3.3 of the book "Geotechnical Earthquake Engineering" by Steven L. Kramer. University of London. Prentice-Hall Inc. Upper Saddle River, NJ 07458, 1996.

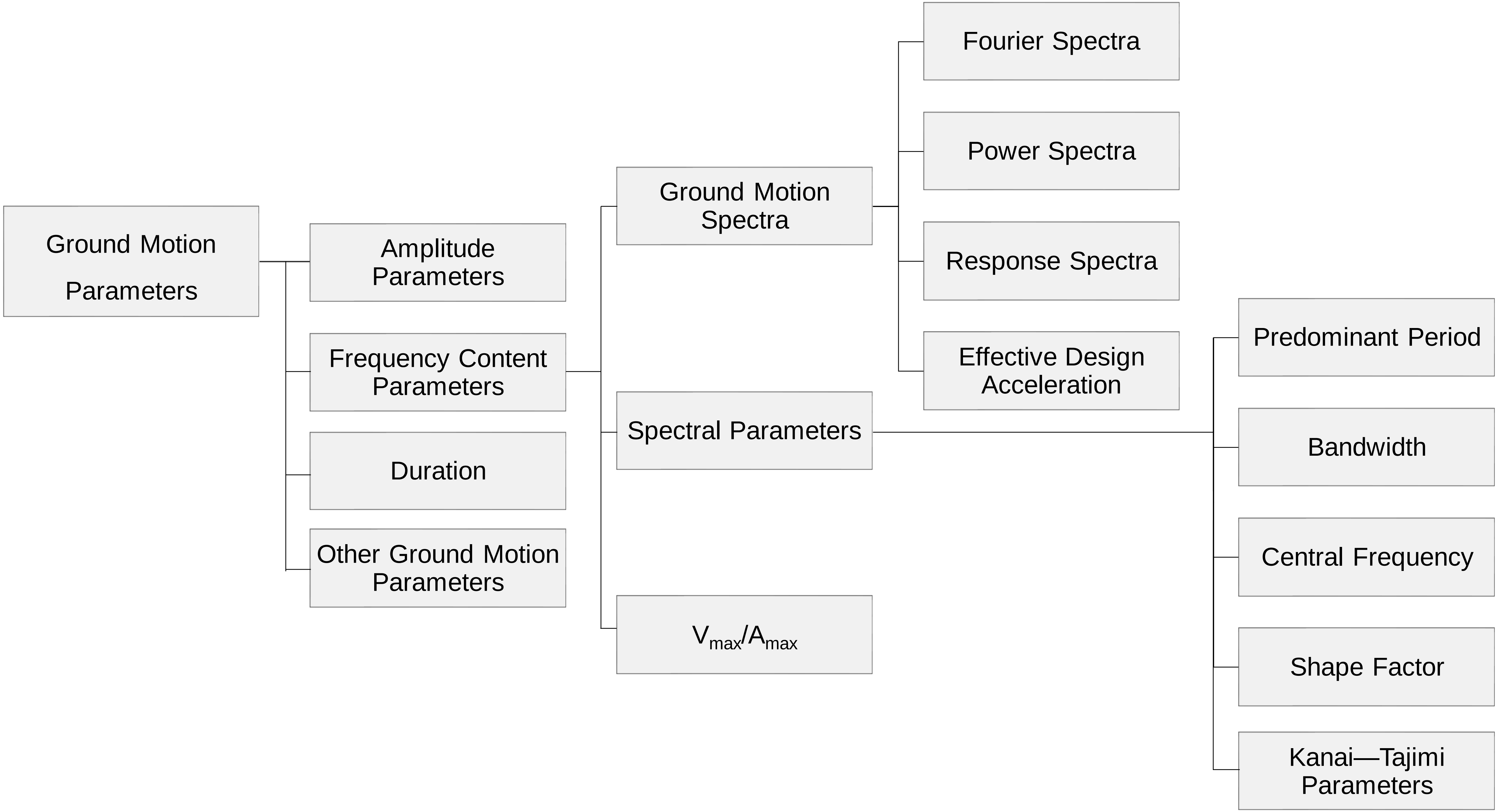
Ground Motion Parameters

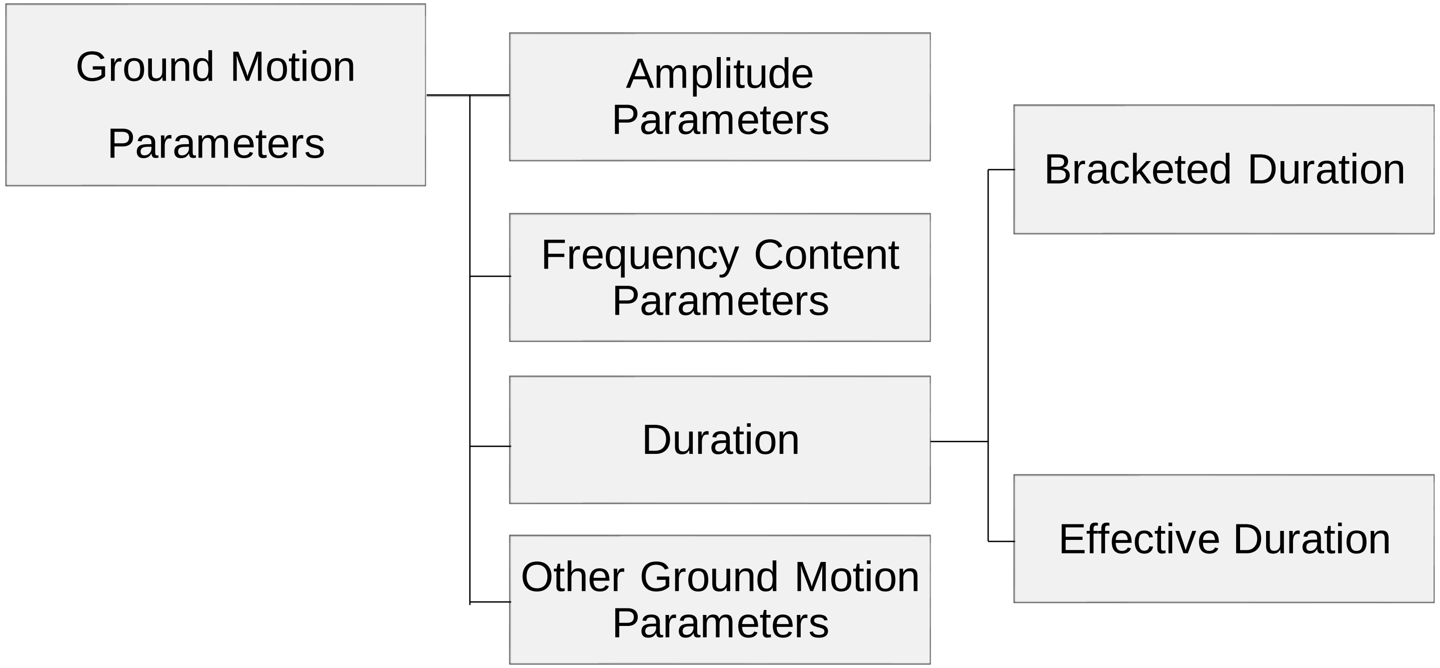


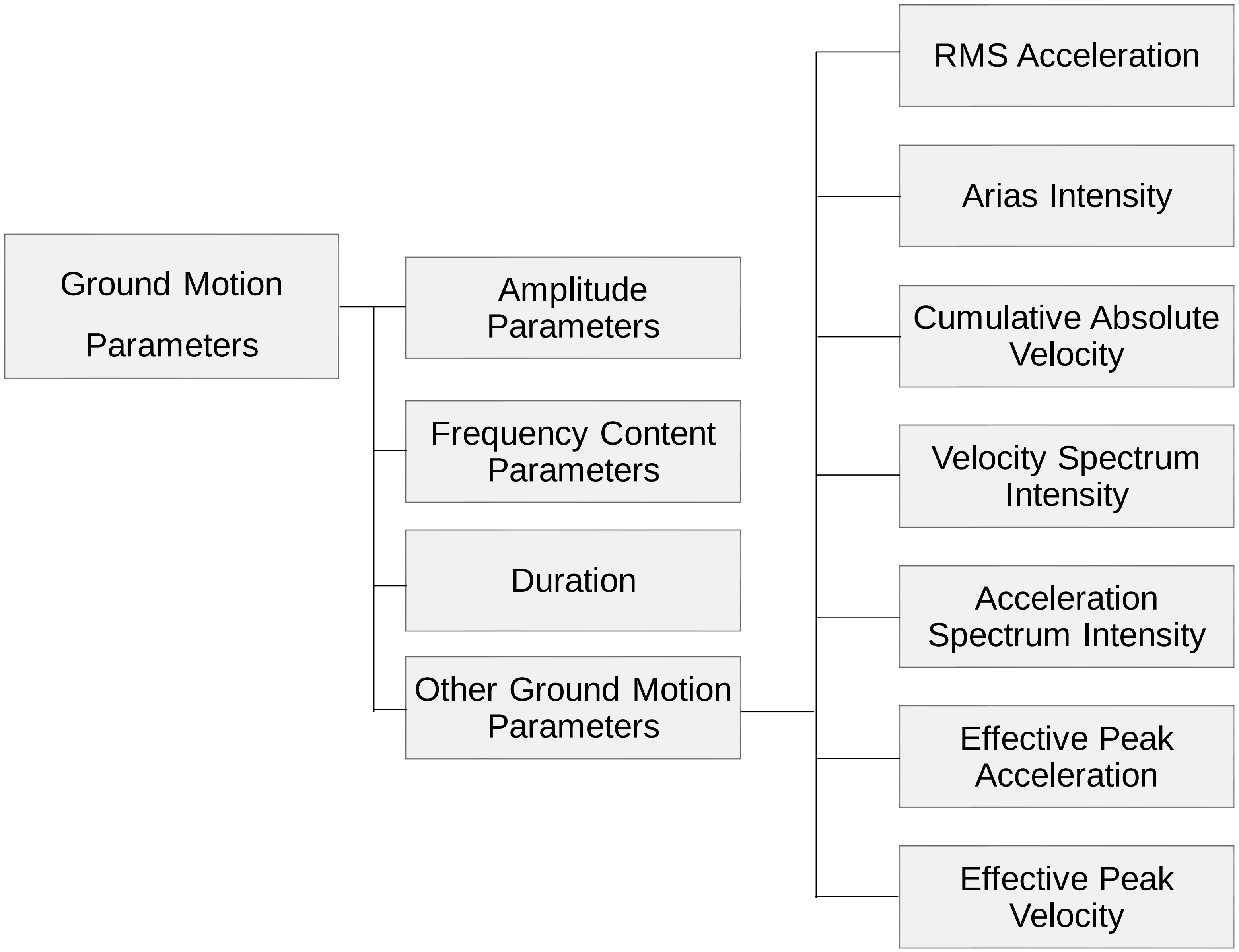
Ground Motion Parameters

- **Ground motion parameters** are essential for describing the important characteristics of strong ground motion in compact, quantitative form.
- Many parameters have been proposed to characterize the amplitude, frequency content, and duration of strong ground motions; some describe only one of these characteristics, while others may reflect two or three.
- Because of the complexity of earthquake ground motions, identification of a single parameter that accurately describes all important ground motion characteristics is regarded as impossible (Jennings, 1985; Joyner and Boore, 1988).


Ground Motion Parameters
Amplitude Parameters
Frequency Content Parameters
Duration
Other Ground Motion Parameters
Peak Ground Acceleration (PGA)
Peak Ground Velocity (PGV)
Peak Ground Displacement (PGD)
Other Amplitude related Parameters
Effective Acceleration
Sustained Maximum Acceleration
Sustained Maximum Velocity
Effective Design Acceleration


Ground Motion Parameters
Amplitude Parameters
Frequency Content Parameters
Duration
Other Ground Motion Parameters
Ground Motion Spectra
Spectral Parameters
V_{max}/A_{max}
Fourier Spectra
Power Spectra
Response Spectra
Effective Design Acceleration
Predominant Period
Bandwidth
Central Frequency
Shape Factor
Kanai—Tajimi Parameters


Ground Motion Parameters
Amplitude Parameters
Frequency Content Parameters
Duration
Other Ground Motion Parameters
Bracketed Duration
Effective Duration


Ground Motion Parameters
Amplitude Parameters
Frequency Content Parameters
Duration
Other Ground Motion Parameters
RMS Acceleration
Arias Intensity
Cumulative Absolute Velocity
Velocity Spectrum Intensity
Acceleration Spectrum Intensity
Effective Peak Acceleration
Effective Peak Velocity

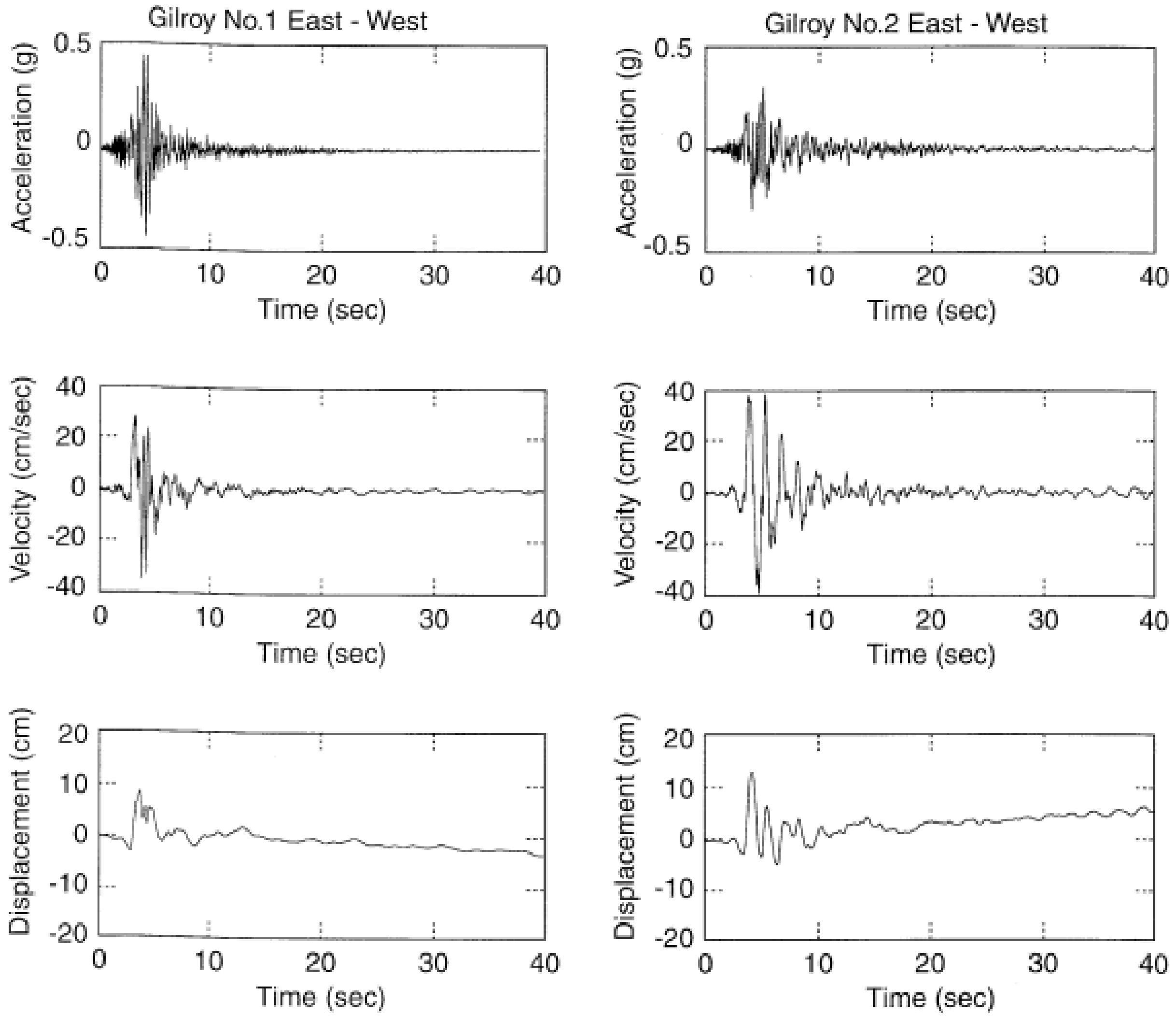
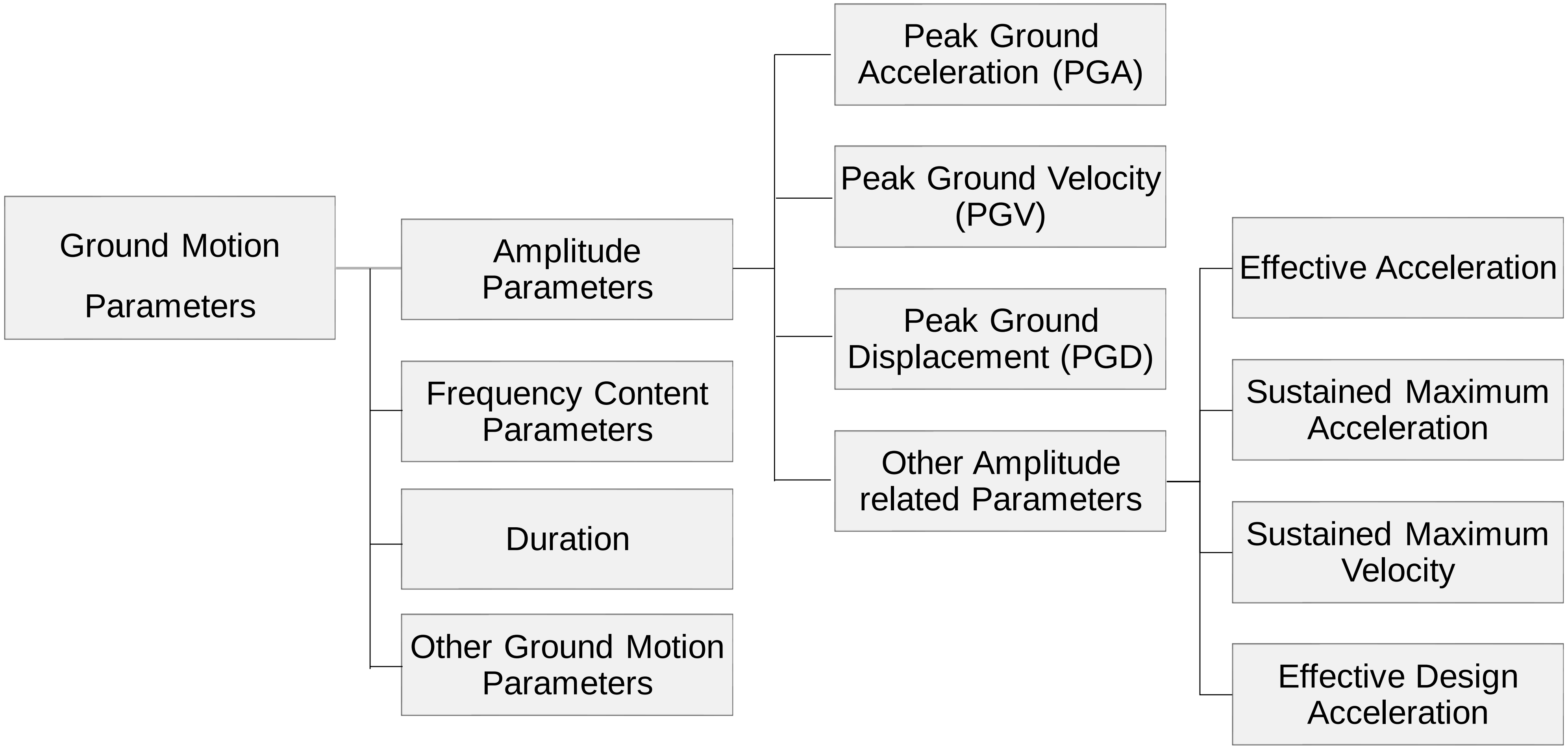


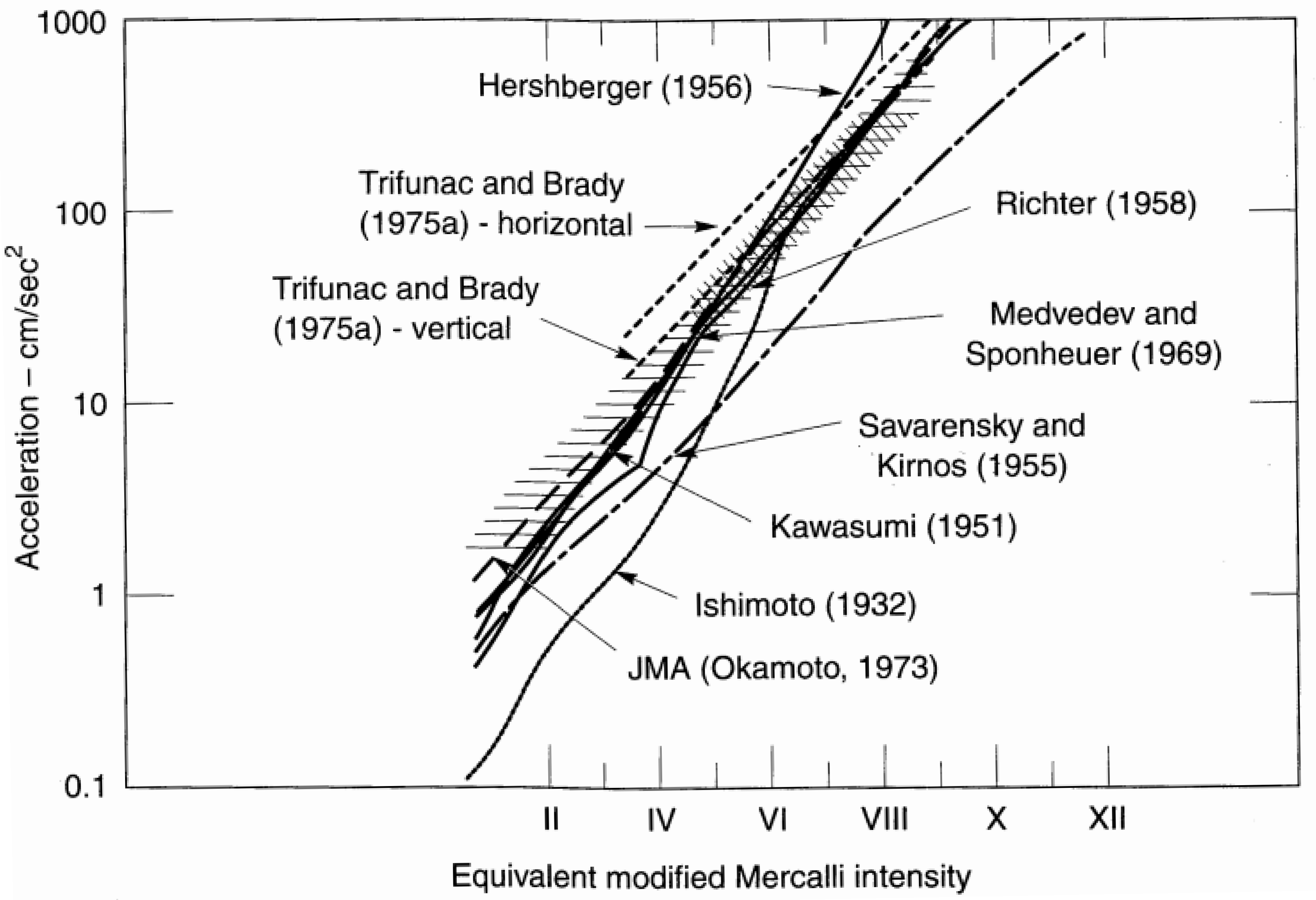
Figure 3.10 Acceleration, velocity, and displacement time histories for the E-W components of the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) strong motion records. The velocities and displacements were obtained by integrating the acceleration records shown in Figure 3.1 using the trapezoidal rule. Note that the Gilroy No. 1 (rock) site experienced higher accelerations, but the Gilroy No. 2 (soil) site experienced higher velocities and displacements.

Converting Acceleration into Velocity and Displacement using Numerical Integration

Note the different predominant frequencies in the acceleration, velocity, and displacement time histories. The acceleration time history shows a significant proportion of relatively high frequencies. Integration produces a smoothing or filtering effect [in the frequency domain, $v = a(\omega)/\omega$ and $v = a(\omega)/\omega$]

Therefore, the velocity time history shows substantially less high-frequency motion than the acceleration time history. The displacement time history, obtained by another round of integration, is dominated by relatively low frequency motion.


Ground Motion Parameters
Amplitude Parameters
Frequency Content Parameters
Duration
Other Ground Motion Parameters
Peak Ground Acceleration (PGA)
Peak Ground Velocity (PGV)
Peak Ground Displacement (PGD)
Other Amplitude related Parameters
Effective Acceleration
Sustained Maximum Acceleration
Sustained Maximum Velocity
Effective Design Acceleration



Peak Ground Acceleration

- **Peak horizontal acceleration** (PHA) is the largest (absolute) value of horizontal acceleration obtained from the accelerogram of that component.
- By taking the vector sum of two orthogonal components, the maximum resultant PHA (the direction of which will usually not coincide with either of the measured components) can be obtained.

- Vertical accelerations have received less attention because the margins of safety against gravity forces usually provide adequate resistance to dynamic forces induced by vertical accelerations during earthquakes.
- The **peak vertical acceleration** (PVA) is often assumed to be two-thirds of the PHA (Newmark and Hall, 1982).

PHV and PHD

- **Peak horizontal velocity (PHV):** Since the velocity is less sensitive to the higher-frequency components of the ground motion, the PHV is more likely than the PHA to characterize ground motion amplitude accurately at intermediate frequencies. For structures or facilities that are sensitive to loading in this intermediate-frequency range (e.g., tall or flexible buildings, bridges, etc.), the PHV may provide a much more accurate indication of the potential for damage than the PHA.

- **Peak horizontal displacement (PHD):** Peak displacements are generally associated with the lower-frequency components of an earthquake motion. They are, however, often difficult to determine accurately (Campbell, 1985; Joyner and Boore, 1988), due to signal processing errors in the filtering and integration of accelerograms and due to long-period noise. As a result, peak displacement is less commonly used as a measure of ground motion than is peak acceleration or peak velocity.

Other Amplitude related Parameters

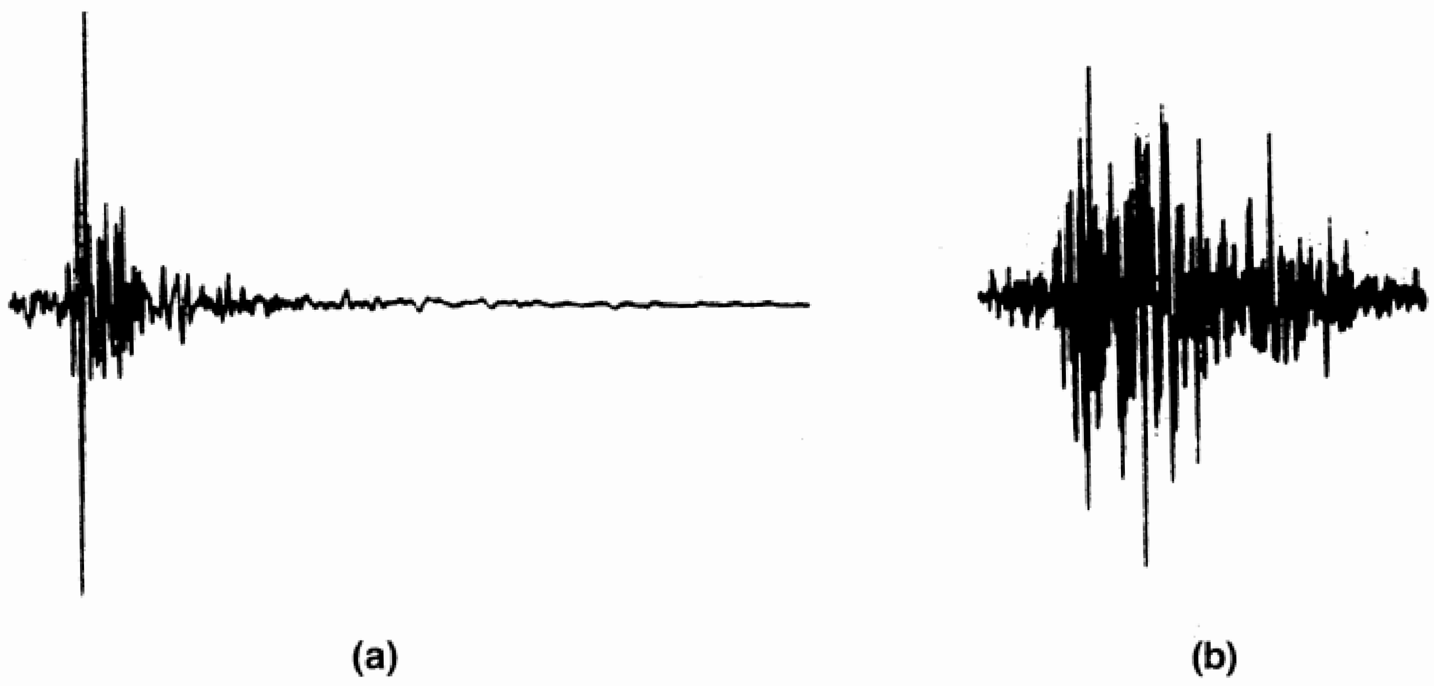


Figure 3.12 Accelerograms from (a) the N29W Melendy Ranch record of the 1972 Stone Canyon ($M = 4.6$) earthquake and (b) the longitudinal record from the 1967 Koyna ($M = 6.5$) earthquake. The time and acceleration scales are identical for both records. Peak accelerations are very close, illustrating the limitations of using peak amplitude as a sole measure of strong ground motion. (After Hudson, 1979; used by permission of EERI.)

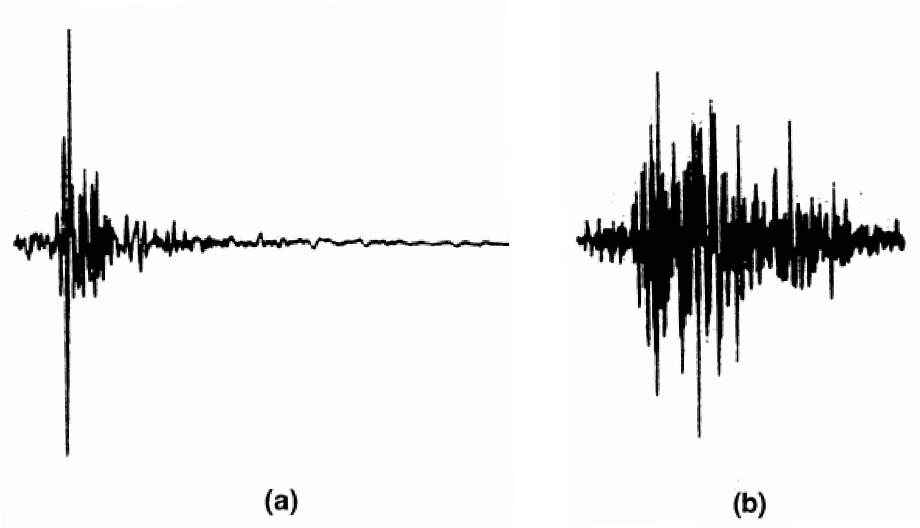
- In some cases, damage may be closely related to the peak amplitude, but in others it may require several repeated cycles of high amplitude to develop.

- Newmark and Hall (1982) described the concept of an **effective acceleration** as “that acceleration which is most closely related to structural response and to damage potential of an earthquake. It differs from and is less than the peak free-field ground acceleration. It is a function of the size of the loaded area and the frequency content of the excitation”.

Other Amplitude related Parameters

- **Sustained Maximum Acceleration and Velocity:** Nuttli (1979) used lower peaks of the accelerogram to characterize strong motion by defining the sustained maximum acceleration for three (or five) cycles as the third (or fifth) highest (absolute) value of acceleration in the time history. The sustained maximum velocity was defined similarly.

- Although the PHA values for the 1972 Stone Canyon earthquake and 1967 Koyna earthquake records (Figure in previous slide) were nearly the same, a quick visual inspection indicates that their sustained maximum accelerations (three- or five-cycle) were very different.
- For a structure that required several repeated cycles of strong motion to develop damage, the Koyna motion would be much more damaging than the Stone Canyon motion, even though they had nearly the same PHA. For these motions, the sustained maximum acceleration would be a better indicator of damage potential than the PHA.



Other Amplitude related Parameters

- **Effective Design Acceleration:** The notion of an effective design acceleration, with different definitions, has been proposed by at least two researchers.

- Since pulses of high acceleration at high frequencies induce little response in most structures, Benjamin and Associates (1988) proposed that an effective design acceleration be taken as the peak acceleration that remains after filtering out accelerations above 8 to 9 Hz.

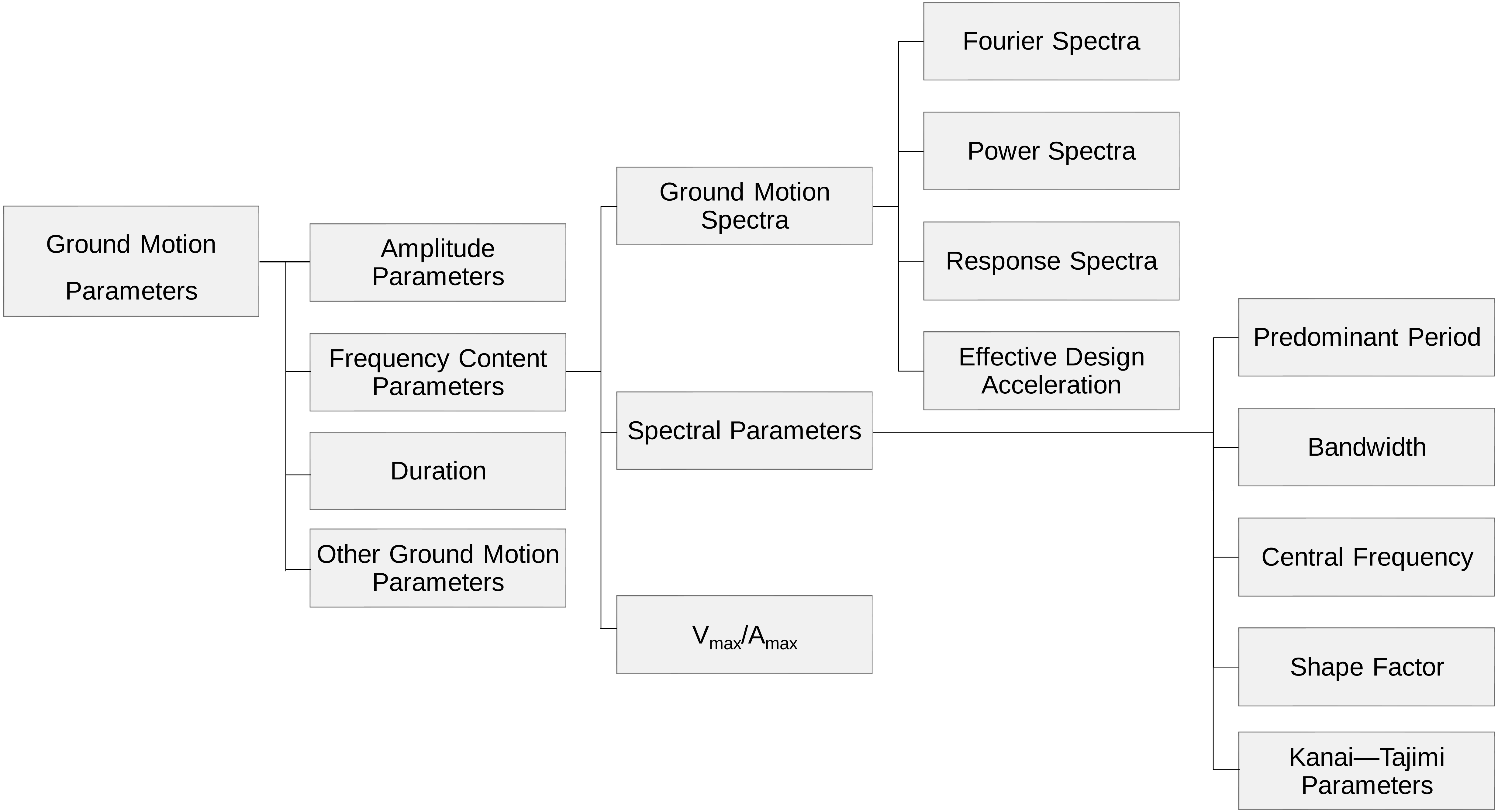
- Kennedy (1980) proposed that the effective design acceleration be 25% greater than the third highest (absolute) peak acceleration obtained from a filtered time history.

Frequency Content Parameters

- The dynamic response of buildings, bridges, slopes, or soil deposits, is very sensitive to the frequency at which they are loaded.

- The frequency content describes how the amplitude of a ground motion is distributed among different frequencies.

- Since the frequency content of an earthquake motion will strongly influence the effects of that motion, characterization of the motion cannot be complete without consideration of its frequency content.



Ground Motion Parameters
Amplitude Parameters
Frequency Content Parameters
Duration
Other Ground Motion Parameters
Ground Motion Spectra
Spectral Parameters
V_{max}/A_{max}
Fourier Spectra
Power Spectra
Response Spectra
Effective Design Acceleration
Predominant Period
Bandwidth
Central Frequency
Shape Factor
Kanai—Tajimi Parameters

Fourier Spectra

- Any periodic function (i.e., any function that repeats itself exactly at a constant interval) can be expressed using Fourier analysis as the sum of a series of simple harmonic terms of different frequency, amplitude, and phase. Using the Fourier series, a periodic function, $x(t)$, can be written as

$$x(t) = c_0 + \sum_{n=1}^{\infty} c_n \sin(\omega_n t + \phi_n)$$

In this form, c_n and ϕ_n are the amplitude and phase angle, respectively, of the nth harmonic of the Fourier series.

The Fourier series provides a complete description of the ground motion since the motion can be completely recovered by the inverse Fourier transform.

Fourier Spectra

- A plot of Fourier amplitude versus frequency (c_n vs. ω_n) is known as a **Fourier amplitude spectrum**.
- A plot of Fourier phase angle (ϕ_n vs. ω_n) gives the **Fourier phase spectrum**.

- The Fourier amplitude spectrum of a strong ground motion shows how the amplitude of the motion is distributed with respect to frequency (or period). It expresses the frequency content of a motion very clearly.

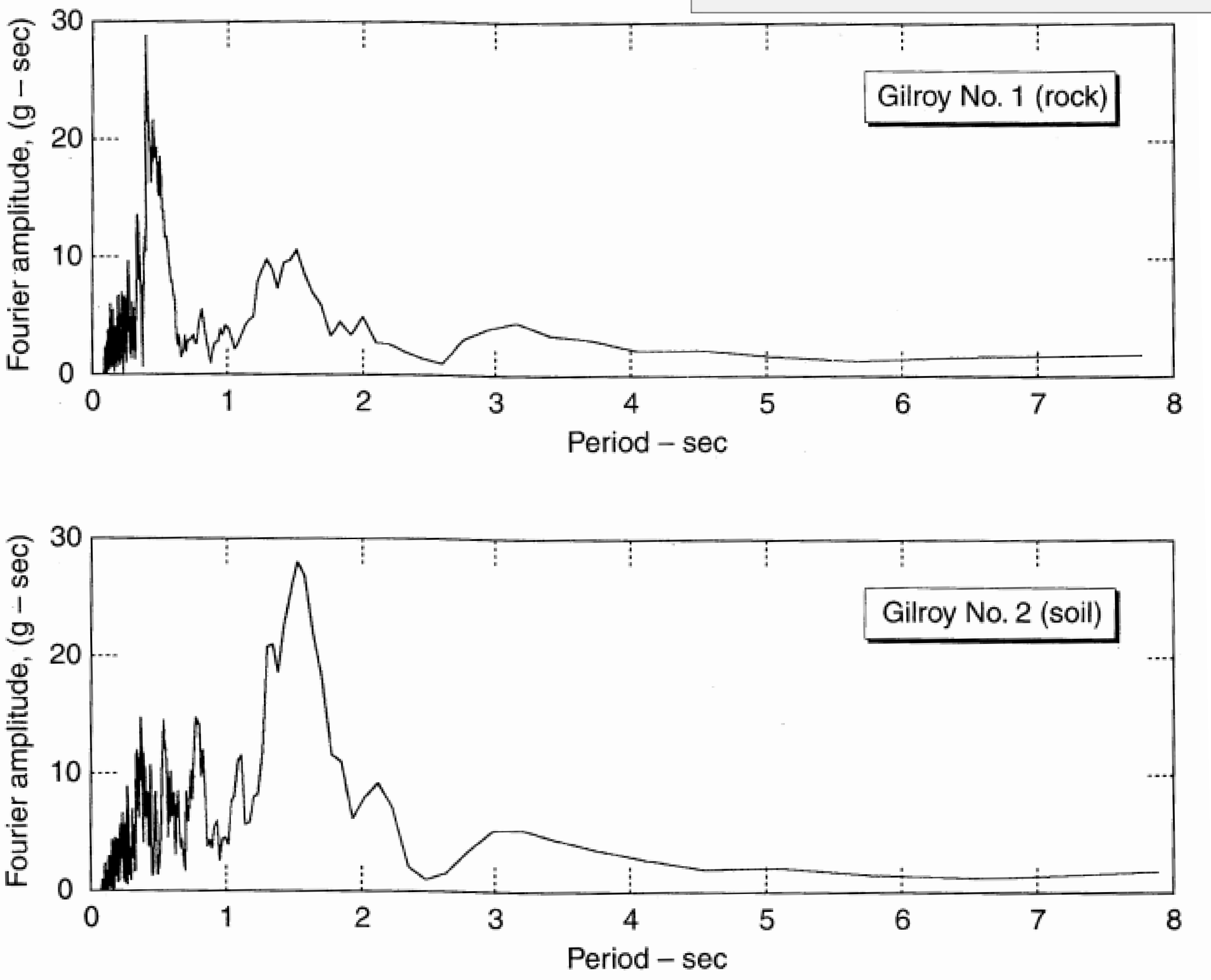


Figure 3.13 Fourier amplitude spectra for the E-W components of the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) strong motion records. Fourier spectra were obtained by discrete Fourier transform (Section A.3.3 of Appendix A) and consequently have units of velocity. Fourier amplitude spectra can also be plotted as functions of frequency (see Figure E3.3).

Fourier Spectra

- The Fourier amplitude spectrum may be narrow or broad.
- A narrow spectrum implies that the motion has a dominant frequency (or period), which can produce a smooth, almost sinusoidal time history.
- A broad spectrum corresponds to a motion that contains a variety of frequencies that produce a more jagged, irregular time history.

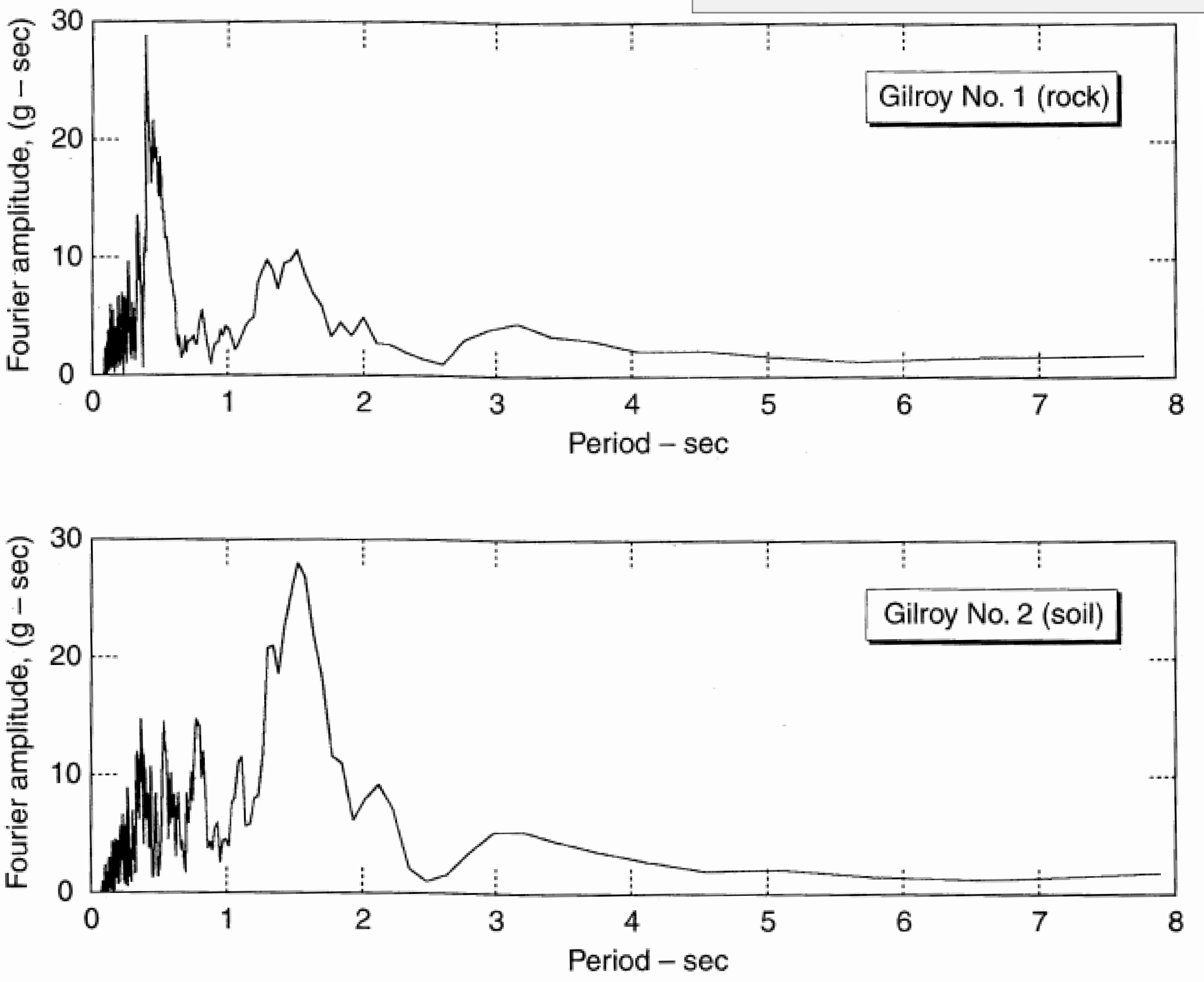


Figure 3.13 Fourier amplitude spectra for the E-W components of the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) strong motion records. Fourier spectra were obtained by discrete Fourier transform (Section A.3.3 of Appendix A) and consequently have units of velocity. Fourier amplitude spectra can also be plotted as functions of frequency (see Figure E3.3).

Fourier Spectra

- The jagged shapes of the spectra are typical of those observed for individual ground motions.
- The shapes of the spectra are quite different: the Gilroy No. 1 (rock) spectrum is strongest at low periods (or high frequencies) while the reverse is observed for the Gilroy No. 2 (soil) record.
- A difference in frequency content can be detected by closely examining the motions in the time domain but the difference is explicitly illustrated by the Fourier amplitude spectra.

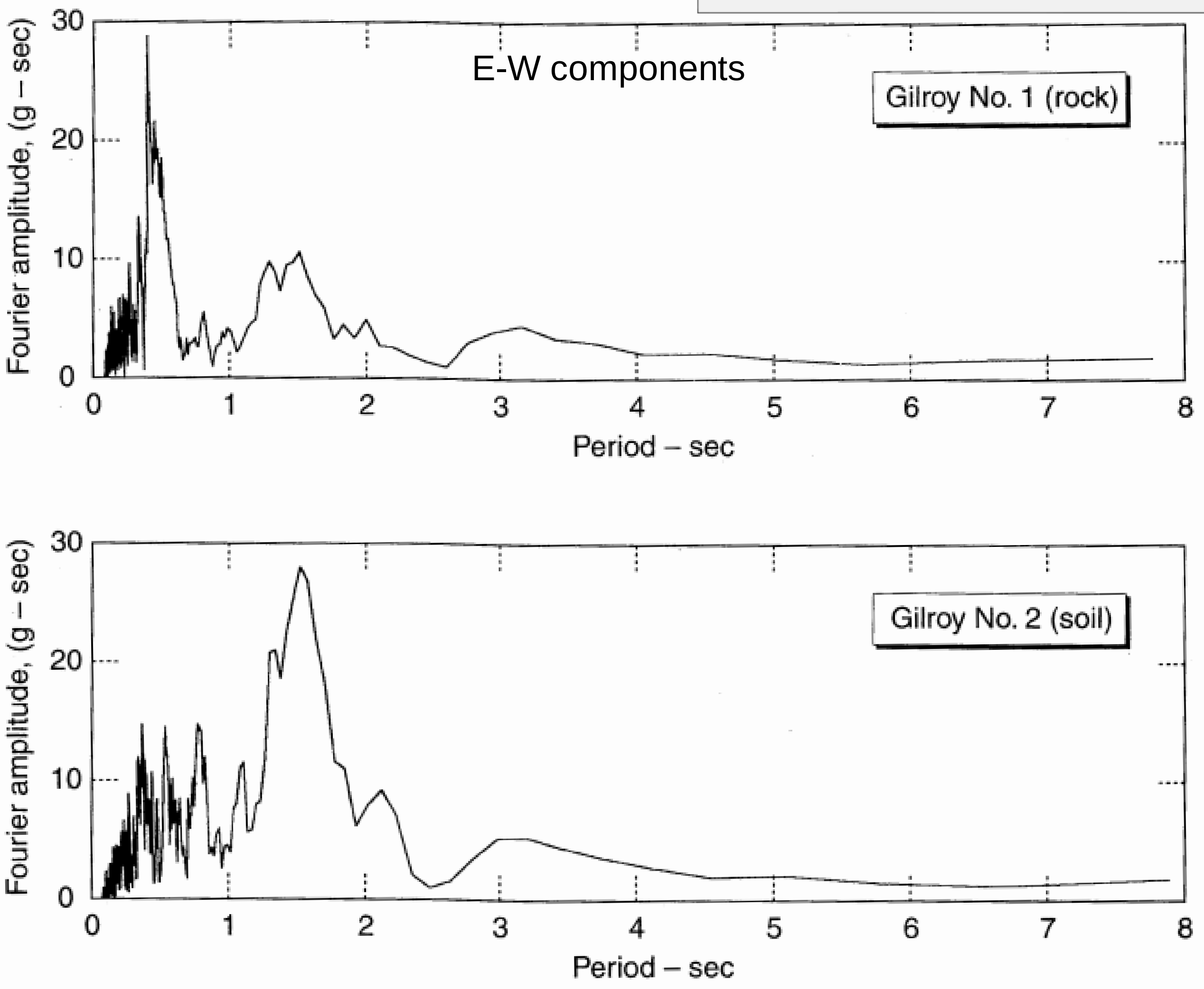
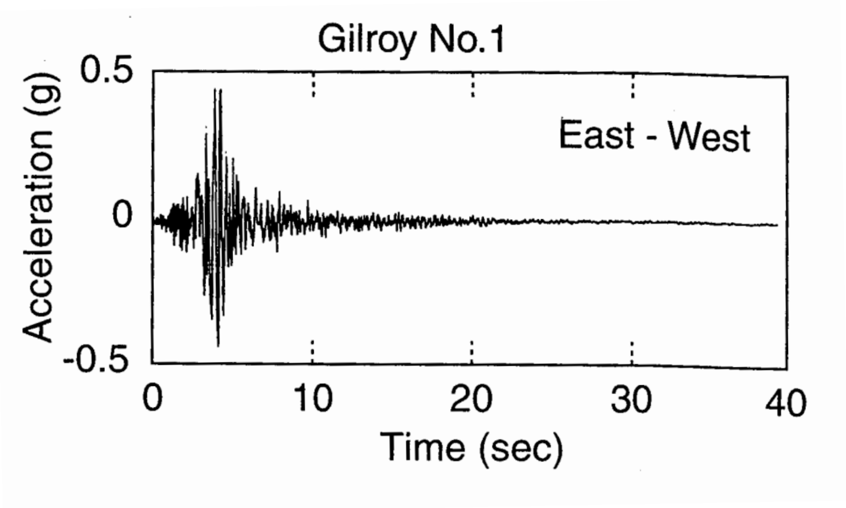
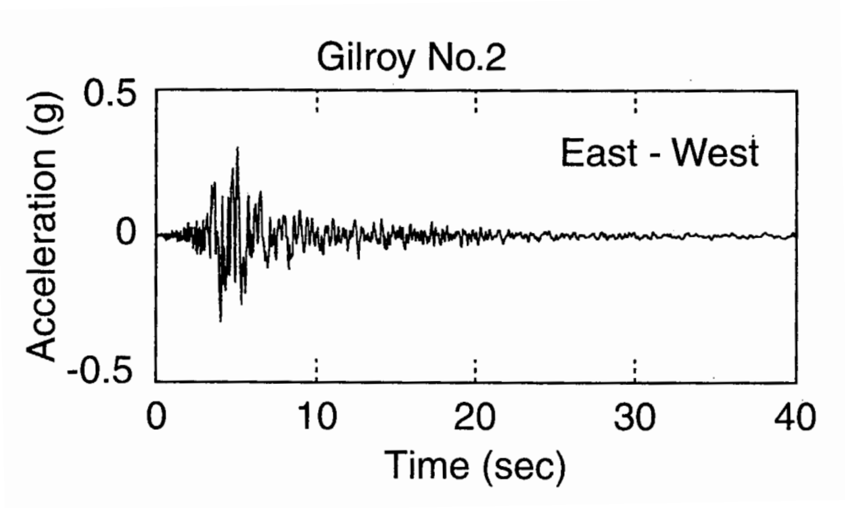


Figure 3.13 Fourier amplitude spectra for the E-W components of the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) strong motion records. Fourier spectra were obtained by discrete Fourier transform (Section A.3.3 of Appendix A) and consequently have units of velocity. Fourier amplitude spectra can also be plotted as functions of frequency (see Figure E3.3).





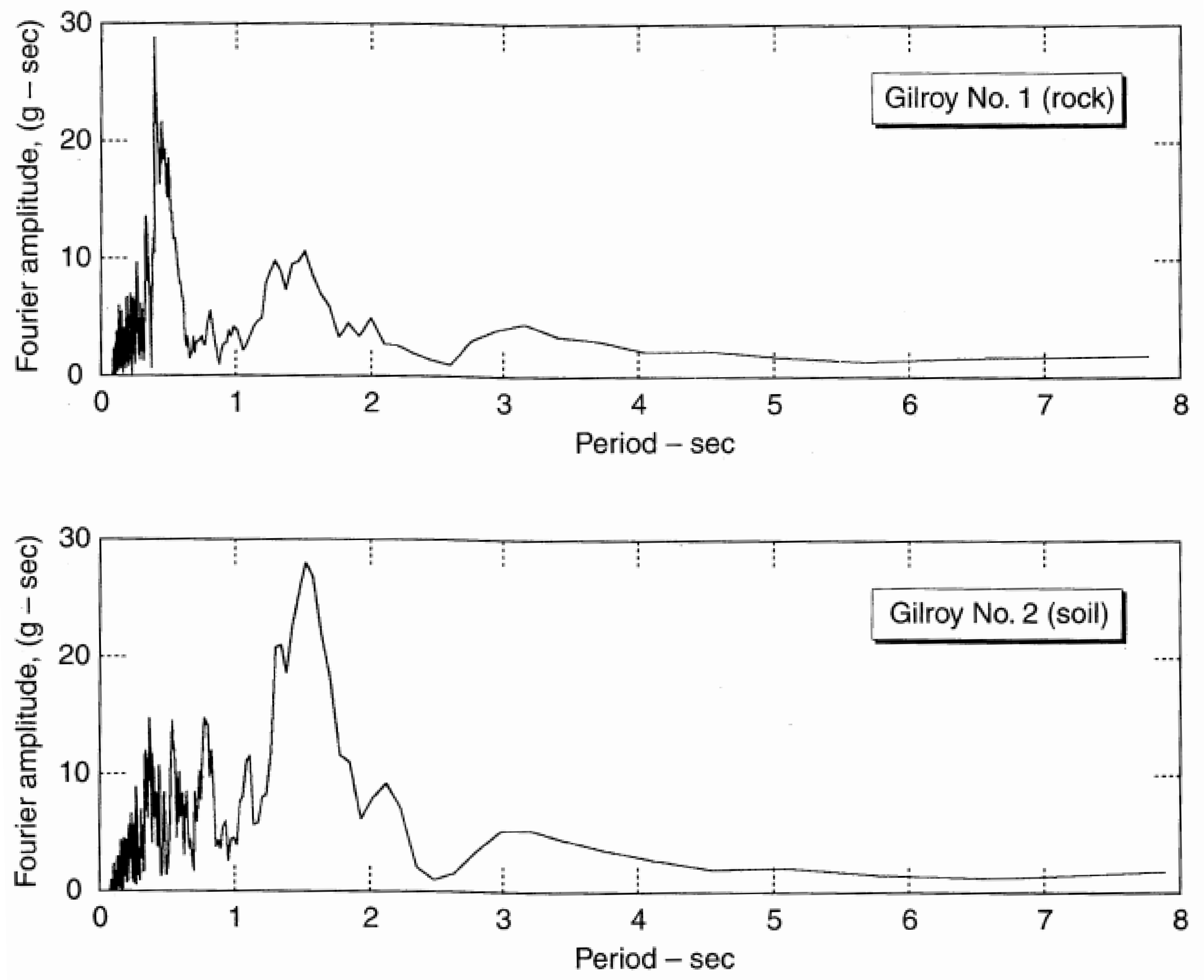


Figure 3.13 Fourier amplitude spectra for the E-W components of the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) strong motion records. Fourier spectra were obtained by discrete Fourier transform (Section A.3.3 of Appendix A) and consequently have units of velocity. Fourier amplitude spectra can also be plotted as functions of frequency (see Figure E3.3).

Power Spectra

- The frequency content of a ground motion can also be described by a **power spectrum or power spectral density function**.
- The power spectral density function can also be used to estimate the statistical properties of a ground motion and to compute stochastic response using random vibration techniques (Clough and Penzien, 1975; Vanmarcke, 1976; Yang, 1986). .
- The power spectral density $G(\omega)$ is defined as:

$$G(\omega) = \frac{1}{\pi T_d} c_n^2$$

T_d is ground motion duration.

c_n is the amplitude of the nth harmonic of the Fourier series of ground motion.

Response Spectra

- A third type of spectrum is used extensively in earthquake engineering practice.
- The **response spectrum** describes the maximum response of a single-degree-of-freedom (SDOF) system to a particular input motion as a function of the natural frequency (or natural period) and damping ratio of the SDOF system.
- Computed response spectra for the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) records are illustrated in Figure.

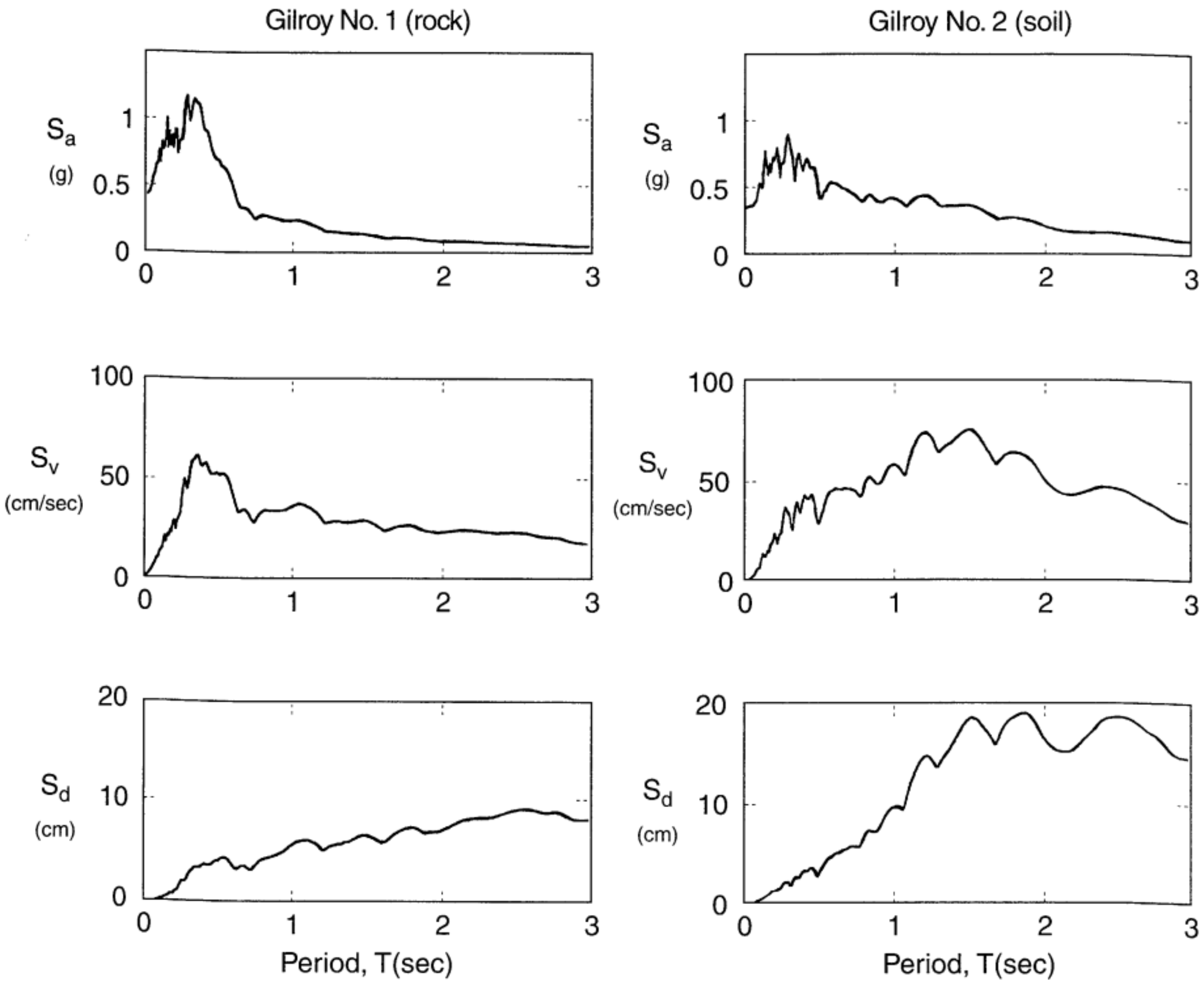


Figure 3.15 Response spectra (5% damping) for Gilroy No. 1 (rock) and Gilroy No. 2 (soil) strong motion records. The frequency contents of the two motions are reflected in the response spectra. The Gilroy 1 (rock) motion, for example, produced higher spectral accelerations at low periods than did the Gilroy 2 (soil) motion, and lower spectral accelerations at higher periods. The higher long-period content of the Gilroy 2 (soil) motion produced spectral velocities and displacements much higher than those of the Gilroy 1 (rock) motion.

Response Spectra

- At low frequencies the average spectral displacement is nearly constant; at high frequencies the average spectral acceleration is fairly constant. In between lies a range of nearly constant spectral velocity. Because of this behavior, response spectra are often divided into acceleration-controlled (high-frequency), velocity-controlled (intermediate-frequency), and displacement-controlled (low-frequency) portions.

- Elastic response spectra assume linear structural force-displacement behavior.

- For many real structures, however, inelastic behavior may be induced by earthquake ground motions.

- An inelastic response spectrum (i.e., one that corresponds to a nonlinear force-displacement relationship, can be used to account for the effects of inelastic behavior.

Response Spectra

- Response spectra reflect strong ground motion characteristics indirectly, since they are "filtered" by the response of a SDOF structure.
- The amplitude, frequency content, and to a lesser extent, duration of the input motion all influence spectral values.

- The different frequency contents of the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) ground motions are clearly illustrated by the different shapes of their respective response spectra.

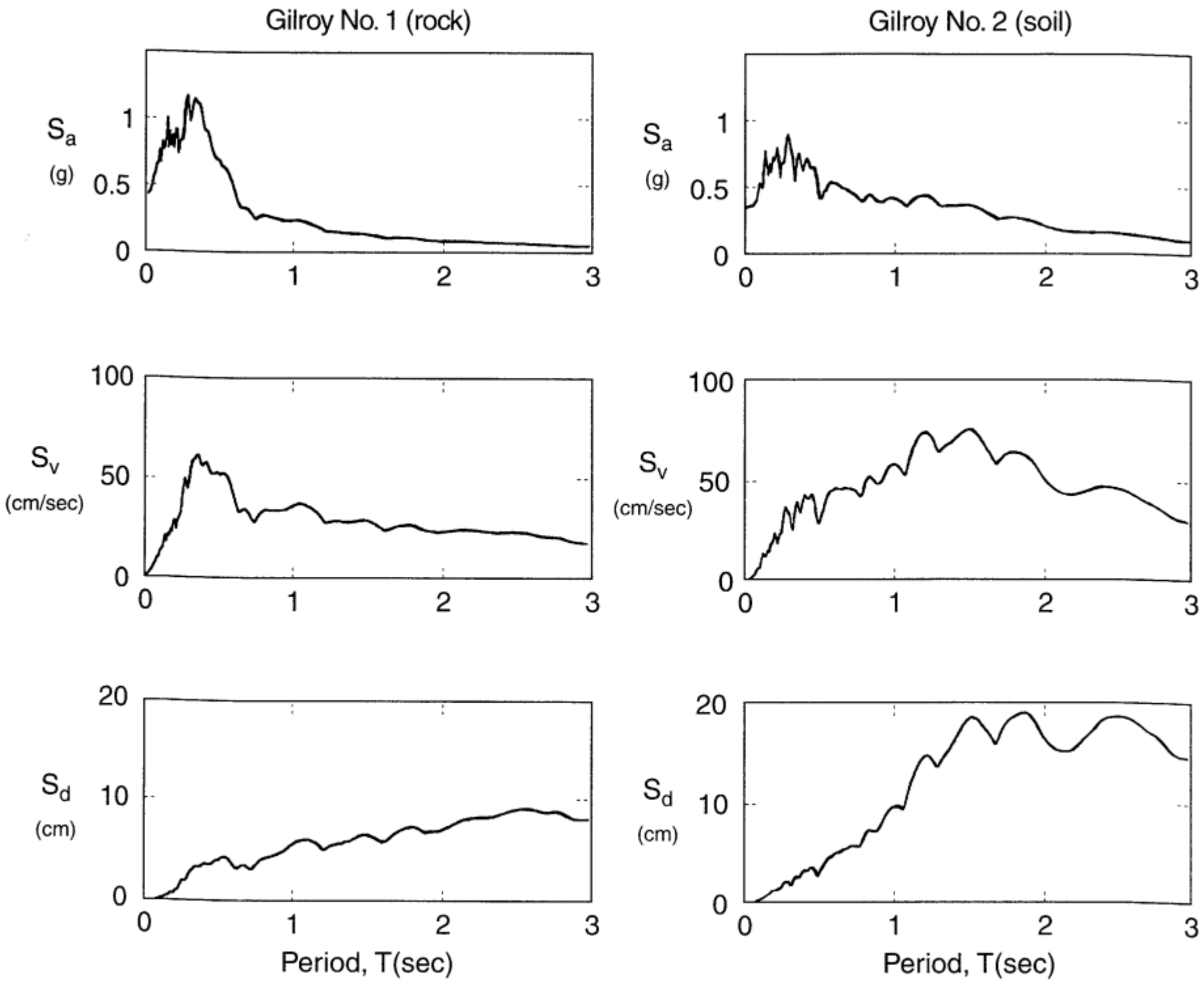


Figure 3.15 Response spectra (5% damping) for Gilroy No. 1 (rock) and Gilroy No. 2 (soil) strong motion records. The frequency contents of the two motions are reflected in the response spectra. The Gilroy 1 (rock) motion, for example, produced higher spectral accelerations at low periods than did the Gilroy 2 (soil) motion, and lower spectral accelerations at higher periods. The higher long-period content of the Gilroy 2 (soil) motion produced spectral velocities and displacements much higher than those of the Gilroy 1 (rock) motion.

Spectral Parameters

- **Predominant Period:** A single parameter that provides a useful, although somewhat crude representation of the frequency content of a ground motion is the predominant period, T_p.
  - The predominant period is defined as the period corresponding to the maximum value of the Fourier amplitude spectrum.
  - To avoid undue influence of individual spikes of the Fourier amplitude spectrum, the predominant period is often obtained from a smoothed spectrum.
  - While the predominant period provides some information regarding the frequency content, it is easy to see that motions with radically different frequency contents can have the same predominant period.

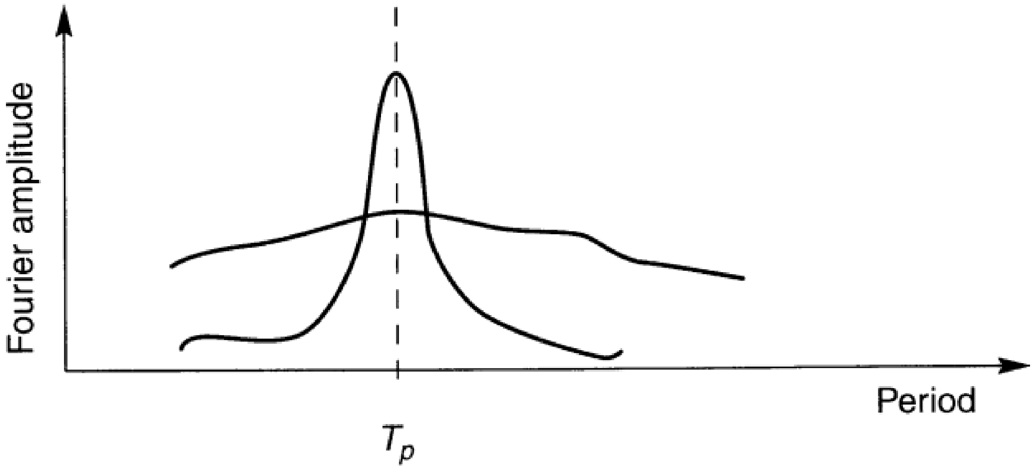


Figure 3.17 Two hypothetical Fourier amplitude spectra with the same predominant period but very different frequency contents. The upper curve describes a wideband motion and the lower a narrowband motion.

Spectral Parameters

- The predominant period can be used to locate the peak of the Fourier amplitude spectrum; however, it provides no information on the dispersion of spectral amplitudes about the predominant period.

- **Bandwidth:** The bandwidth of the Fourier amplitude spectrum is the range of frequency over which some level of Fourier amplitude is exceeded.

- Bandwidth is usually measured at the level where the power of the spectrum is half its maximum value; this corresponds to a level of $1/\sqrt{2}$ times the maximum Fourier amplitude.

- The irregular shape of individual Fourier amplitude spectra often renders bandwidth difficult to evaluate. It is determined more easily for smoothed spectra.

Spectral Parameters

- The power spectral density function can be used to estimate statistical properties of the ground motion.
- **Central Frequency:** Defining the nth spectral moment of a ground motion by

$$\lambda_n = \int_0^{\omega_N} \omega^n G(\omega)\, d\omega$$

the central frequency Ω (Vanmarcke, 1976) is given by:

$$\Omega = \sqrt{\frac{\lambda_2}{\lambda_0}}$$

- The central frequency is a measure of the frequency where the power spectral density is concentrated.

Spectral Parameters

- **Shape Factor:** The shape factor (Vanmarcke, 1976) indicates the dispersion of the power spectral density function about the central frequency:

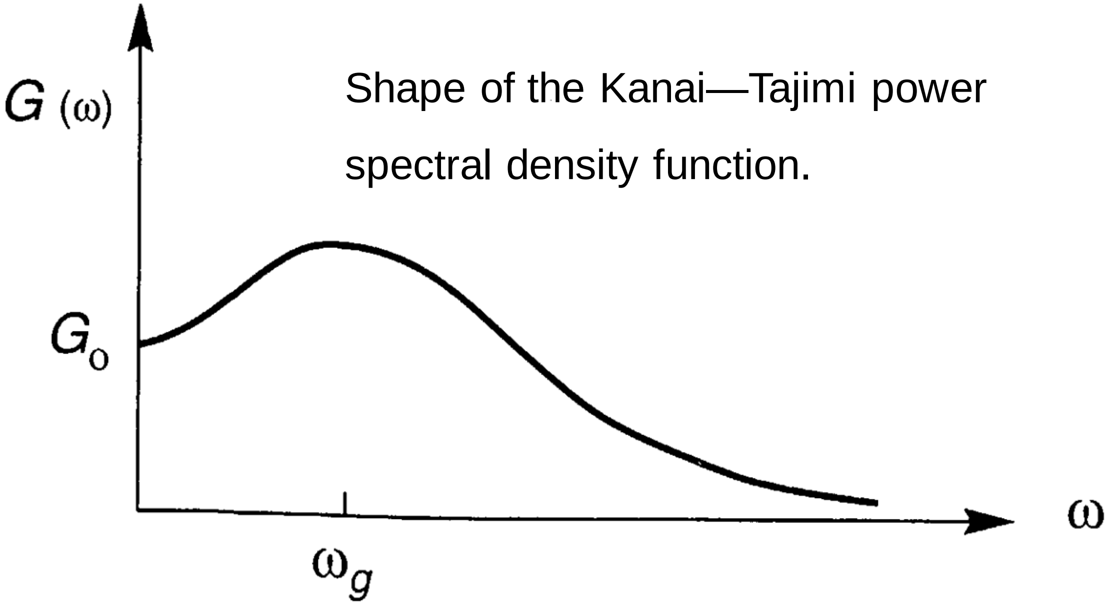
$$\delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0 \lambda_2}}$$

- The shape factor always lies between 0 and 1, with higher values corresponding to larger bandwidths.

Spectral Parameters

- **Kanai-Tajimi Parameters:** Although individual power spectral density functions may have highly irregular shapes, averaging a number of normalized power spectral density functions for similar strong ground motions reveals a smooth characteristic shape.
- Kanai (1957) and Tajimi (1960) used a limited number of strong motion records to propose the following three-parameter model for power spectral density:

$$G(\omega) = G_0 \frac{1 + [2\xi_g(\omega/\omega_g)]^2}{[1-(\omega/\omega_g)^2]^2 + [2\xi_g(\omega/\omega_g)]^2}$$



Shape of the Kanai—Tajimi power spectral density function.

where the parameters G_0, ξ_g , and ω_g determine the shape of the function.

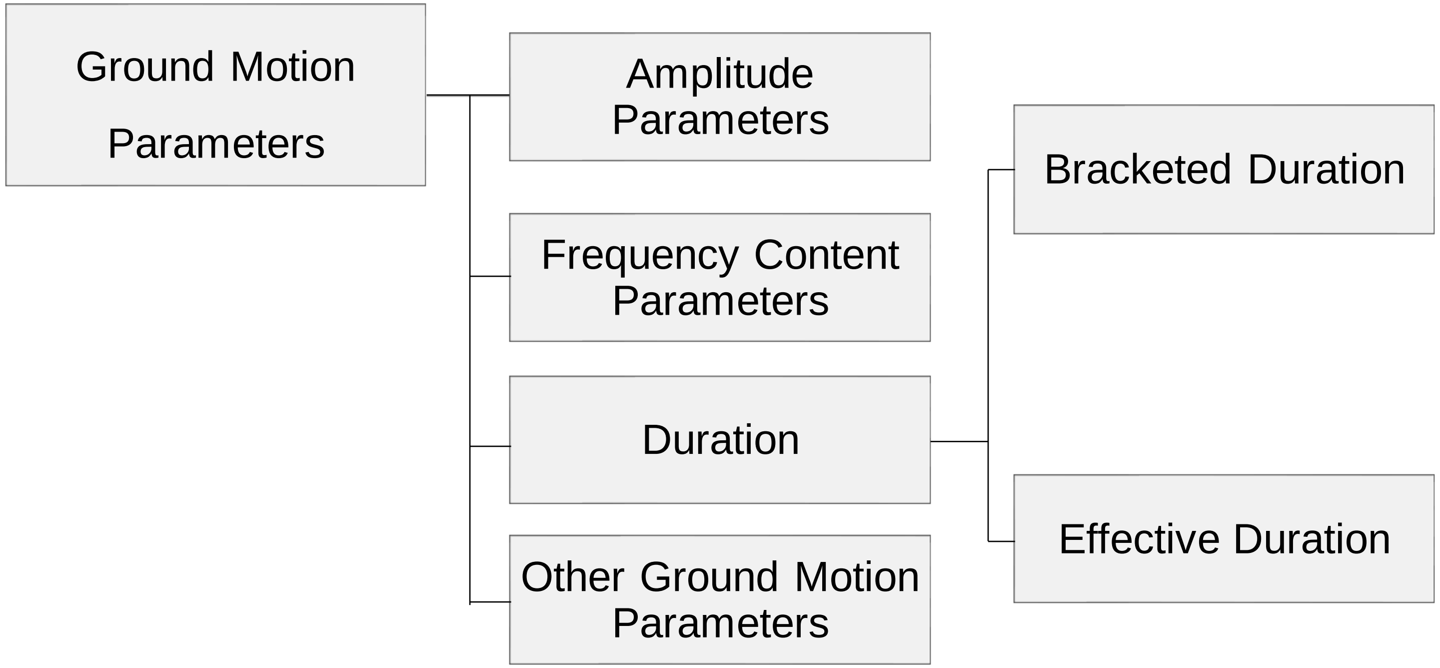
Spectral Parameters

- v_{max}/a_{max}: Because peak velocities and peak accelerations are usually associated with motions of different frequency, the ratio v_{max}/a_{max} should be related to the frequency content of the motion (Newmark, 1973; Seed et al., 1976; McGuire, 1978).

- For a simple harmonic motion of period T, for example, v_{max}/a_{max} = $T/2\pi$. For earthquake motions that include many frequencies, the quantity $2\pi(v_{max}/a_{max})$ can be interpreted as the period of vibration of an equivalent harmonic wave, thus providing an indication of which periods of the ground motion are most significant.

Duration Parameters

- The duration of strong ground motion can have a strong influence on earthquake damage.
- Many physical processes, such as the degradation of stiffness and strength of certain types of structures and the build up of pore water pressures in loose, saturated sands, are sensitive to the number of load or stress reversals that occur during an earthquake.
- A motion of short duration may not produce enough load reversals for damaging response to build up in a structure, even if the amplitude of the motion is high. On the other hand, a motion with moderate amplitude but long duration can produce enough load reversals to cause substantial damage.
- Different approaches have been taken to the problem of evaluating the duration of strong motion in an accelerogram.


Ground Motion Parameters
Amplitude Parameters
Frequency Content Parameters
Duration
Other Ground Motion Parameters
Bracketed Duration
Effective Duration

Duration Parameters

- The **bracketed duration** (Bolt, 1969) is defined as the time between the first and last exceedances of a threshold acceleration (usually 0.05g).

- Another definition of duration (Trifunac and Brady, 1975b) is based on the time interval between the points at which 5% and 95% of the total energy has been recorded (**effective duration**).

- Boore (1983) has taken the duration to be equal to the corner period (i.e., the inverse of the corner frequency).

- The rate of change of cumulative root-mean-square (rms) acceleration has also been used as the basis for evaluation of strong-motion duration (McCann and Shah, 1979).

Duration Parameters

- Power spectral density concepts can also be used to define a strong-motion duration (Vanmarcke and Lai, 1977).

- Other definitions of strong-motion duration have been proposed (Perez, 1974; Trifunac and Westermo, 1977).

- Because it implicitly reflects the strength of shaking, the bracketed duration is most commonly used for earthquake engineering purposes.

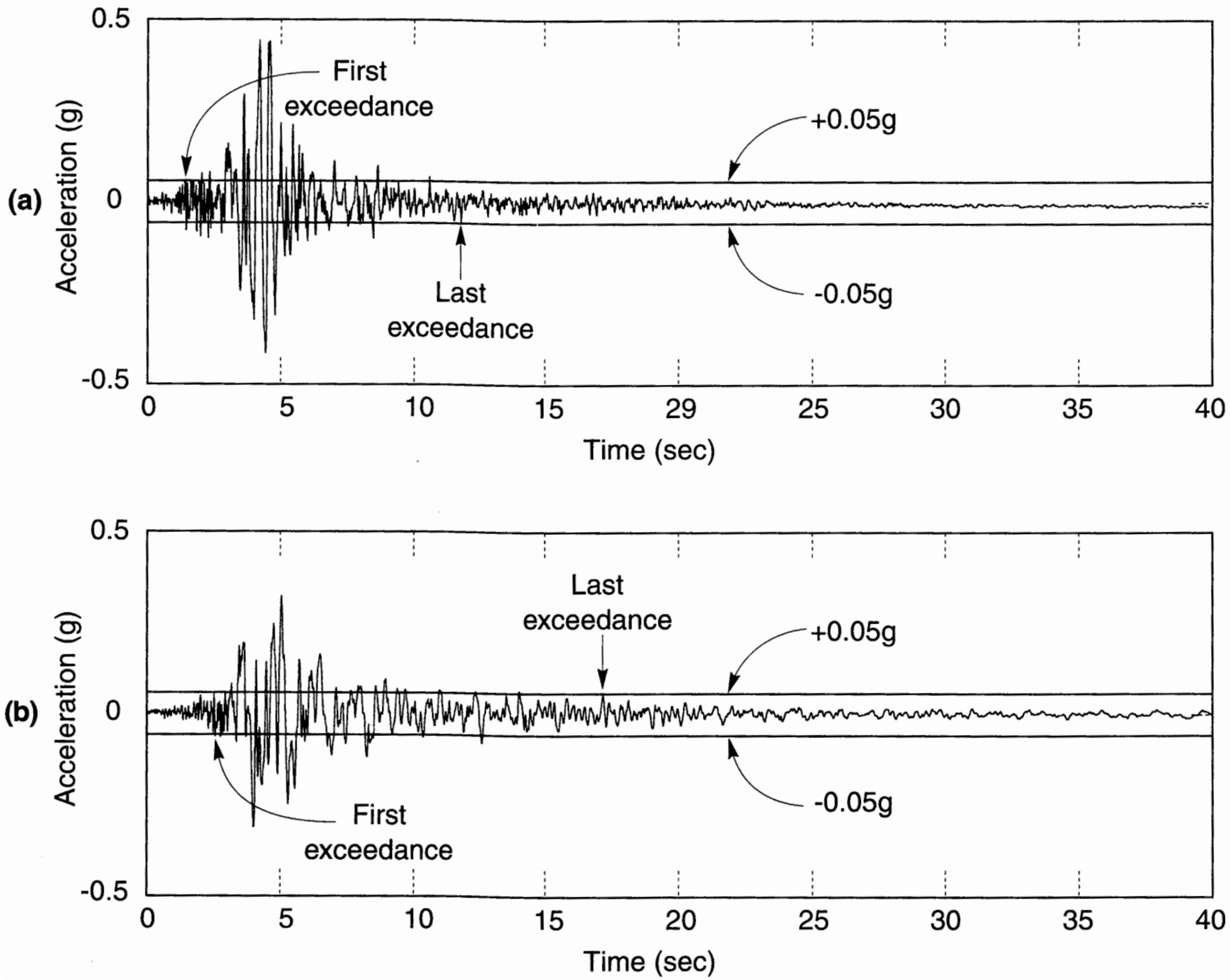
Bracketed Duration

Gilroy No.1 (rock): $T_d = 9.8$ sec

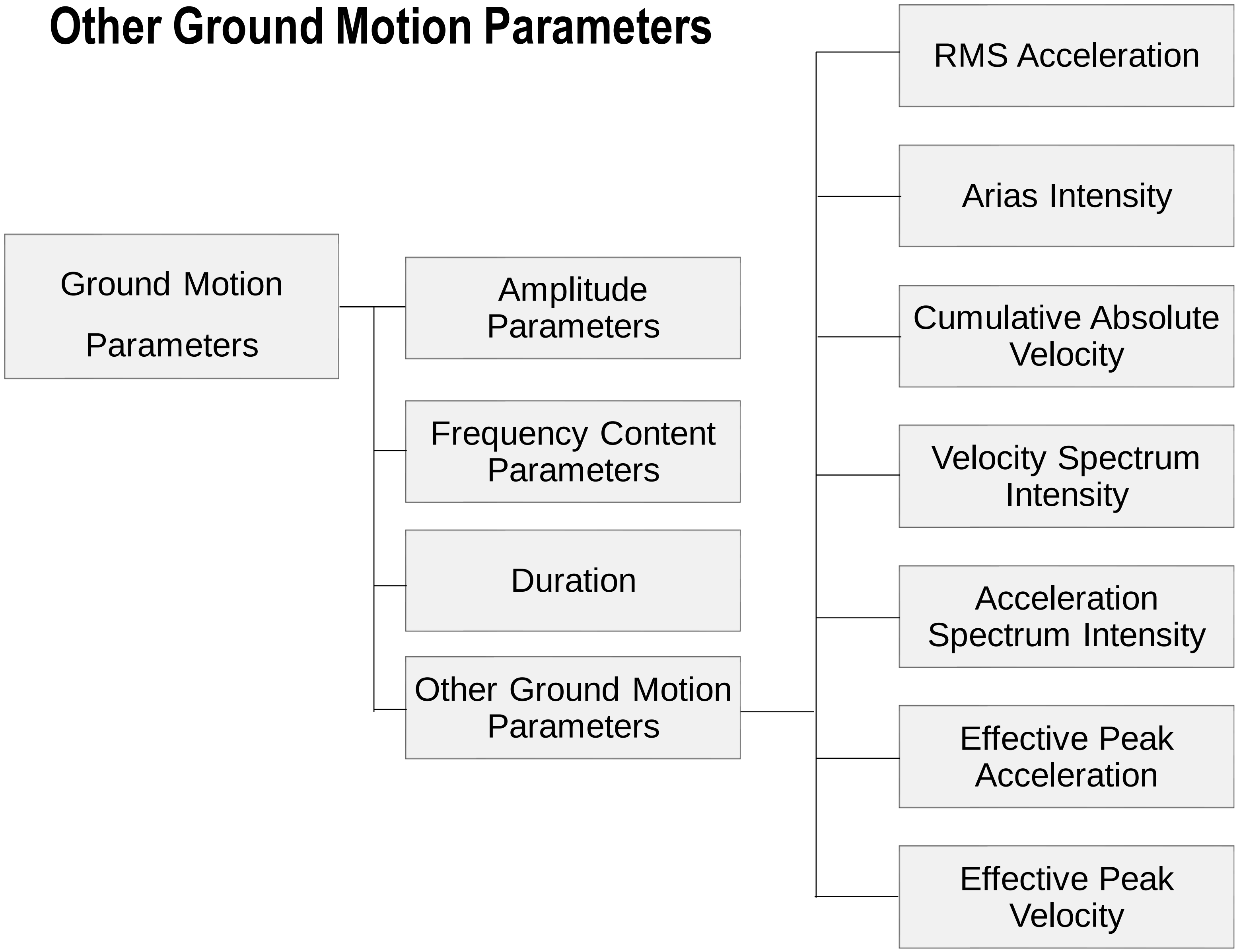
Gilroy No.2 (soil): $T_d = 14.7$ sec

Determine the bracketed durations of the E-W components of the Gilroy No. 1 (rock) and Gilroy No. 2 (soil) ground motions.

Solution Based on a threshold acceleration of $0.05g$, the bracketed durations can be obtained graphically from the accelerograms shown in Figure E3.5.



Other Ground Motion Parameters



Other Ground Motion Parameters

- A single parameter that includes the effects of the amplitude and frequency content of a strong motion record is the **rms acceleration**, defined as

$$a_{\text{rms}} = \sqrt{\frac{1}{T_d}\int_0^{T_d}[a(t)]^2 dt} = \sqrt{\lambda_0}$$

Where T_d is the duration of the strong motion and λ_o is the average intensity (or mean-squared acceleration).

- Because the integral in above equation is not strongly influenced by large, high-frequency accelerations (which occur only over a very short period of time) and because it is influenced by the duration of the motion, the rms acceleration can be very useful for engineering purposes. Its value, however, can be sensitive to the method used to define the duration of strong motion.

Other Ground Motion Parameters

- A parameter closely related to the rms acceleration is the **Arias intensity** (Arias, 1970), defined as:

$$I_a = \frac{\pi}{2g}\int_0^\infty [a(t)]^2 dt$$

- The Arias intensity has units of velocity and is usually expressed in meters per second.

- Since it is obtained by integration over the entire duration rather than over the duration of strong motion, its value is independent of the method used to define the duration of strong motion.

Other Ground Motion Parameters

- The **characteristic intensity** is defined as:

$$I_c = a_{\text{rms}}^{1.5} T_d^{0.5}$$

- It is related linearly to an index of structural damage due to maximum deformations and absorbed hysteretic energy (Ang, 1990).

Other Ground Motion Parameters

- The **cumulative absolute velocity** is simply the area under the absolute accelerogram:

$$\mathrm{CAV} = \int_0^{T_d} |a(t)|\, dt$$

- The cumulative absolute velocity has been found to correlate well with structural damage potential.

- For example, a CAV of 0.30g-sec (obtained after filtering out frequencies above 10 Hz) corresponds to the lower limit for MMI VII shaking (Benjamin and Associates, 1988).

Other Ground Motion Parameters

- Since many structures have fundamental periods between 0.1 and 2.5 sec, the response spectrum ordinates in this period range should provide an indication of the potential response of these structures.
- The **response spectrum intensity** (Housner, 1959) was therefore defined as

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

- It is the area under the pseudo velocity response spectrum between periods of 0.1 sec and 2.5 sec.

- The response spectrum intensity, as indicated in above equation, can be computed for any structural damping ratio. It captures important aspects of the amplitude and frequency content (in the range of primary importance for structures) in a single parameter.

Other Ground Motion Parameters

- Von Thun et al. (1988) referred to the response spectrum intensity for 5% damping as the **velocity spectrum intensity**. The velocity spectrum intensity was suggested as being useful for evaluation of the response of earth and rockfill dams, which typically have fundamental periods between 0.6 and 2.0 sec (Makdisi and Seed, 1978).
- To characterize strong ground motion for analysis of concrete dams, which generally have fundamental periods of less than 0.5 sec, Von Thun et al. (1988) introduced the **acceleration spectrum intensity**, defined as

$$\mathrm{ASI} = \int_{0.1}^{0.5} S_a(\xi = 0.05, T)\, dT$$

(i.e., the area under the acceleration response spectrum between periods of 0.1 sec and 0.5 sec).

Other Ground Motion Parameters

- The Applied Technology Council (1978) defined two factors by which standard response spectra could be normalized.

- The **effective peak acceleration (EPA)** was defined as the average spectral acceleration over the period range 0.1 to 0.5 sec divided by 2.5 (the standard amplification factor for a 5% damping spectrum).

- The **effective peak velocity (EPV)** was defined as the average spectral velocity at a period of 1 sec divided by 2.5.

Other Ground Motion Parameters

- Determination of EPA and EPV is shown schematically in Figure.
- The process of averaging the spectral accelerations and velocities over a range of periods minimizes the influence of local spikes in the response spectrum on the EPA and EPV.
- The EPA and EPV have been used in the specification of smoothed design response spectra in building codes.

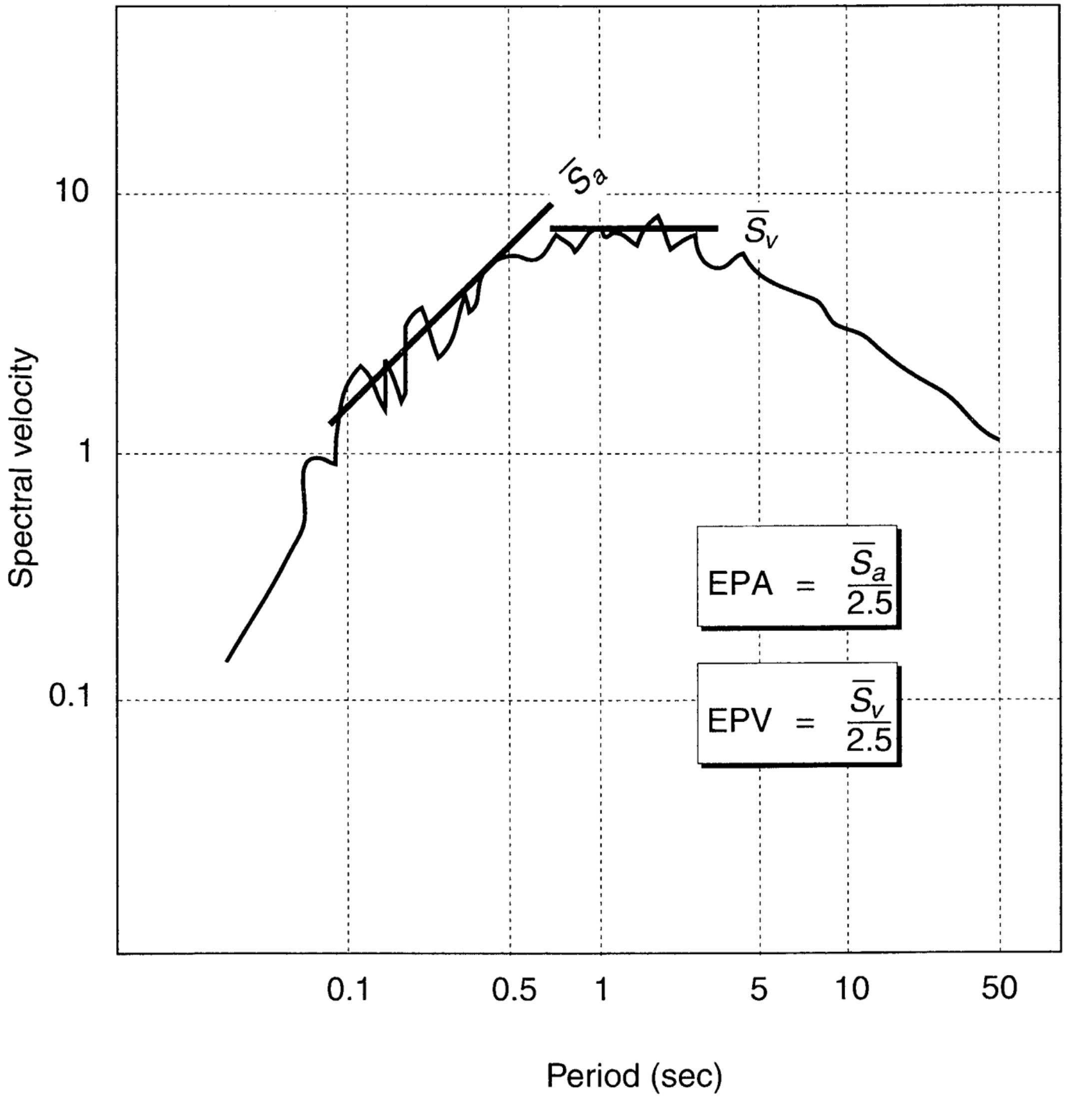


Figure 3.19 Determination of effective peak acceleration and effective peak velocity from response spectra. (After Applied Technology Council, 1978.)

Thank you for your attention