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Some Problems in SHA for Performance-based EE

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7th Workshop on Three-Dimensional Modelling of Seismic Waves Generation, Propagation and their Inversion
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Some problems in SHA for Performance-based EE

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SH assessment

	Deterministic ⟷			Probabilistic
Risk mitigation decision	Emergency response			Design/Retrofit
Seismic environment	Next to active fault	High hazard, plate margin	Moderate hazard, anywhere	Low hazard, midplate
Scope of the project	Regional risk		Multiple properties lifelines	Specific site
	Qualitative			**Quantitative**

Modified from: **Mc Guire, 2001**

Traditional DASH

The practice focused on the“maximum” magnitude each fault could produce, its closest distance to the site, and then predicted PGA for these events

In this way, PGA became the primary scalar measure of ground motion intensity for use in structural analysis and design schemes

Typically PGA was used to scale a standard response spectral shape or recorded accelerograms

DSHA vs. PSHA

In practice, the estimated “maximum” magnitude values used with DSHA were softened often by adjectives such as “probable”, “credible”, or “design”

Using an elementary probabilistic analysis an estimate of the “hazard” was defined as the mean annual rate exceedance of the intensity for any specified ground motion

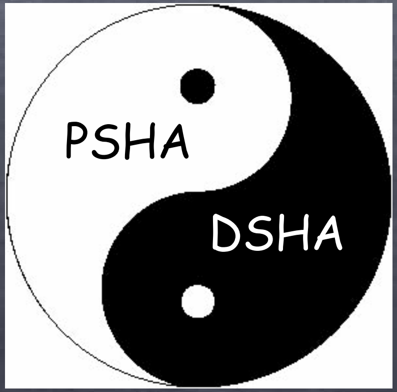
For each fault, the hazard was derived from a convolution of the mean annual rate of earthquakes with the probability that the ground motion level will be exceeded given that event

PBEE

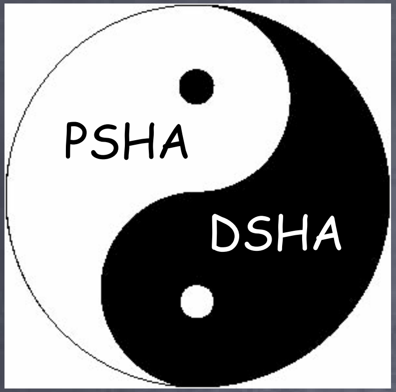
PSHA produces response spectral ordinates (or other intensity measures) for each of the annual probabilities that are specified for performance-based design.

In PBEE, the ground motions may need to be specified not only as intensity measures such as response spectra, but also by suites of strong motion time histories for input into time-domain nonlinear analyses of structures.

It is necessary to use a suite of time histories having phasing and spectral shapes that are appropriate for the characteristics of the earthquake source, wave propagation path, and site conditions that control the design spectrum.



Estimation of Ground Motion

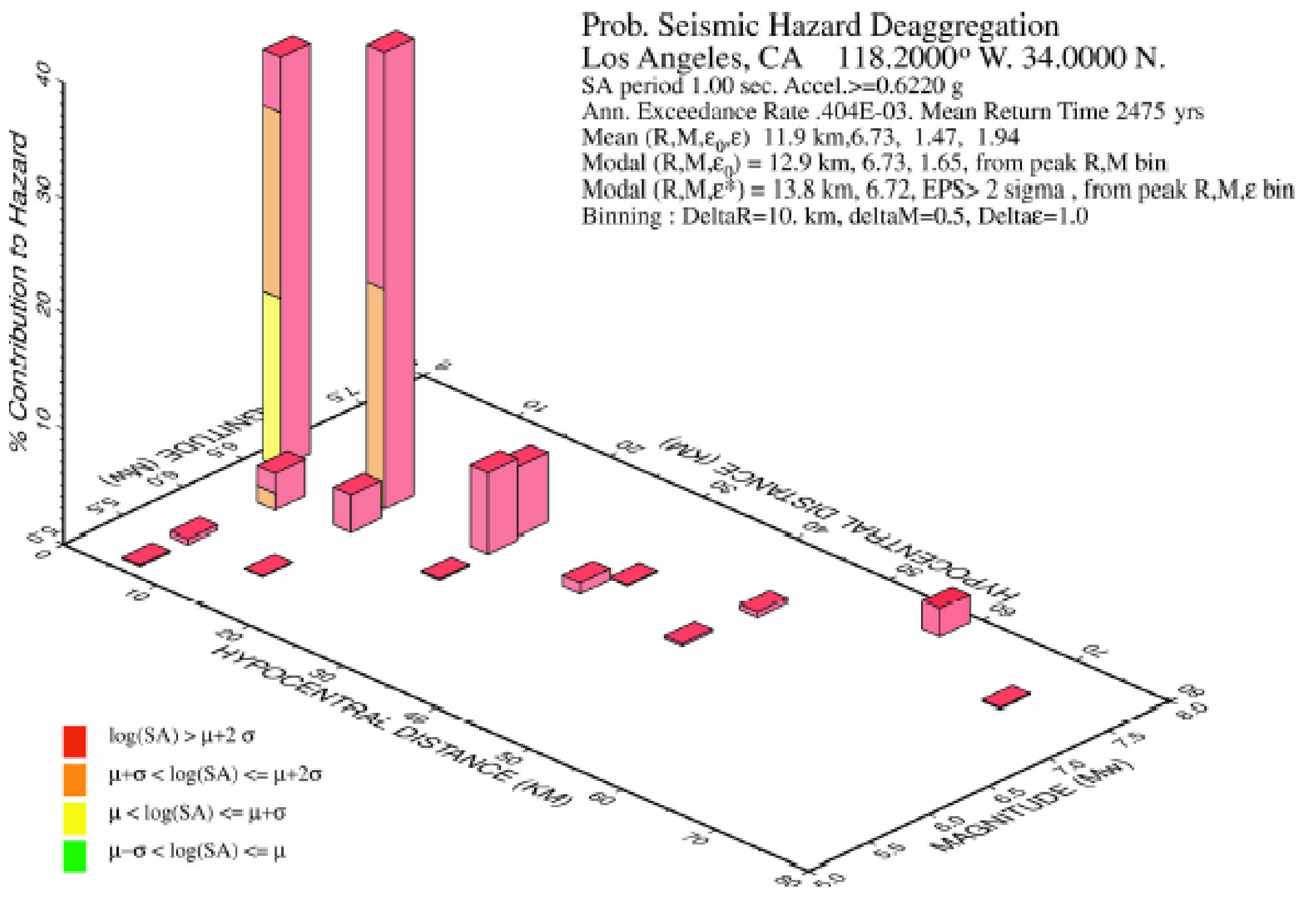


PSHA	Waveform modelling
Accounts for all potentially damaging earthquakes in a region	Focus on selected controlling earthquakes
Single parameter	Complete time series
Deeply rooted in engineering practice (e.g. building codes)	Dynamic analyses of critical facilities

Disaggregation, recursive analysis → ← Study of attenuation relationships

In many applications a **recursive analysis**, where deterministic interpretations are triggered by probabilistic results and vice versa, will give the greatest insight and allow the most informed decisions to be made.

PEER Report



Parameters extraction

- Particularly, in the case of **forward rupture directivity** most of the energy arrives in a single large pulse of motion which may give rise to particularly severe ground motion at sites toward which the fracture propagation progresses.
  - it involves the transmission of large energy amounts to the structures in a very short time.
- These shaking descriptors, strictly linked with energy demands, are relevant (even more than acceleration), especially when dealing with seismic isolation and passive energy dissipation in buildings.

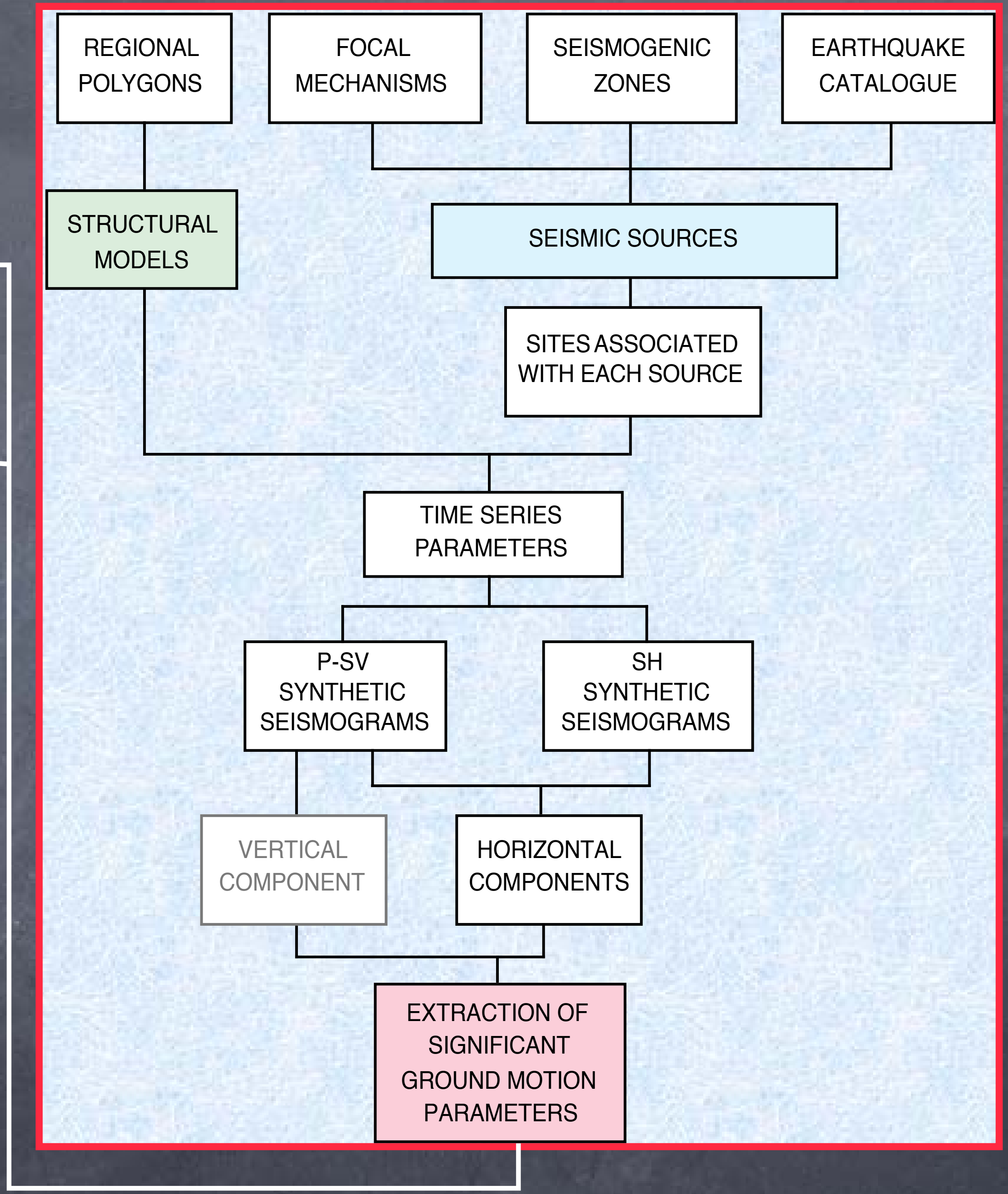
Modern DSHA

DSHA Maps
national, regional scale

Site-specific DSHA
urban-local scale

Site effects

Microzonation



REGIONAL POLYGONS

FOCAL MECHANISMS

SEISMOGENIC ZONES

EARTHQUAKE CATALOGUE

STRUCTURAL MODELS

SEISMIC SOURCES

SITES ASSOCIATED WITH EACH SOURCE

TIME SERIES PARAMETERS

P-SV SYNTHETIC SEISMOGRAMS

SH SYNTHETIC SEISMOGRAMS

VERTICAL COMPONENT

HORIZONTAL COMPONENTS

EXTRACTION OF SIGNIFICANT GROUND MOTION PARAMETERS

Surface topography effects (convexity)

sensitivity to:

a) type of wavefield
b) angle of incidence
c) shape and sharpness

SITE EFFECTS

Soft surface layering

a) 1-D: trapping of waves for impedance contrast
  (vertical resonances)
  $f_n=(2n+1)\rho/4H$
  $A \approx (\rho_2 v_2)/(\rho_1 v_1)$
b) 2-D 3-D: complex energy focusing
  for diffraction effects
  (basin edge waves)

Empirical techniques for Site effect estimation

Weak (and strong) motion

a) S/B spectral ratio
(Borcherdt, 1970)

b) generalized inversion scheme
(Andrews, 1986)

c) coda waves analysis
(Margheriti et al., 1994)

d) parametrized source and path inversion
(Boatwright et al., 1991)

e) H/V spectral ratio (receiver function)
(Lermo et al., 1993)

$$R_{ij}(\cdot\ ) = So_i(\cdot\ )\cdot P_{ij}(\cdot\ )\cdot S_j(\cdot\ )$$

Microtremors

a) peak frequencies examination

b) S/B spectral ratio

c) H/V spectral ratio
(Nagoshi, 1971; Nakamura, 1989)

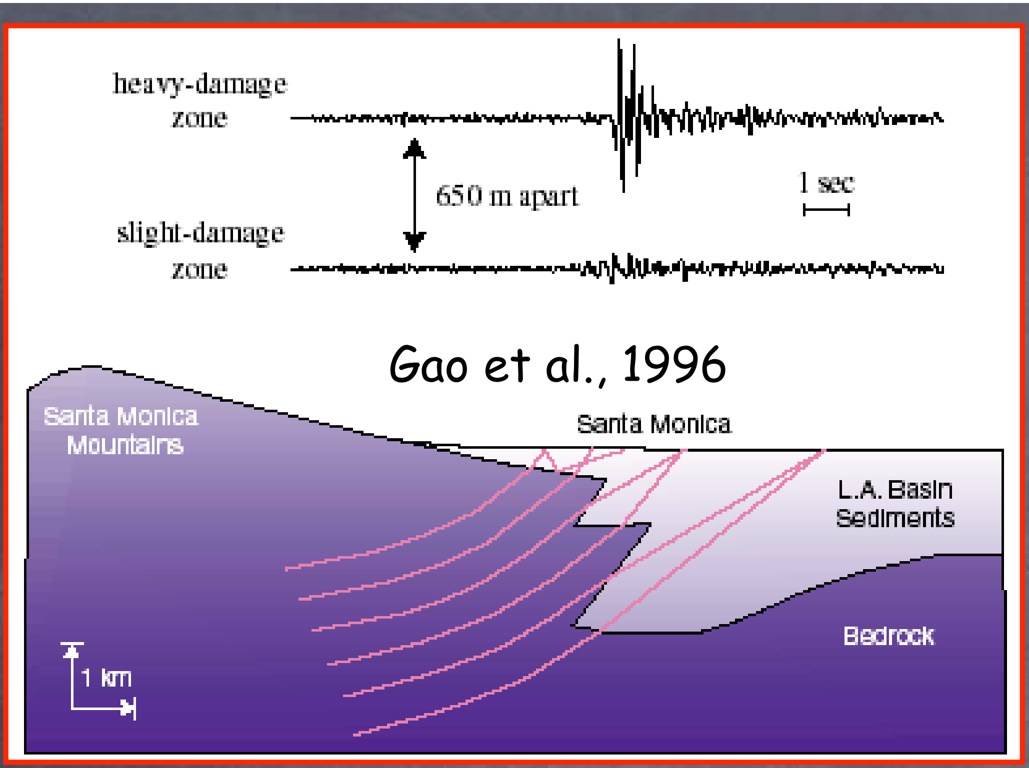
d) array analysis
(Malagnini et al., 1993)

Important issues in SRE

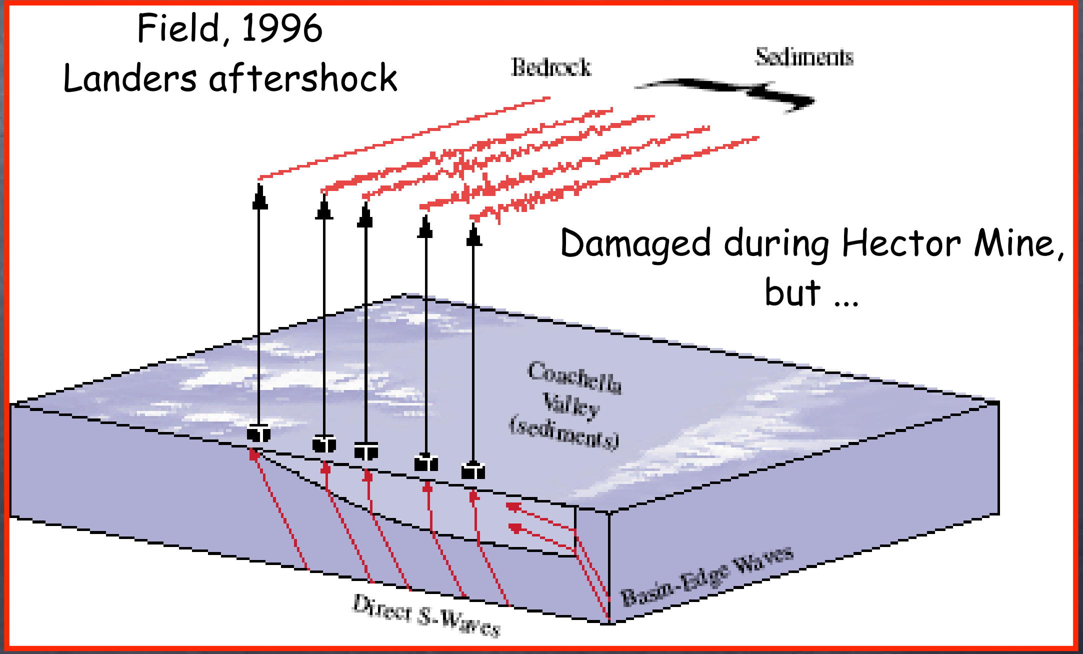
Modified from: Field et al., 2000

- **Near surface effects**: impedance contrast, velocity
  - geological maps, v_{30}, $v_{1/4}$, ??
- **Basin effects**
  - Basin-edge induced waves
  - Subsurface focusing

The convolutional model is ultimately artificial
(e.g. fault rupturing along the edge of a deep basin)



Gao et al., 1996



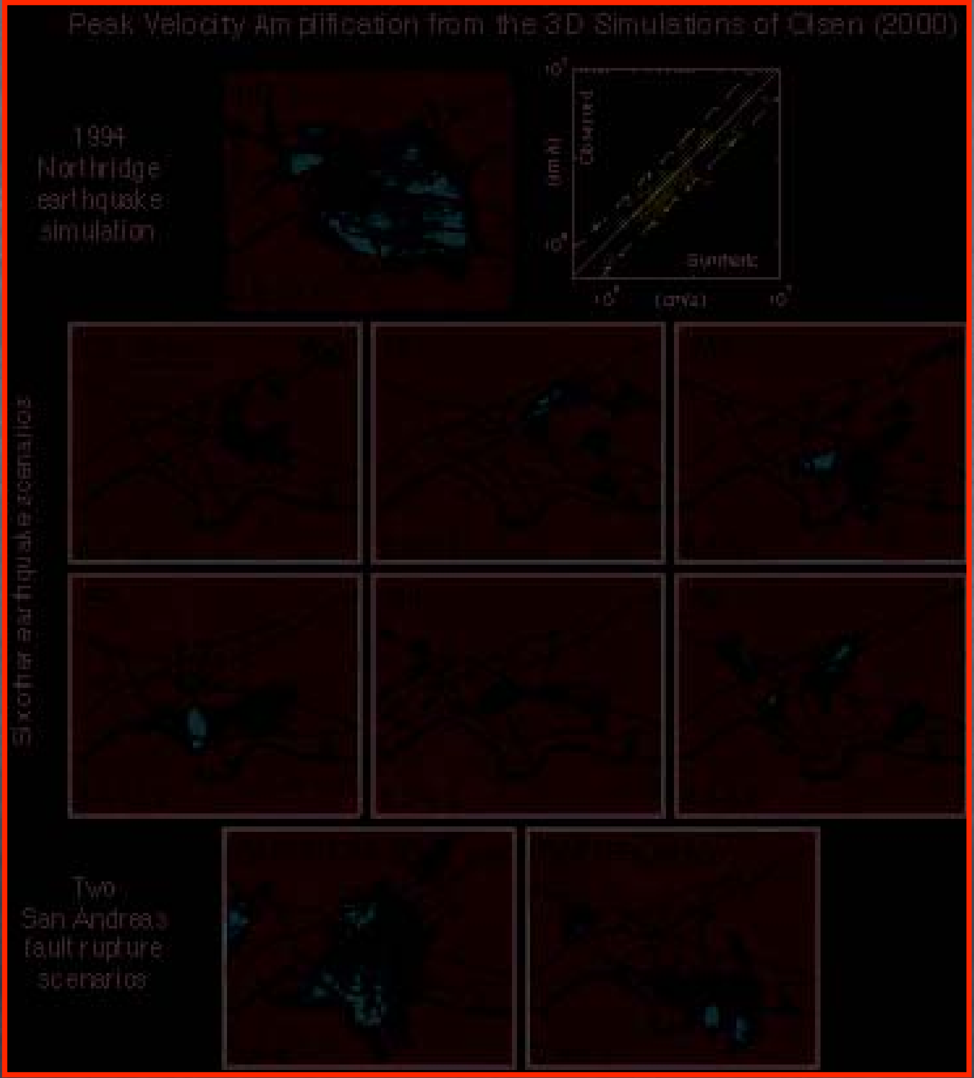
Field, 1996
Landers aftershock

Damaged during Hector Mine, but ...

Problems in SHA-Site effects

SRE and SHA

Amplification patterns may vary greatly among the earthquake scenarios, considering different **source locations** (and rupture ?)



SRE and PSHA

- In PSHA the site effect should be defined as the **average behavior**, relative to other sites, given **all** potentially damaging earthquakes
- This produces an intrinsic variability with respect to different earthquake locations, that cannot exceed the difference between sites
- Site characterization:
  - which velocity?
  - use of basin depth effect? Is it a proxy for backazimuth distance?
  - how to reduce aleatoric uncertainty?

Seismic Input

A proper definition of the seismic input at a given site can be done following two main approaches:

The first approach is based on the analysis of the available **strong motion databases**, collected by existing seismic networks, and on the grouping of those accelerograms that contain similar source, path and site effects

The second approach is based on **modelling techniques**, developed from the knowledge of the seismic source process and of the propagation of seismic waves, that can realistically simulate the ground motion

Validation

- The ideal procedure is to follow the two complementary ways, in order to **validate** the numerical modelling with the available recordings.
- Validation and calibration should consider intensity measures (PGA, PGV, PGD, SA, etc.) as well as other characteristics (e.g. duration).
- The misfits can be due to variability in the physical (e.g. point-source) and/or the parameters models adopted.

Prediction

- The result of a simulation procedure should be a set of intensity estimates, as the result of a parametric study for different "events" and/or for different model parameters
- The modeling variability, estimated through validation, can be associated to "models" or "parameters"

Epistemic	Modeling (point source, 1D-2D-3D)	Parametric (incomplete data)
Aleatory	Modeling (scattering, rupture)	Parametric (rupture)

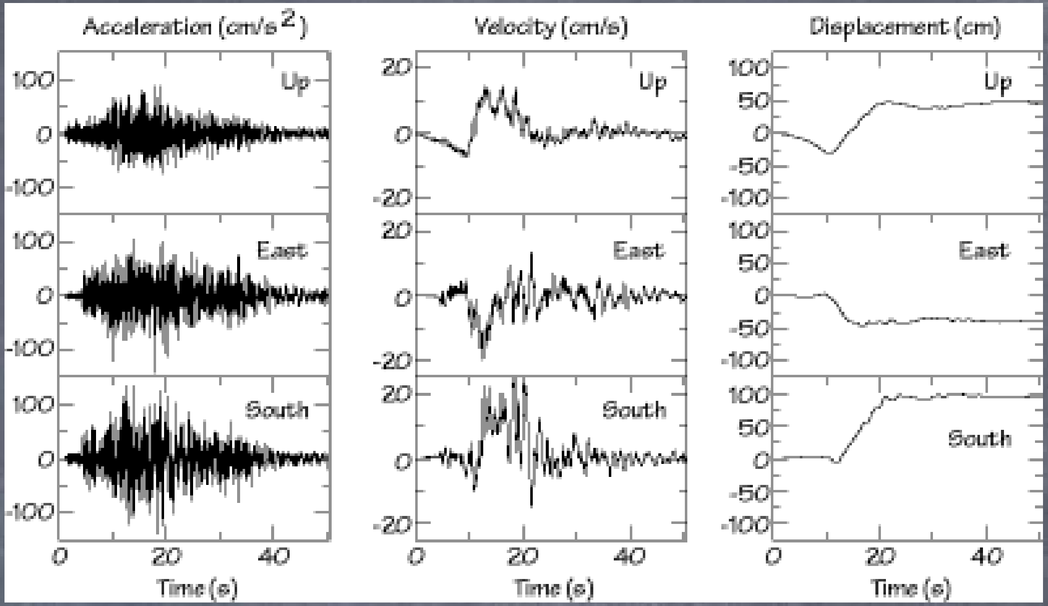
Time histories selection

- They are used to extract a measure, representing adequately:
  - Magnitude, distance
  - Source characteristics (fling, directivity)
  - Path effects (attenuation, regional heterogeneities)
  - Site effects (amplification, duration)

The scenarios have to be based on significant ground motion parameters (e.g. velocity and displacement).

Example of Recordings

Ground acceleration, velocity and displacement, recorded at a strong-motion seismometer that was located directly above the part of a fault that ruptured during the 1985 Mw = 8.1, Michoacan, Mexico earthquake.



Strong-motion instruments were designed to record the high accelerations that are particularly important for designing buildings and other structures. The left panel is a plot of the three components of acceleration: strong, high-frequency shaking lasted almost a minute and the peak acceleration was about 150 cm/s^2 (or about 0.15g). The middle panel shows the velocity of ground movement: the peak velocity for this site during that earthquake was about 20-25 cm/sec. Integrating the velocity, we can compute the displacement, which is shown in the right-most panel: the permanent offsets near the seismometer were up, west, and south, for a total distance of about 125 centimeters.

Strong-motion seismology

Concerned with the measurement, interpretation and estimation of **strong shaking** generated by **potentially** damaging earthquakes.

Principal goal: improve the scientific understanding of the **physical processes** that control strong shaking and to develop reliable estimates of **seismic hazards**. Input for improving earthquake resistant design and retrofit.

But what **threshold**?? 10 or 100cms^{-2}???

Demand parameters

DAMAGE POTENTIAL OF EARTHQUAKE GROUND MOTION

A demand parameter is defined as a quantity that relates seismic input (ground motion) to structural response

Damage depends on intensity of the various earthquake hazard parameters: ground motion accelerations levels, frequency content of the waves arriving at the site, duration of strong ground motion, etc.

Damage also depends on the earthquake resistance characteristics of the structure, such as its lateral force-resisting system, dynamic properties, dissipation capacity, etc.

PGA…

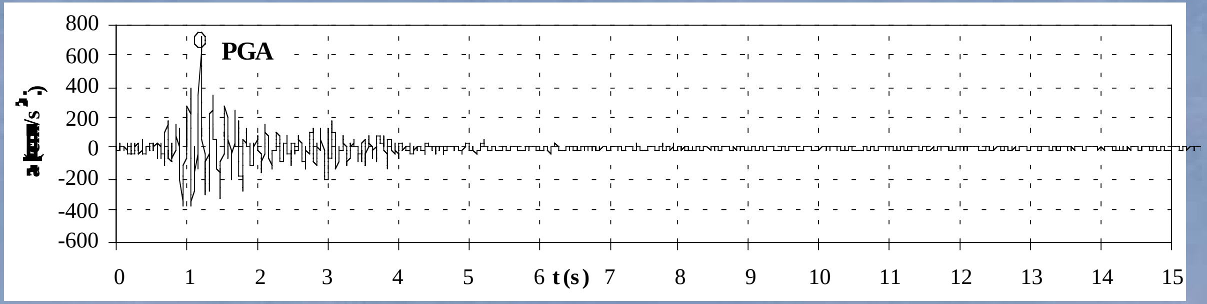


Figure 1 – Acceleration time history. Rocca NS record. 1971 Ancona earthquake (M_L=4.7)

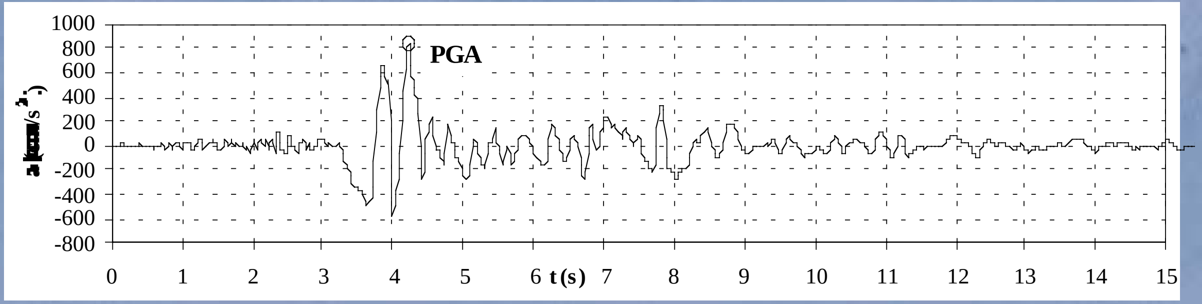


Figure 2 – Acceleration time history. Sylmar N360 record. 1994 Northridge earthquake (M_w=6.7)

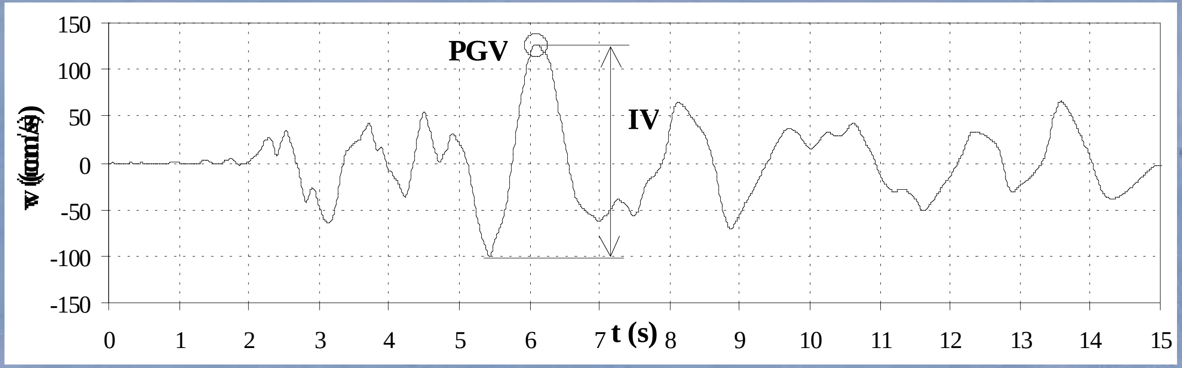


Figure 3 – Velocity time history. Takatori 000 record. 1995 Kobe earthquake (M_w=6.9)

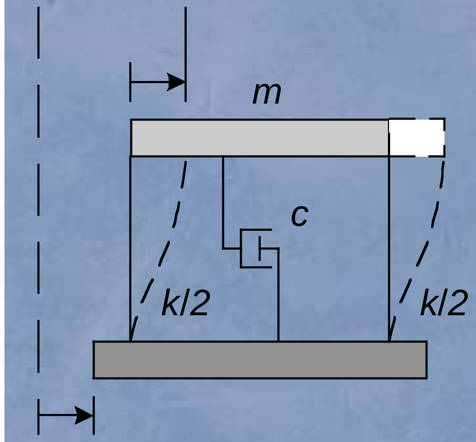
Response spectra

SDF SYSTEMS

A SDF system is subjected to a ground motion $u_g(t)$. The deformation response $u(t)$ is to be calculated.

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

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



The ground acceleration can be registered using accelerographs:

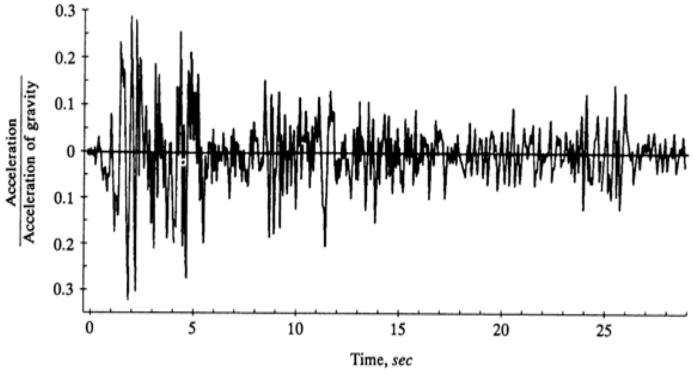
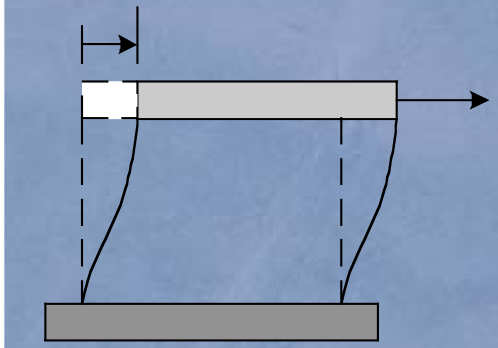


FIGURE 24-15
Accelerogram from El Centro earthquake, May 18, 1940 (*NS* component).

EQUIVALENT STATIC FORCE



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

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

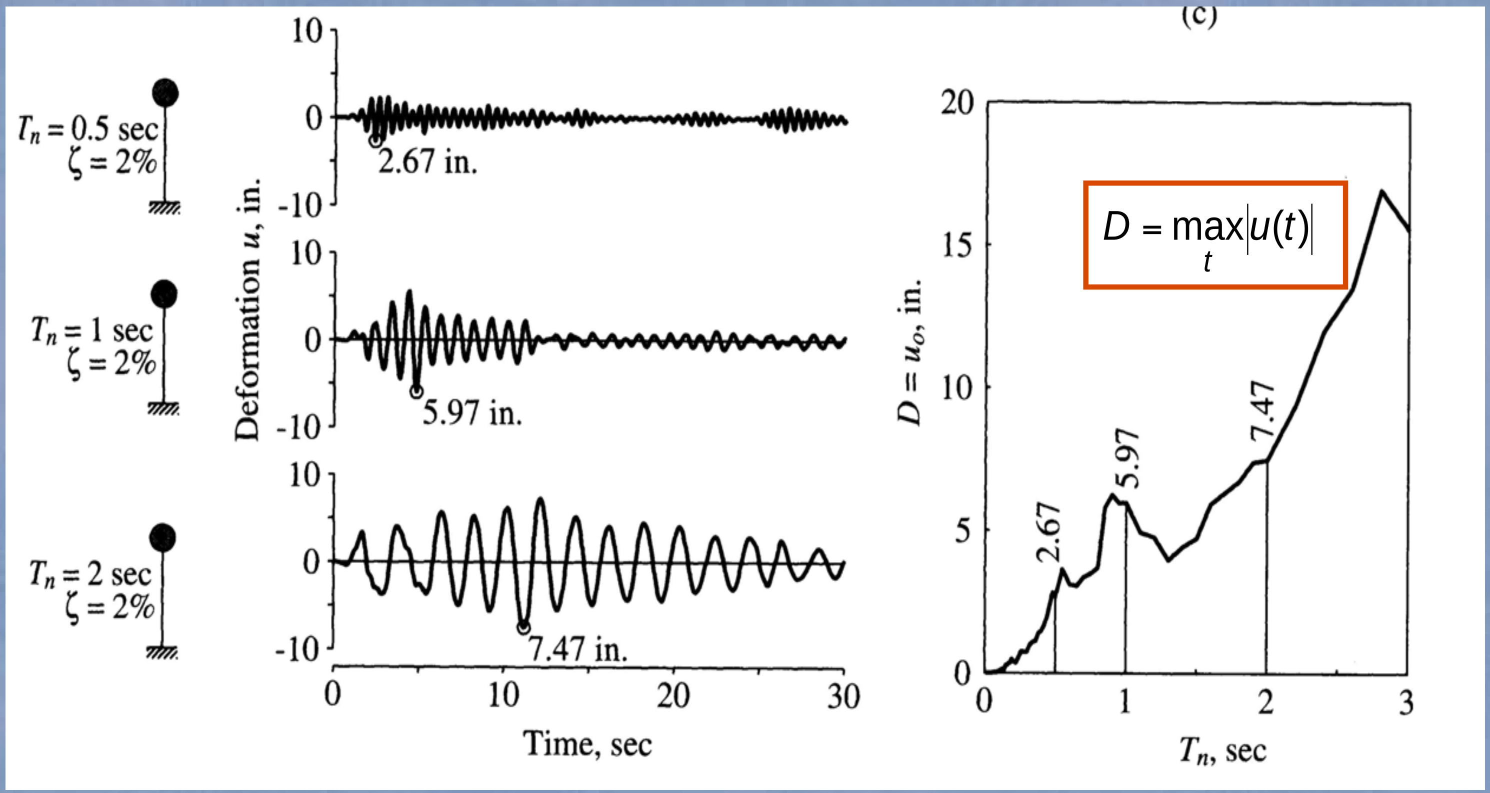
Pseudo acceleration

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

REPONSE 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 , ≤).

Example : Deformation response spectrum for El Centro earthquake



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

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

Peak Deformation $D = \max|u(t)|$

Peak Pseudo– velocity $V = -_{n} D$

Peak Pseudo– acceleration $A = -_{n}^{2} D$

≤$_n$: natural circular frequency of the SDF system.

COMBINED D-V-A SPECTRUM

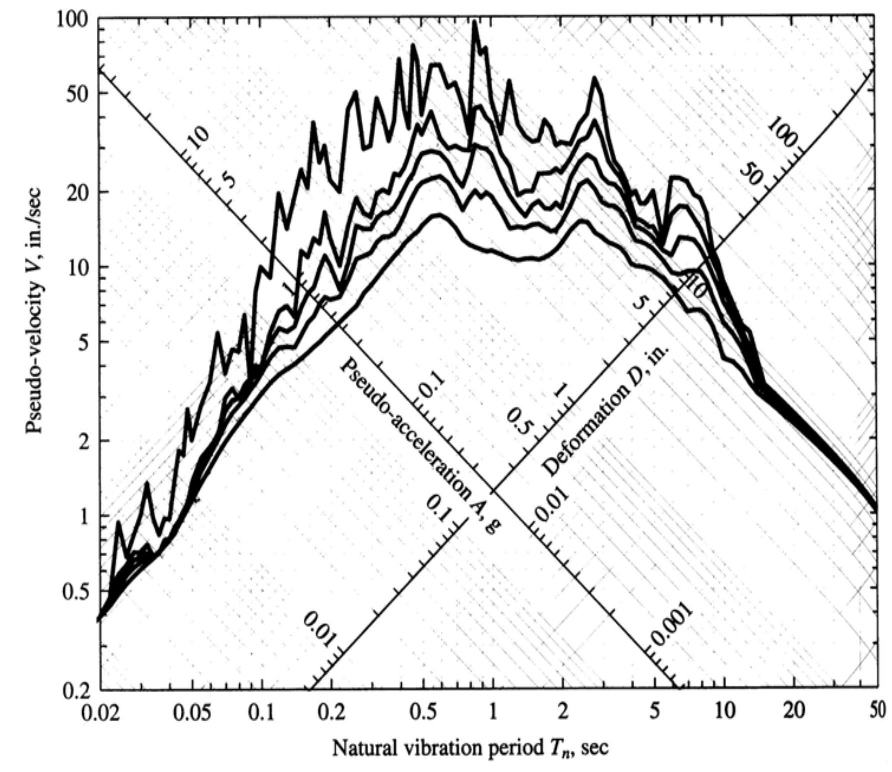
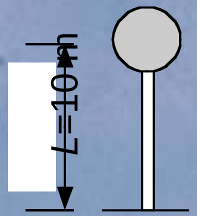


Figure 6.6.4 Combined D–V–A response spectrum for El Centro ground motion; ζ = 0, 2, 5, 10, and 20%.

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

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

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

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

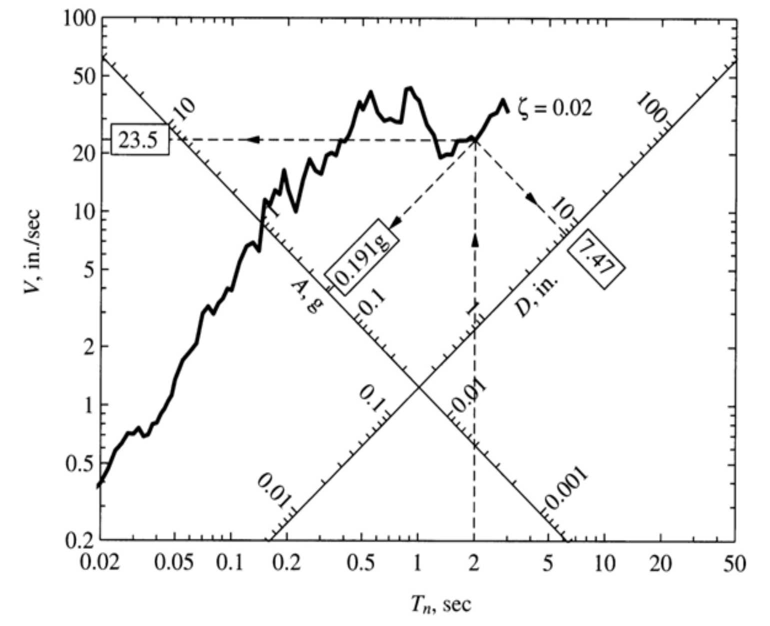


Figure 6.6.3 Combined *D–V–A* response spectrum for El Centro ground motion; $\zeta = 2\%$.

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

Parameters extraction

RESPONSE SPECTRUM CHARACTERISTICS

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

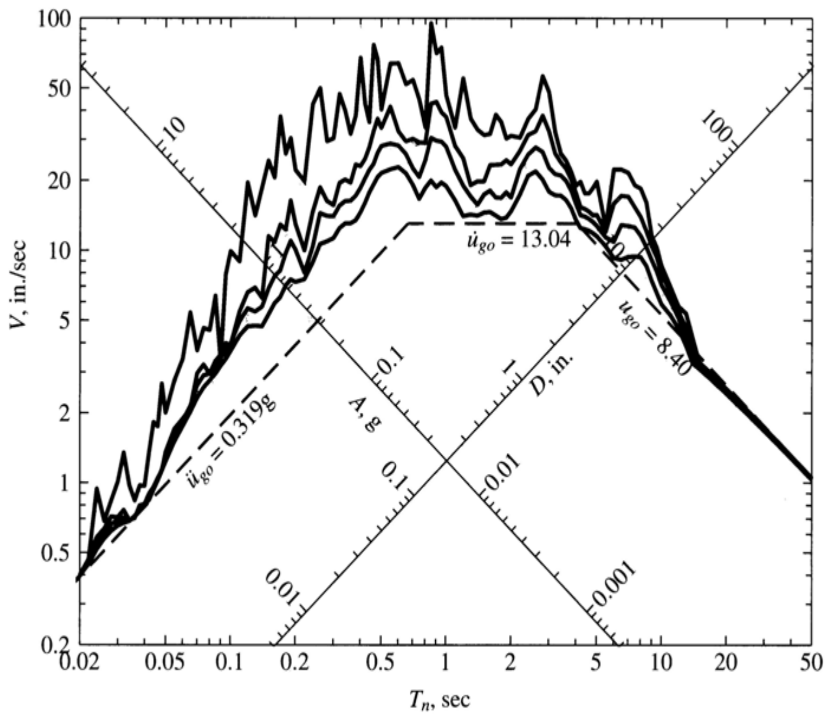


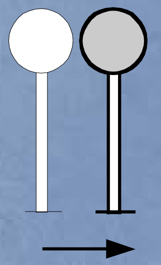
Figure 6.8.1 Response spectrum ($\zeta = 0, 2, 5,$ and 10%) and peak values of ground acceleration, ground velocity, and ground displacement for El Centro ground motion.

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

T_n < 0.03 s : rigid system

no deformation

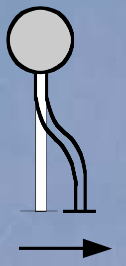
u(t) ≈ 0 ≤ D ≈ 0



T_n > 15 s : flexible system

no total displacement

u(t) = u_g(t) ≤ 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

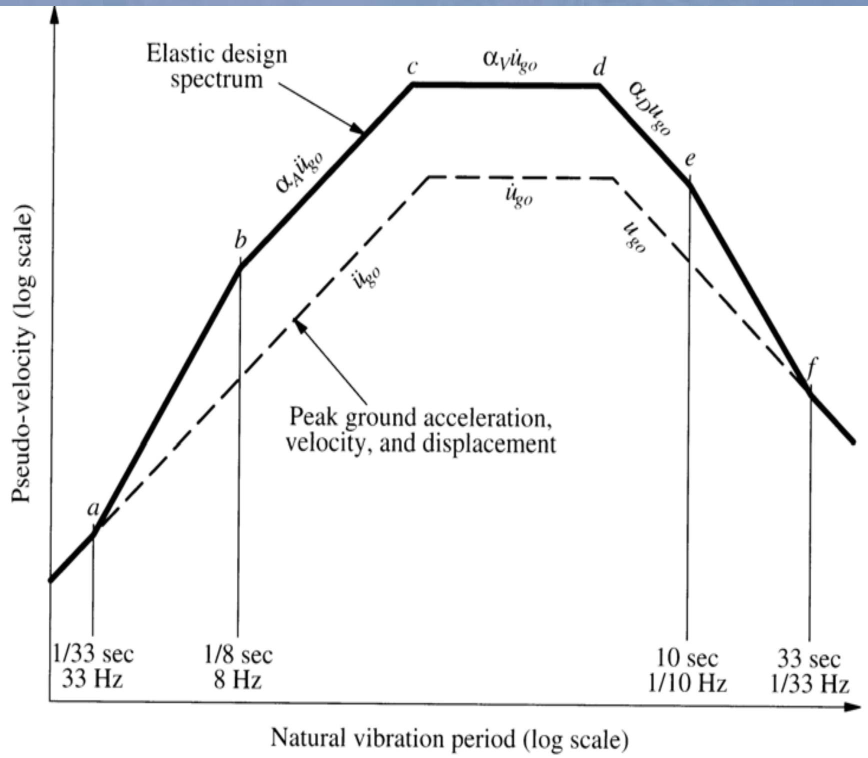


Figure 6.9.3 Construction of elastic design spectrum.

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:

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

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 frequency components, EPA will be obviously smaller than the real peak value.
It represents the acceleration which is most closely related to the structural response and to the damage potential of an earthquake. The EPA values for the two records of Ancona and Sylmar stations are 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:

$$I_H = \overset{2.5}{\underset{0.1}{\pi}} S_{pv}(T,\pi)dT = \frac{1}{2\pi} \overset{2.5}{\underset{0.1}{\pi}} S_{pa}(T,\pi)TdT$$

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.

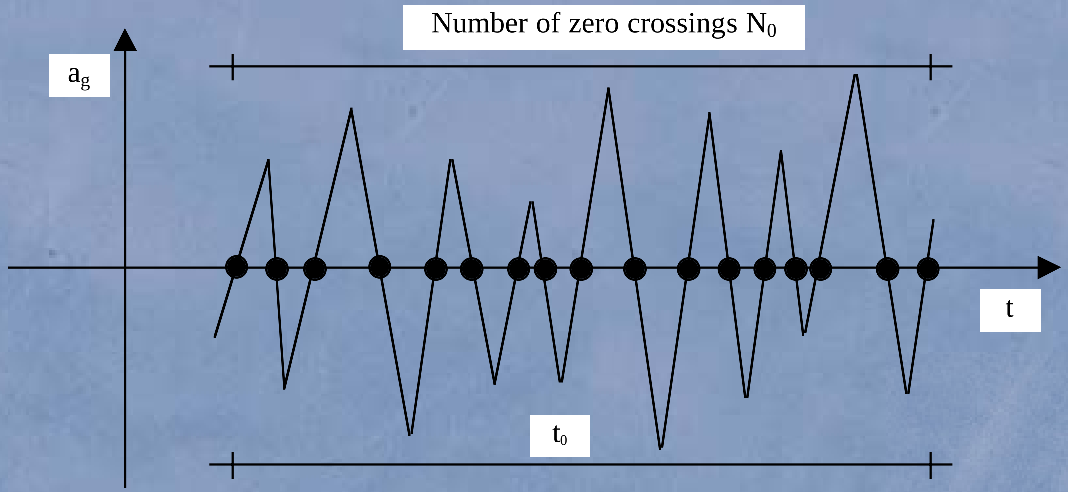
Housner's spectral intensity is the first moment of the area of S_{pa} ($0.1<T<2.5$) about the S_{pa} axis, implying that the Housner spectral intensity is larger for ground motions with a significant amount of low frequency content.
The I_H parameter captures important aspects of the amplitude and frequency 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.

Yelding 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:

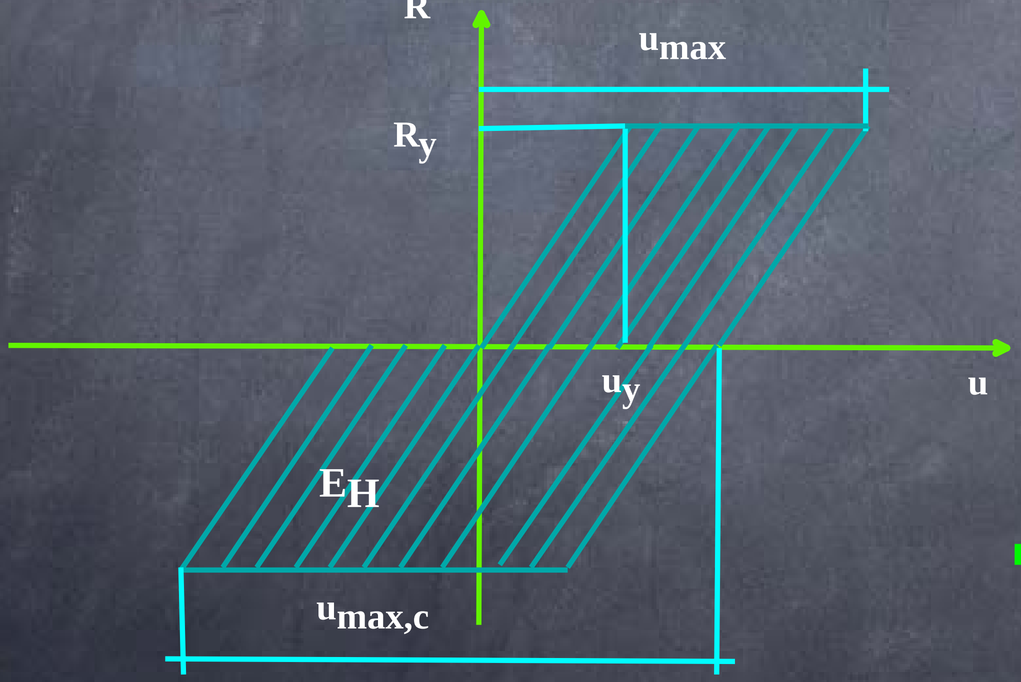
$$C_y = \frac{R_y}{mg} \quad \eta = \frac{R_y}{m\ddot{u}_{g(\max)}} = \frac{C_y}{\ddot{u}_{g(\max)}/g}$$

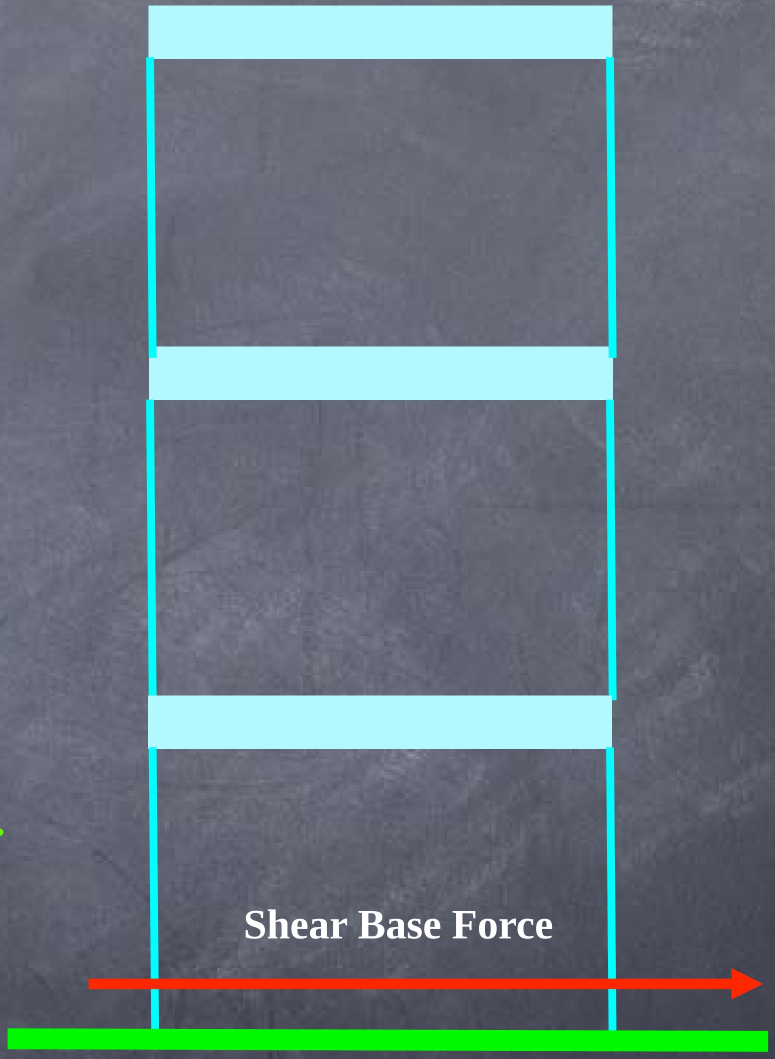
where R_y is the yielding resistance, m is the mass of the system, and $\ddot{u}_{g(\max)}$ is the maximum ground acceleration.

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

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

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



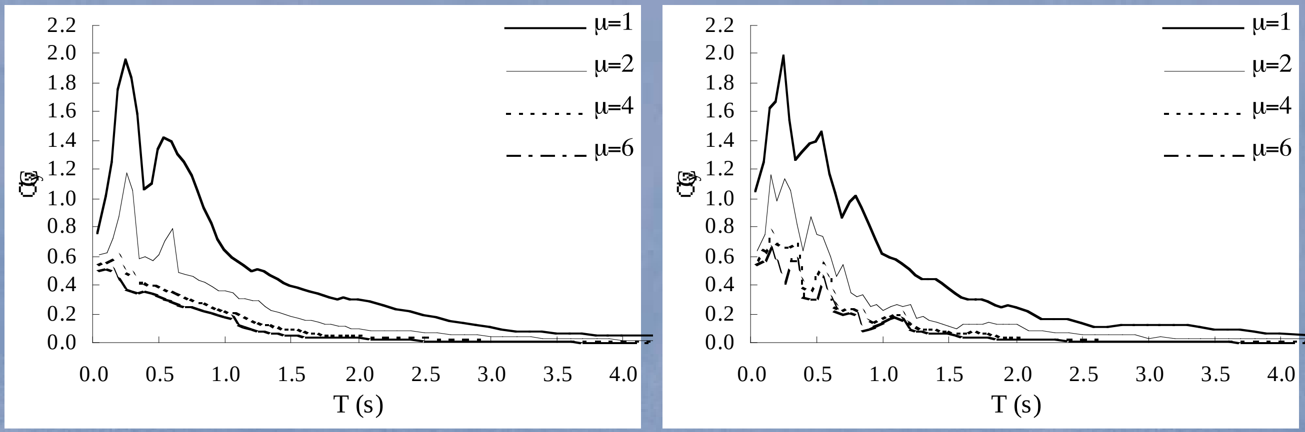


Parameters extraction

Yelding resistance 2

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 energy 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, periodic with long durations pulses, etc.) which may correspond to an earthquake, could provide more insight into the seismic performance.

The most promising is the Earthquake Input Energy (E_I) and associate parameters (the damping energy E_ξ and the plastic hysteretic energy E_H) introduced by Uang & Bertero (1990). This parameter considers the inelastic behavior of a structural system and depends on the dynamic features of both the strong motion and the structure.

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

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

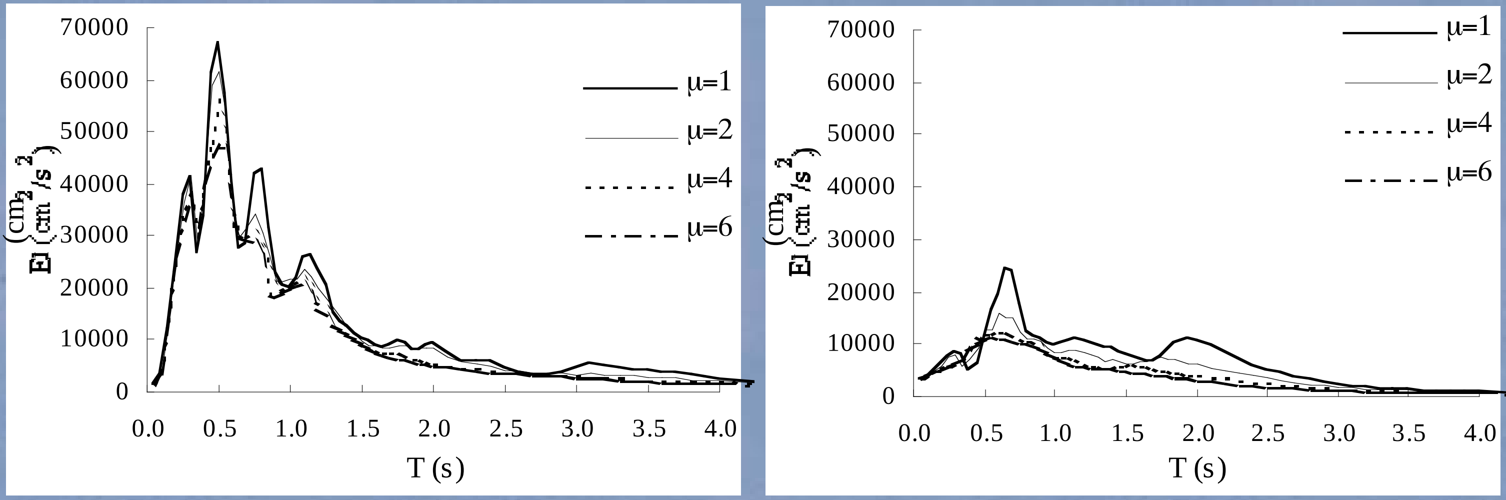
where (E_I) is the input energy, (E_k) is the kinetic energy, (E_ξ) is the damping energy, (E_s) is the elastic strain energy, and (E_H) is the hysteretic energy.

Input energy

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

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

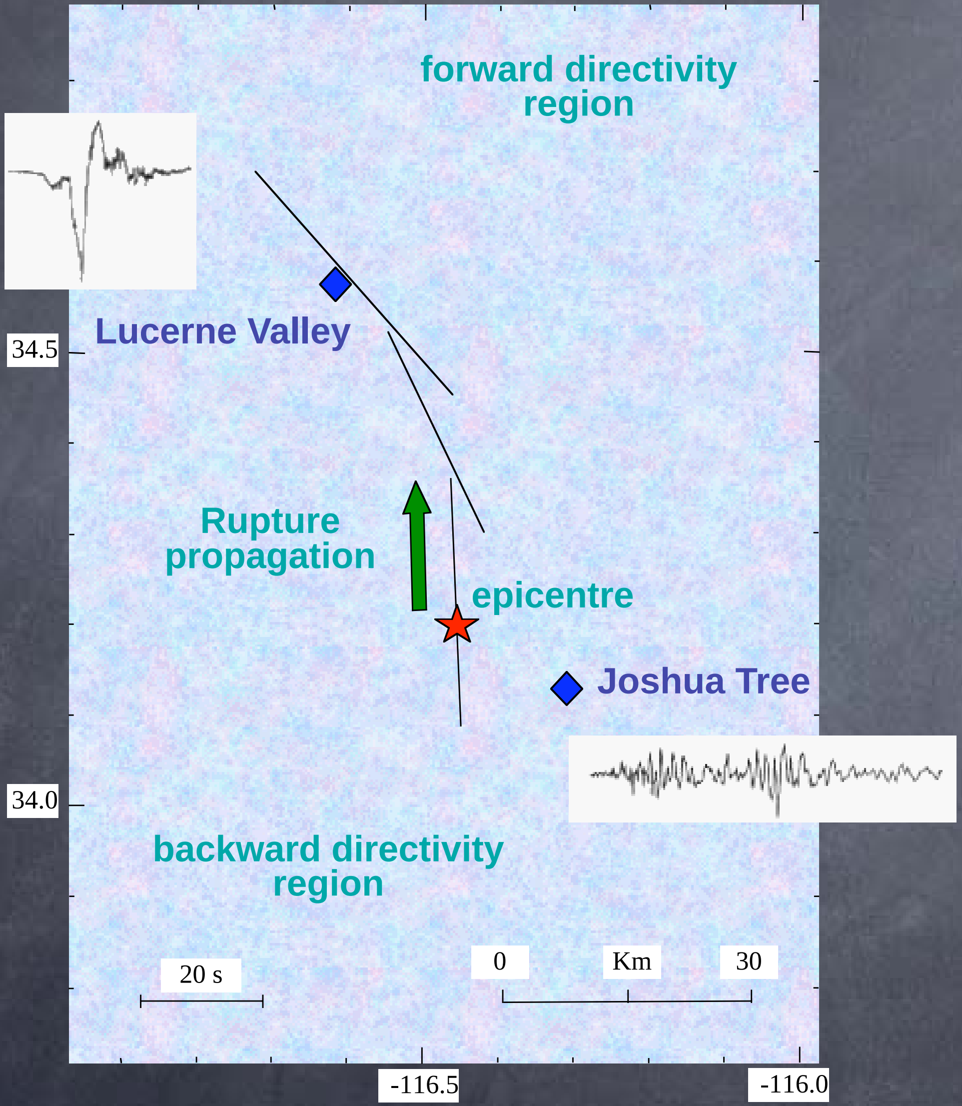
where m is the mass, $u_t = u + u_g$ is the absolute displacement of the mass, and u_g is the earthquake ground displacement. Usually the input energy per unit mass, i.e. E_I/m, is simply denoted as E_I.

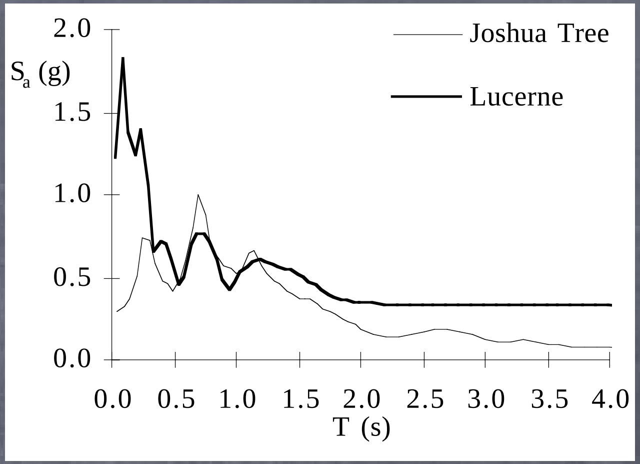


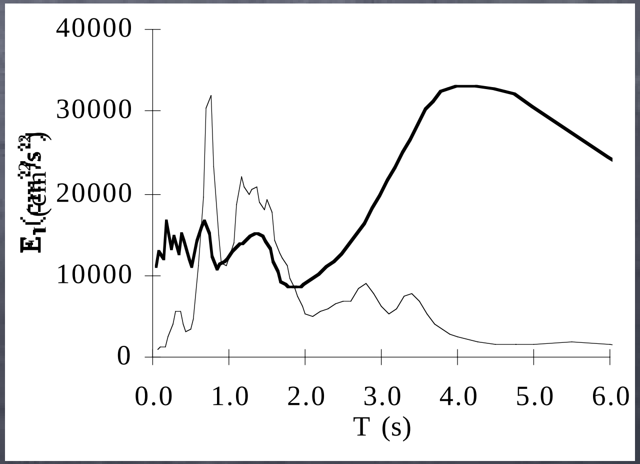
(a) (b)

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

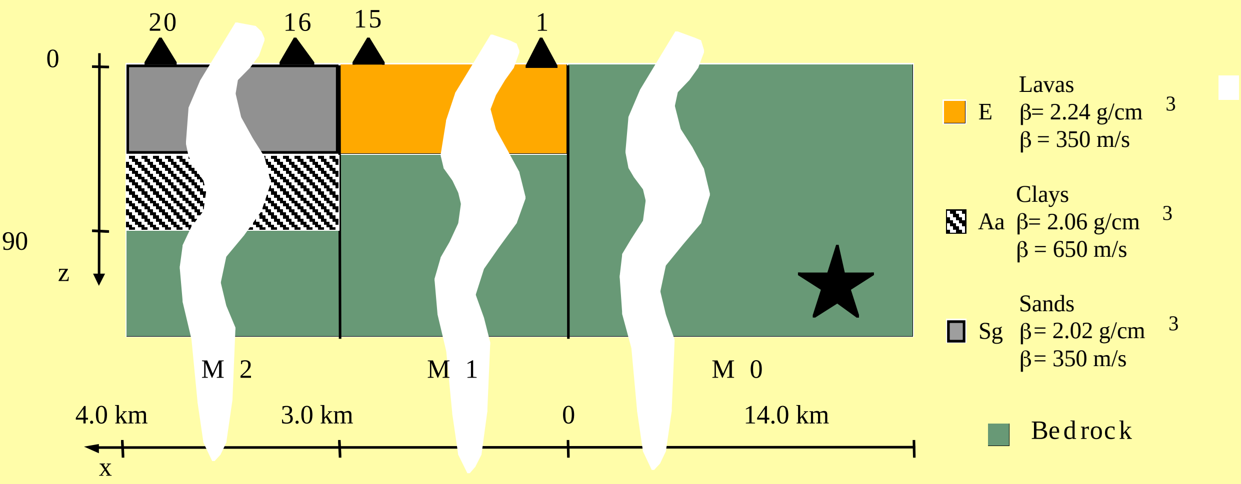
Landers, 1992

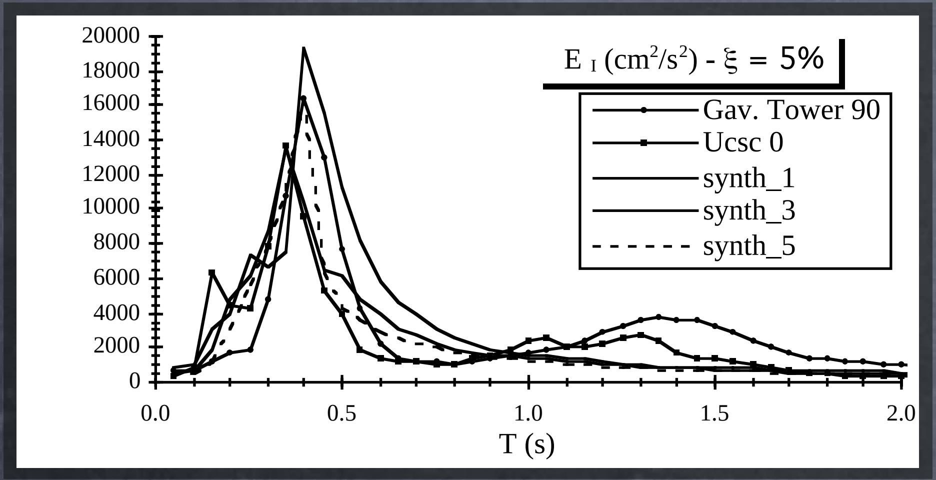


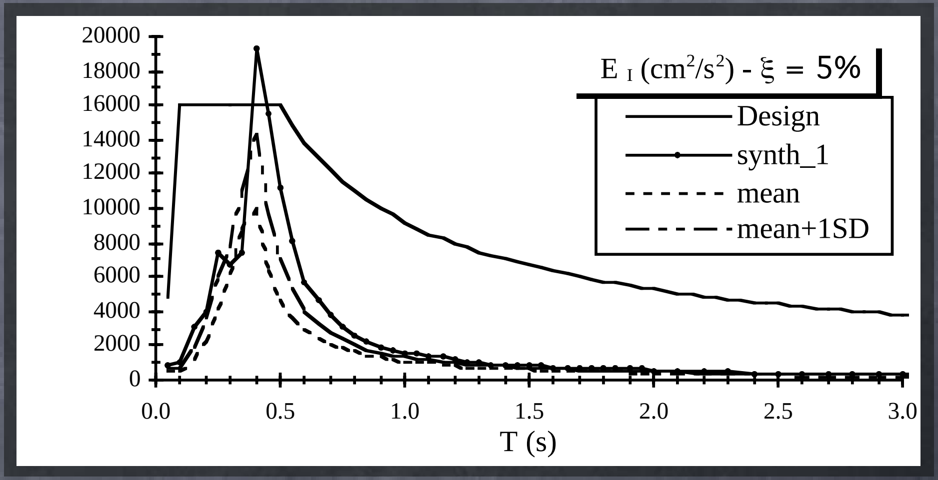




Damage potential evaluation of synthetic signals



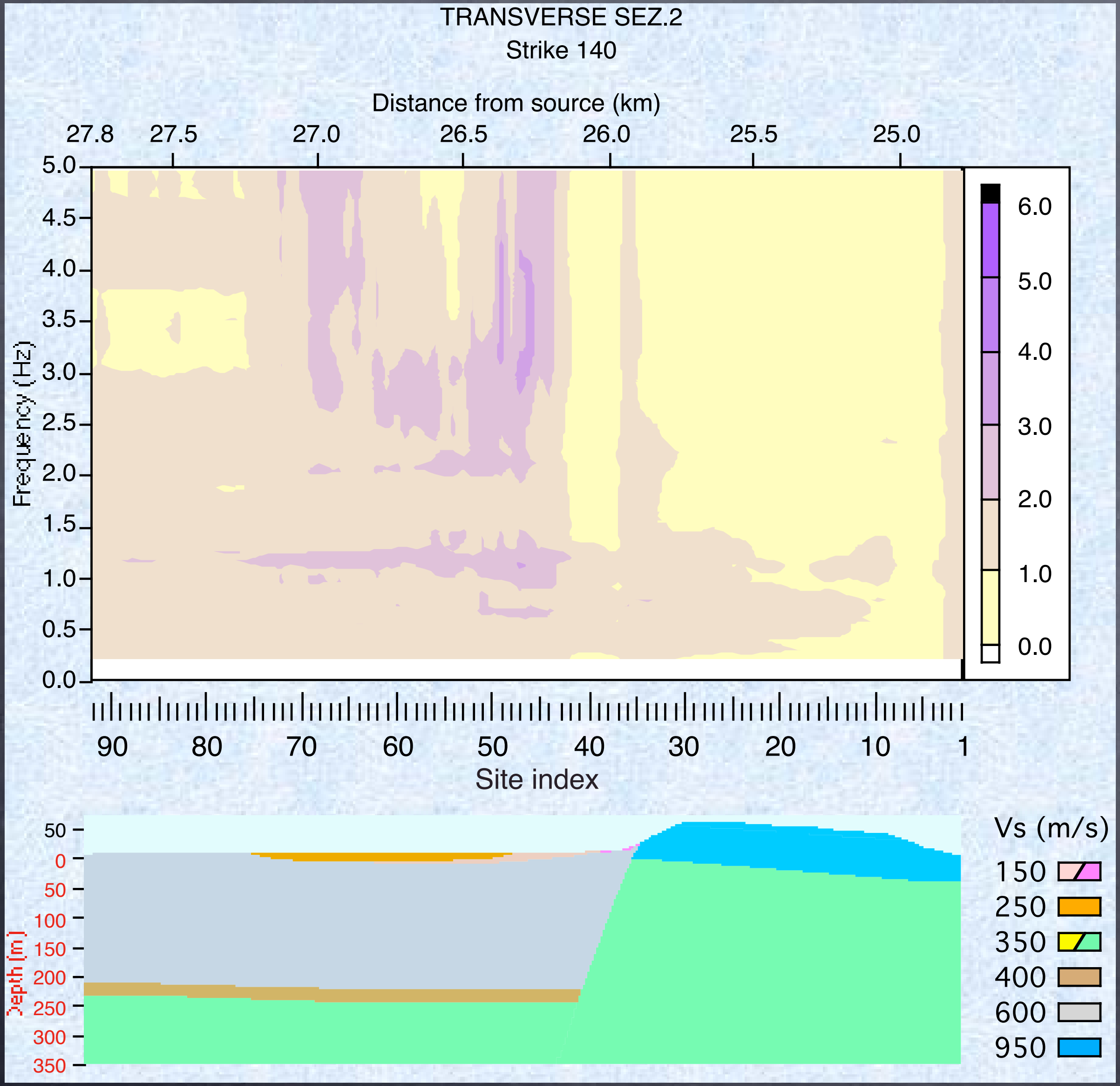




Elastic E_I (cm^2/s^2) spectra. Comparison between synthetic signals and strong motion records of Loma Prieta earthquake (1989), Soil S1.

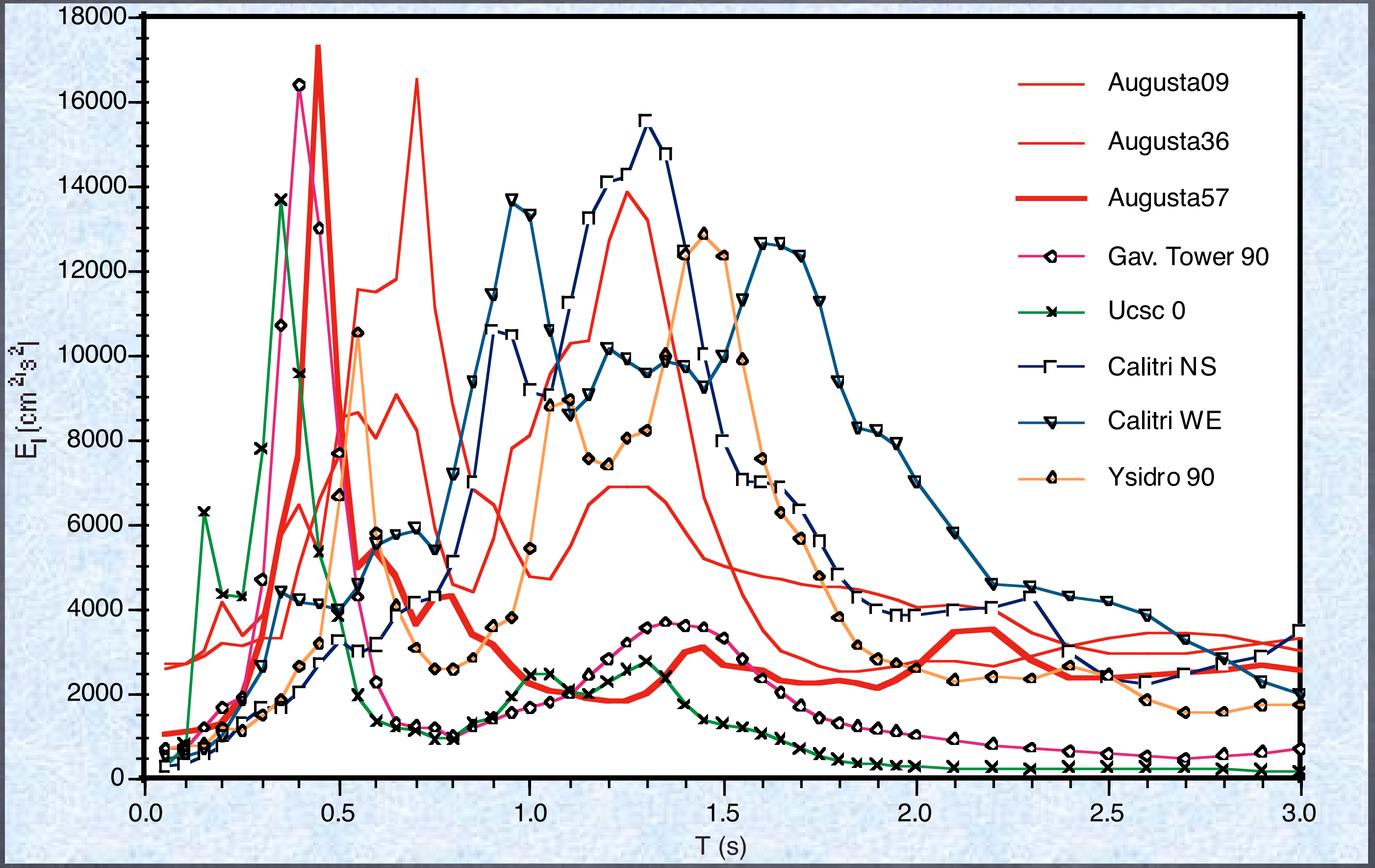
Elastic E_I (cm^2/s^2) spectra. Comparison between synthetic signals and design elastic input energy spectrum. Soil S1, $12 \leq D_f \leq 30$ km, $6.5 \leq M \leq 7.1$)

Site response estimation in Augusta - transverse



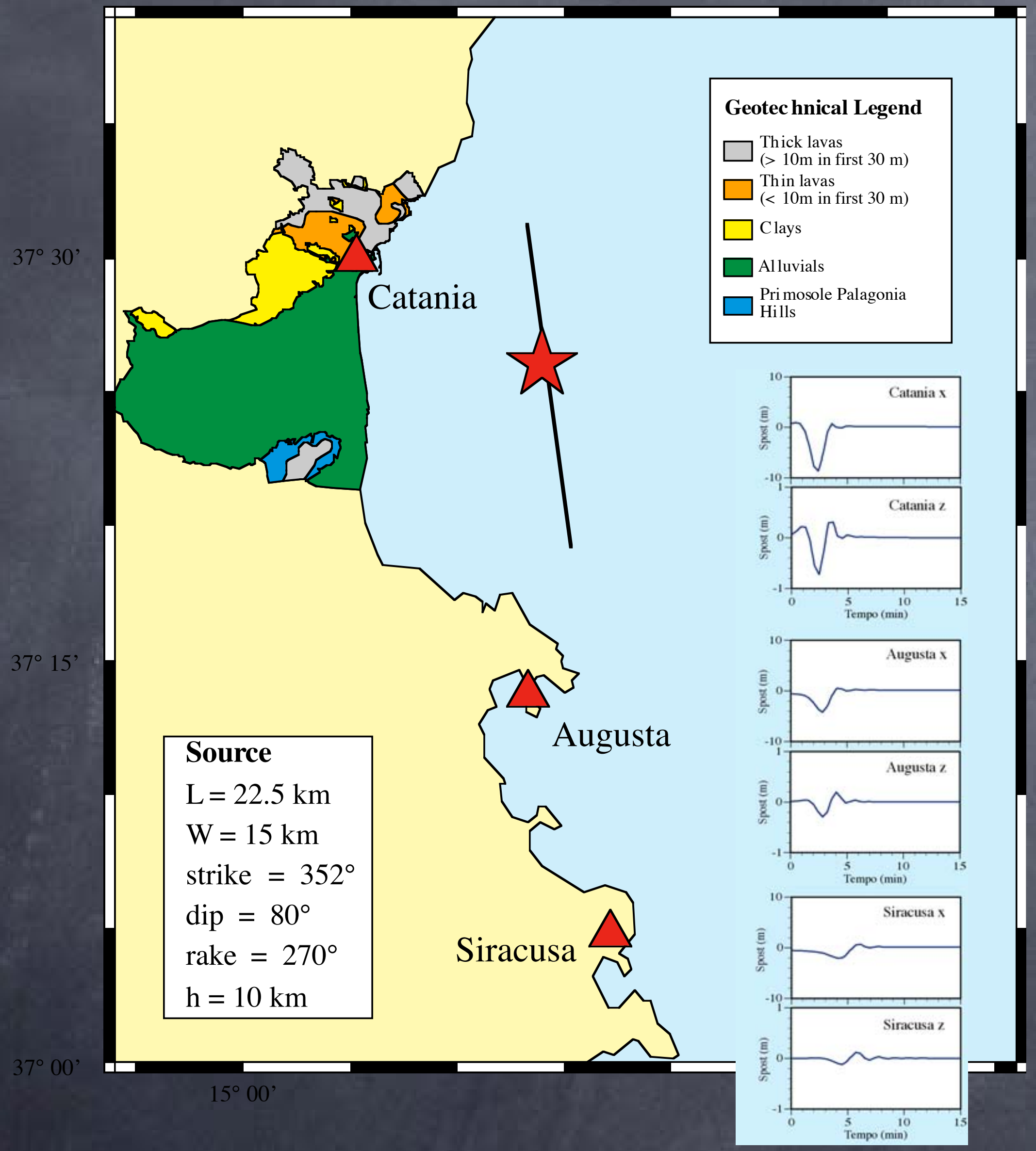
Damage potential evaluation of synthetic signals

Seismic Energy Input analysis



On the basis of the parameters characterizing the earthquake destructiveness power, e.g. Seismic Energy Input, of the available strong motion records, the results show that the synthetic signals provide an energy response which is typical of recorded accelerograms.

Eastern Sicily



Source

L = 22.5 km

W = 15 km

strike = 352°

dip = 80°

rake = 270°

h = 10 km

Catania Area

and the

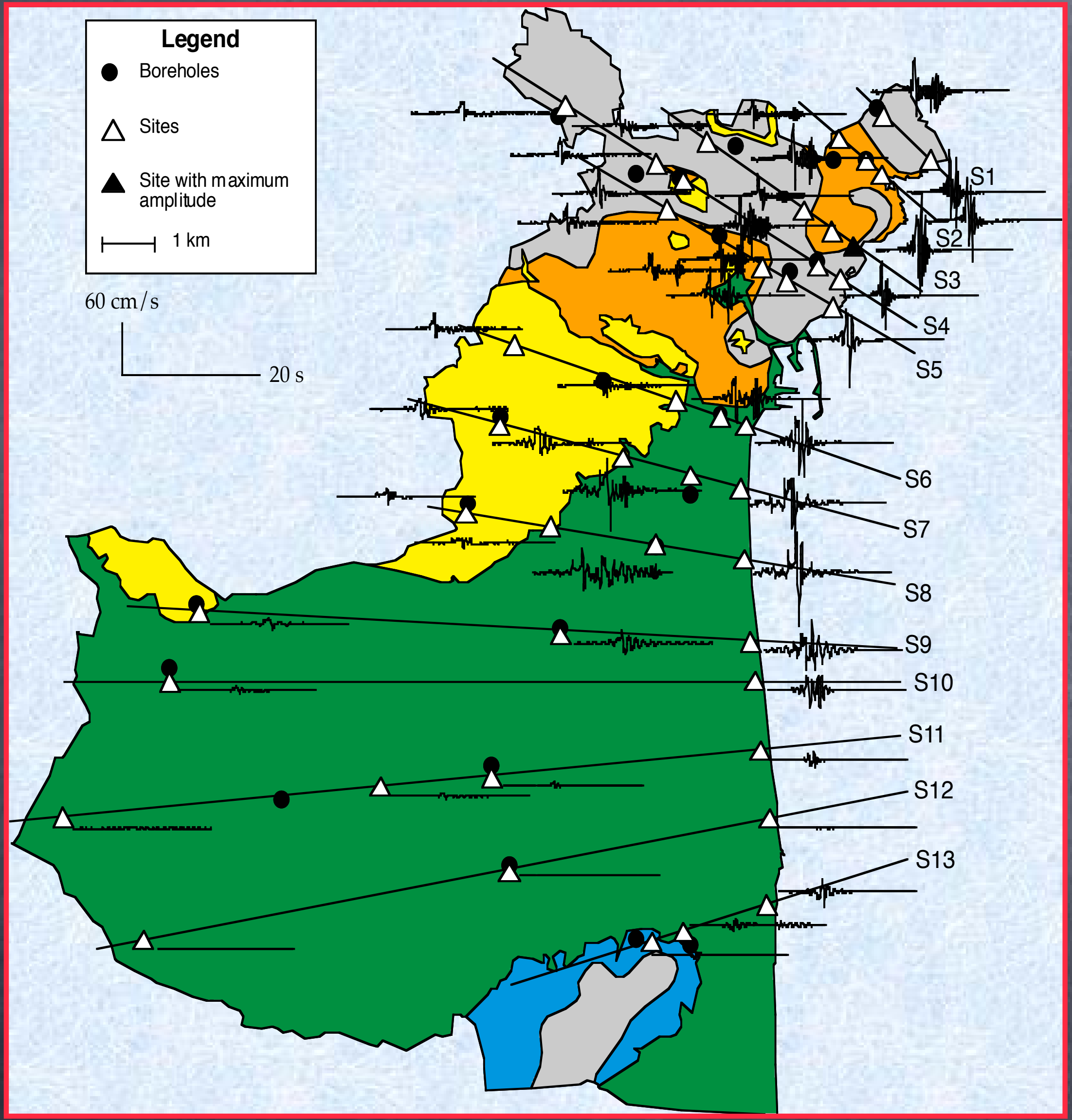
seismic source

considered for the

scenario earthquake

(Hyblean fault)

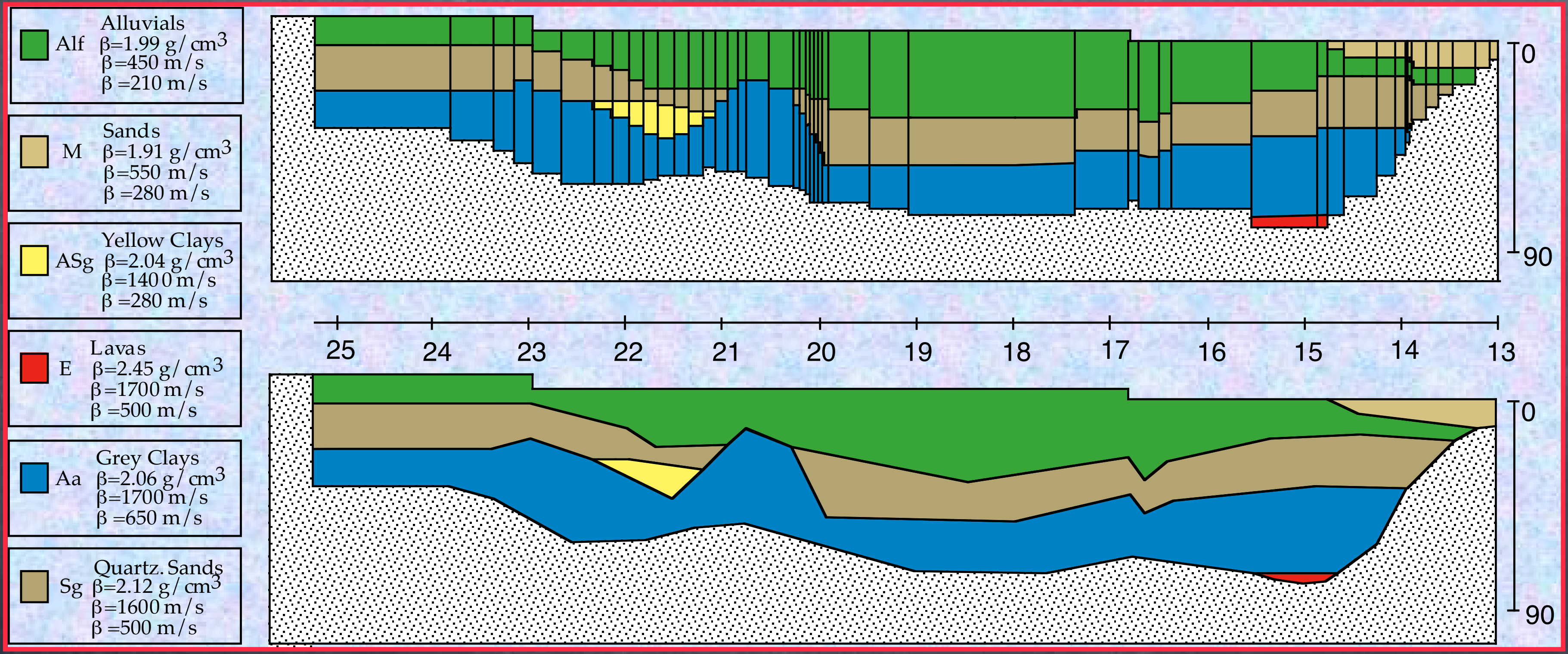
Synthetic time series (velocity)

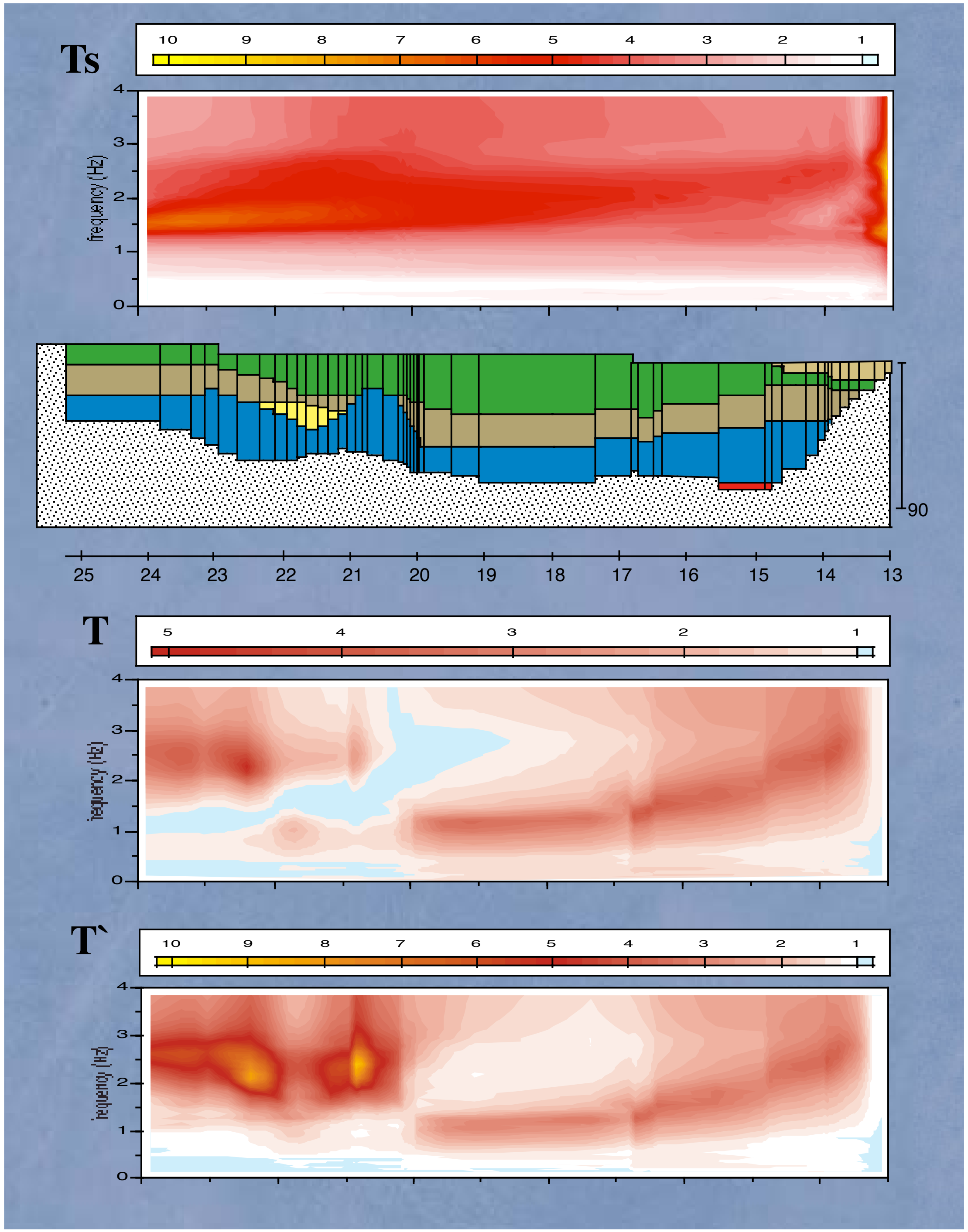


Ground shaking scenario corresponding to an earthquake of the same size as the destructive event that occurred on January 11, 1693

Making use of the simplified geotechnical map for the Catania area, we produce maps of the expected ground motion over the entire area

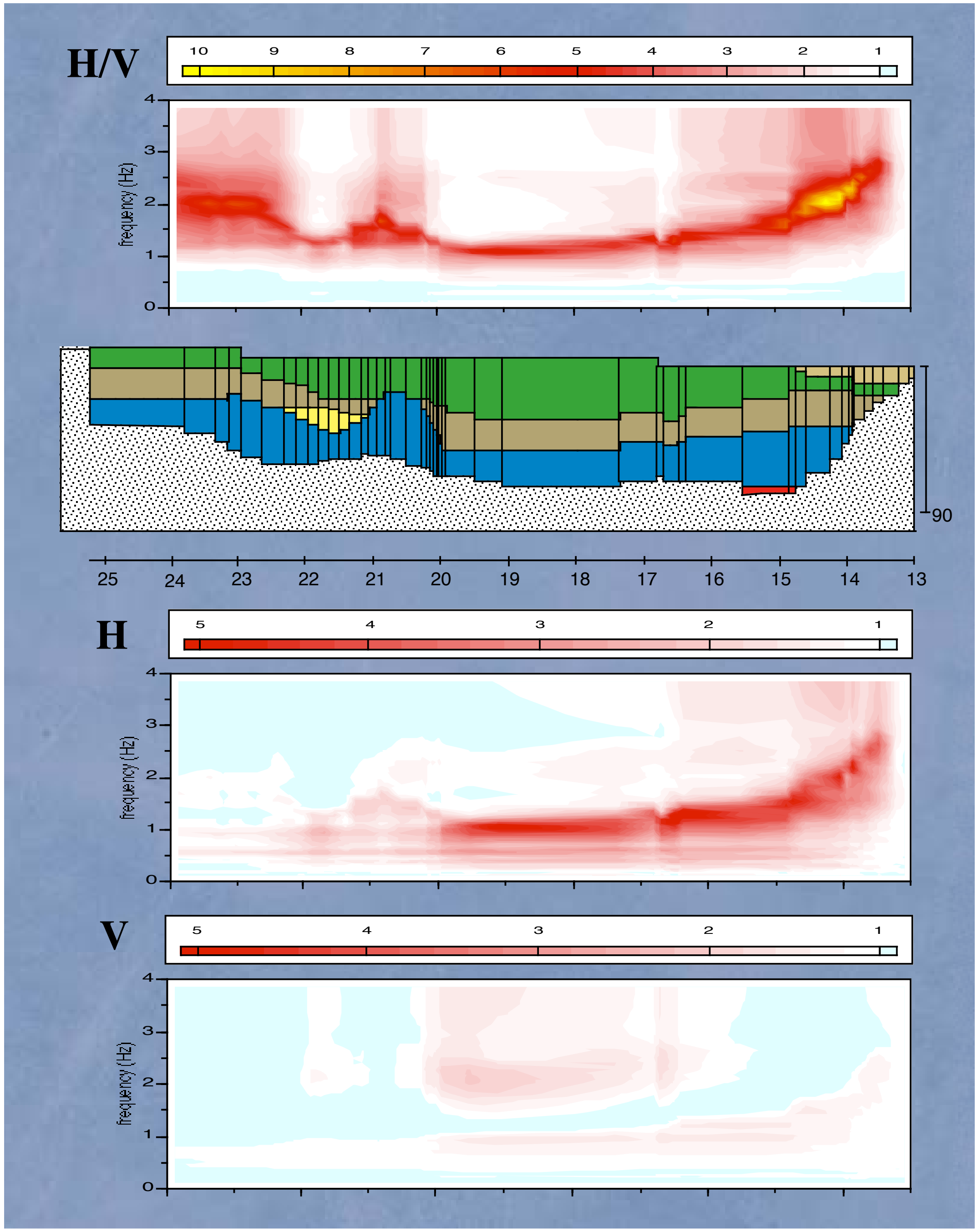
Using the detailed geological and geotechnical information along a selected cross section, we study the site response in a very realistic case.

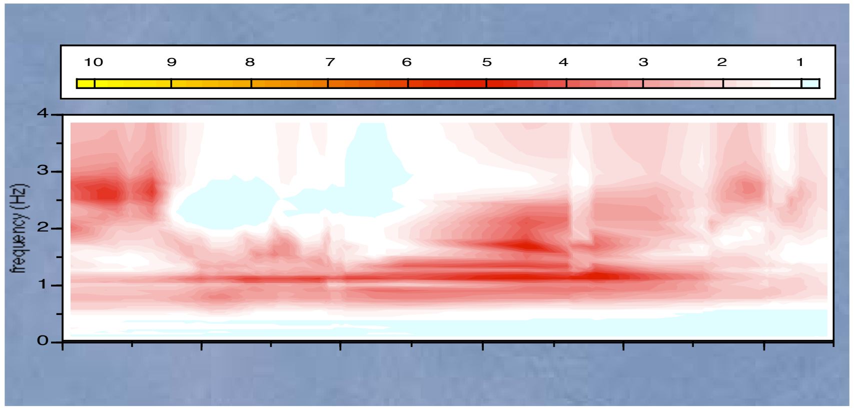




Site effect estimation (amplification)

Spectral ratios
for
transverse
component
(SH motion)





Spectral ratios
for
radial and vertical
component
(P-SV motion)

Site effect estimation (amplification)

Some conclusions

The main result, so far, is that, in order to perform an accurate estimate of the site effects:

(1) it is necessary to make a parametric study that takes into account the complex combination of the source and propagation parameters,

(2) that results obtained with simplified structural models have a limited applicability and detailed models should be preferred.

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