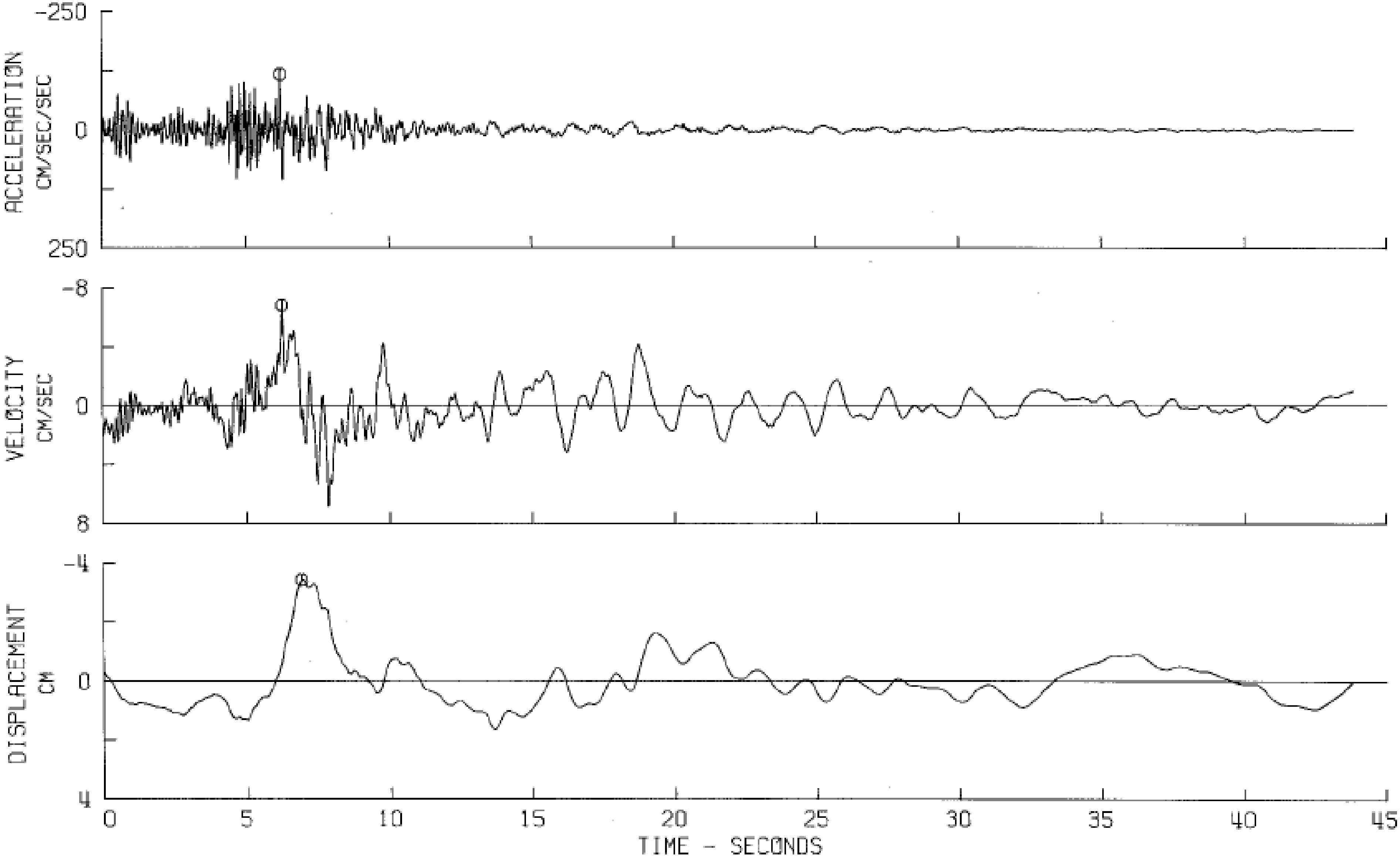
Ground Motion Parameters

Ahmed Elgamal

Acknowledgements:
1)The assistance of Dr. Liangcai He is most appreciated.
2) Some material is based on: Geotechnical Earthquake Engineering
By Steven Kramer, Prentice-Hall.



PARKFIELD, CALIFORNIA EARTHQUAKE JUNE 27, 1966 - 2026 PST

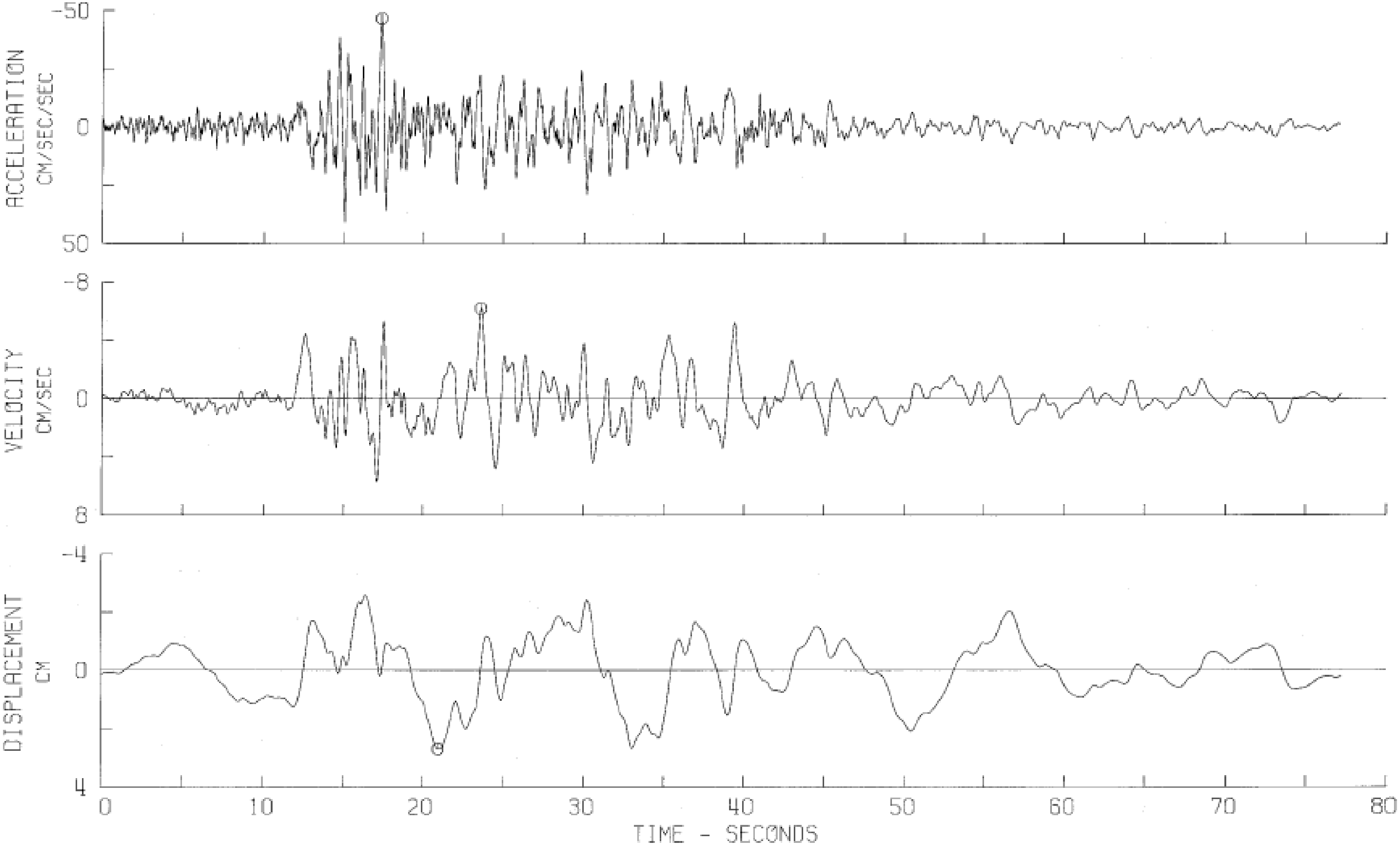
IIB034 66.002.0 CHOLAME.SHANDON, CALIFORNIA ARRAY NO. 5 COMP DOWN

⊙ PEAK VALUES : ACCEL = -116.9 CM/SEC/SEC VELOCITY = -6.8 CM/SEC DISPL = -3.4 CM

KERN COUNTY, CALIFORNIA EARTHQUAKE JULY 21, 1952 - 0453 PDT

IIA003 52.001.0 PASADENA - CALTECH ATHENAEUM COMP S00E

⊙ PEAK VALUES : ACCEL = -46.5 CM/SEC/SEC VELOCITY = -6.2 CM/SEC DISPL = 2.7 CM



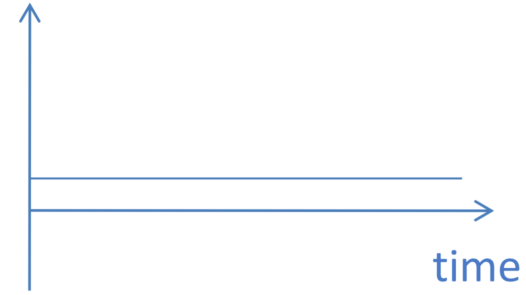
For a given earthquake ground excitation record (time history), ground motion parameters describe the earthquake shaking characteristics of importance (e.g., amplitude, frequency content, and duration).

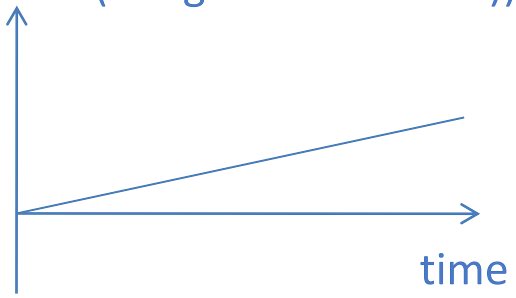
Examples of “corrected” recorded ground motions (accelerations) is shown below. “Corrected” denotes removal of errors due to the recording instrument inaccuracy, digitization, and the involved time integration algorithm to calculate the corresponding velocity and displacement time histories.

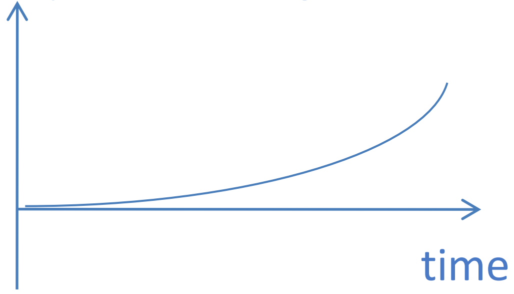
As such (particularly for older records, the shown velocity and displacement records are not the direct outcome of time integration of the recorded acceleration record. Mainly, offset and drift in these records (with time) have been removed.

Note: When a strong motion instrument “triggers” to record (save) an earthquake motion, the prior five seconds of excitation are also stored as part of the record. This helps ensure tat the recording starts from a near zero value.

Nevertheless, any small error can be greatly magnified when integration is performed to calculate the corresponding displacement and velocity time histories.

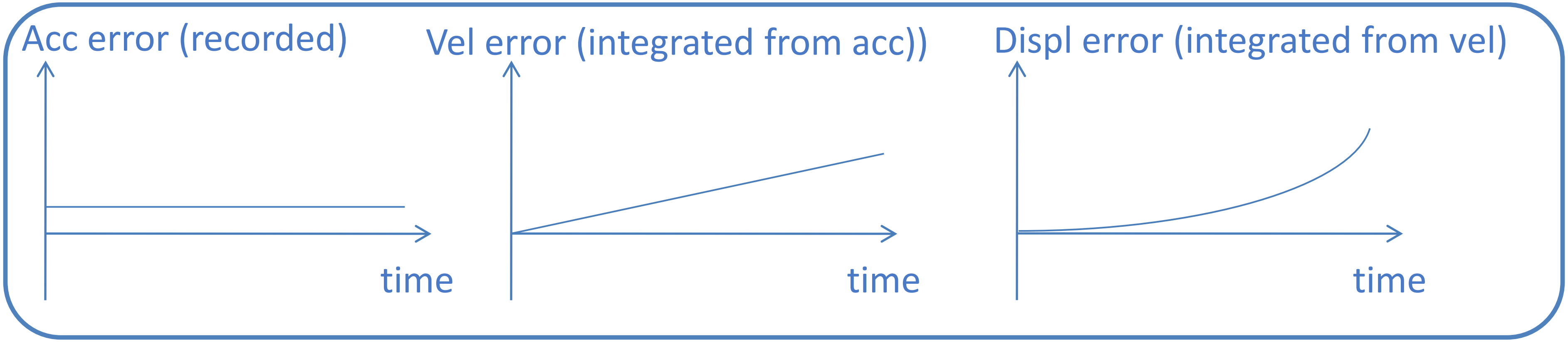

Acc error (recorded)


Vel error (integrated from acc))

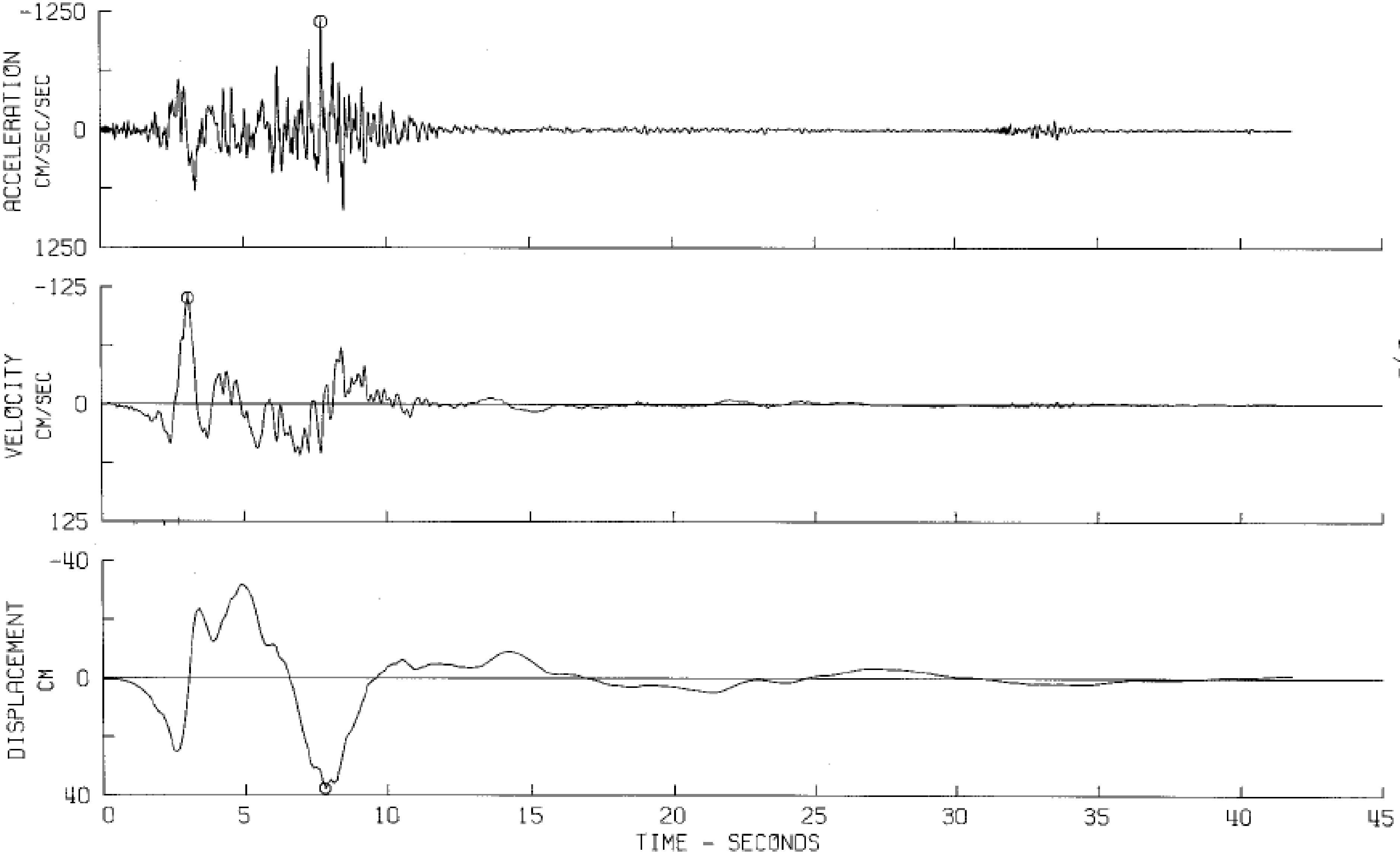

Displ error (integrated from vel)

For instance, if the entire recorded acceleration time history is erroneously offset by 0.0001 m/sec and the record duration is 100 seconds, this error will translate into a velocity of .0001 x 100 = .01 m/sec at the end of the record, and a permanent displacement of 0.5 m (also at the end of the record).

Unfortunately, any actual permanent ground displacement is also removed when performing the correction process. The good news is that sometimes a better correction can be made, if (perhaps via GPS or satellite measurement) the actual Earthquake-induced permanent ground displacement (at the recording location) is known.



A typical x-y-z published earthquake record is shown below:

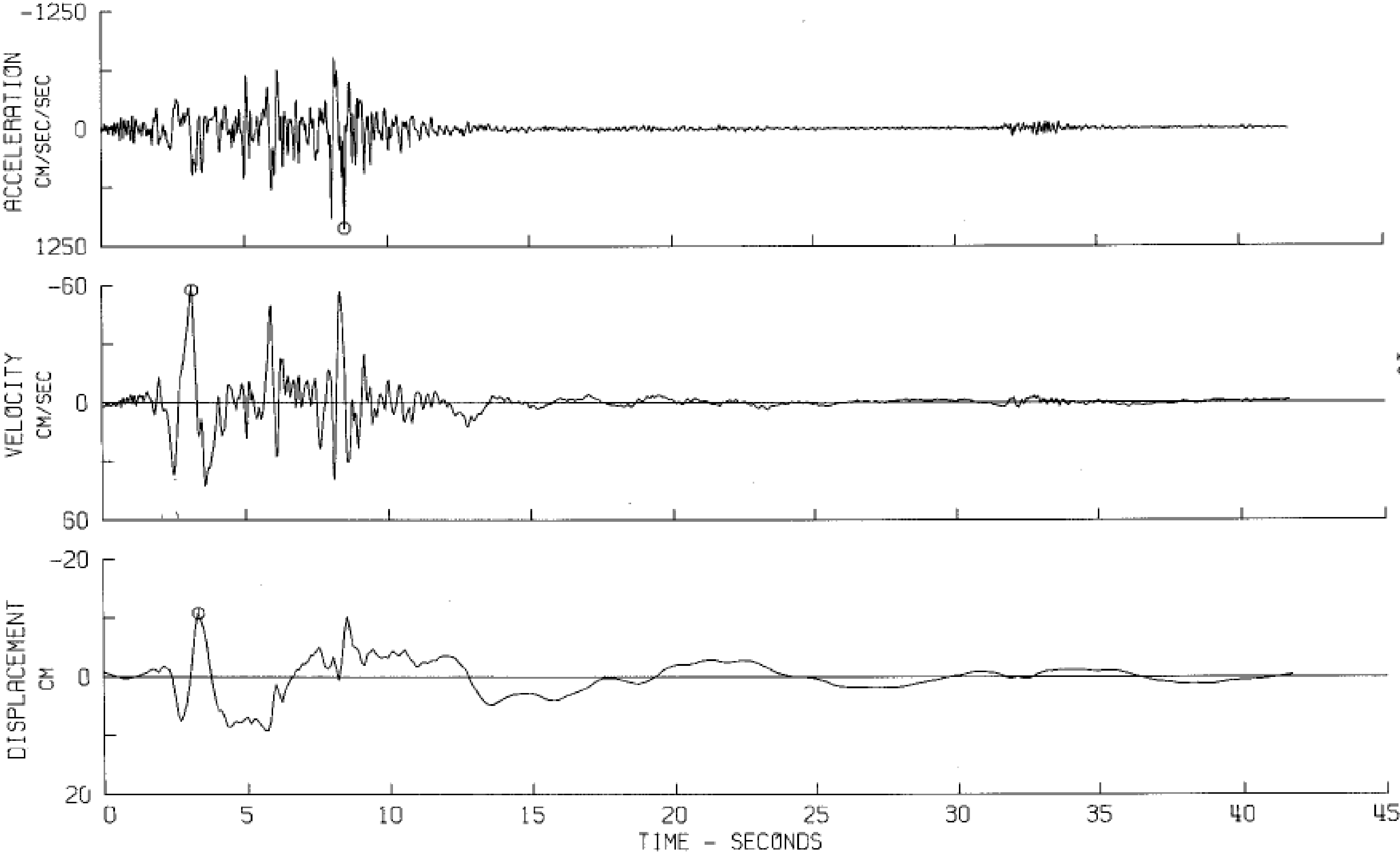


SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIC041 71.001.0 PACOIMA DAM, CAL. COMP S16E

⊙ PEAK VALUES : ACCEL = -1148.1 CM/SEC/SEC VELOCITY = -113.2 CM/SEC DISPL = 37.7 CM

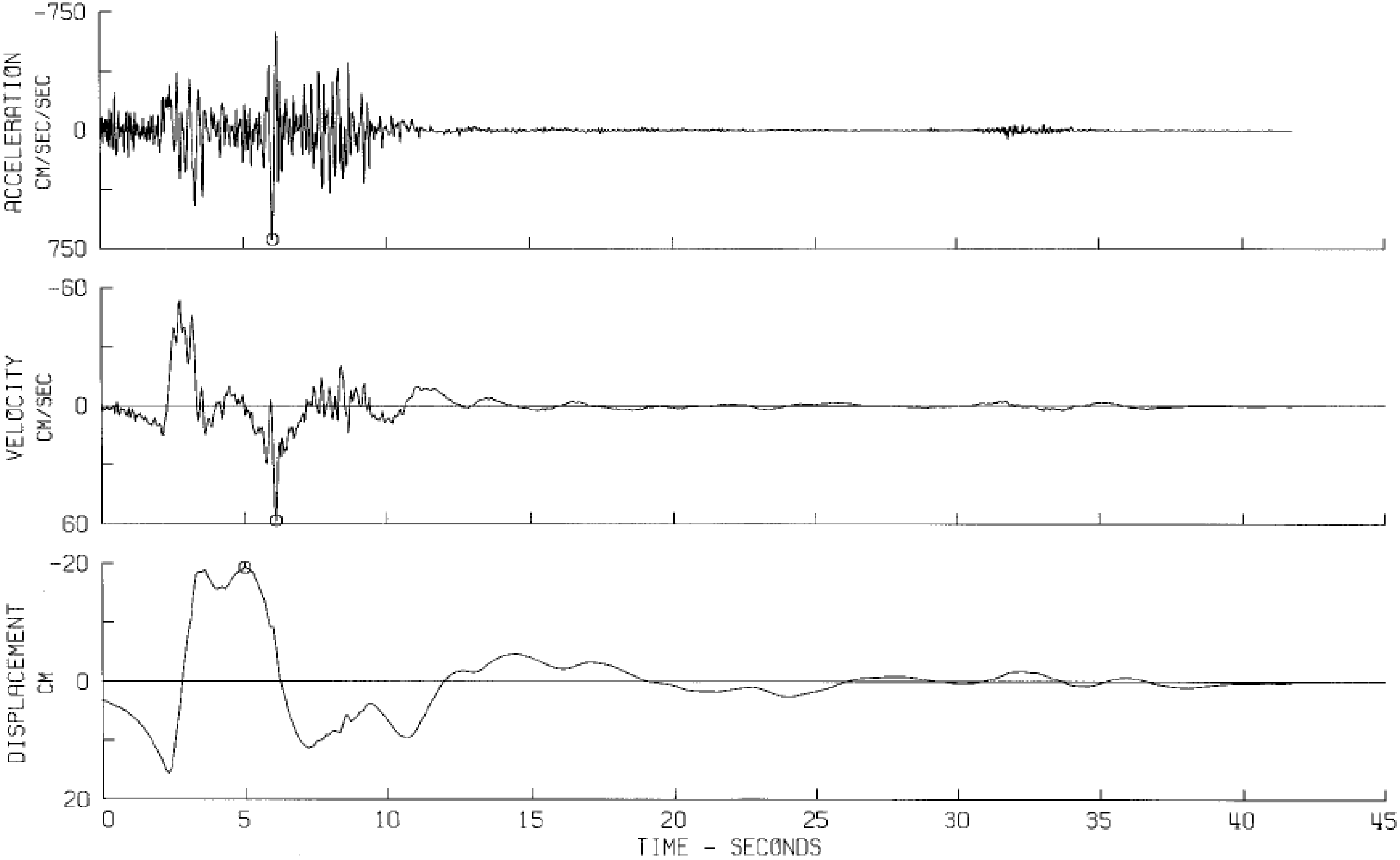
SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST
IIC041 71.001.0 PACOIMA DAM, CAL. COMP S74W
⊙ PEAK VALUES : ACCEL = 1054.9 CM/SEC/SEC VELOCITY = -57.7 CM/SEC DISPL = -10.8 CM



SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIC041 71.001.0 PACOIMA DAM, CAL. COMP DOWN

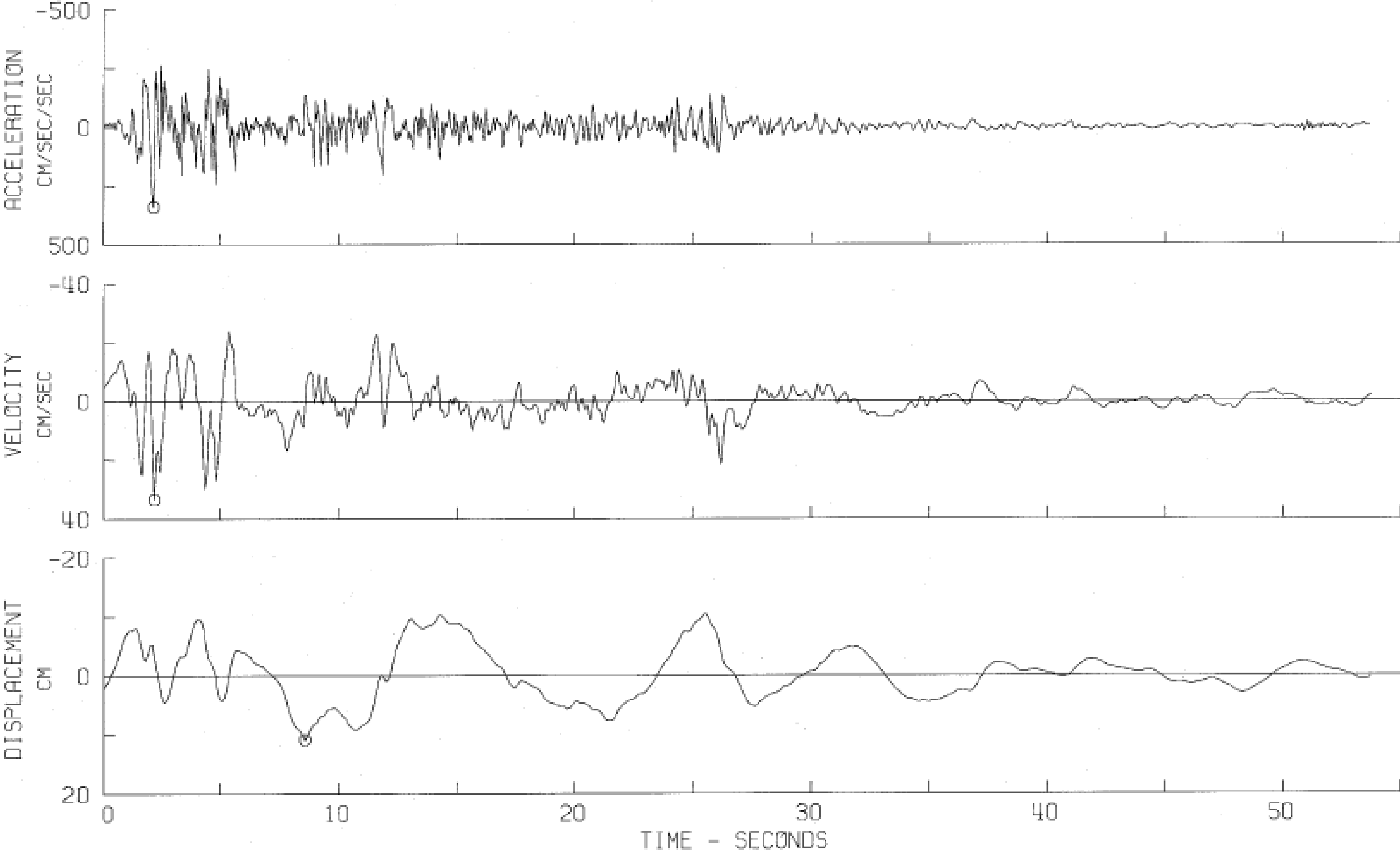
⊙ PEAK VALUES : ACCEL = 696.0 CM/SEC/SEC VELOCITY = 58.3 CM/SEC DISPL = -19.3 CM



IMPERIAL VALLEY EARTHQUAKE MAY 18. 1940 - 2037 PST

IIA001 40.001.0 EL CENTRO SITE IMPERIAL VALLEY IRRIGATION DISTRICT COMP S00E

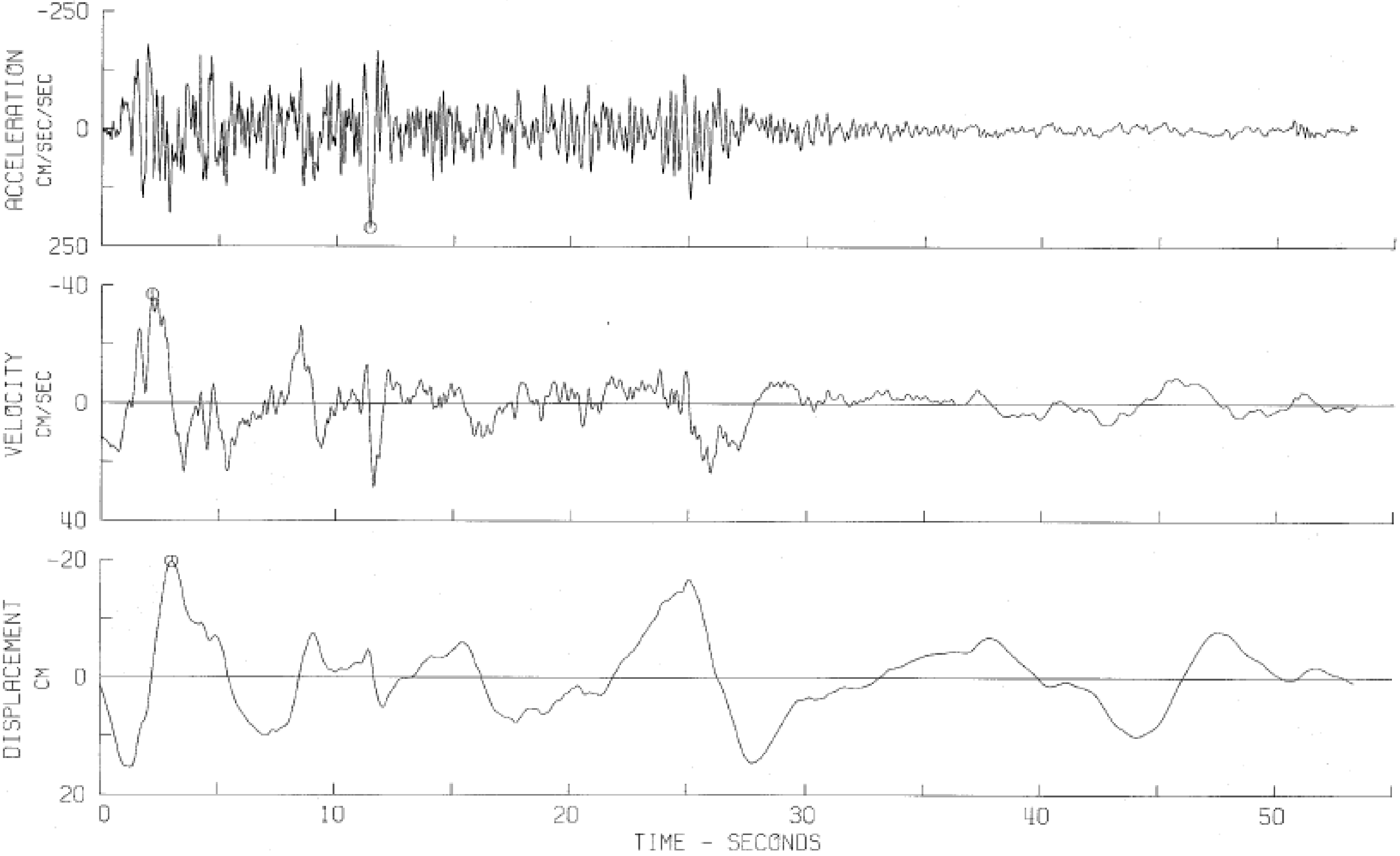
⊙ PEAK VALUES : ACCEL = 341.7 CM/SEC/SEC VELOCITY = 33.4 CM/SEC DISPL = 10.9 CM



IMPERIAL VALLEY EARTHQUAKE   MAY 18, 1940 - 2037 PST

IIA001 40.001.0 EL CENTRO SITE IMPERIAL VALLEY IRRIGATION DISTRICT   COMP S90W

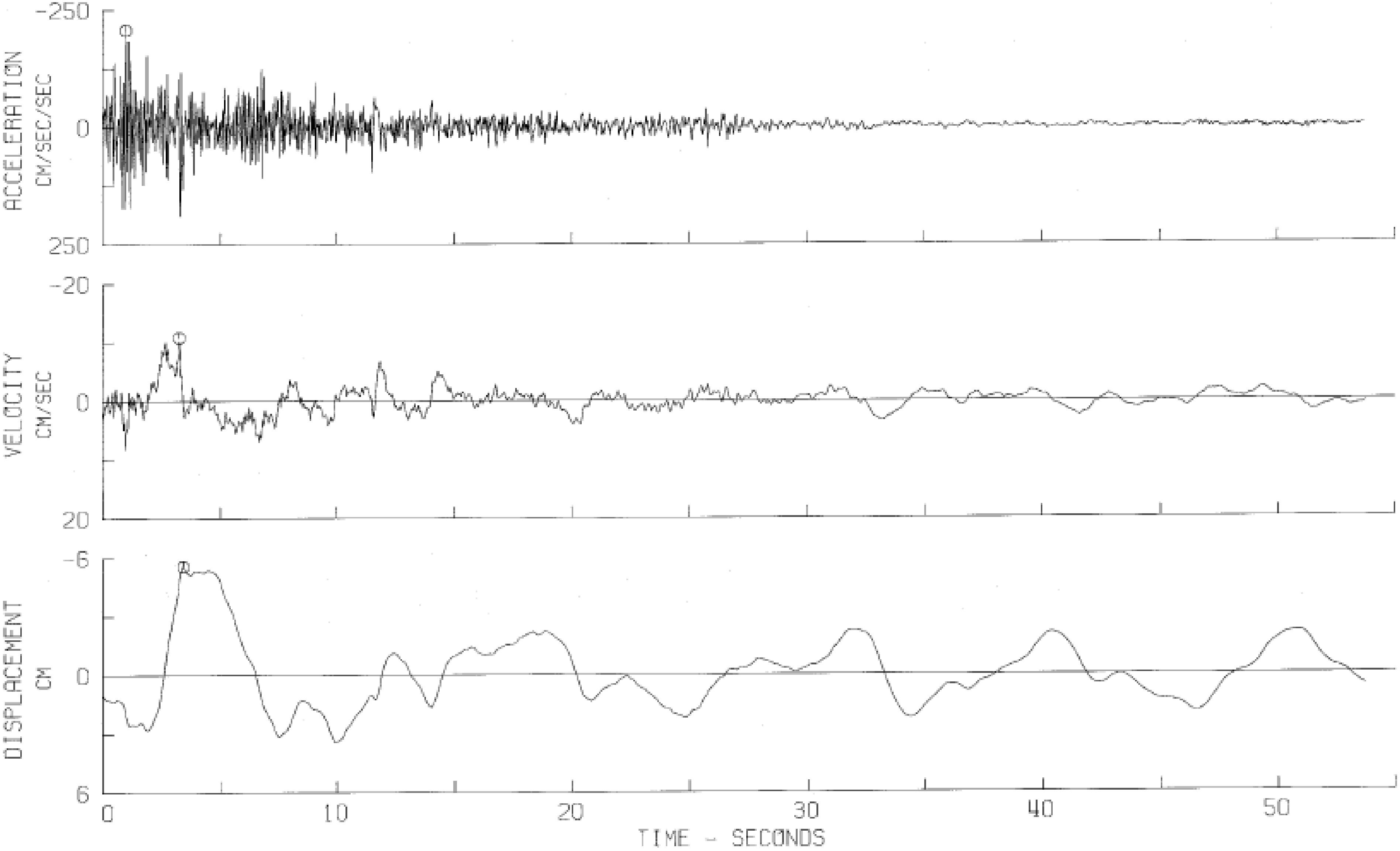
⊙ PEAK VALUES : ACCEL = 210.1 CM/SEC/SEC   VELOCITY = -36.9 CM/SEC   DISPL = -19.8 CM



IMPERIAL VALLEY EARTHQUAKE MAY 18, 1940 - 2037 PST

IIA001 40.001.0 EL CENTRO SITE IMPERIAL VALLEY IRRIGATION DISTRICT COMP VERT

⊙ PEAK VALUES : ACCEL = -206.3 CM/SEC/SEC VELOCITY = -10.8 CM/SEC DISPL = -5.6 CM



Amplitude parameters

As shown in these figures, the most common way of describing a ground motion is through the time history.

- Acceleration time history,
- Velocity time history, and
- Displacement time history

Acceleration is typically recorded directly with the others computed by integration. Note that integration results in a smoothing effect. Thus, the acceleration time history will more vividly display more high frequency content than the velocity, and (in turn) the velocity more so than the displacement.

Example of parameters that correlate to the Earthquake-induced inertial force

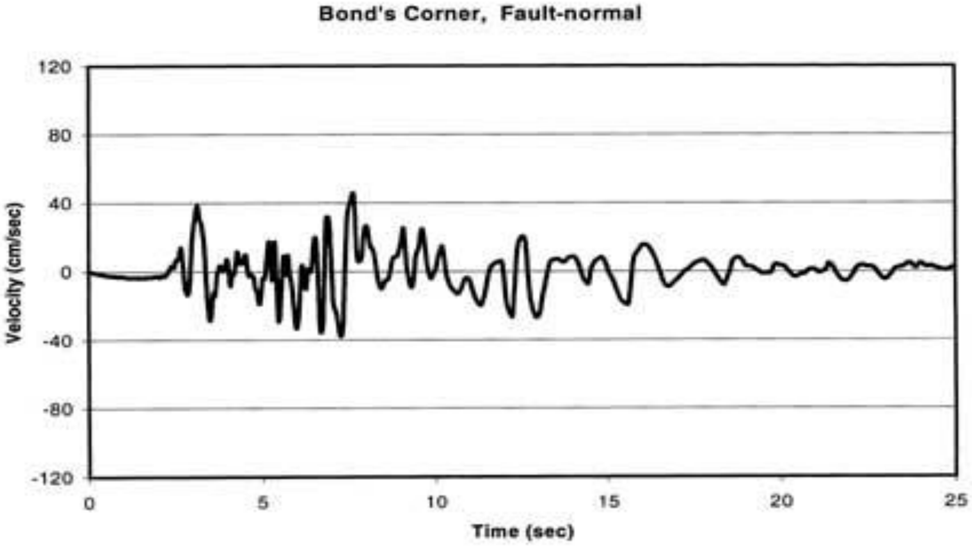
-PHA (Peak horizontal acceleration as an absolute value)

- PVA (Peak Vertical acceleration as an absolute value)

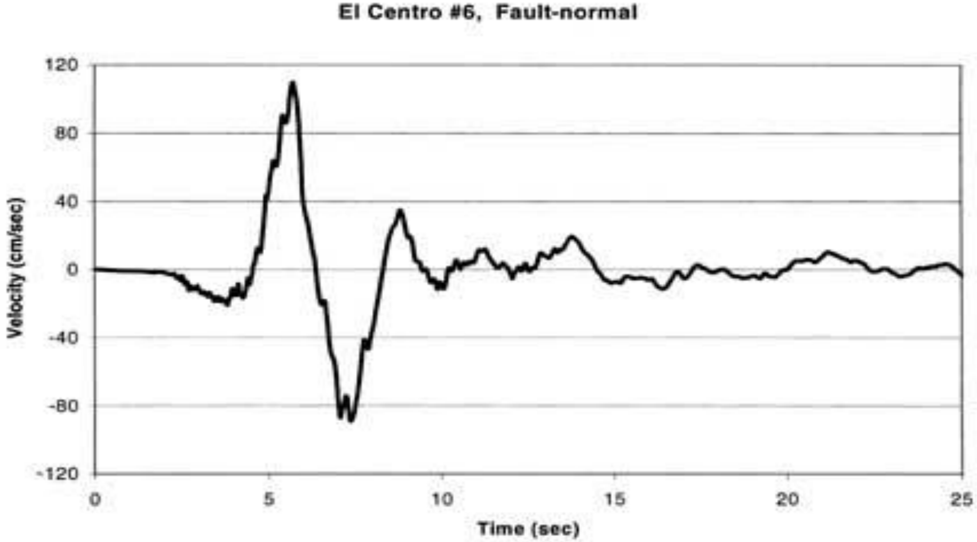
Note:
It is sometimes assumed that the ratio of PVA to PHA is 2/3. Actually, PVA/PHA is generally greater than 2/3 near the earthquake source and less than 2/3 at large distance (e.g., see Elgamal, A. and Liangcai He, "Vertical Earthquake Ground Motion Records: An Overview", Journal of Earthquake Engineering, Vol. 8, Issue 5, pages 663 – 697, September 2004).

- PGV (Peak Horizontal Velocity, absolute value)
Can be an important parameter for correlation to damage (or strong shaking). Examples include the scenario of a near source “fling” in an earthquake record where PGV can approach values as high as 1.7 m/sec or more (approaching 2.0 m/sec).

This figure illustrates the variability of near-field ground motions. Velocity time histories in the direction normal to the fault strike are presented for two sites that are both within 3 km of the fault trace during the 1979 Imperial Valley, California, earthquake. Clearly, the El Centro #6 (E06) recording shows a large velocity pulse that is not evident in the Bonds Corner (BCR) record. This difference in amplitude between the recordings at the two stations is primarily attributed to rupture directivity. The E06 station is in the forward directivity direction (i.e., the fault rupture propagates toward E06), while the BCR station is close to the epicenter.

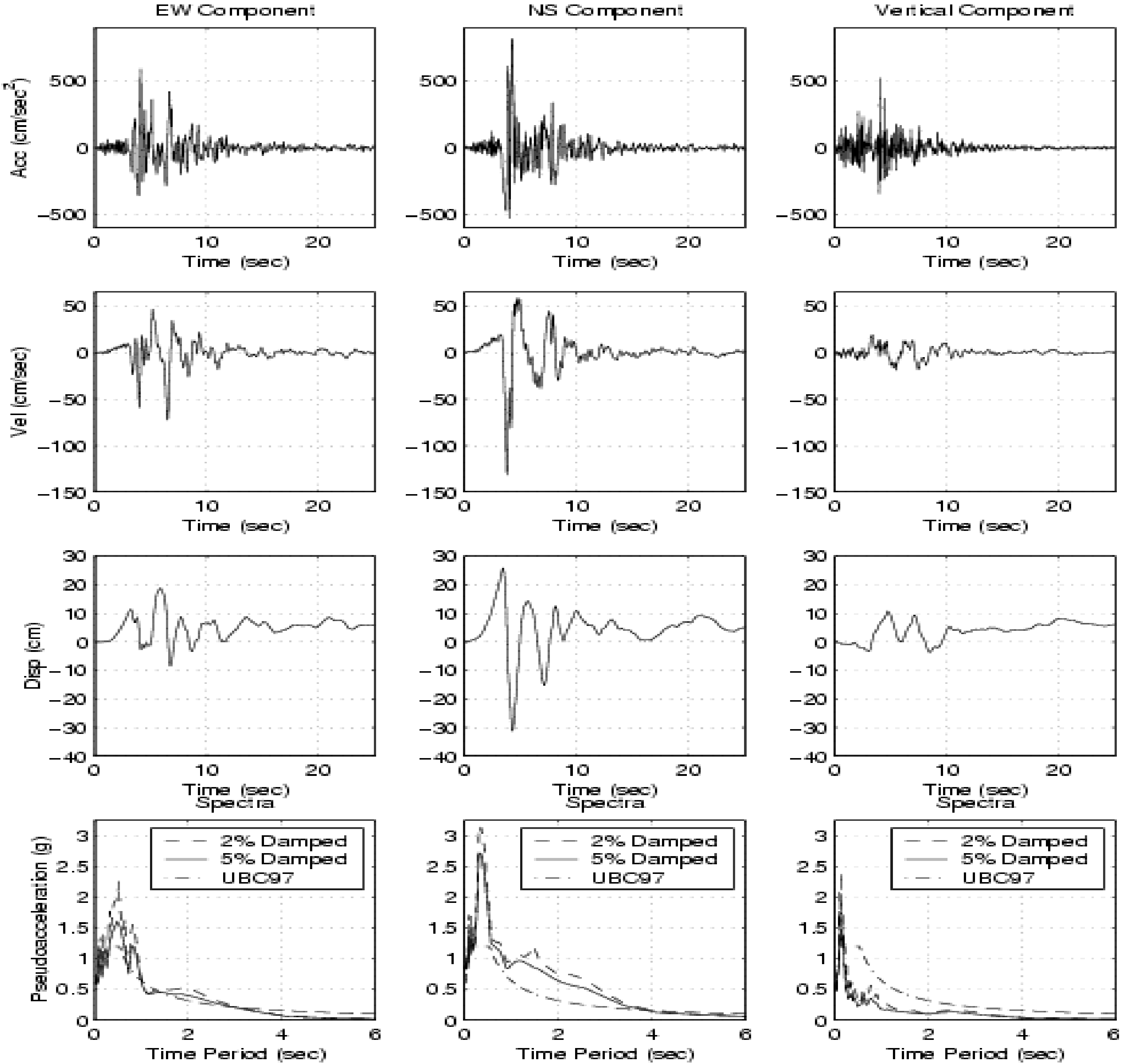

Bond's Corner, Fault-normal

http://peer.berkeley.edu/news/2001spring/lifelines.html


El Centro #6, Fault-normal

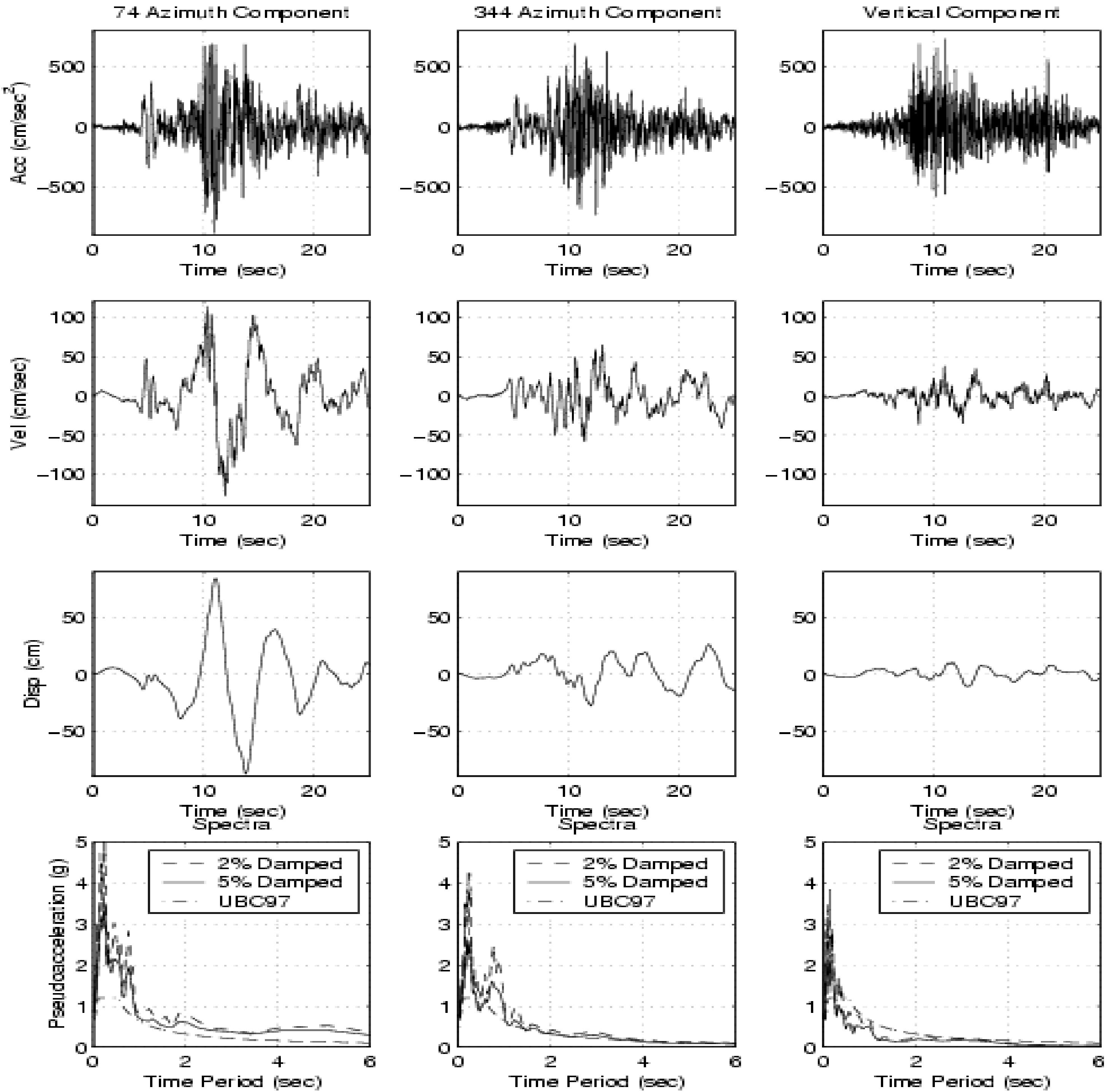
http://www.frame3d.caltech.edu/gmdb.html

(1) 1994 Northridge earthquake, Sylmar record.



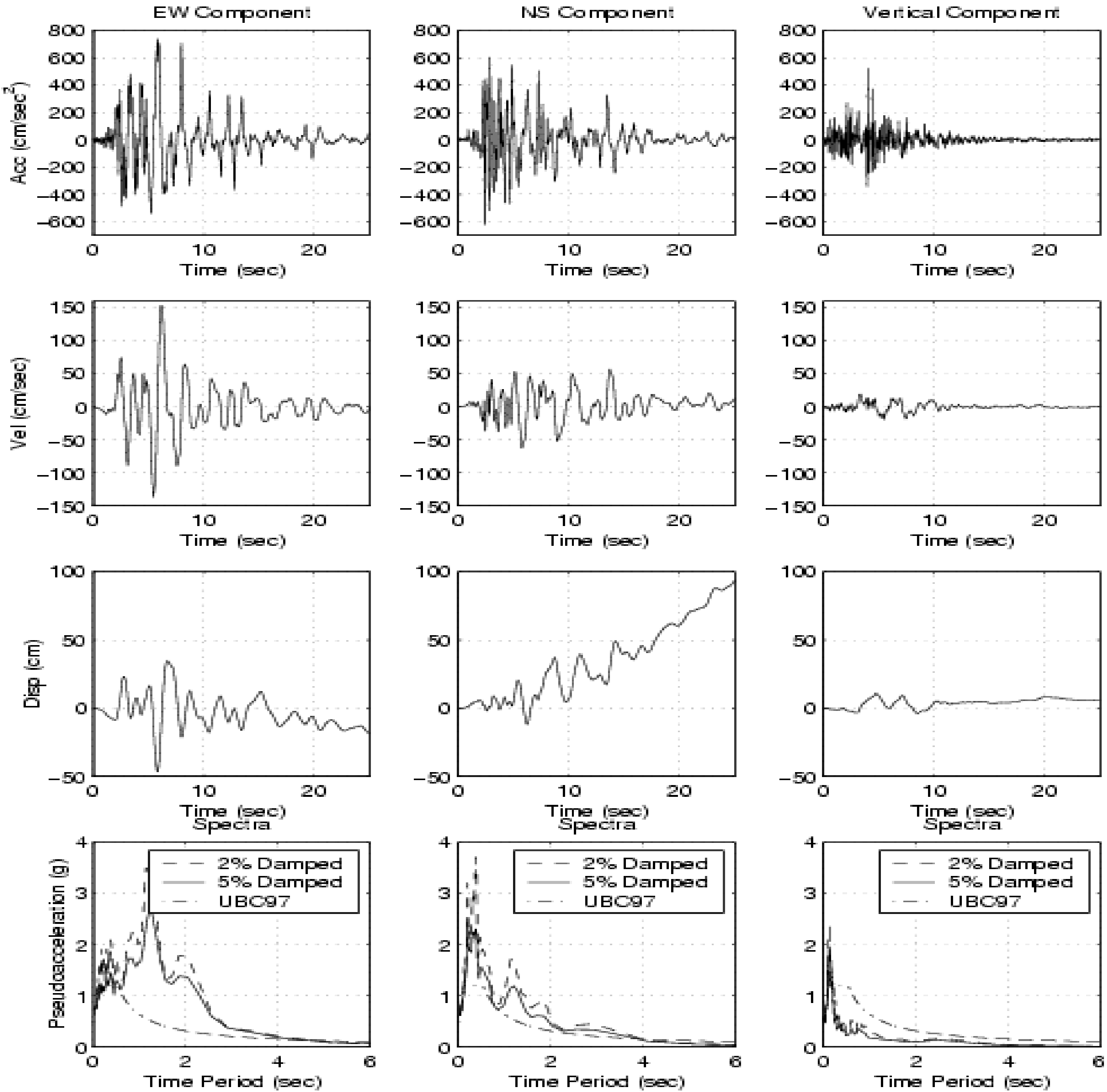
(2) 1978 Iran earthquake, Tabas record.

http://www.frame3d.caltech.edu/gmdb.html



http://www.frame3d.caltech.edu/gmdb.html

(3) 1995 Kobe earthquake, Takatori record.



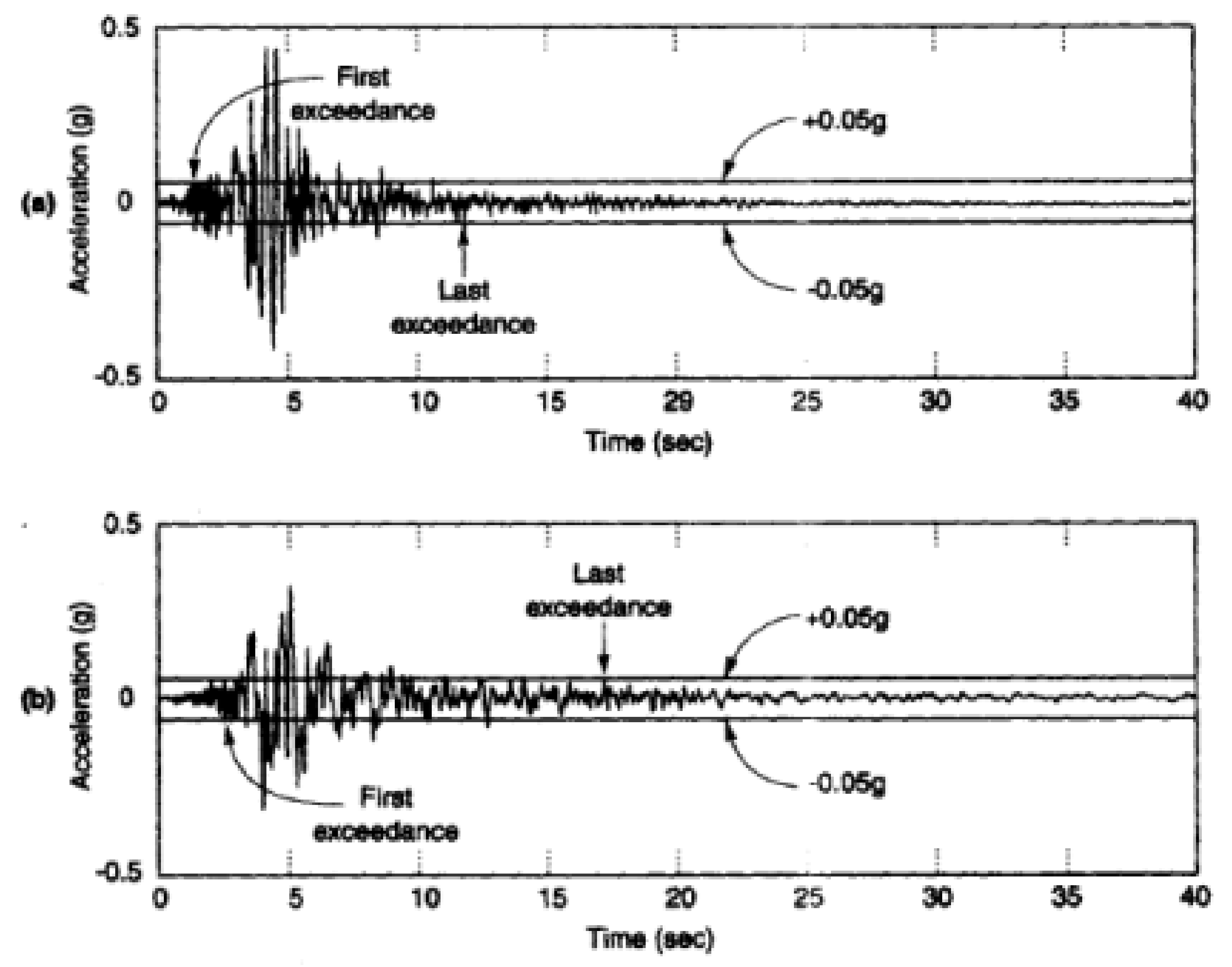
- Sustained maximum ground acceleration and velocity are measures of the strongest prolonged, rather than peak, acceleration and velocity (as an indication of acceleration causing repeated cycling during the earthquake). Sometimes, the 3rd or 5th largest peak in an acceleration or velocity time history is taken to represent this value.

- Strong Shaking Duration

The imparted cycles of ground shaking occur, may degrade a nonlinear structure and can cause build-up of excess pore water pressure in loose cohesionless soils, thus leading to liquefaction.

This parameter is often gauged by the bracketed duration, that being the time between the first and last exceedance of a threshold acceleration of interest.

Bracketed duration is the measure of time between the first and last exceedence of a threshold acceleration 0.05 g.



- Effective Design Acceleration

Since, pulses of high acceleration at high frequencies induce little response in most structures, the notion of effective design acceleration, with different definitions, has been proposed.

- Benjamin and Associates (1988): peak acceleration that remains after filtering out accelerations above 8-9 Hz.

- Kennedy (1980): 25% higher than the third highest peak acceleration obtained from a filtered time history.

V_{max}/a_{max}

Because of the filtering effects when integrating acceleration to obtain velocity, peak velocity and peak acceleration are usually associated with motions of different frequency.

The ratio V_{max}/a_{max} is related to the frequency content of the motion. For a simple harmonic motion of period T, $V_{max}/a_{max} = T/2\pi$.

For earthquake motions, V_{max}/a_{max} can be interpreted as the period of an equivalent harmonic motion, thus providing an indication of which periods of the ground motion are most significant.

rms (Root mean square of acceleration)

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

Note that the integral is over the duration of strong motion phase 0-T_d.

T_d depends on the approach used to define strong motion duration.

Frequency content parameters

Ground motion spectra

Fourier spectra: The Fourier amplitude spectrum is a plot of Fourier amplitude versus frequency, showing the distribution of the amplitude of a motion with respect to frequency (showing the frequency content of a motion). These spectra are sometimes smoothed to reduce jaggedness and display more clearly the frequency range(s) of predominant energy.

Response spectra: The response spectrum shows the maximum response of a SDOF system to a particular input motion (based on the natural frequency and damping ratio of the SDOF). As such, it is valuable in quickly inferring effect of this input motion on any building that is represented by the SDOF of interest. Examples include:

- The (linear) response spectrum (linear stiffness or force-displacement relationship).
- The nonlinear response spectrum (often bi-linear elastic perfectly-plastic structural force-displacement relationship).
- Examples include:
- Displacement or Deformation response spectra depicting the maximum relative Displacement response versus natural frequency and damping ratio.
- Velocity response spectra (often Pseudo spectra).
- Acceleration response spectra (often Pseudo-spectra)

Spectral parameters

Predominant period: the period corresponds to the peak Fourier amplitude.

Bandwidth: the range of frequency over which some level of Fourier amplitude is exceeded.

Estimation of Ground motion parameters

Development of a predicative relationship

Such a relationship usually represents the ground motion parameter of interest as a function of earthquake magnitude, distance, source characteristics, site characteristics, etc. A typical predicative relationship be of the form (Kramer 1996):

$$\ln Y = C_1 + C_2 M + C_3 M^{C_4} + C_5 \ln[R + C_6 \exp(C_7 M)] + C_8 R + f(source) + f(site)$$

$$\sigma_{\ln Y} = C_9$$

where *Y* is the ground motion parameter of interest, *M* the magnitude of the earthquake, *R* a measure of the distance from the source to the site being considered. C_1-C_9 are constants to be determined. The σ_{lnY} term describes the uncertainty in the value of the ground motion parameter given by the predicative relationship.

Peak acceleration

Based on world-wide data, Campbell (1981) proposed:

$$\ln PHA(g) = -4.141 + 0.868M - 1.09\ln[R + 0.606\exp(0.7M)]$$

$$\sigma_{\ln Y} = 0.37$$

where *M* is the local magnitude or surface wave magnitude ($\geq$ 6), *and R* is the closest distance to the fault rupture in km (≤ 50).

<u>From Kramer (1996)</u>

Toro et al. (1994) proposed an attenuation relationship for the mid-continental portion of the eastern North America where the continental crust is stronger and more intact than that in western North America.

Young’s et al. (1988) proposed an attenuation relationship for subduction zoned where earthquakes generally occur at greater hypocentral depths.

Campbell and Bozorgnia (1994) proposed:

$$
\begin{aligned}
\ln PHA(gals) = {} & 3.512 + 0.904 M_w - 1.328 \ln \sqrt{R^2 + [0.149 \exp(0.647 M_w)]^2} \\
& + (1.125 - 0.112 \ln R - 0.0957 M_w) F + (0.940 - 0.171 \ln R) S_{SR} \\
& + (0.405 - 0.222 \ln R) S_{HR}
\end{aligned}
$$

$$
\sigma_{\ln PHA} = \begin{cases} 0.889 - 0.0691 M_w & M_w \le 7.4 \\ 0.38 & M_w > 7.4 \end{cases}
$$

where M_w is the moment magnitude, R is the closest distance to seismic rupture in km (≤ 60, with minimum values of 7.3, 5.8, 3.5, and 3.0 km for magnitudes of 5.0, 5.5, 6.0, and 6.5, respectively), F is the source term (0 for strike-slip and normal faulting, and 1 for reverse faulting), $S_{SR}=1$ for soft-rock sites, $S_{HR}=1$ for hard rock sites, and $S_{SR}=S_{HR}=0$ for alluvium sites.

Based on western North America data, Boore et al. (1993) proposed:

$$\log PHA(g) = b_1 + b_2(M_w - 6) + b_3(M_w - 6)^2 + b_4 R + b_5 \log R + b_6 G_B + b_7 G_C$$

$$G_B = \begin{cases} 0 & for \quad site \quad class \quad A \\ 1 & for \quad site \quad class \quad B \\ 0 & for \quad site \quad class \quad C \end{cases}$$

$$G_C = \begin{cases} 0 & for \quad site \quad class \quad A \\ 0 & for \quad site \quad class \quad B \\ 1 & for \quad site \quad class \quad C \end{cases}$$

where $R = \sqrt{d^2 + h^2}$

and *d* is the closest distance to the surface projection of the fault in km, *h* is focal depth in km, and $b_1 - b_7$ are coefficients.. Site classes are defined on the basis of the average shear wave velocity in the upper 30 m layer of the ground.

Peak velocity

Joyner and Boore (1988) proposed:

$$\log PHV(cm/s) = j_1 + j_2(M_w - 6) + j_3(M_w - 6)^2 + j_4 \log R + j_5 R + j_6$$

where $R = \sqrt{r_0^2 + j_7^2}$

r_0 is the shortest distance in km from the site to the vertical projection of the earthquake fault rupture on the surface of the earth, j_1-j_7 are coefficients.

Total Intensity I_0 of A Ground Motion of Duration T_d

- In time domain, I_0 is given by the area under the squared acceleration time history ($a(t)^2$):

$$I_0 = \int_0^{T_d} [a(t)^2]dt \tag{1}$$

- In frequency domain, I_0 is given by the area under the squared Fourier amplitude spectrum ($c(\omega)^2$) divided by π:

$$I_0 = \frac{1}{\pi}\int_0^{\omega_N} [c(\omega)^2]d\omega \tag{2}$$

Where $c(\omega)$ is Fourier amplitude spectrum, and $\omega_N = \frac{2\pi}{2\Delta t}$ is the Nyquist frequency (the highest frequency in Fourier spectrum.

Parseval's theorem can show that (1) and (2) are equal. The average intensity or mean squared acceleration λ_0 is given by dividing (1) or (2) by the duration T_d.

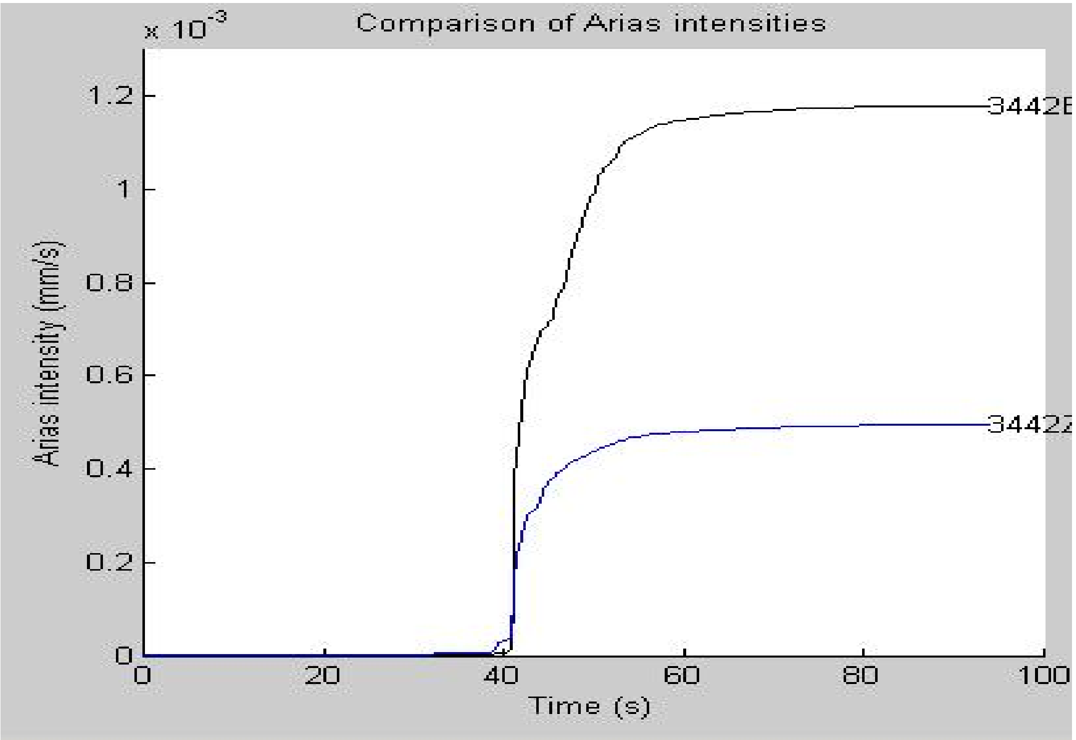
Arias Intensity

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

where I_a *is the Arias Intensity in units of length per time, a(t) is the acceleration-time history, and g is the acceleration of gravity*.

Note that the integral is over the entire duration rather than over the duration of strong motion. Arias intensity is thus independent of the method used to define strong motion duration.

Arias Intensity is sometimes shown as a function of time during an earthquake as shown in figure for 2 different earthquake motions



Arias, A. (1970). "A Measure of Earthquake Intensity," R.J. Hansen, ed. *Seismic Design for Nuclear Power Plants, MIT Press, Cambridge, Massachusetts, pp. 438-483.*

Cumulative Absolute Velocity (CAV)

It is the area under the absolute accelerogram, used to correlate to structural damage potential.

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

Hwk:

For the 1940 El Centro S00E ground motion record , define or calculate/compute (using a spreadsheet when needed):

1. Peak ground acceleration, velocity, and displacement (from the time history figure in this handout).
2. Bracketed duration for a threshold acceleration of 0.05 g
3. Sustained maximum ground acceleration
4. Compute (by integration) and Plot Arias intensity as a function of time
5. Compute (by integration) and Plot CAV as a function of time
6. Repeat 4. and 5 for the Rinaldi record available on the course website (under Other Earthquake Input Motions or go to: http://webshaker.ucsd.edu/kashima/sdof/input_motion.html).
7. Discuss very briefly the results of 4. - 6. above (shape of the curves)

Note: For 4. and 5. above, use the time history text file available to download on the course website (or go to: http://webshaker.ucsd.edu/homework/ElCentro_Vector.txt).