PARAMETERS CHARACTERIZING THE SEISMIC DEMAND FOR EARTHQUAKE DAMAGE SCENARIO EVALUATION

Response spectra

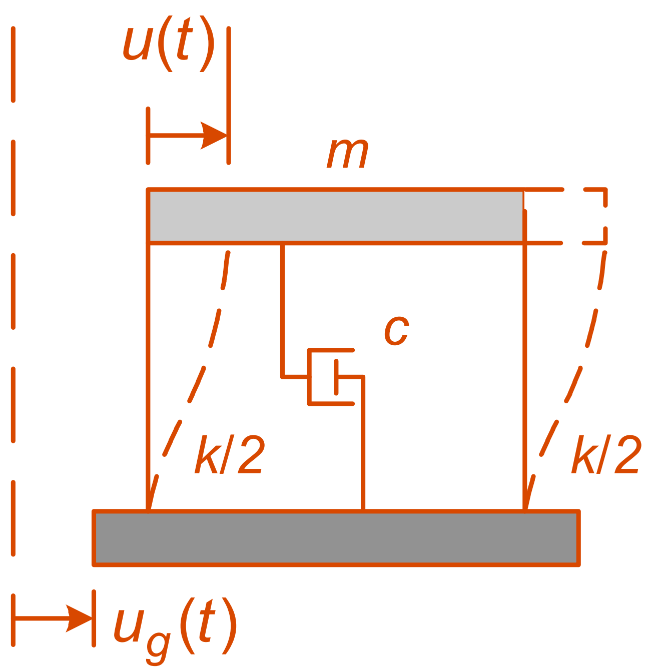
SDF SYSTEMS

A SDF system is subjected to a ground motion $u_g(t)$.

The deformation response $u(t)$ is to be calculated.

$$m\,(\ddot{u}_g + \ddot{u}) + c\,\dot{u} + k\,u = 0$$

$$\ddot{u} + 2\xi\omega_n\,\dot{u} + \omega_n^2\,u = -\ddot{u}_g(t)$$



The ground acceleration can be registered using accelerographs:

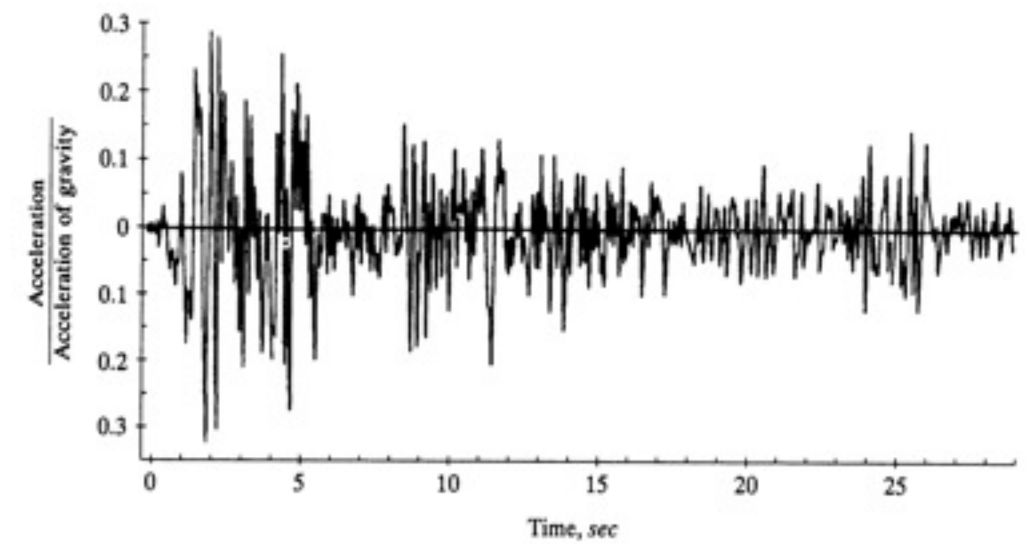
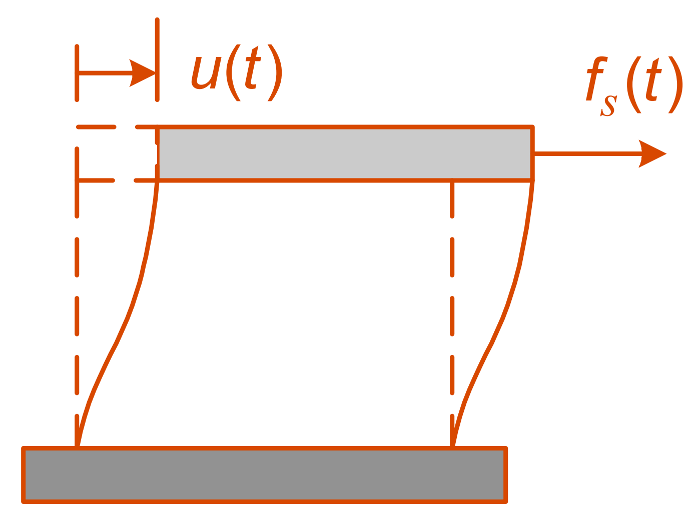


FIGURE 24-15
Accelerogram from El Centro earthquake, May 18, 1940 (*NS* component).

EQUIVALENT STATIC FORCE



$$f_s(t) = k\,u(t)$$

$$= m\,\omega_n^2\,u(t)$$

$$= m\,A(t)$$

$$A(t) = \omega_n^2 u(t) \neq \ddot{u}(t)$$

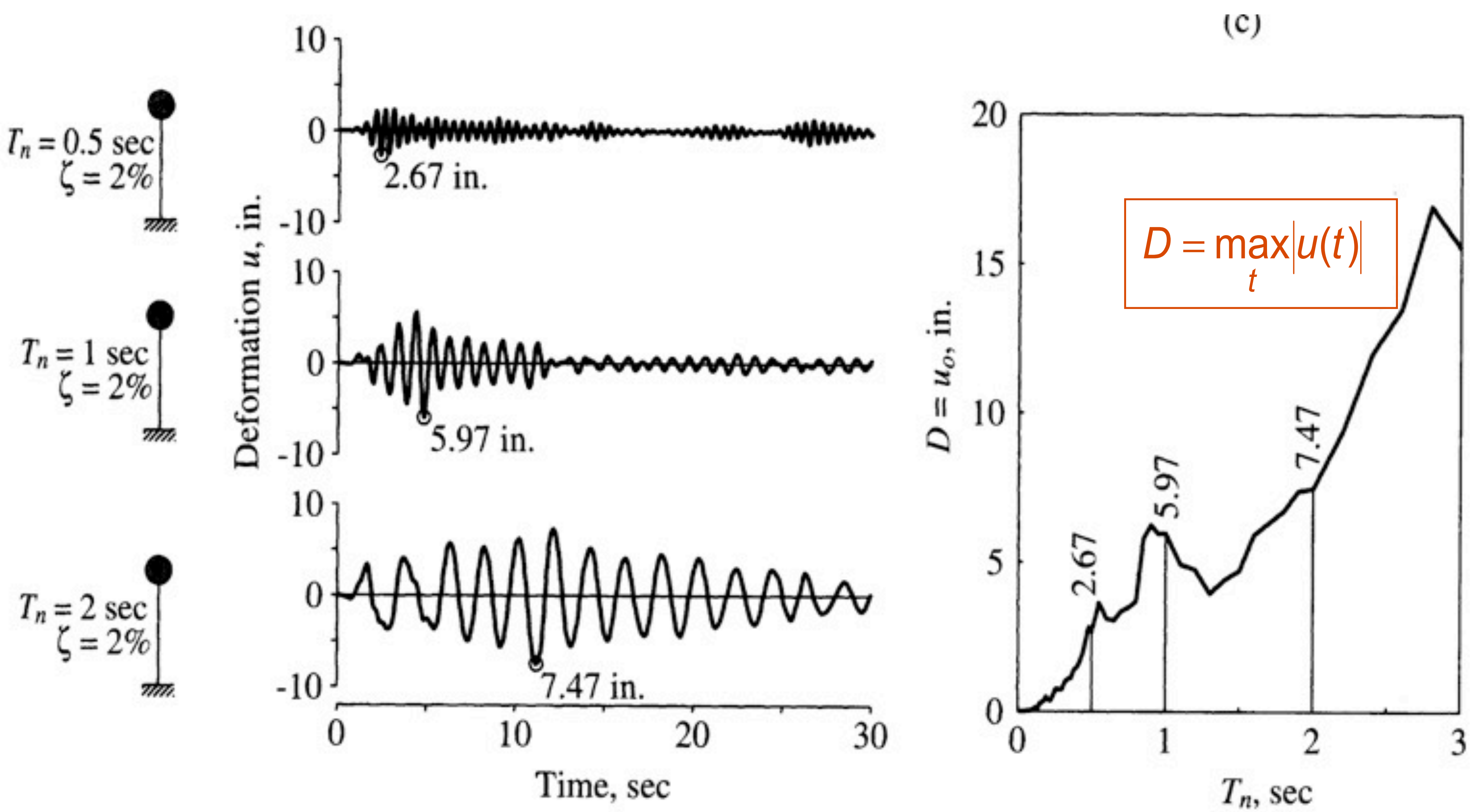
Pseudo acceleration

$f_s(t)$ is the force which must be applied statically in order to create a displacement $u(t)$.

Response spectra

A response spectrum is a plot of maximum response (e.g. displacement, velocity, acceleration) of SDF systems to a given ground acceleration versus systems parameters (T_n , ξ).

Example : Deformation response spectrum for El Centro earthquake



$$D = \max_t |u(t)|$$

Response spectra

Deformation, pseudo-velocity and **pseudo-acceleration** response spectra can be defined and ploted on the same graphs

Peak Deformation	$D = \max\lvert u(t) \rvert$
Peak Pseudo– velocity	$V = \omega_n D$
Peak Pseudo– acceleration	$A = \omega_n^2 D$

ω_n : natural circular frequency of the SDF system.

COMBINED D-V-A SPECTRUM

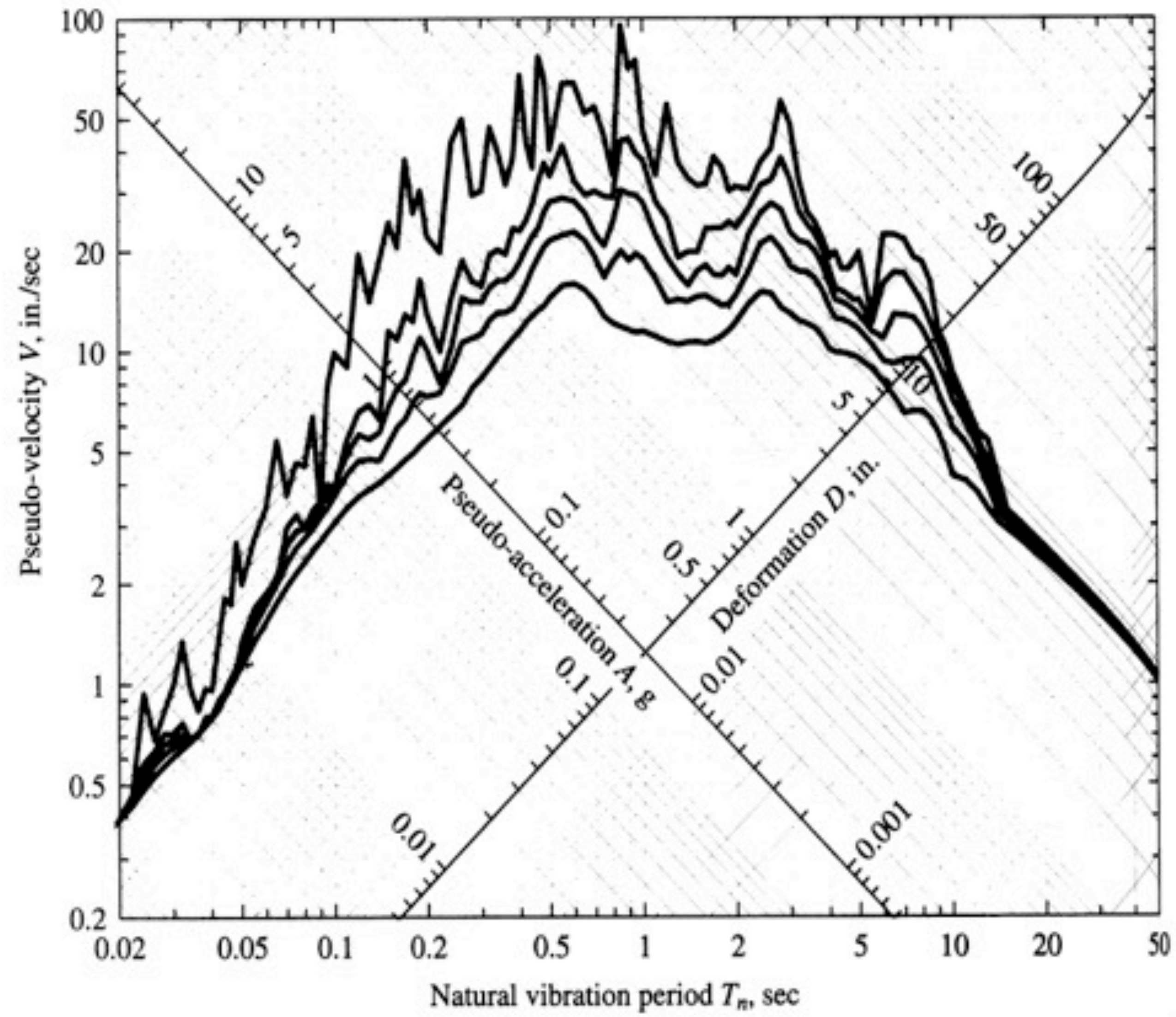
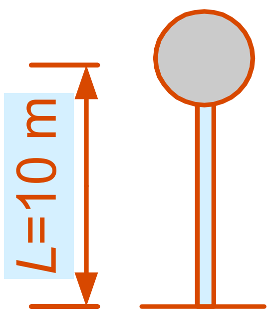


Figure 6.6.4 Combined D–V–A response spectrum for El Centro ground motion; ζ = 0, 2, 5, 10, and 20%.

EXAMPLE

A water tank is subjected to the El Centro earthquake. Calculate the maximum bending moment during the earthquake.



m = 10000 kg

k = 98.7 kN/m

$\xi = 2\%$

$$\omega_n = \sqrt{\frac{k}{m}} = 3.14 \text{ rad/s} \rightarrow \quad T_n = \frac{2\pi}{\omega_n} = 2 \text{ s}$$

$$\text{Spectrum} \rightarrow \begin{cases} D = 7.47 \times 25.4 = 190 \text{ mm} \\ A = 0.191 \times 9.81 = 1.87 \text{ ms}^{-2} \end{cases}$$

$$(\text{obs}: \ A = \omega_n^2 D)$$

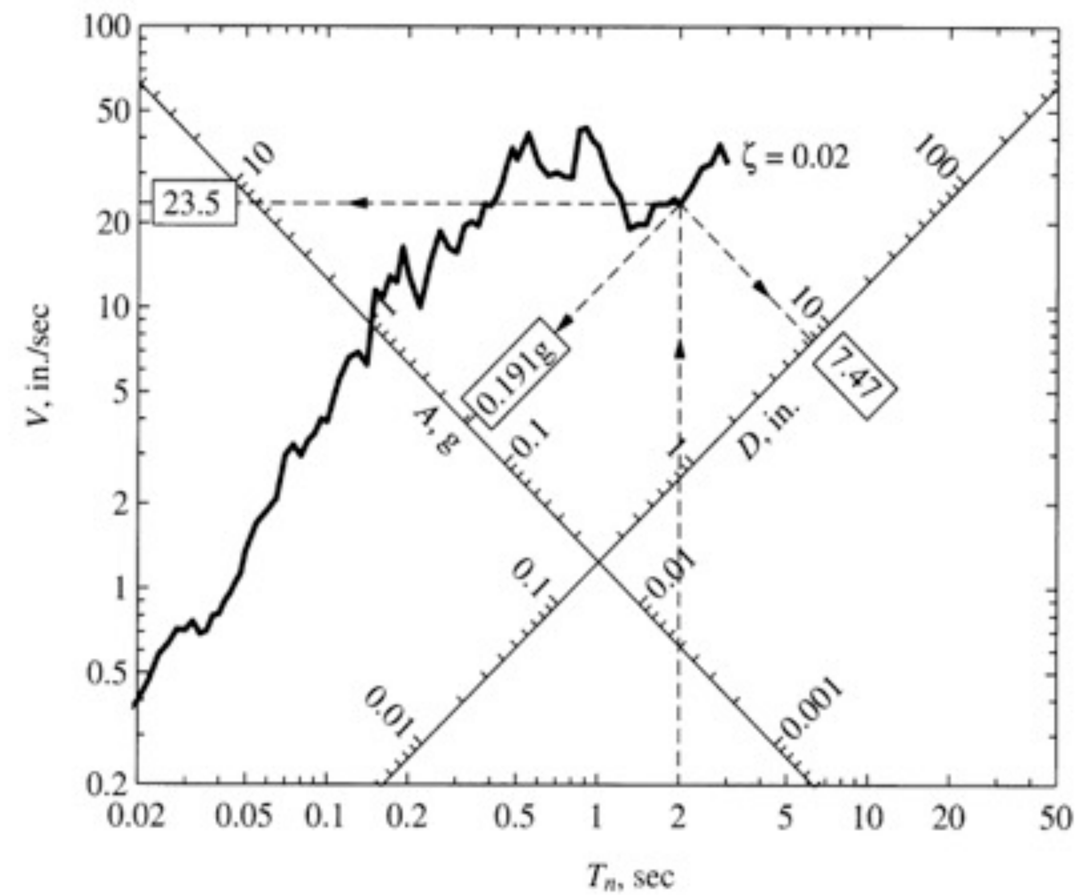
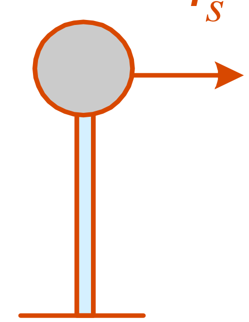
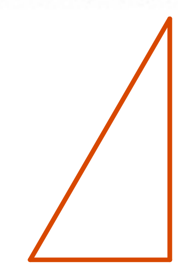


Figure 6.6.3 Combined *D–V–A* response spectrum for El Centro ground motion; $\zeta = 2\%$.

$$f_s = k \cdot D = 18.7 \text{ kN}$$





$$M_{max} = 187 \text{ kNm}$$

When the equivalent static force has been determined, the internal forces and stresses can be determined using statics.

Response spectrum characteristics

General characteristics can be derived from the analysis of response spectra.

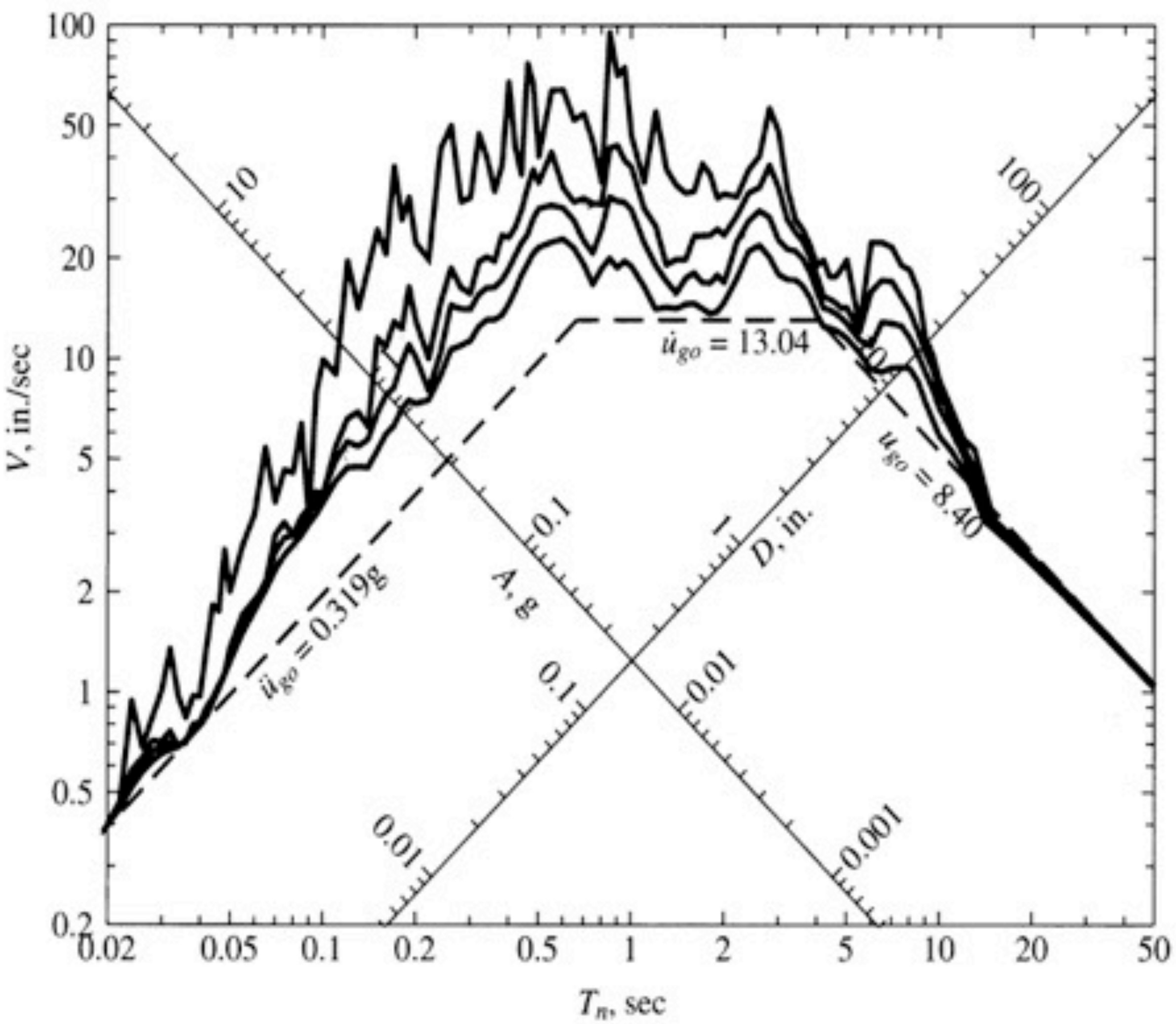


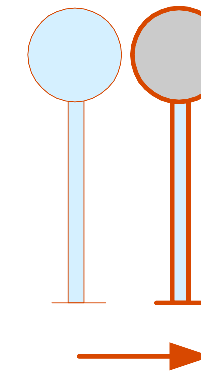
Figure 6.8.1 Response spectrum (ζ = 0, 2, 5, and 10%) and peak values of ground acceleration, ground velocity, and ground displacement for El Centro ground motion.

$T_n = 2\pi\sqrt{m/k}$

T_n < 0.03 s : rigid system

no deformation

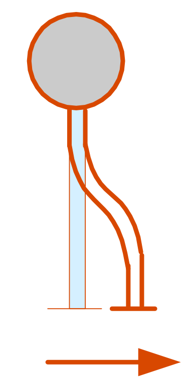
u(t) ≈ 0 → D ≈ 0



T_n > 15 s : flexible system

no total displacement

$u(t) = u_g(t) \rightarrow D = u_{go}$



The spectrum can be divided in 3 period ranges :

$T_n < 0.5\text{s}$: acceleration sensitive region

$0.5 < T_n < 3\text{s}$: velocity sensitive region

$T_n > 3\text{s}$: displacement sensitive region

Elastic design spectrum

Problem: how to ensure that a structure will resist future earthquakes.

The elastic design spectrum is obtained from ground motions data recorded during past earthquakes at the site or in regions with near-similar conditions

EXAMPLE

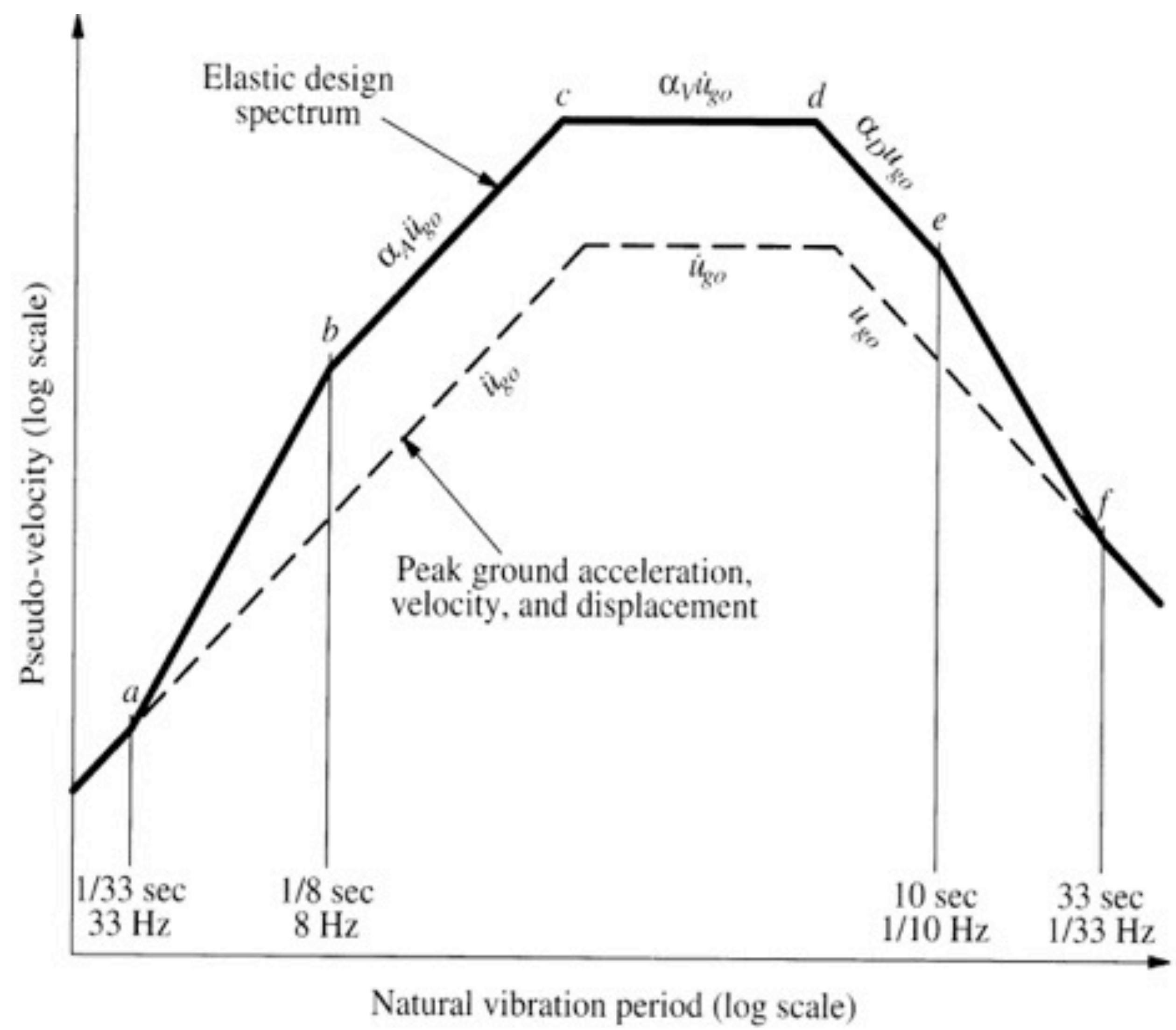


Figure 6.9.3 Construction of elastic design spectrum.

EPA

The effective peak acceleration EPA is defined as the average spectral acceleration over the period range 0.1 to 0.5 s divided by 2.5 (the standard amplification factor for a 5% damping spectrum), as follows:

$$EPA = \frac{\overline{S}_{pa}}{2.5}$$

where $\overline{S}_{pa}$ is mean pseudo-acceleration value. The empirical constant 2.5 is essentially an amplification factor of the response spectrum obtained from real peak value records.

EPA is correlated with the real peak value, but not equal to nor even proportional to it. If the ground motion consists of high f requency components, EPA will be obviously smaller than the real peak value.

It represents the acceleration which is most closely rel ated to the structural response and to the damage potential of an earthquake. The EPA values for the two records of Ancona and Sylmar stations a re 205 cm/s^2 and 774 cm/s^2 respectively, and describe in a more appropriate way, than PGA values, the damage caused by the two earthquakes.

Duration

The bracketed duration is defined as the time between the first and the last exceedances of a threshold acceleration (usually .05g).

Among the different duration definitions that can be found in the literature, one commonly used is that proposed by Trifunac e Brady (1975):

$$t_D = t_{0.95} - t_{0.05}$$

where $t_{0.05}$ and $t_{0.95}$ are the time at which respectively the 5% and 95%, of the time integral of the history of squared accelerations are reached, which corresponds to the time interval between the points at which 5% and 95% of the total energy has been recorded.

Arias Intensity

The Arias Intensity (Arias, 1969), I_A, is defined as follows:

$$I_A = \frac{\pi}{2g}\int_0^{t_t} a_g^2(t)dt$$

where t_t and a_g are the to tal duration and ground acceleration of a ground motion record, respectively.
The Arias intensity has units of velocity. I_A represents the sum of the total energies, per unit mass, stored, at the end of the earthquake ground motion, in a population of undamped linear oscillators.

Arias Intensity, which is a measure of the global energy transmitted to an elastic system, tends to overestimate the intensity of an earthquake with long duration, high acceleration and broad band frequency content. 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.

Housner Intensity

Housner (1952) defined a measure expressing the relative severity of earthquakes in terms of the area under the pseudo-velocity spectrum between 0.1 and 2.5 seconds. Housner's spectral intensity I_H is defined as:

$$I_H = \int_{0.1}^{2.5} S_{pv}(T,\xi)\,dT = \frac{1}{2\pi}\int_{0.1}^{2.5} S_{pa}(T,\xi)\,T\,dT$$

where S_{pv} is the pseudo-velocity at the undamped natural period T and damping ratio ξ, and S_{pa} is the pseudo-acceleration at the undamped natural period T and damping ratio ξ.

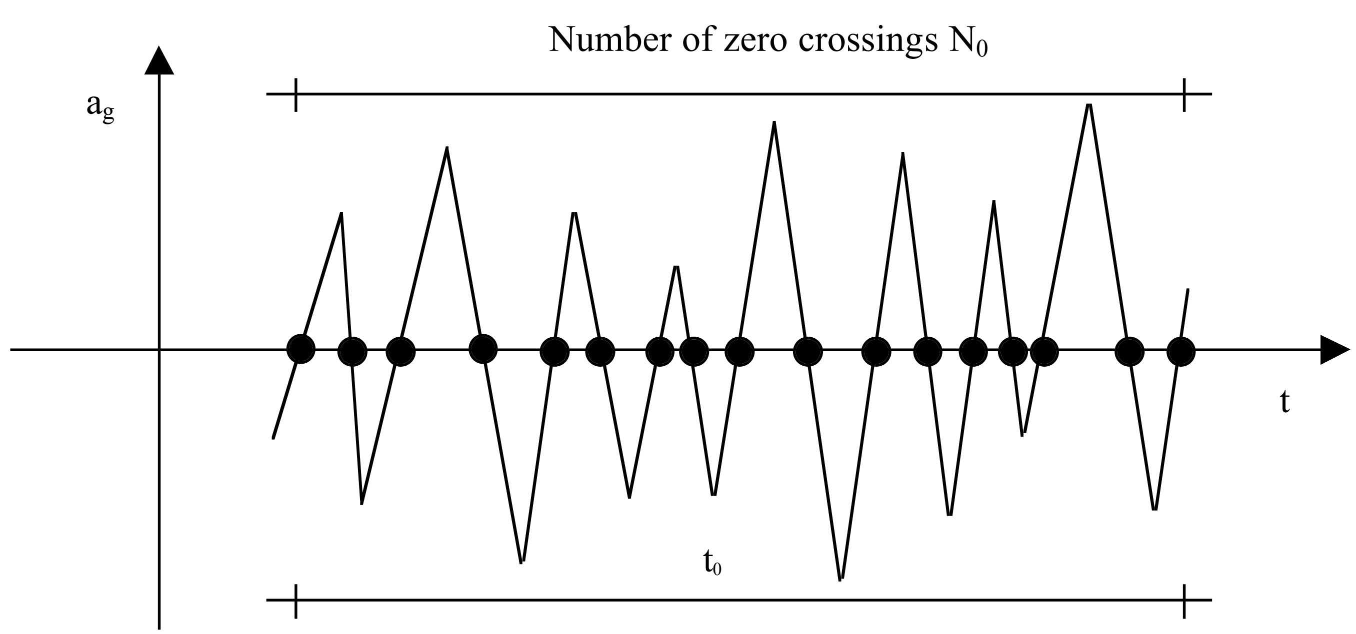
Housner's spectral intensity is the first moment of the area of S_{pa} $(0.1<T<2.5)$ about the S_{pa} axis, implying that the Housner spectral intensity is larger for ground motions with a significant amount of low frequency content.
The I_H parameter captures important aspects of the amplitude and frequency content in a single parameter, however, it does not provide information on the strong motion duration which is important for a structural system experiencing inelastic behaviour and yielding reversals.

Destructiveness potential

Araya & Saragoni (1984) proposed the destructiveness potential factor, P_D, that considers both the Arias Intensity and the rate of zero crossings, ν_0 and agrees with the observed damage better than other parameters. The destructiveness potential factor, which simultaneously considers the effect of the ground motion amplitude, strong motion duration, and frequency content on the relative destructiveness of different ground motion records, is defined as:

$$P_D = \frac{\pi}{2g} \frac{\int_0^{t_0} a_g^2(t)dt}{\nu_0^2} = \frac{I_A}{\nu_0^2} \qquad \nu_0 = \frac{N_0}{t_0}$$

where t is the time, a_g is the ground acceleration, $\nu_0 = N_0/t_0$ is the number of zero crossings of the acceleration time history per unit of time, N_0 is the number of the crossings with the time axis, t_0 is the total duration of the examined record (sometimes it could be a particular time-window), and I_A is the Arias intensity.

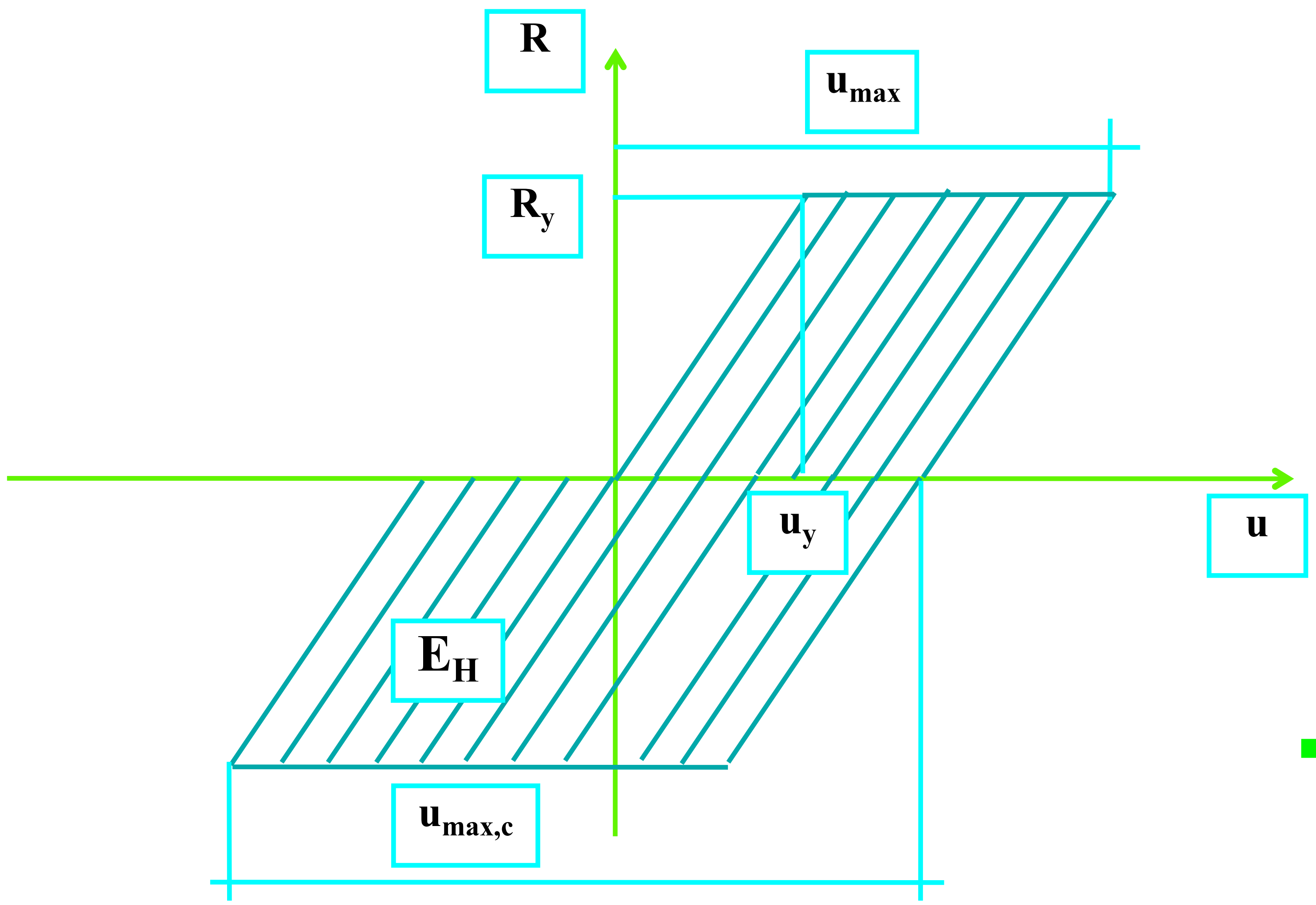


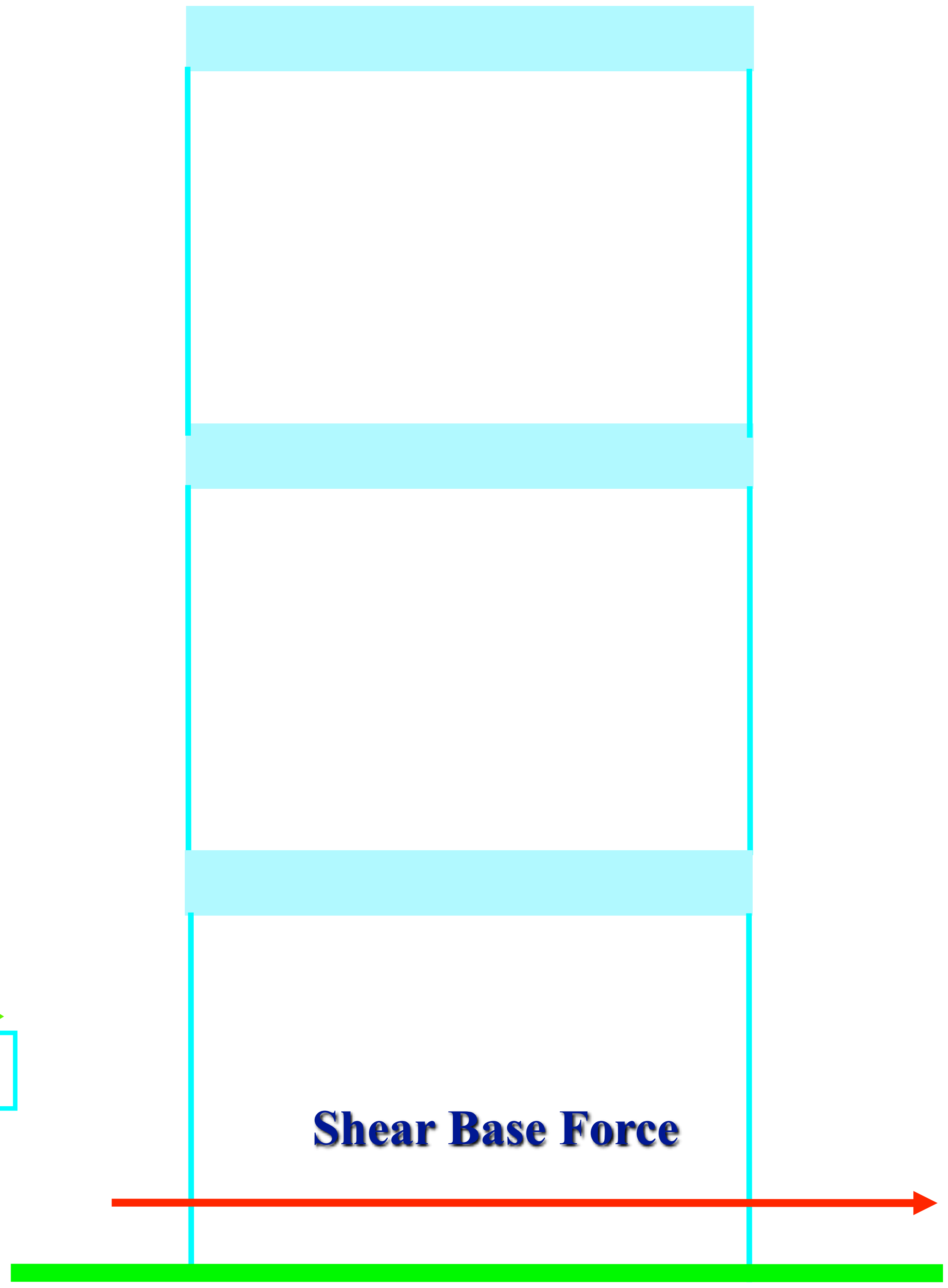
Evaluation of the parameter ν_0.

$$C_y = \frac{R_y}{mg} \qquad (R_y = \text{yielding strength})$$

$$\eta = \frac{R_y}{m\ddot{u}_{g(max)}} = \frac{C_y}{\ddot{u}_{g(max)}/g}$$

$$\mu = \frac{u_{max}}{u_y}$$





Yielding resistance

Linear elastic response spectra recommended by seismic codes have been proved to be inadequate by recent seismic events, as they are not directly related to structural damage. Extremely important factors such as the duration of the strong ground motion and the sequence of acceleration pulses are not taken into account adequately.

Therefore response parameters based on the inelastic behaviour of a structure should be considered with the ground motion characteristics.

In current seismic regulations, the displacement ductility ratio μ is generally used to reduce the elastic design forces to a level which implicitly considers the possibility that a certain degree of inelastic deformations could occur. To this purpose, employing numerical methods, constant ductility response spectra were derived through non-linear dynamic analyses of viscously damped SDOF systems by defining the following two parameters:

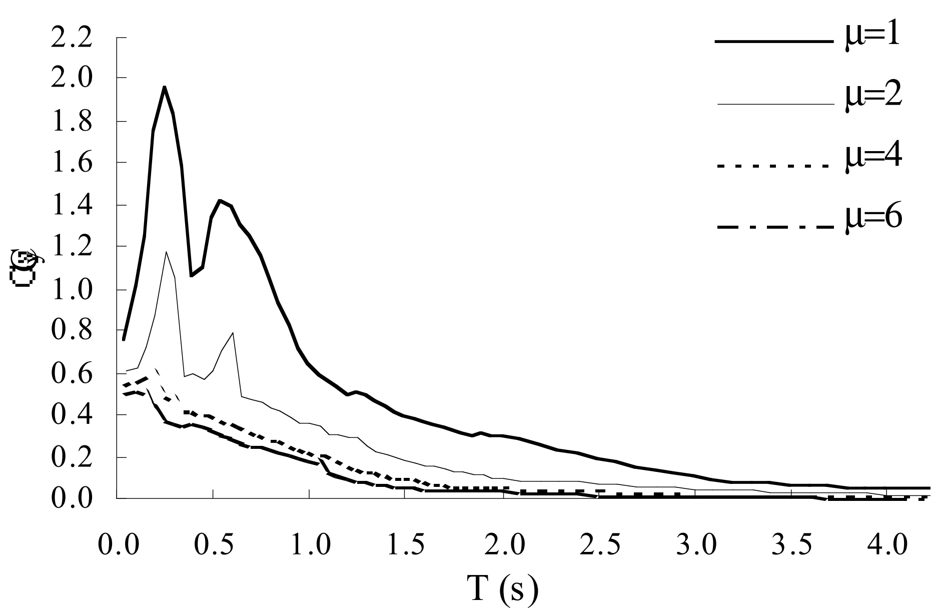
$$C_y = \frac{R_y}{mg}\eta = \frac{R_y}{m\ddot{u}_{g(max)}} = \frac{C_y}{\ddot{u}_{g(max)}/g}$$

where R_y is the yielding resistance, m is the mass of the system, and $\ddot{u}_{g(max)}$ is the maximum ground acceleration.

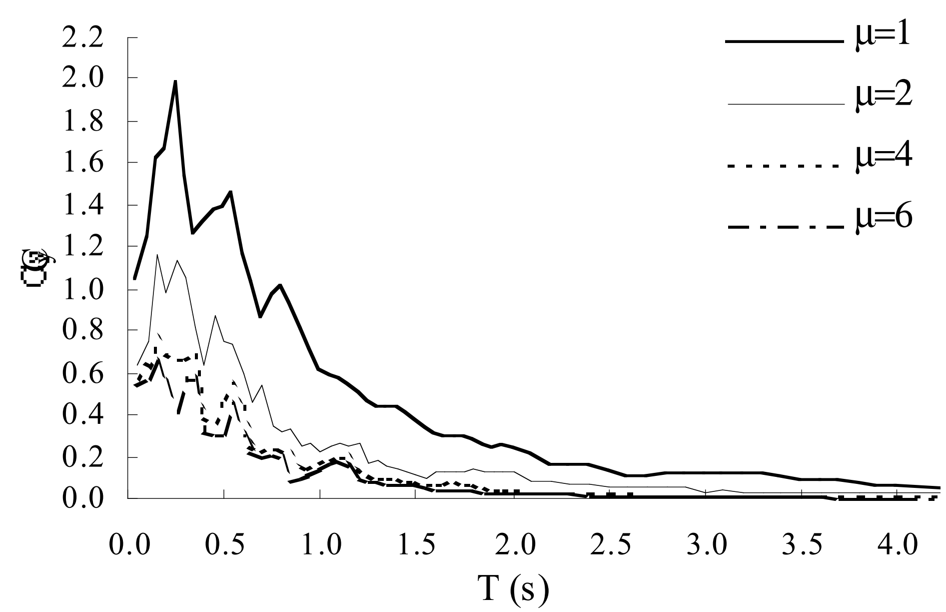
Yielding resistance

The parameter C_y represents the structure's yielding seismic resistance coefficient and η expresses a system's yield strength relative to the maximum inertia force of an infinitely rigid system and reveals the strength of the system as a fraction of its weight relative to the peak ground acceleration expressed as a fraction of gravity. Traditionally, displacement ductility was used as the main parameter to measure the degree of damage sustained by a structure.

One significant disadvantage of seismic resistance (C_y) spectra is that the effect of strong motion duration is not considered. An example of constant ductility C_y spectra, corresponding to the 1986 San Salvador earthquake (CIG record) and 1985 Chile earthquake (Llolleo record):it seems that the damage potential of these ground motions is quite similar, even though the CIG and Llolleo are records of two earthquakes with very different magnitude, 5.4 and 7.8, respectively.



(a)



(b)

Input energy

Introduction of appropriate parameters defined in terms of energy can lead to more reliable estimates, since, more than others, the concept of e nergy provides tools which allow to account rationally for the mechanisms of generation, transmission and destructiveness of seismic actions.

Energy-based parameters, allowing us to characterize properly the different types of time histories (impulsive, peri odic with long durations pulses, etc.) which may correspond to an earthquake, could provid e more insight into th e seismic performance.

The most promising is the Earthquake Input Energy (E_I) and associate parameters (the damping energy E_ξ and the plast ic hysteretic energy E_H) introduced by Uang & Bertero (1990). This parameter considers the inelastic behavior of a str uctural system and depends on the dynamic features o f both the strong m otion and the structure.

The formulation of the energy parameters derives from the following balance energy equation (Uang & Bertero, 1990):

$$E_I = E_k + E_\xi + E_s + E_H$$

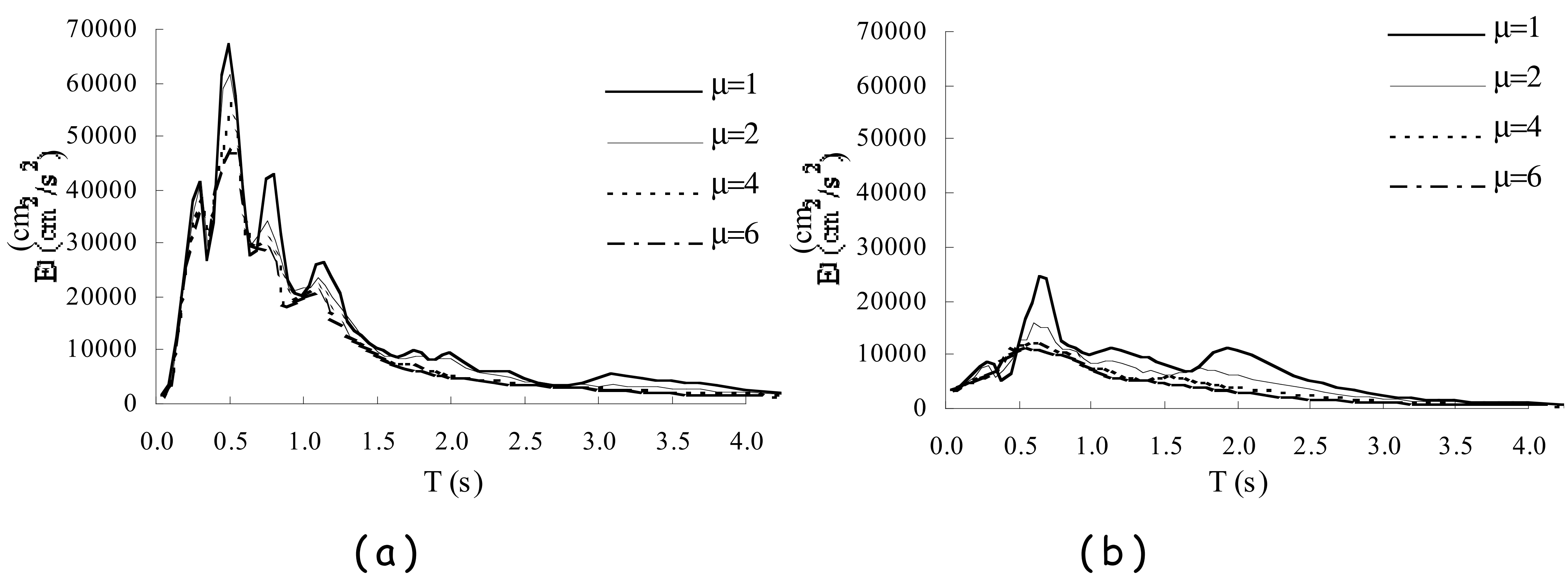
where (E_I) is the input energy, (E_k) is the kinetic energy, (E_ξ) is the damping energy, (E_s) is the elastic strain energy, and (E_H) is the hysteretic energy.

Yielding resistance

E_I represents the work done by the total base shear at the foundation displacement. The input energy can be expressed by:

$$\frac{E_I}{m} = \int \ddot{u}_t du_g = \int \ddot{u}_t \dot{u}_g dt$$

where m is the mass, $u_t = u + u_g$ is the absolute displacement of the mass, and u_g is the earthquake ground displacement. Usually the input energy per unit mass, i.e. E_I/m, is simply denoted as E_I.



Comparison between constant ductility input energy E_I spectra. (a) 1986 San Salvador earthquake (CIG record); 1985 Chile earthquake (Llolleo record)