The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

International Atomic Energy Agency

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**Seismic Hazard in Asia**

**4 - 8 December 2006**

# Ground Motion Modelling for Seismic Hazard Assessement Source and Site Effects

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# Ground motion modelling for seismic hazard assessment: source and site effects


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&

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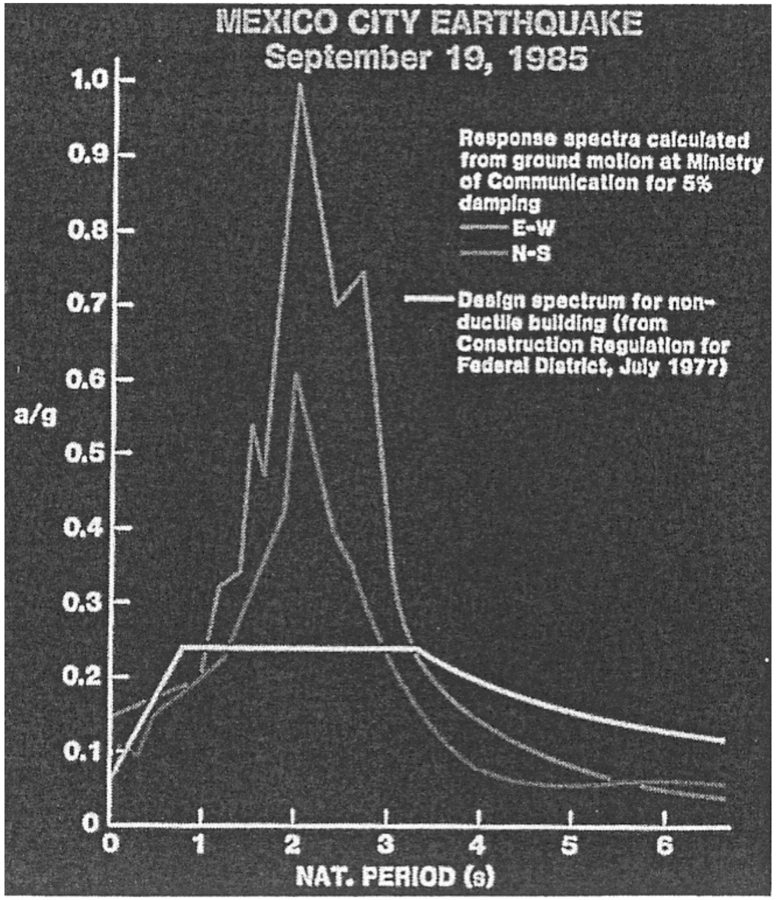
# the road to earthquake safety...

Know the input - Bound the output...




Mitigate the difference...

Any strategy for **seismic risk reduction** should be outlined trying to answer two basic questions:

**When, where and how big we have to expect a strong earthquake to strike a region?**

**What should we expect when it occurs?**

The answer to the first question is matter for **earthquake prediction**, while the second one is matter for **seismic hazard assessment**...

# Outline

**Some remarks on SHA**

- SHA & PBDE
- Source & site effects in SHA
- Demand parameters
- Definition of seismic input

**Seismic input for a critical facility**

- Parametric studies
  - Focal mechanism
  - Site effects
  - Directivity

# SHA dualism

| | 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**

# SHA Dualism

Deterministic vs. probabilistic approaches to assessing earthquake hazards and risks have differences, advantages, and disadvantages that often make the use of one advantageous over the other.

Probabilistic methods can be viewed inclusive of all deterministic events with a finite probability of occurrence. In this context, proper deterministic methods that focus on a single earthquake ensure that that event is realistic, i.e. that it has a finite probability of occurrence.

**Determinism vs. probabilism is not a bivariate choice but a continuum in which both analyses are conducted, but more emphasis is given to one over the other. Emphasis here means weight in the decision-making process...**

Modified from: **Mc Guire, 2001**

# PBDE

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

In PBDE, 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**.

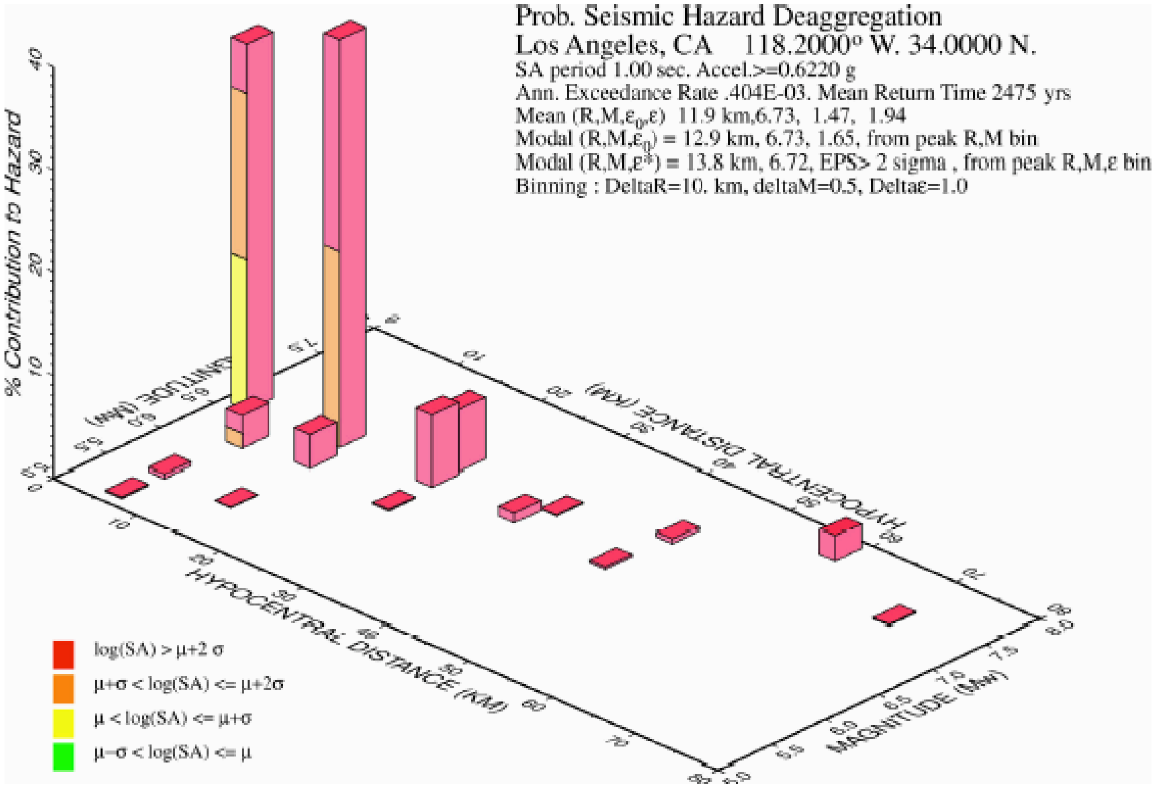
# Modern PSHA & DSHA dualism


| 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 |

Deaggregation, 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



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**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)
$f_n=(2n+1)\beta/4H$
$A \approx (\rho 2\ v2)/(\rho 1\ v1)$
b) 2-D 3-D: complex energy focusing
for diffraction effects
(basin edge waves)

**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)

## Empirical techniques for Site effect estimation

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

**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

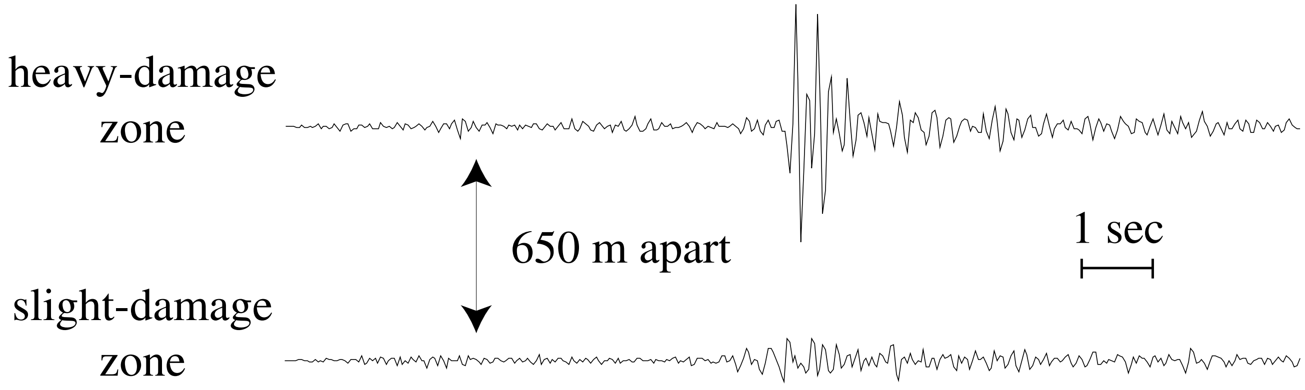
**Near surface effects**: impedance contrast,  velocity

- geological maps, $v_{30}$, $v_{1/4}$, ??

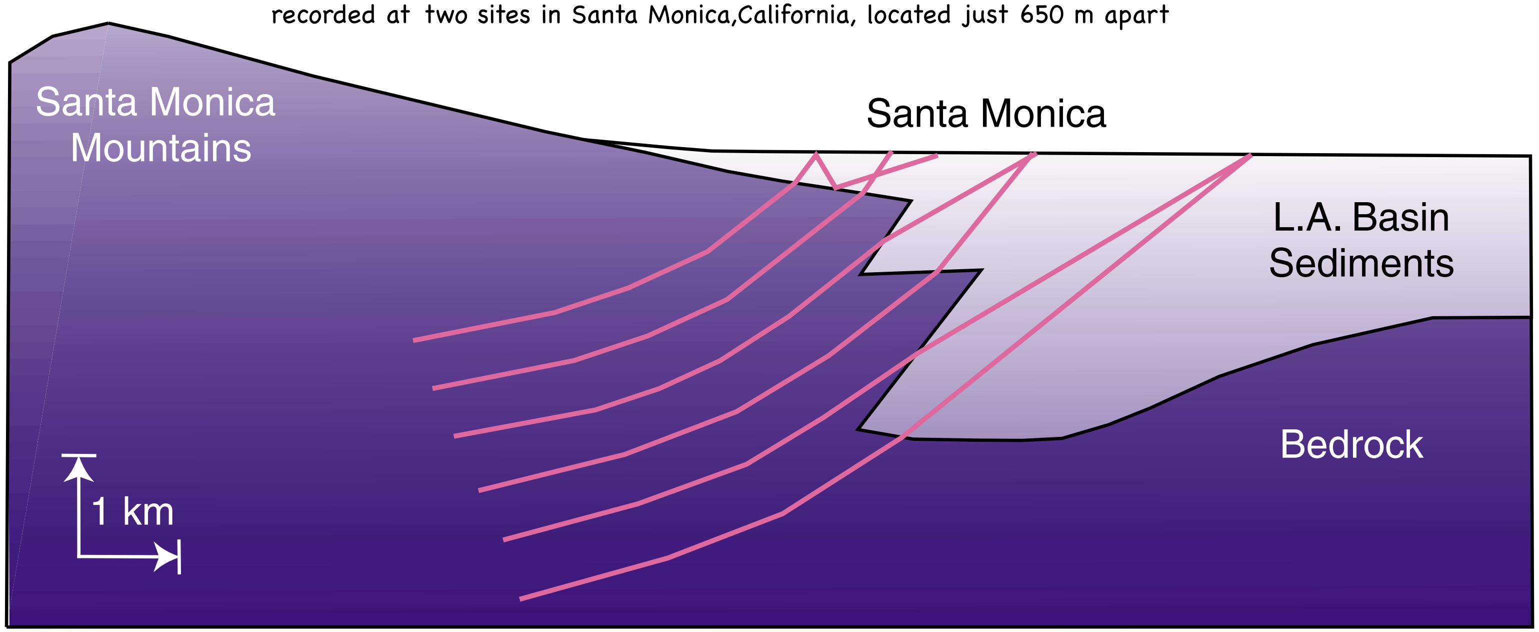
**Basin effects**

- Basin-edge induced waves
- Subsurface focusing

# Important issues in SRE

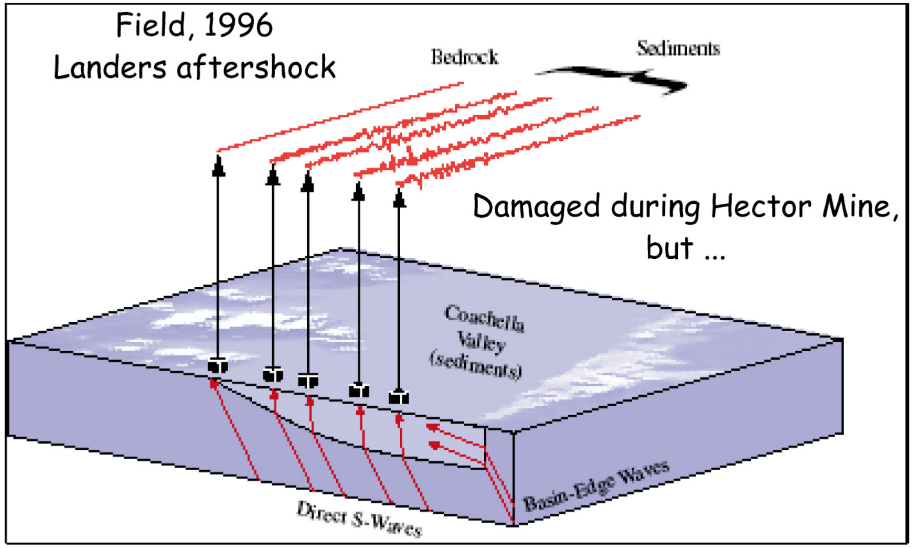



Particle-velocity seismograms of a 1994 Northridge earthquake aftershock recorded at two sites in Santa Monica,California, located just 650 m apart




Problems in SHA-Site effects

# Important issues in SRE



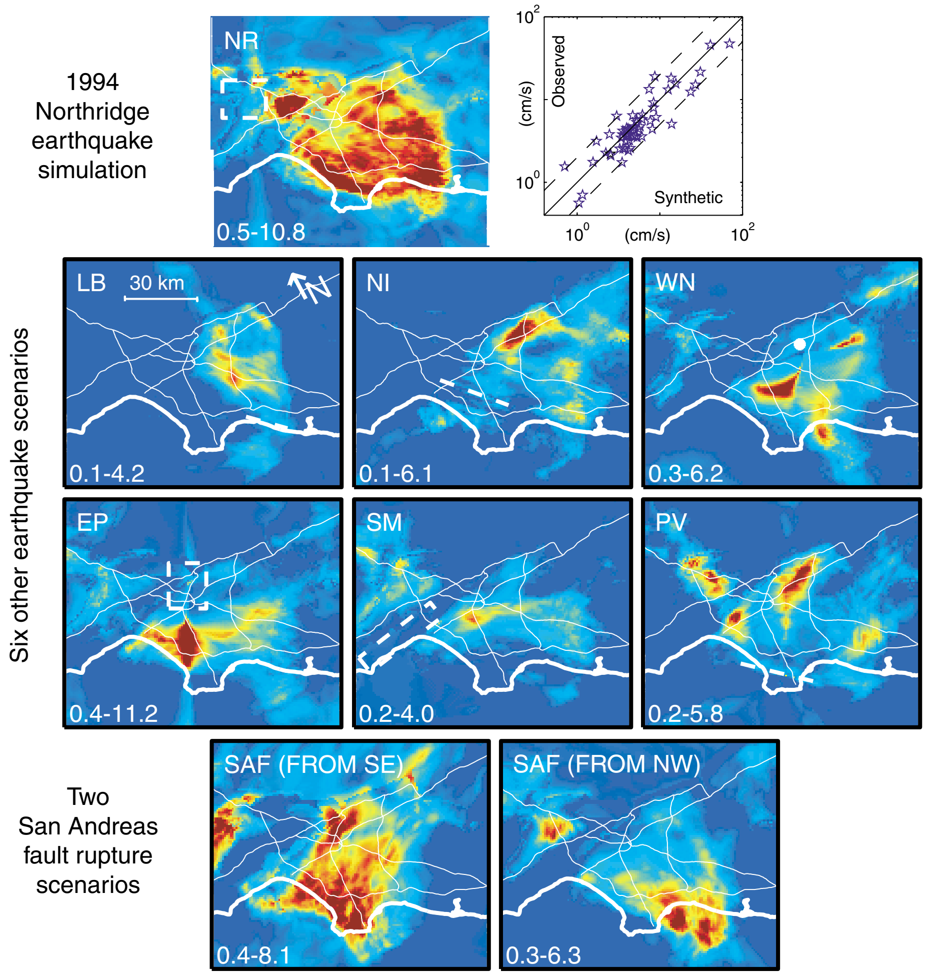
# SRE and SHA

Amplification patterns may vary greatly among

the earthquake scenarios, considering different **source locations** (and rupture …)

Peak Velocity Amplification from the 3D Simulations of Olsen (2000)

SCEC
Phase 3
Report



# SRE and SHA

In SHA 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?

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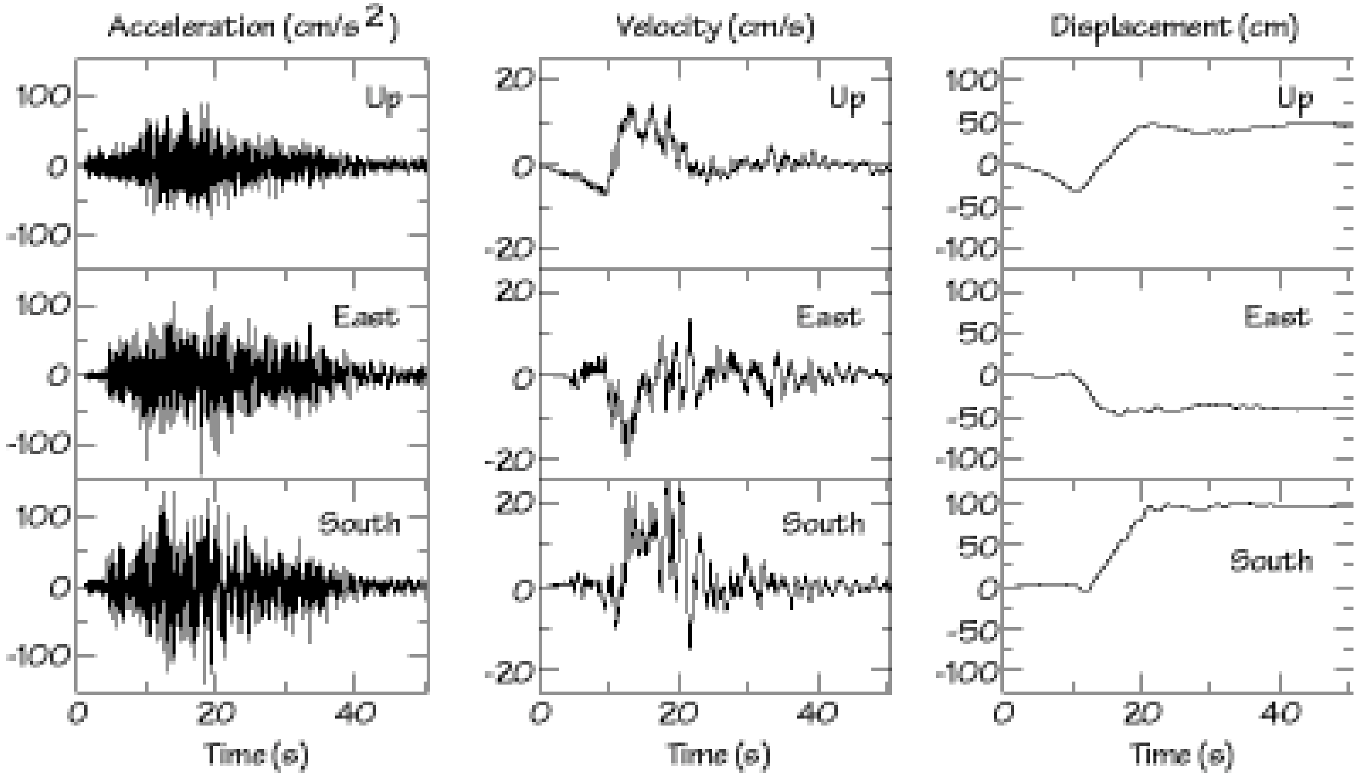
# Fling

## permanent tectonic deformation related to near field effect ("killer pulse")

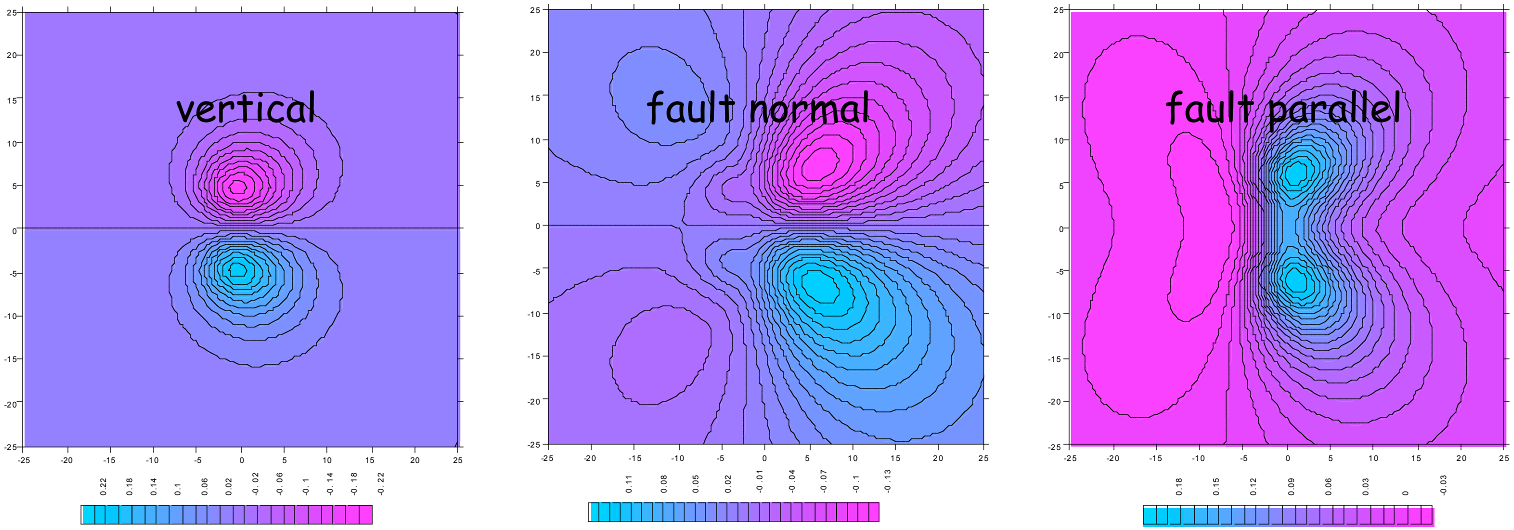



Ground acceleration, velocity and displacement, recorded at a strong-motion seismometer that was located directly above the part of a fault that ruptured during the 1985 Mw = 8.1, Michoacan, Mexico earthquake.

Source effect

# Static near-field term from a finite fault

near field term (Stokes, 1848)
+ dislocation theory (Chinnery, 1961)




dip=45°, rake=0°, H=6, L=10,W=8

Source effect

# Static near-field term from a finite fault

near field term (Stokes, 1848)
+ dislocation theory (Chinnery, 1961)

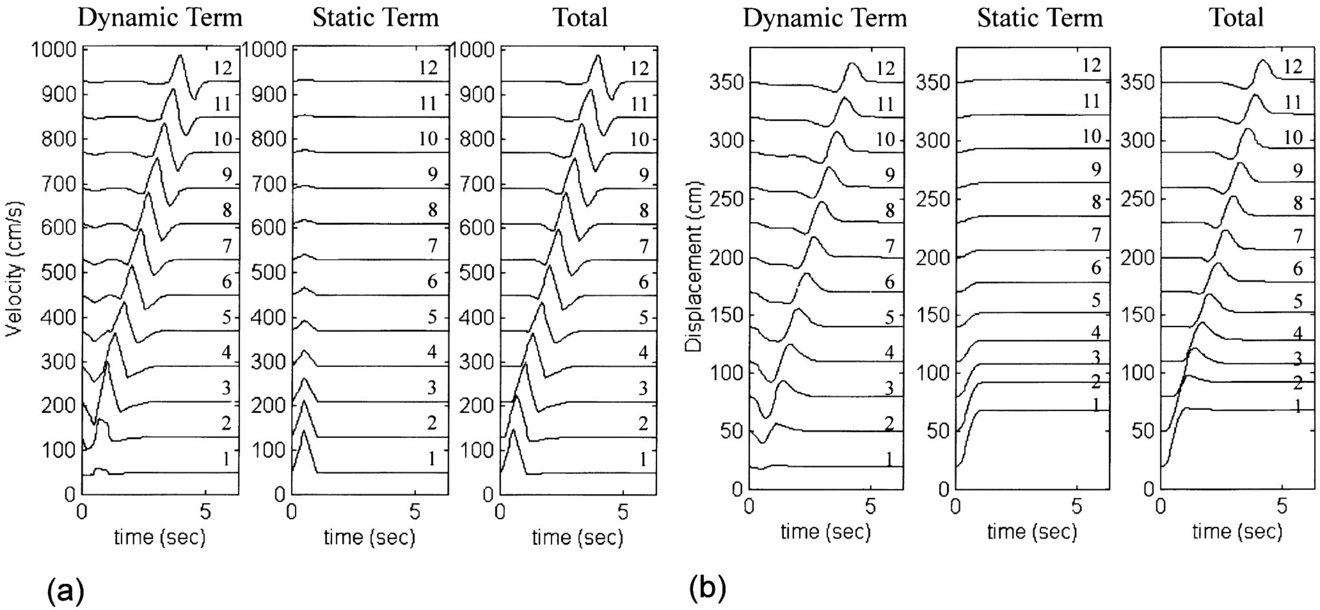
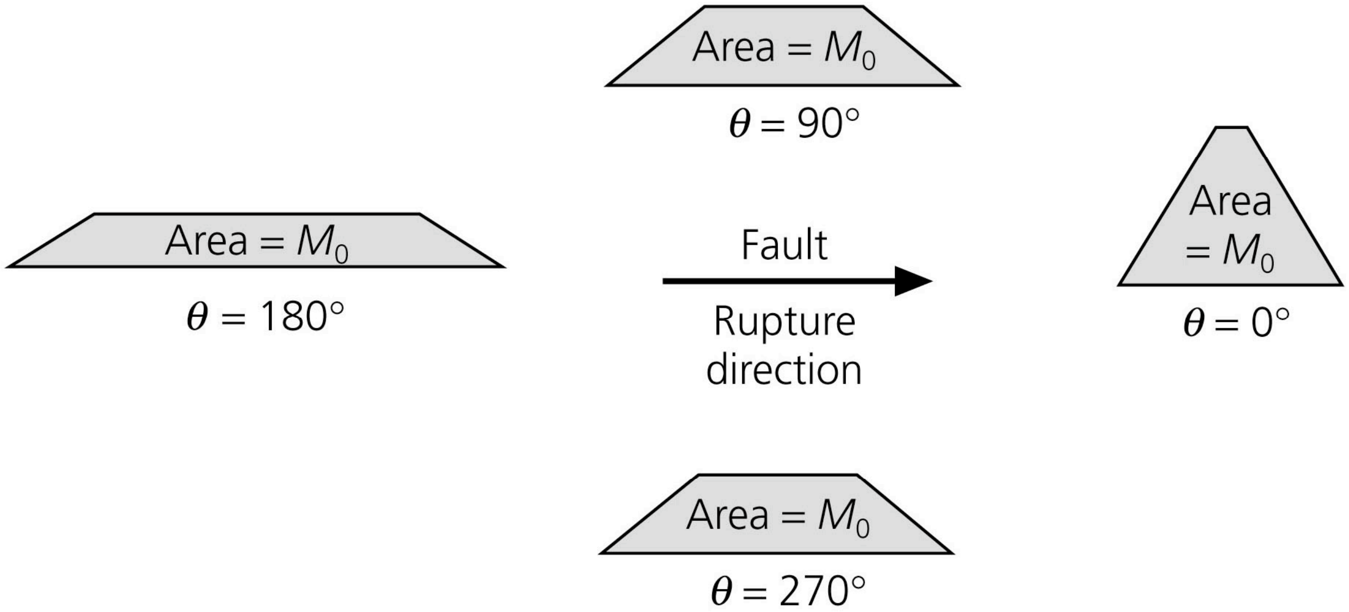


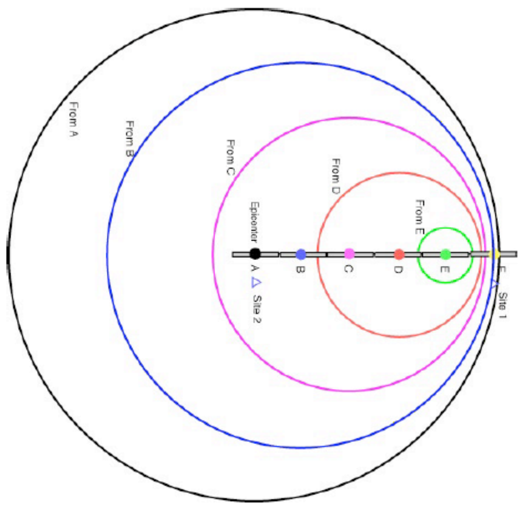

Figure 7. (a) Velocities and (b) displacements of the fault-parallel components at 12 observation points in Figure 6, using the first (dynamic; left), second (static; center), and total (right) integrations of equation (11).

+directivity (Hisada&Bielak, 2003)

Source effect

# Directivity (near fault)




Source effect

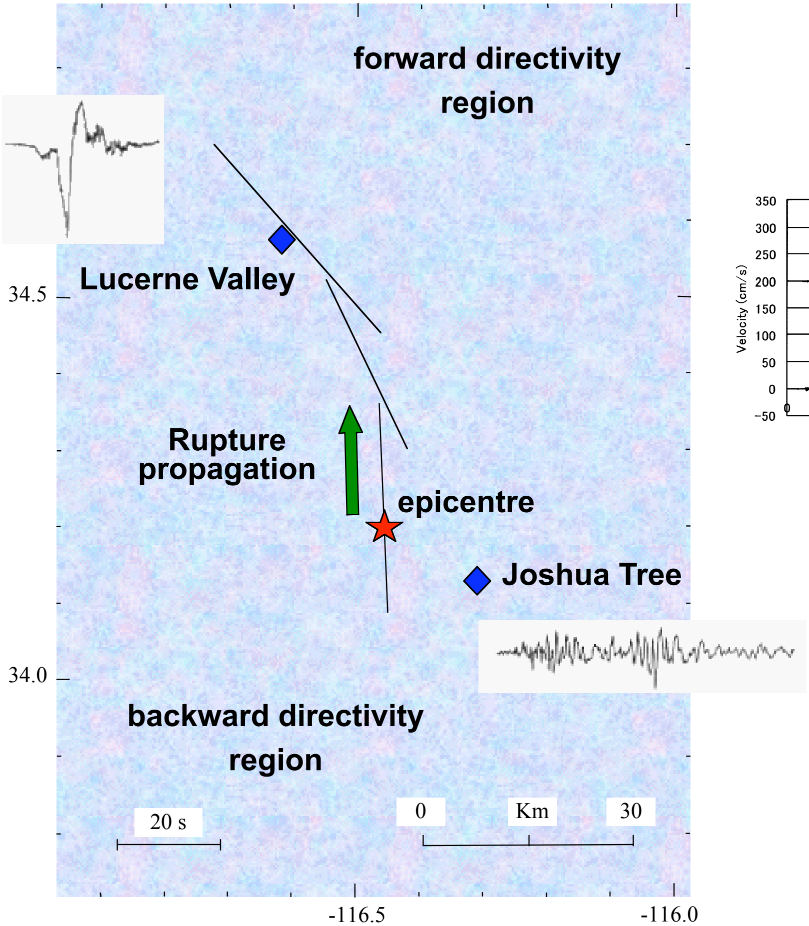
# Directivity (near fault)

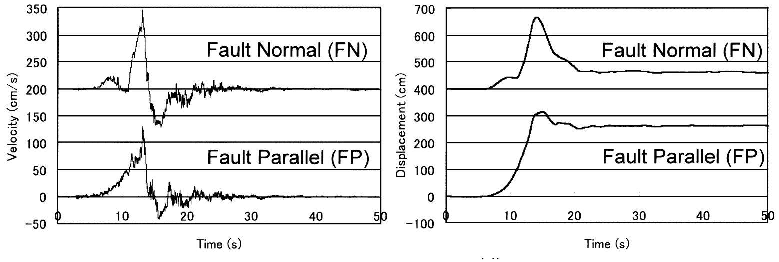
Particularly, in the case of **forward rupture directivity** most of the energy arrives in a single large pulse of motion which may give rise to particularly severe ground motion at sites toward which the fracture propagation progresses.

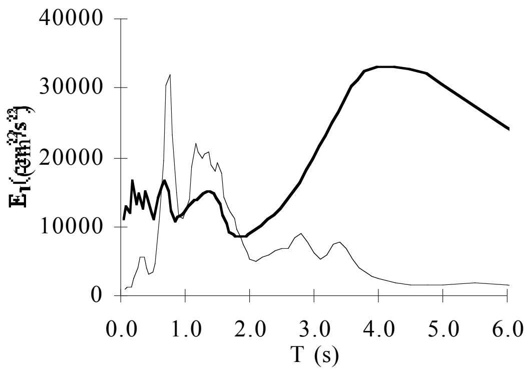
it involves the transmission of large energy amounts to the structures in a very short time.

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.

# Landers, 1992

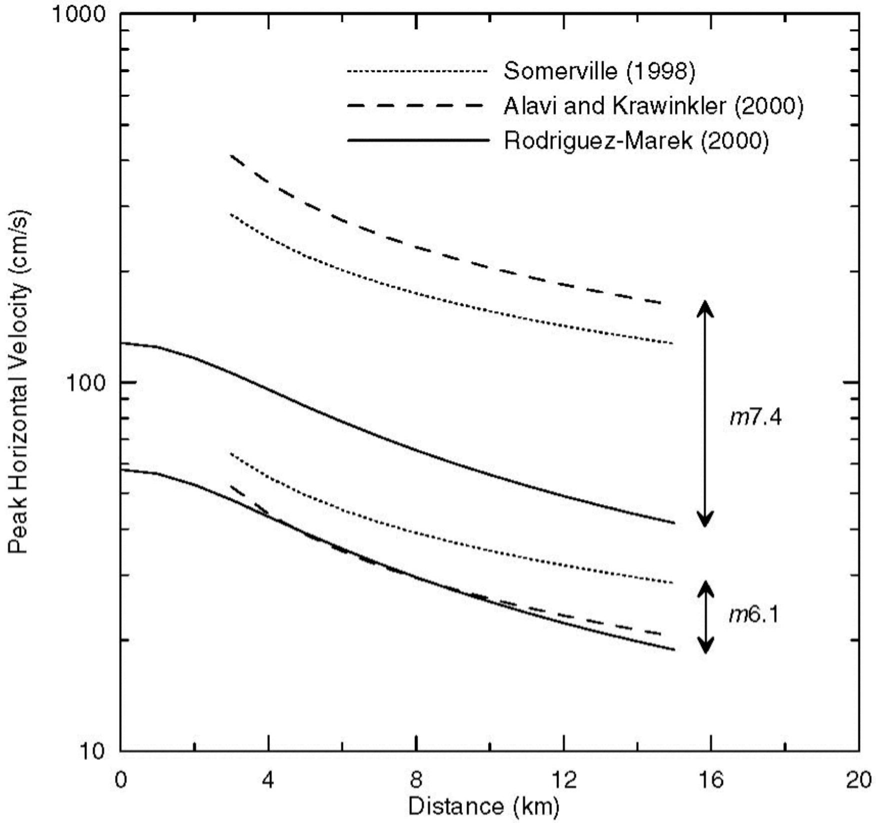



Source effect

# regression example...




Rodriguez-Marek (2000):

$$\ln(\mathrm{PHV}) = 2.44 + 0.5\,m - 0.41\,\ln(r^2 + 3.93^2)$$

Somerville (1998):

$$\ln(\mathrm{PHV}) = -2.31 + 1.15\,m - 0.5\,\ln(r)$$

Alavi and Krawinkler (2000):

$$\ln(\mathrm{PHV}) = -5.11 + 1.59\,m - 0.58\,\ln(r)$$

Source effect

# Near fault ground motion

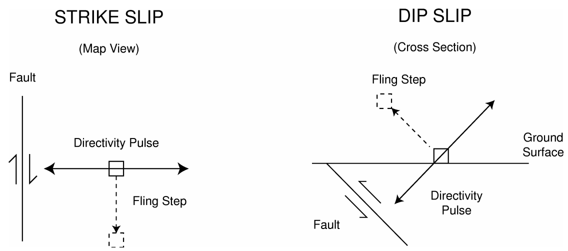



**Fig. 4.3. Schematic diagram showing the orientations of fling step and directivity pulse for strike-slip and dip-slip faulting.**

Peer report, 2001

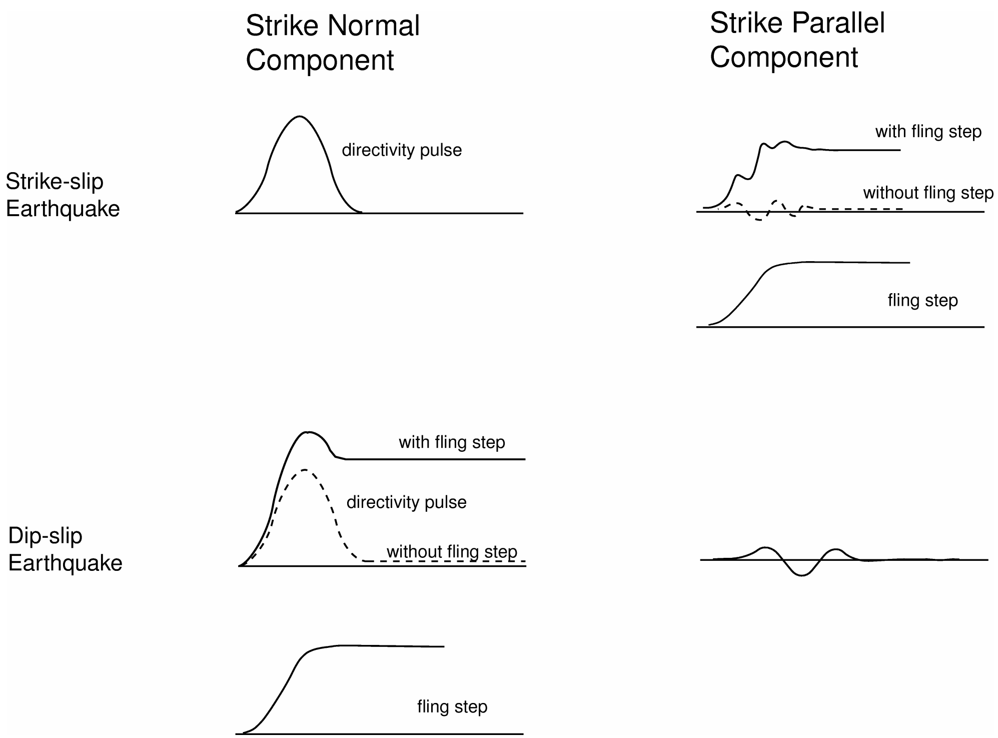



**Fig. 4.4. Schematic diagram of time histories for strike-slip and dip-slip faulting in which the fling step and directivity pulse are shown together and separately.**

Source effect

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# 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…

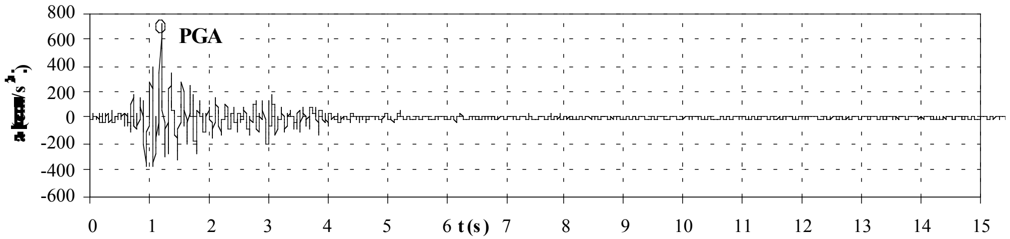



Figure 1 – Acceleration time history. Rocca NS record. 1971 Ancona earthquake ($M_L$=4.7)

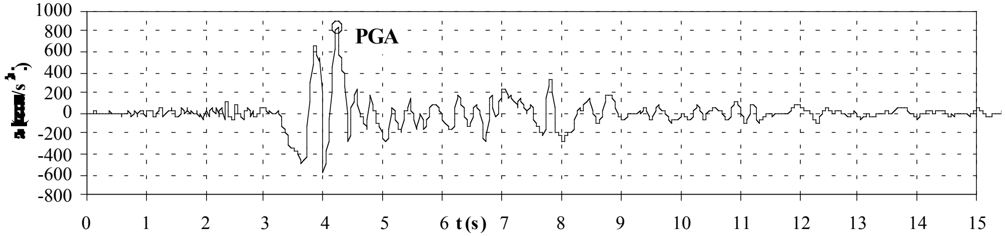



Figure 2 – Acceleration time history. Sylmar N360 record. 1994 Northridge earthquake ($M_w$=6.7)

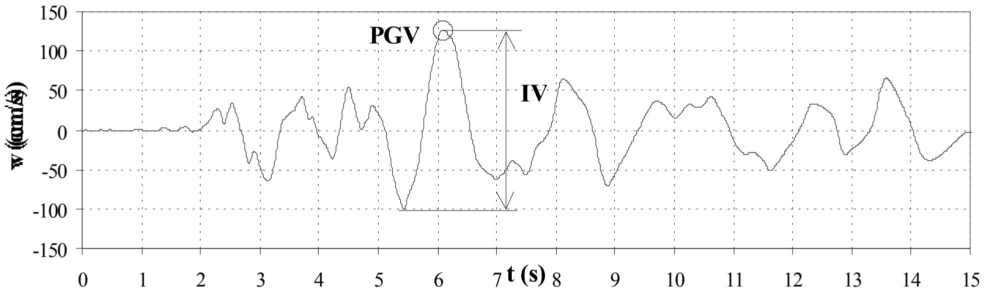



Figure 3 – Velocity time history. Takatori 000 record. 1995 Kobe earthquake ($M_w$=6.9)

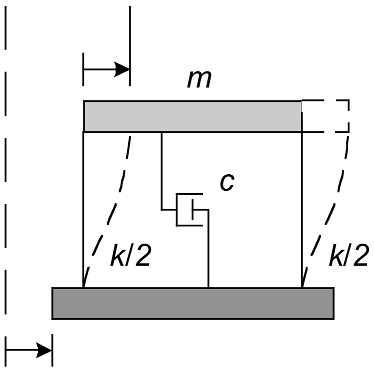
# Response spectra

## SDF SYSTEMS

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

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

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




The ground acceleration can be registered using accelerographs:

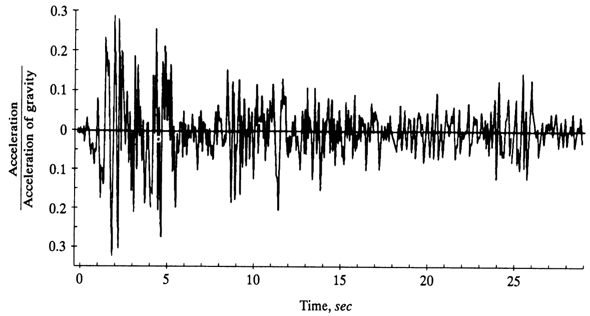
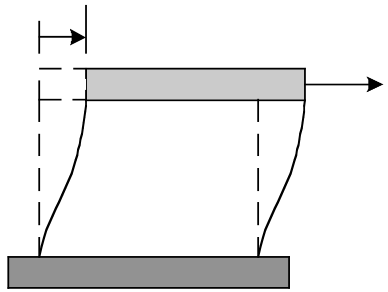



**FIGURE 24-15**
Accelerogram from El Centro earthquake, May 18, 1940 (*NS* component).

## EQUIVALENT STATIC FORCE



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

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

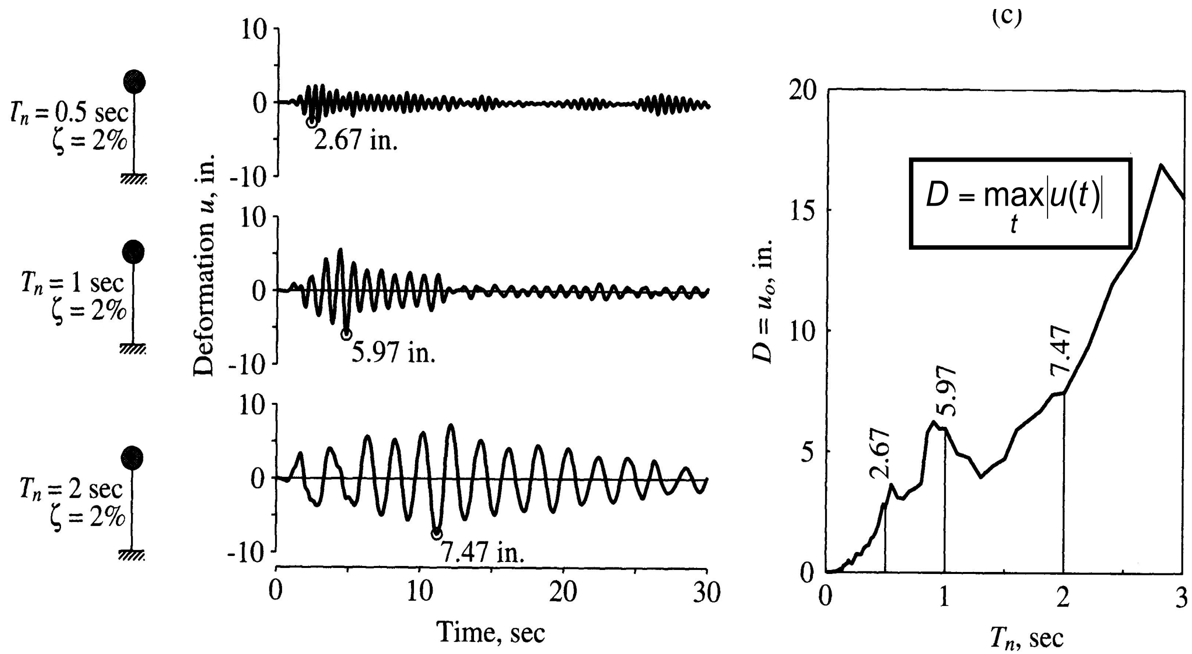
Pseudo acceleration

$f_S(t)$ 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 ($T_n$ , $\xi$).

**Example** : Deformation response spectrum for El Centro earthquake




Parameters extraction

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

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

Peak Pseudo-velocity $V = \omega_n D$

Peak Pseudo-acceleration $A = \omega_n^2 D$

$\omega_n$ : natural circular frequency of the SDF system.

## COMBINED D-V-A SPECTRUM

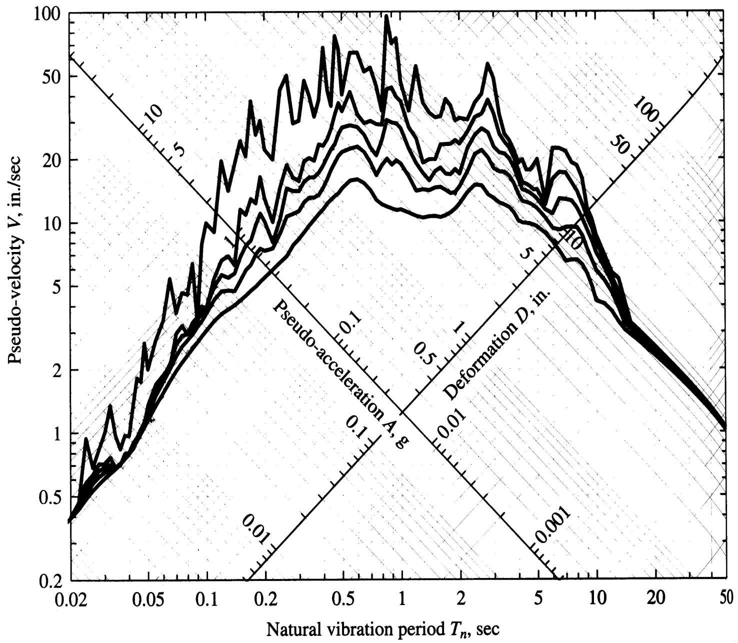
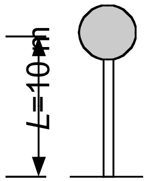



**Figure 6.6.4** Combined *D–V–A* response spectrum for El Centro ground motion; $\zeta$ = 0, 2, 5, 10, and 20%.

**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

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

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

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

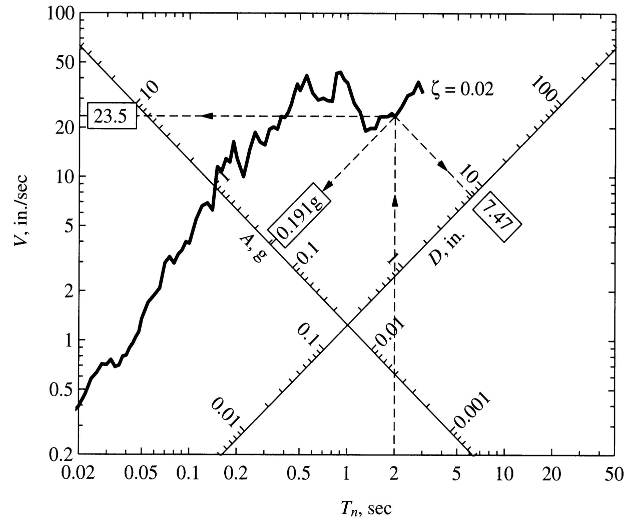
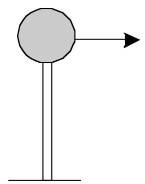
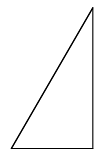



**Figure 6.6.3** Combined $D$–$V$–$A$ response spectrum for El Centro ground motion; $\zeta = 2\%$.





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.

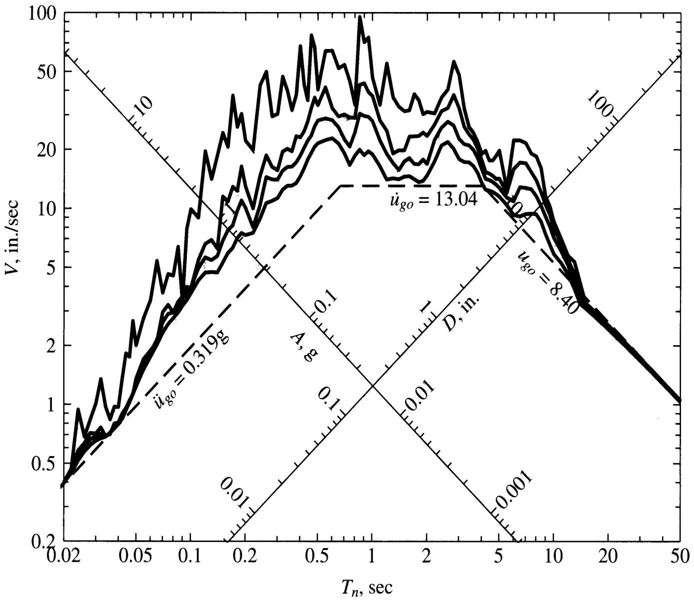


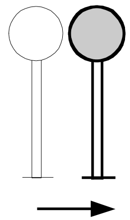

**Figure 6.8.1** Response spectrum ($\zeta$ = 0, 2, 5, and 10%) and peak values of ground acceleration, ground velocity, and ground displacement for El Centro ground motion.

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

$T_n$ < 0.03 s : rigid system

no deformation

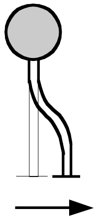
u(t) ≈ 0 → D ≈ 0



$T_n$ > 15 s : flexible system

no total displacement

u(t) = $u_g$(t) → D = $u_{go}$



The spectrum can be divided in 3 period ranges :

- $T_n < 0.5$s : acceleration sensitive region
- $0.5 < T_n < 3$s : velocity sensitive region
- $T_n > 3$s : displacement sensitive region

Parameters extraction

## 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

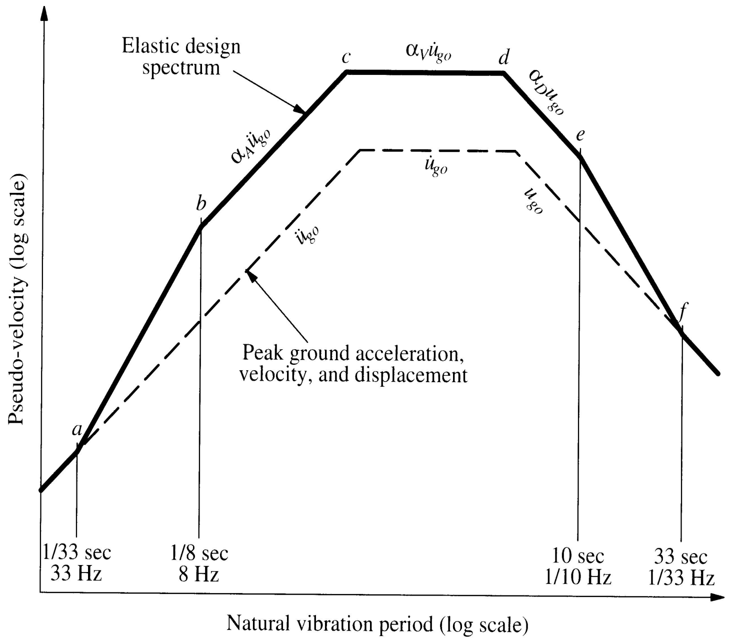



**Figure 6.9.3** Construction of elastic design spectrum.

# 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 $\xi$, and $S_{pa}$ is the pseudo-acceleration at the undamped natural period T and damping ratio $\xi$.

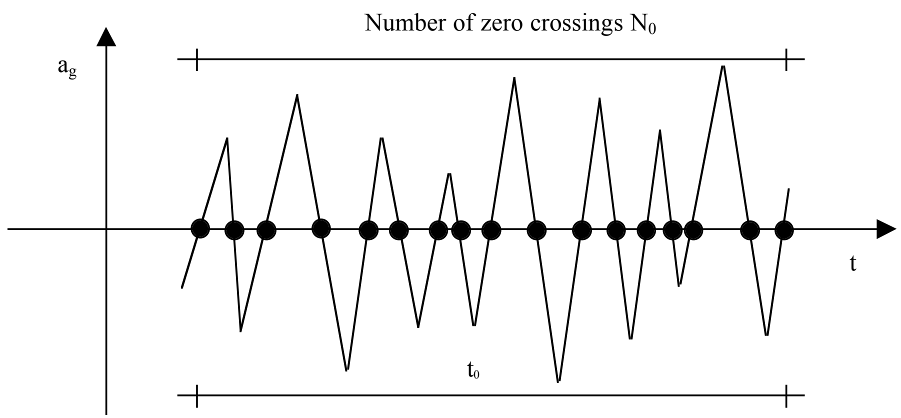
Housner's spectral intensity is the first moment of the area of $S_{pa}$ $(0.1<T<2.5)$ about the $S_{pa}$ axis, implying that the Housner spectral intensity is larger for ground motions with a significant amount of low frequency content.
The $I_H$ parameter captures important aspects of the amplitude 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, $\nu_0$ 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 $\nu_0$.

# 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 $\mu$ 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:

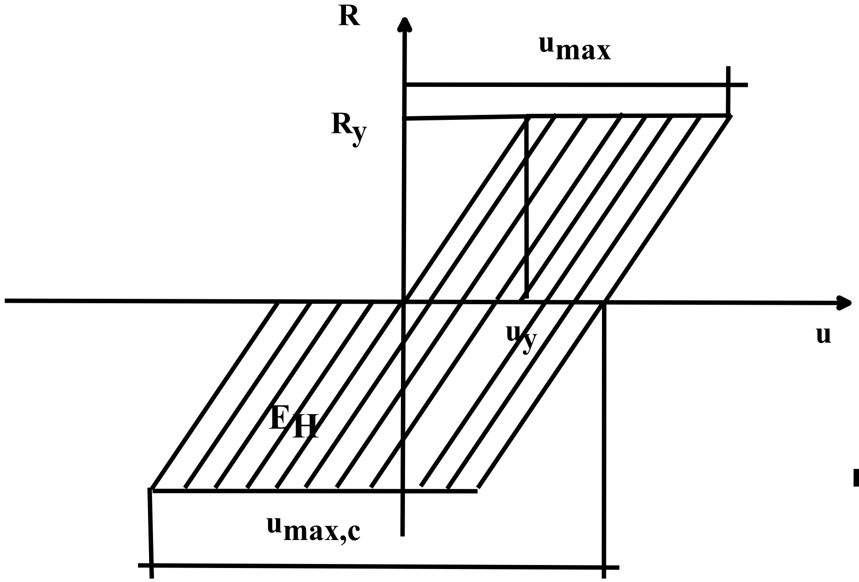
$$C_y = \frac{R_y}{mg} \quad \eta = \frac{R_y}{m\ddot{u}_{g(max)}} = \frac{C_y}{\ddot{u}_{g(max)}/g}$$

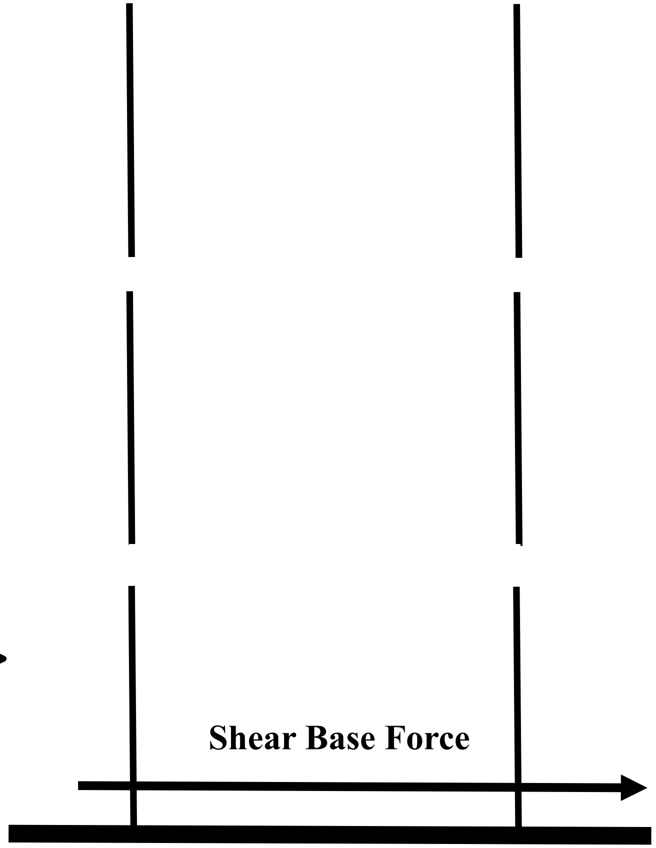
where $R_y$ is the yielding resistance, m is the mass of the system, and $\ddot{u}_{g(max)}$ is the maximum ground acceleration.

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

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

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



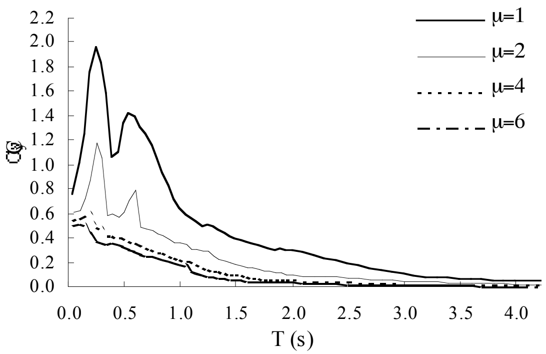




Parameters extraction

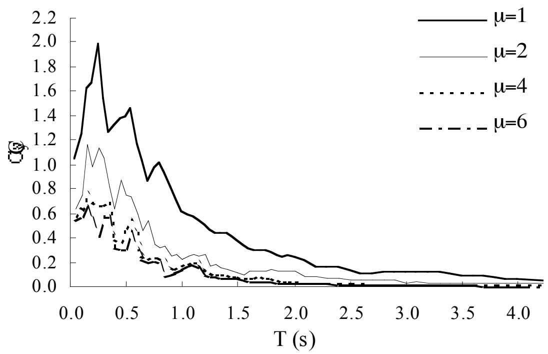
# Yielding resistance 2

The parameter $C_y$ represents the structure's yielding seismic resistance coefficient and $\eta$ 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 $E_\xi$ 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):

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

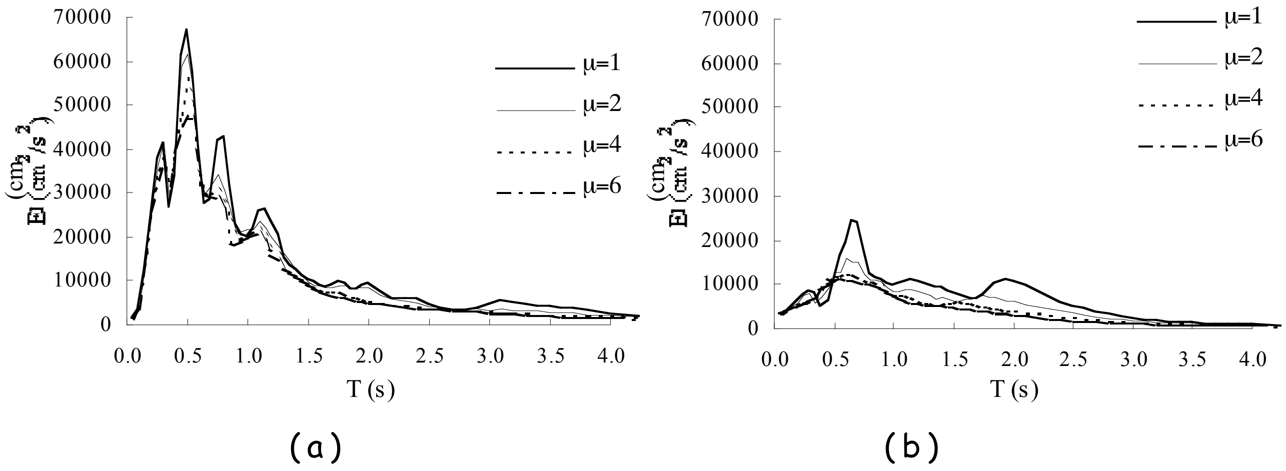
where ($E_I$) is the input energy, ($E_k$) is the kinetic energy, ($E_\xi$) is the damping energy, ($E_s$) is the elastic strain energy, and ($E_H$) is the hysteretic energy.

# 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 $E_I$.




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

# Outline

## Some remarks on SHA

SHA & PBDE

Source & site effects in SHA

Demand parameters

Definition of seismic input

## Seismic input for a critical facility

Parametric studies

Focal mechanism

Site effects

Directivity

# know the input...

A proper definition of the seismic input for PBD 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

# ...to bound the output!

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

# 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) |

e.g. Stewart et al., 2001

# 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.

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**PEER 2001/09** - Ground Motion Evaluation Procedures for Performance-Based Design, J. Stewart, S. Chiou, J. Bray, R. Graves, P. Somerville, N. Abrahamson

# Outline

**Some remarks on SHA**

SHA & PBDE

Source & site effects in SHA

Demand parameters

Definition of seismic input

**Seismic input for a critical facility**

Parametric studies

- Focal mechanism
- Site effects
- Directivity

# VAB Project (EC)

ADVANCED METHODS FOR ASSESSING
THE SEISMIC VULNERABILITY
OF EXISTING MOTORWAY BRIDGES

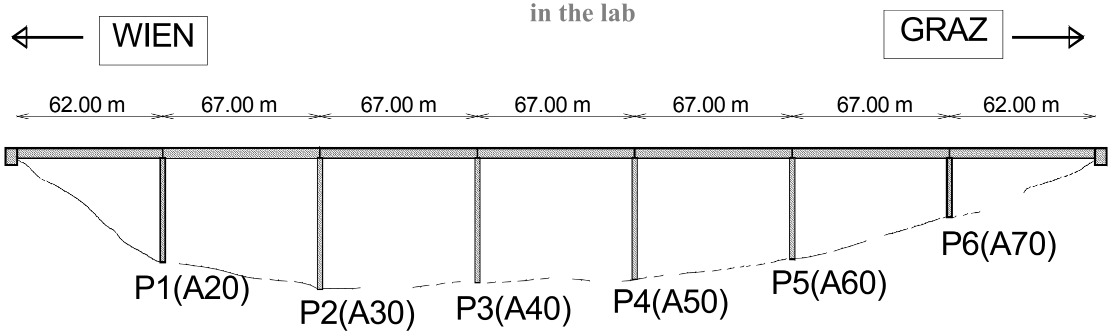
**ARSENAL RESEARCH**, Vienna, Austria; **ISMES S.P.A**,. Bergamo, Italy;
**ICTP**, Trieste, Italy; **UPORTO**, Porto, Portugal; **CIMNE**, Barcelona, Spain;
**SETRA**, Bagneaux, France; **JRC-ISPRA**, EU.

Effects on bridge seismic response of
asynchronous motion at the base of bridge piers

# Warth bridge

The bridge was designed for a horizontal acceleration of 0,04 g using the quasi static method.

According to the new Austrian seismic code the bridge is situated in zone 4 with a horizontal design acceleration of about 0,1 g: a detailed seismic vulnerability assessment was necessary.



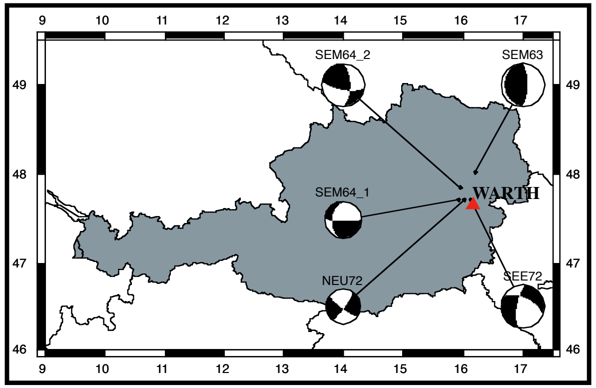

Case study

# Examples from EU project

## Databank of geological, geophysical and seismotectonic data

### SEISMIC SOURCES

1) **Database of focal mechanism**




2) **Parametric study on focal mechanism:**

**strike**
**dip**
**rake**
**depth**

Maximum Credible Earthquake

Maximum Design Earthquake

Maximum Historical Earthquake

## Databank of geological, geophysical and seismotectonic data

### STRUCTURAL MODELS

**Bedrock model**

1) EUR-I Data set

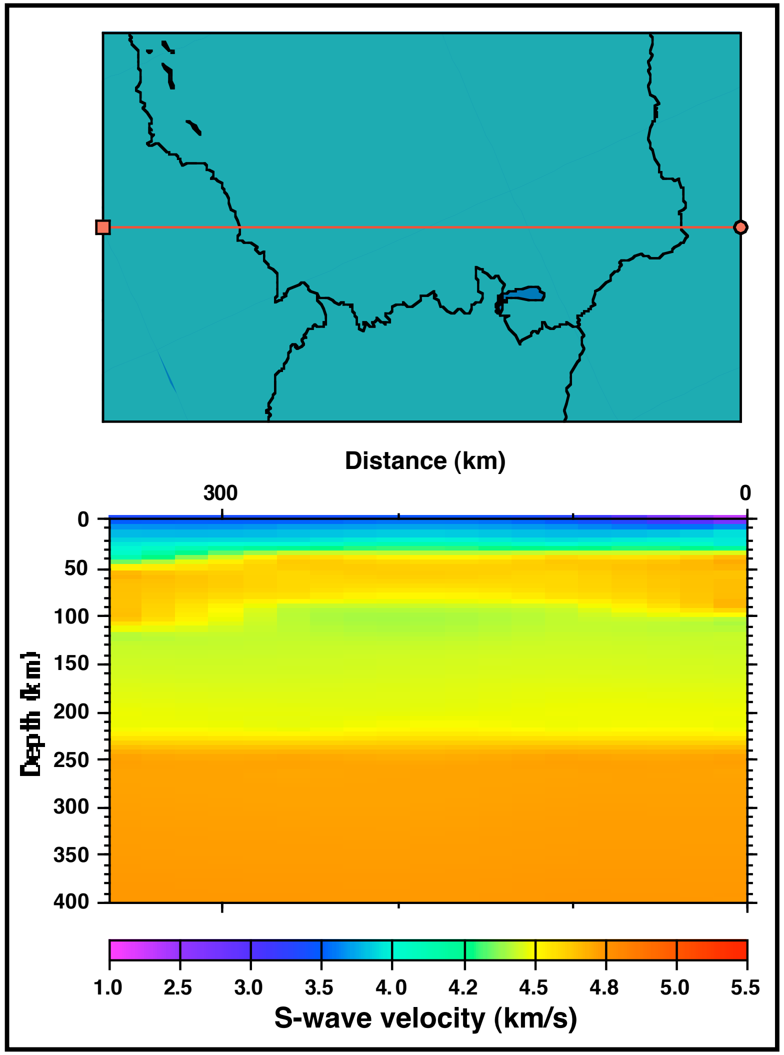
2) updated on the basis of the geological informations collected by CIMG

**Local LHET model**

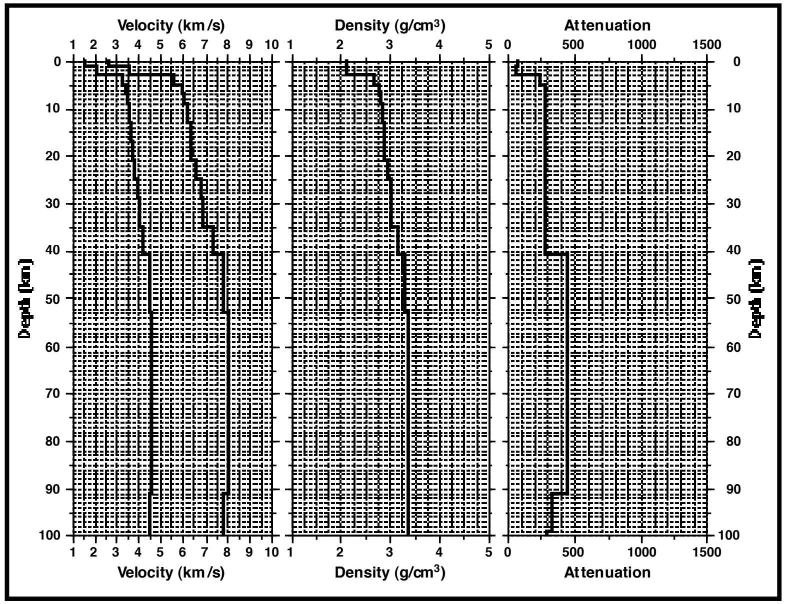
1) available Warth bridge section plan

2) updated on the basis of the refraction surveys by CIMG

# Initial regional model

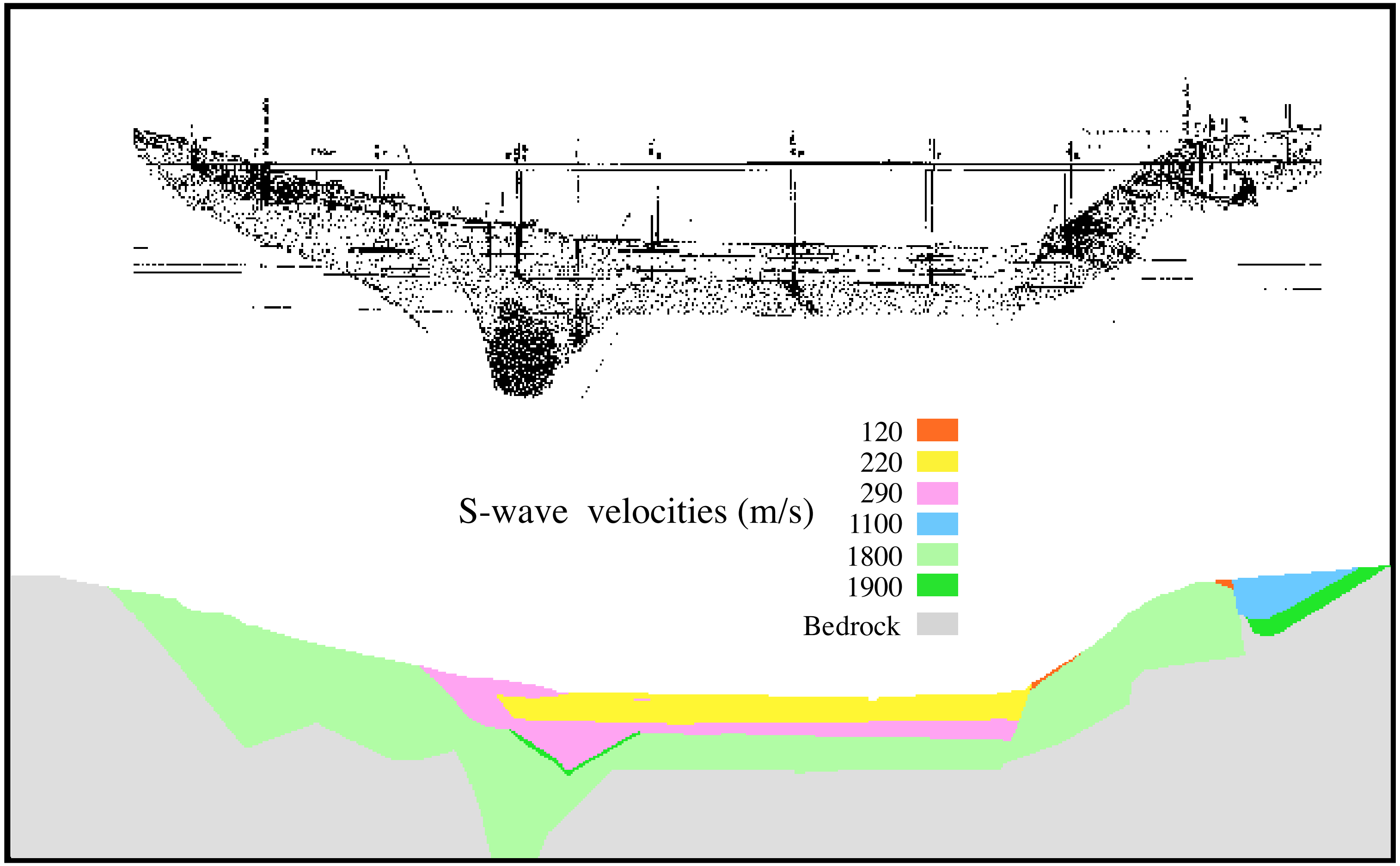



EUR I data set

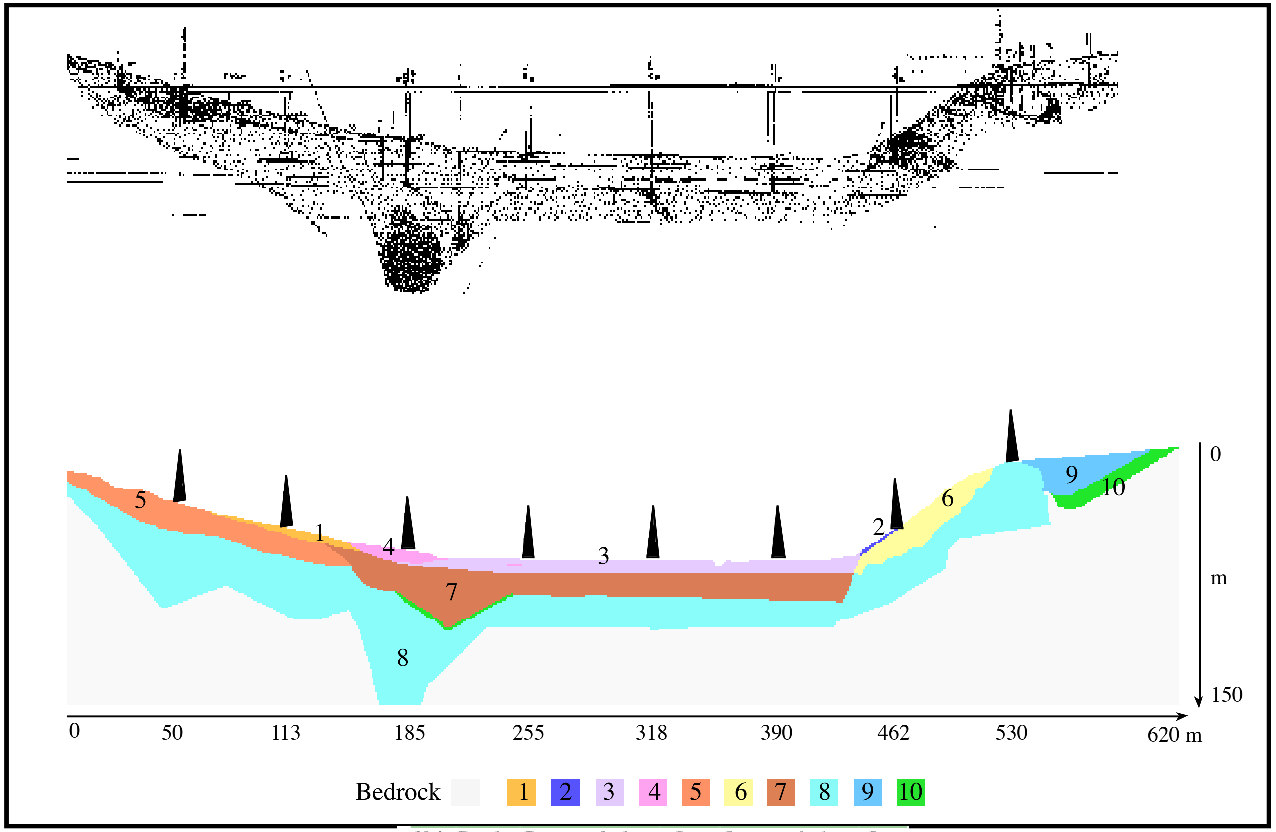



Definition of str. models

# Initial LHM - Warth bridge - model



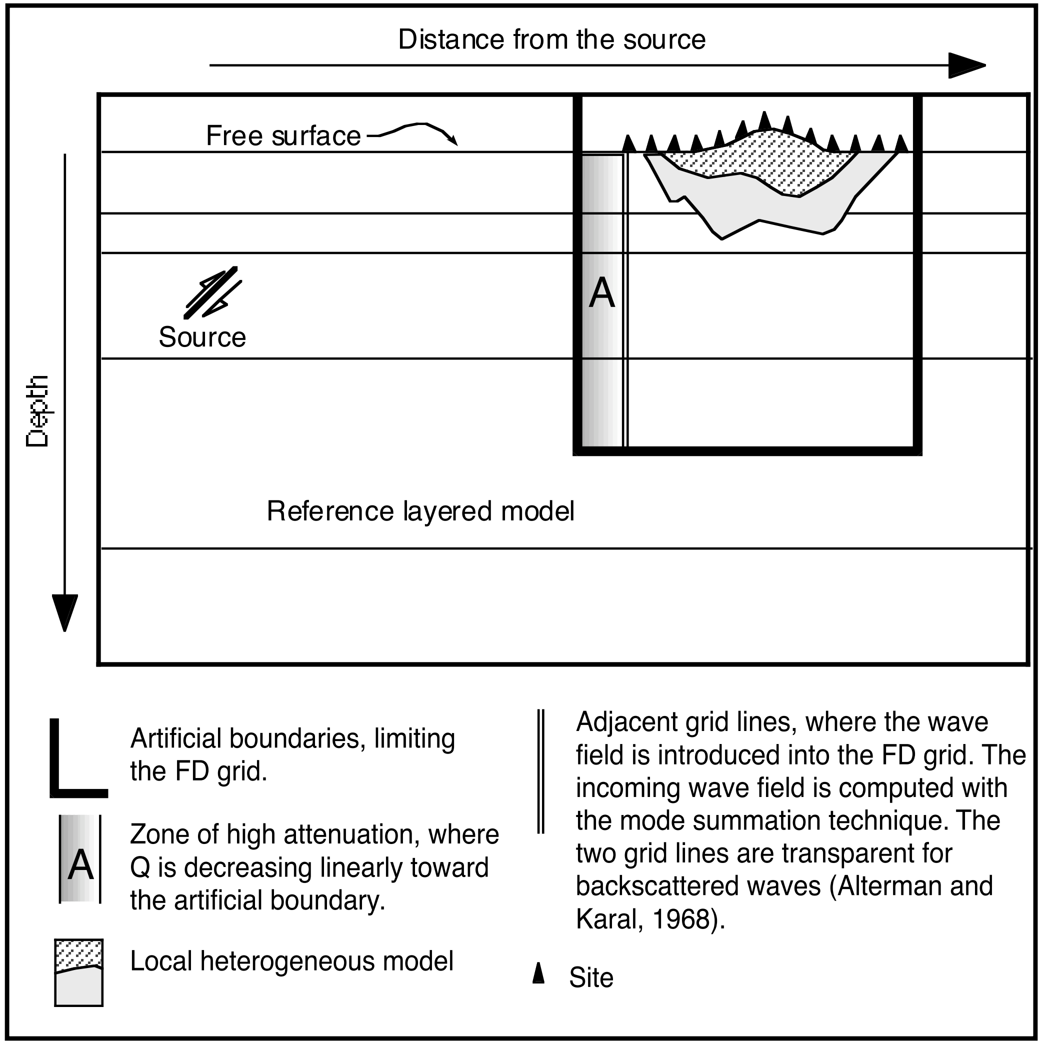
# LHM - Warth bridge - model



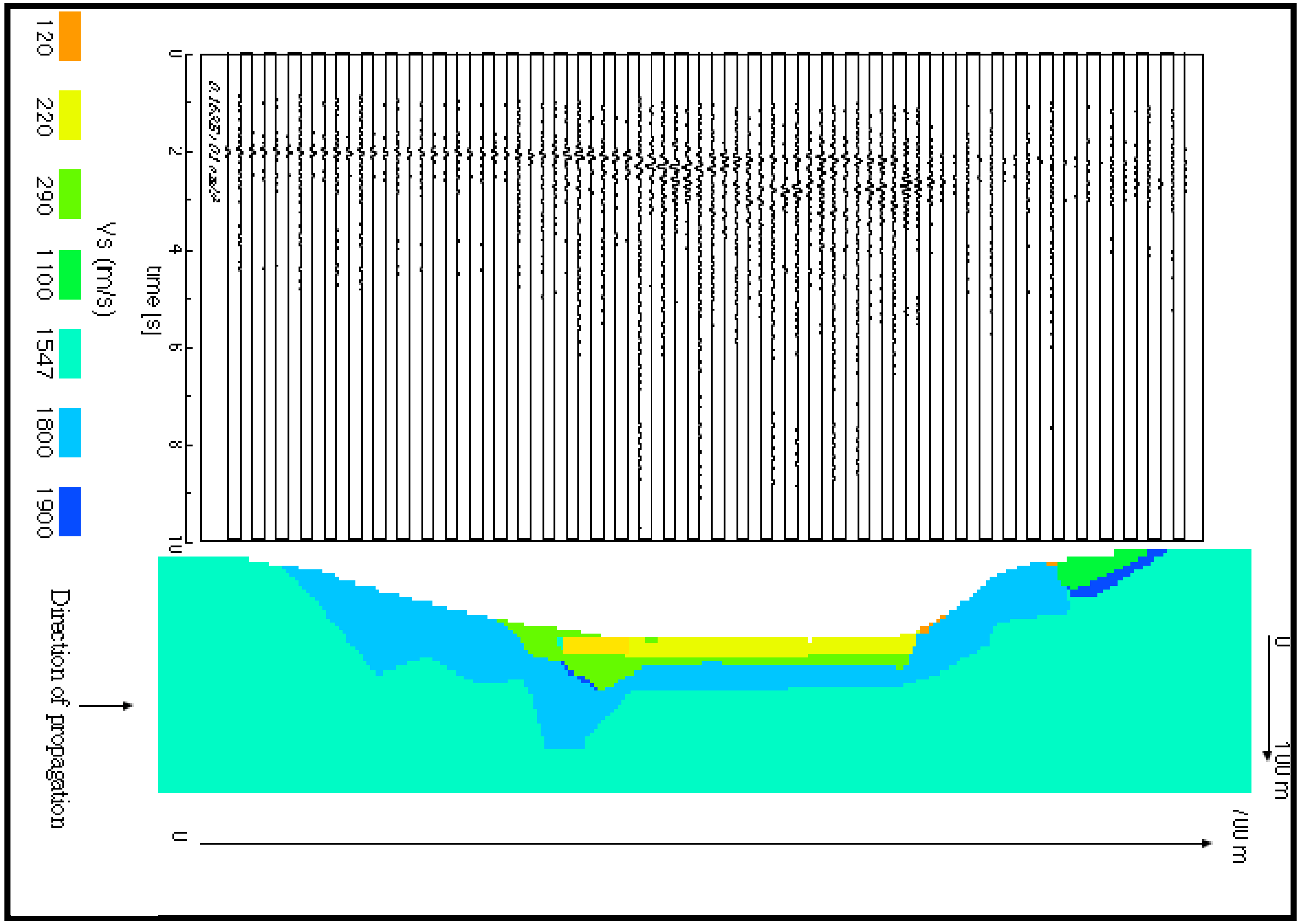

| Unit | Density g/cm$^3$ | P-wave velocity km/s | $Q_P$ | S-wave velocity km/s | $Q_S$ |
|---|---|---|---|---|---|
| 1 | 1.5 | 0.30 | 40.0 | 0.20 | 15.0 |
| 2 | 1.7 | 0.49 | 40.0 | 0.25 | 15.0 |
| 3 | 2.0 | 0.70 | 50.0 | 0.26 | 20.0 |
| 4 | 1.8 | 0.70 | 50.0 | 0.29 | 20.0 |
| 5 | 2.3 | 0.80 | 50.0 | 0.30 | 20.0 |
| 6 | 2.3 | 0.80 | 50.0 | 0.40 | 20.0 |
| 7 | 1.8 | 1.70 | 50.0 | 0.50 | 20.0 |
| 8 | 2.3 | 2.10 | 150.0 | 1.00 | 60.0 |
| 9 | 2.3 | 3.00 | 150.0 | 1.90 | 60.0 |
| 10 | 2.2 | 1.80 | 100.0 | 1.10 | 40.0 |

Definition of str. models

# Hybrid method: MS-FD

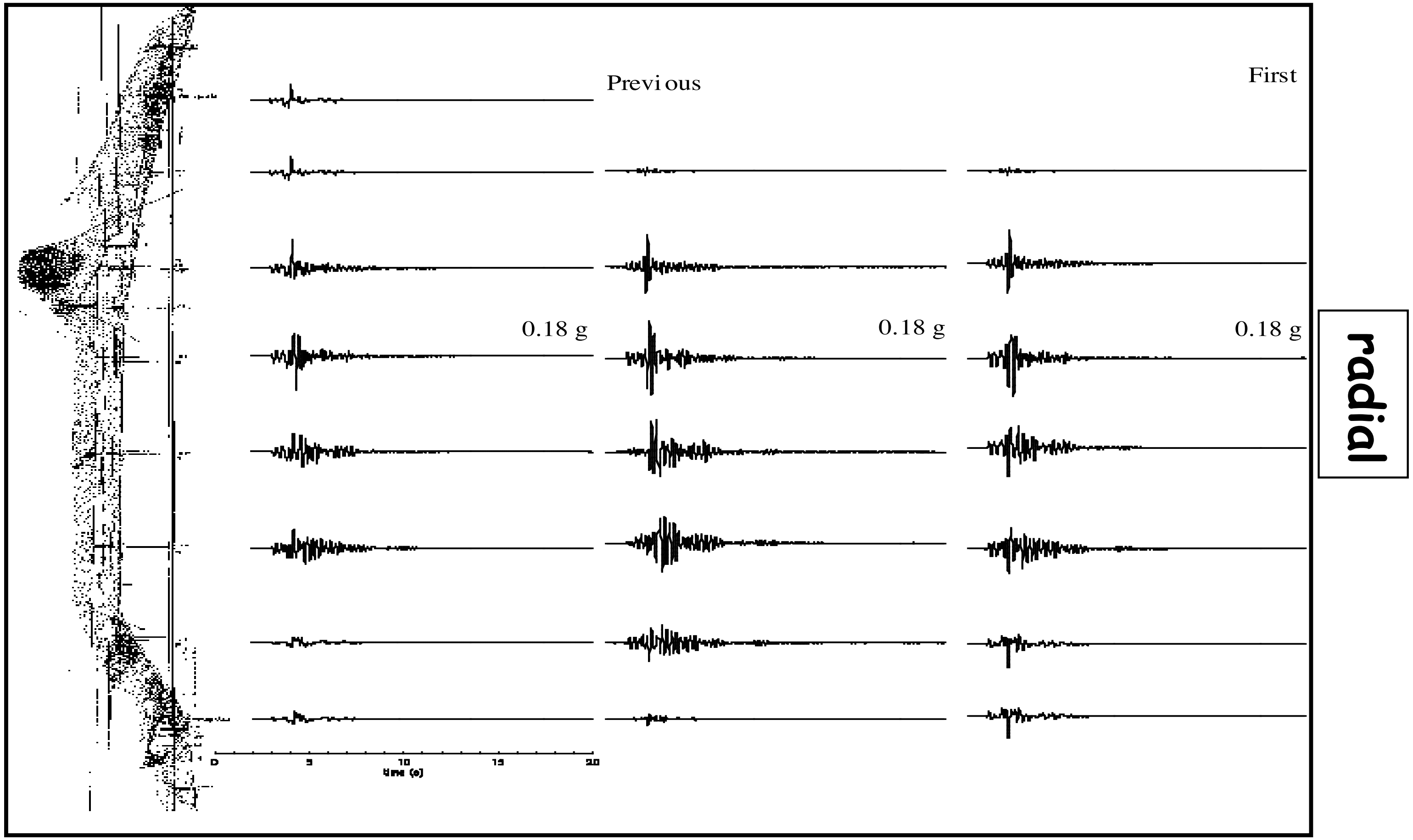


# Initial synthesis - radial



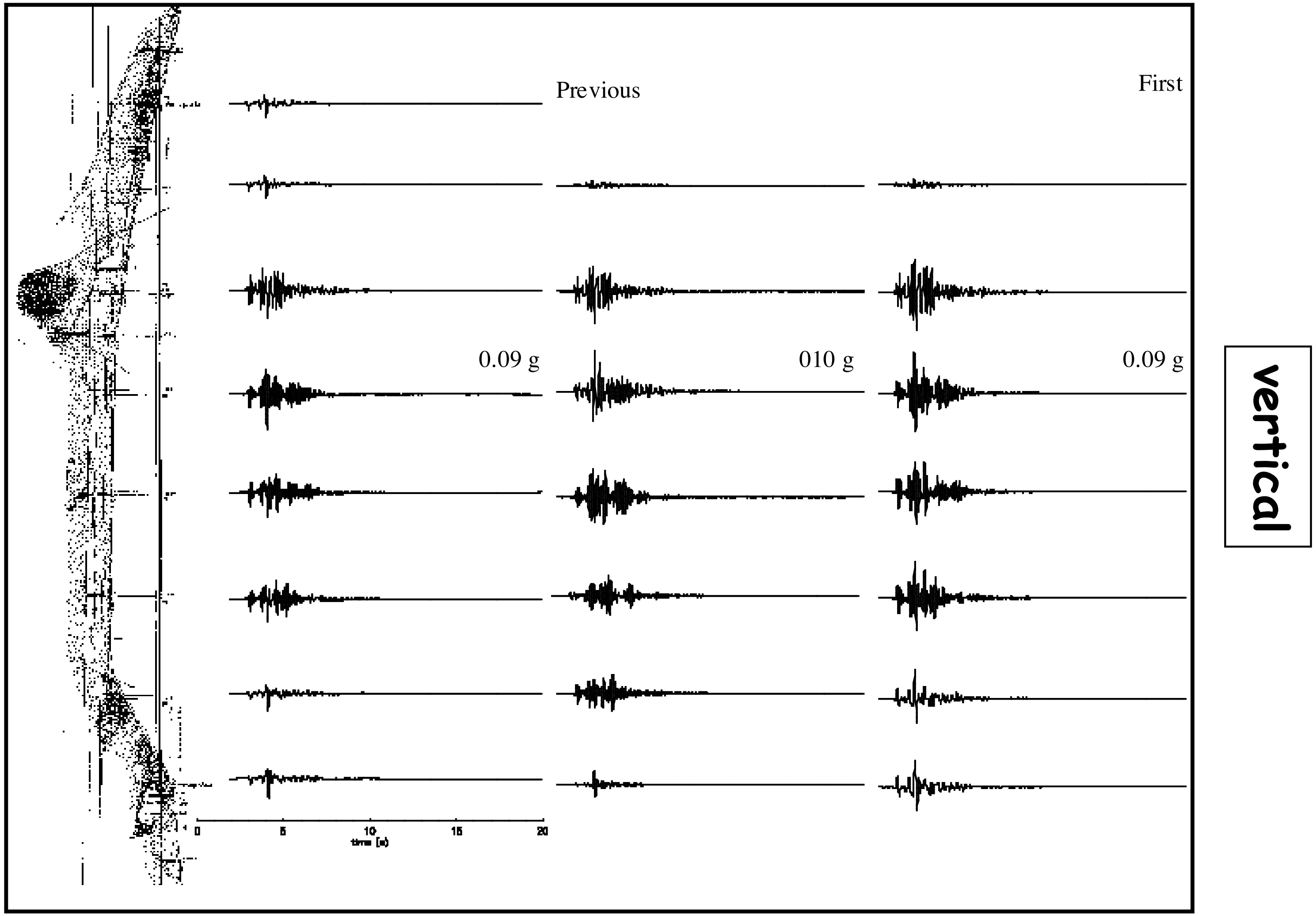

Case study: initial scenario

# Synthetic accelerations and diffograms



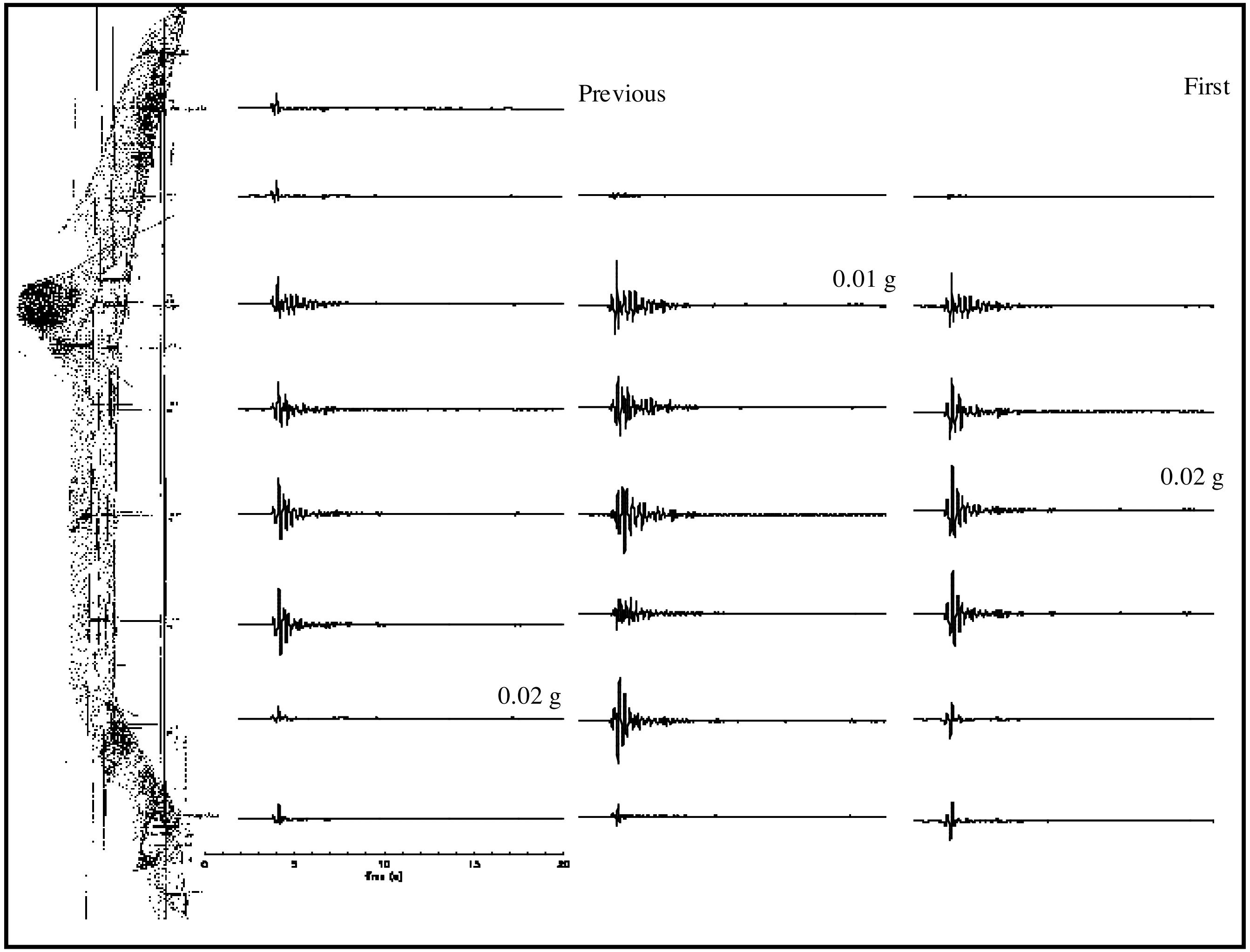

Case study: initial scenario

# Synthetic accelerations and diffograms




Case study: initial scenario

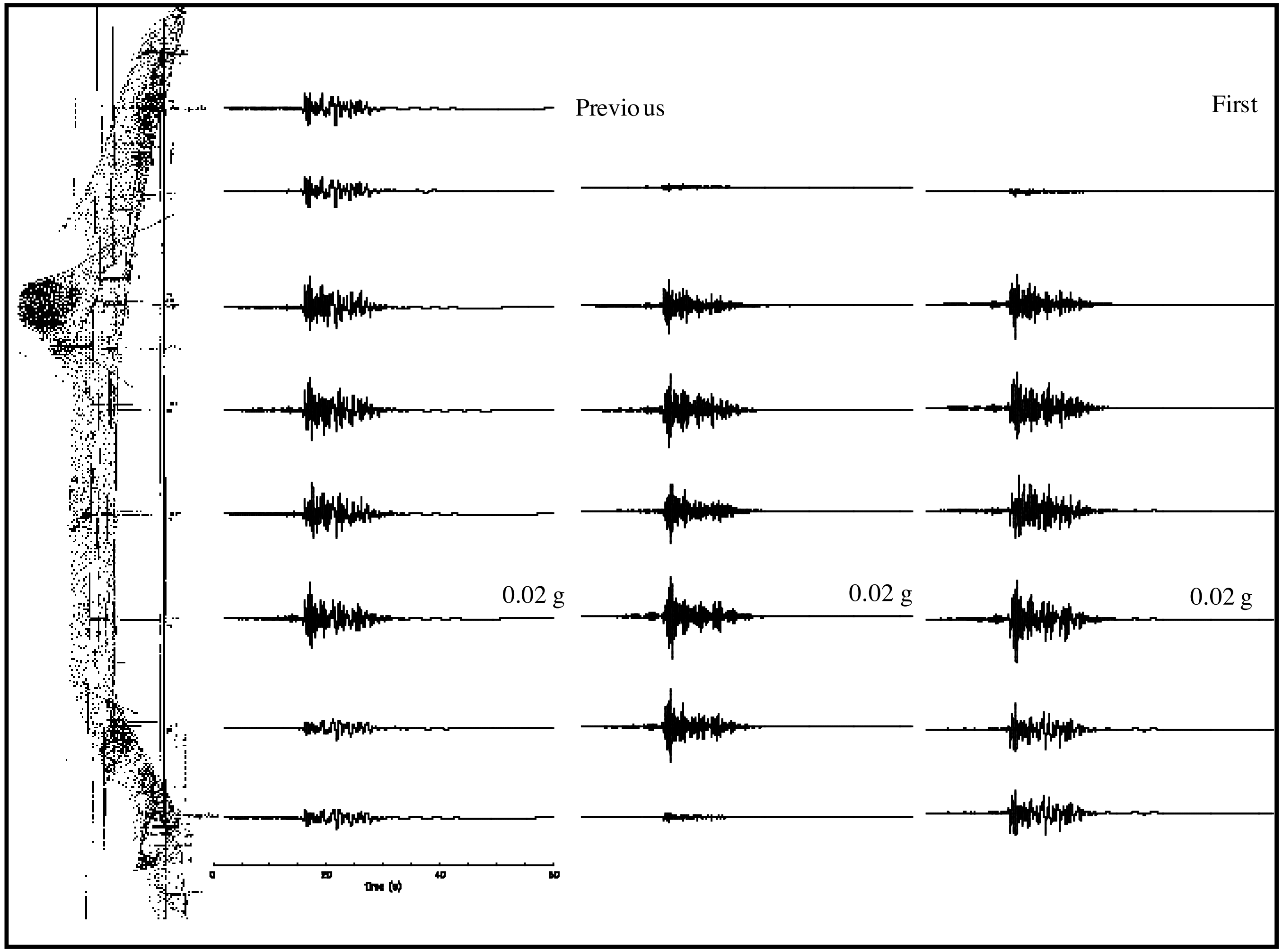
# Synthetic accelerations and diffograms




transverse

Case study: initial scenario

# Synthetic accelerations and diffograms




S3 - radial

Case study: initial scenario

# Outline

**Seismic input for a critical facility**

Parametric studies

Focal mechanism

Site effects

Directivity

# PARAMETRIC STUDY 1
# Focal Parameters towards MCE

All the focal mechanism parameters of the original source model have been varied in order to find the combination producing the maximum amplitude of the various ground motion components.

| Longitude (°) | Latitude (°) | Focal Depth (km) | Strike (°) | Dip (°) | Rake (°) | Magnitude Ms (Mb) |
|---|---|---|---|---|---|---|
| **16.120** | **47.730** | **18** | **190** | **70** | **324** | **5.5 (4.9)** |

1) Strike angle (Depth=5km)

2) Rake angle

3) Strike-Rake angles variation (Dip=45°)

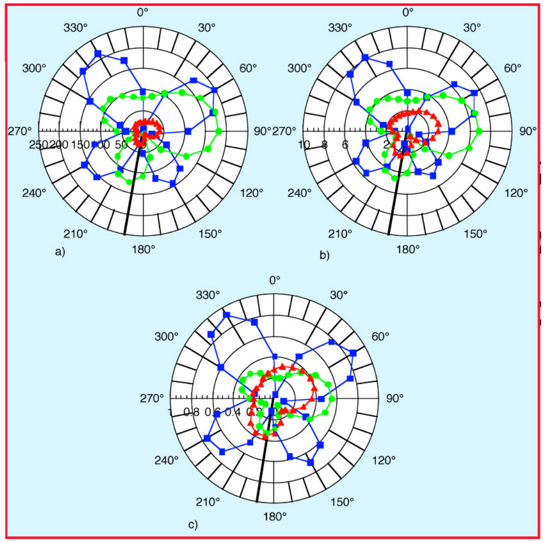
4) Strike-Rake angles variation (Dip=70°)

5) Strike-Rake angles variation (Dip=90°)

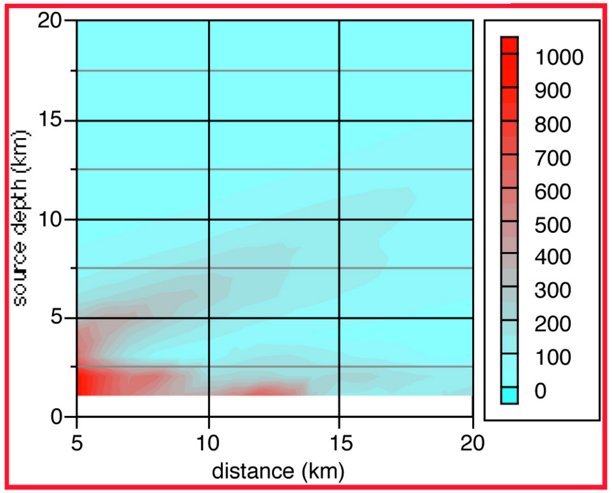
6) Depth-Distance variation

(Strike=60°, Dip=70°,Rake=0, 90°)

# PARAMETRIC STUDY 1
# Focal Parameters towards MCE

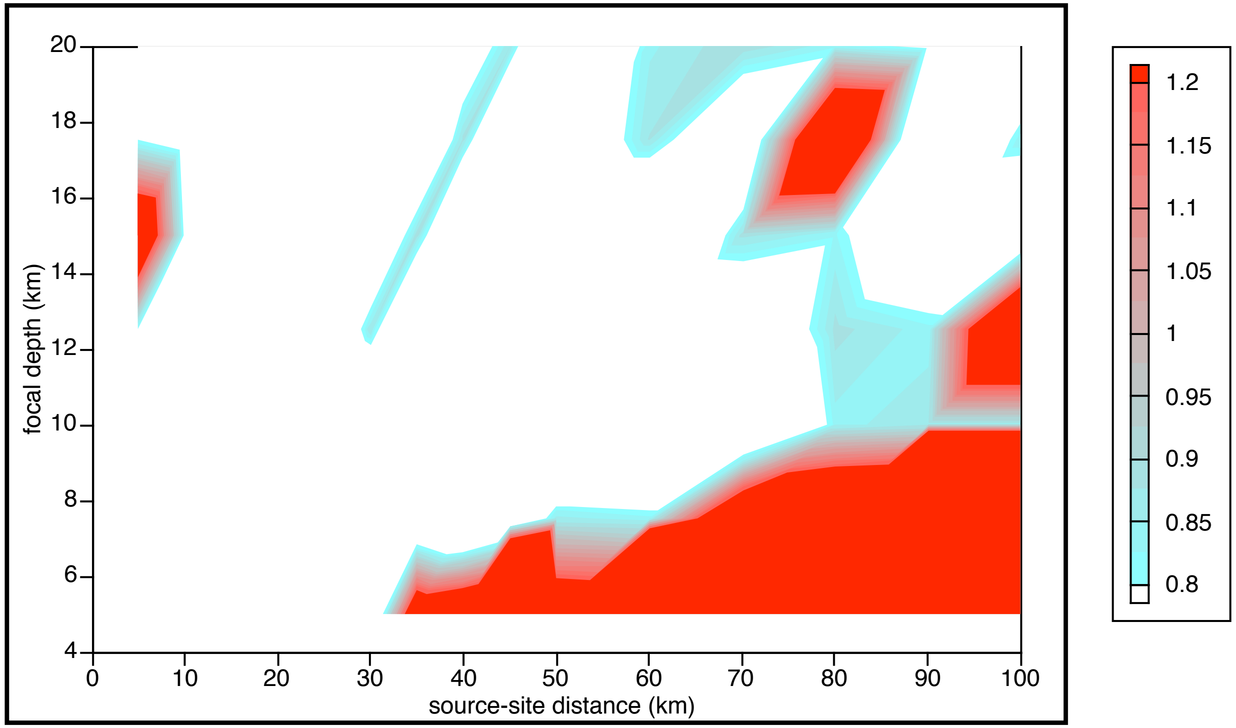


# PARAMETRIC STUDY 1
# Focal Parameters towards MCE



# PARAMETRIC STUDY 2 - Fp towards 1Hz

Another parametric study has been performed in order to find a seismic source-Warth site configuration providing a set of signals whose seismic energy is concentrated around 1 Hz, frequency that corresponds approximately to that of the fundamental transverse mode of oscillation of the bridge.



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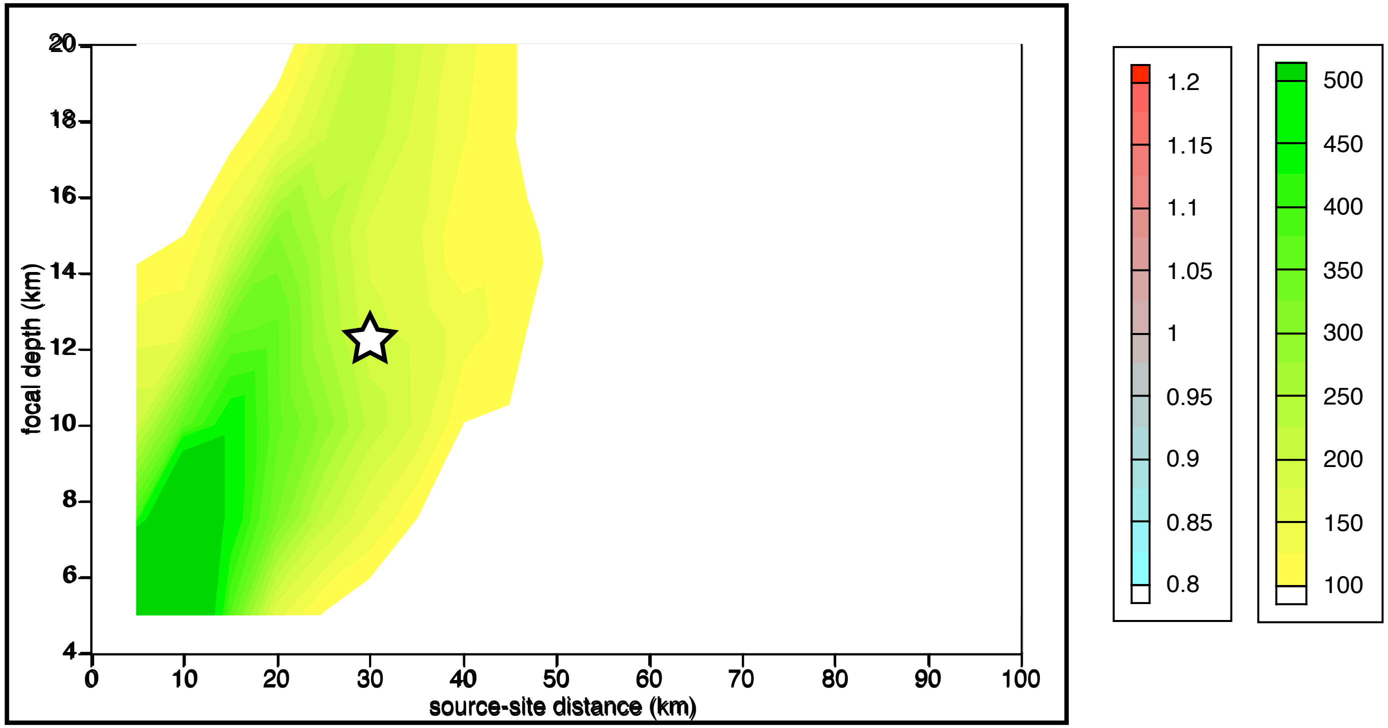
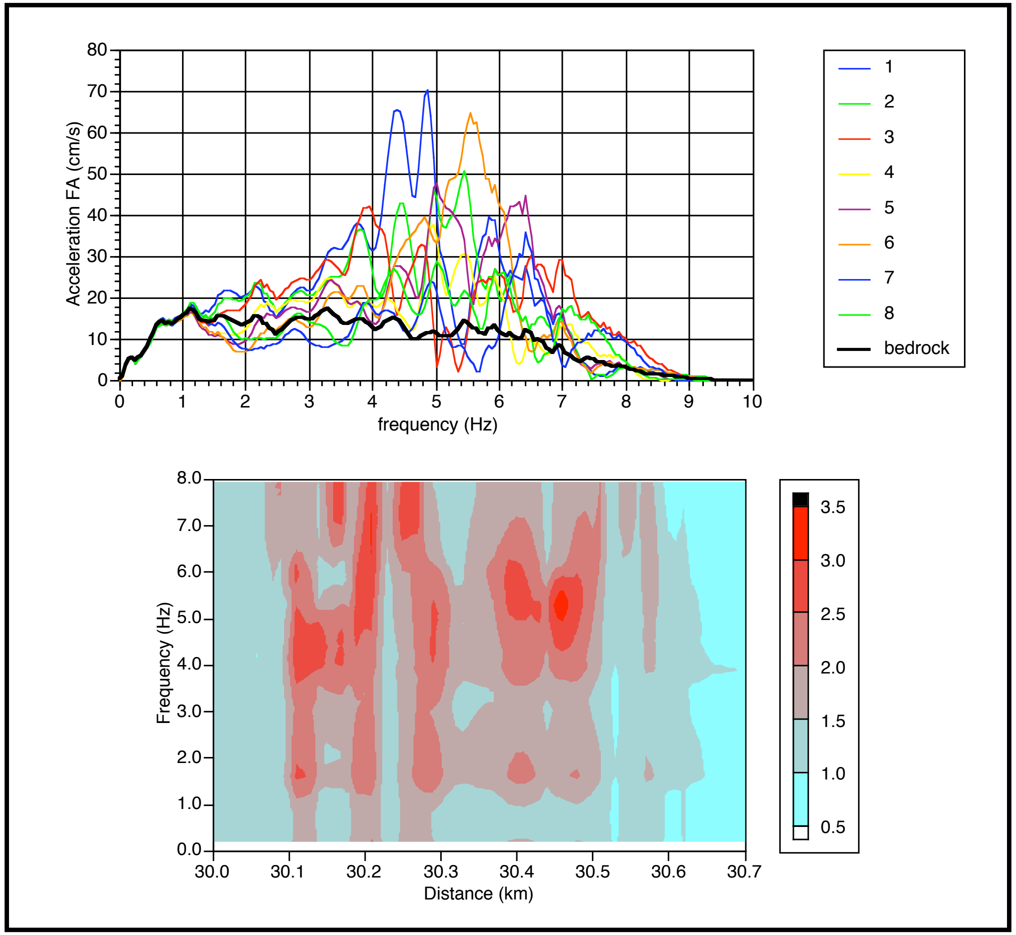



The results show that, in order to reach a relevant value of PGA (e.g. greater than 0.1g) in the desired period range (i.e. 0.8-1.2 s), an alternative and suitable configuration is a source
12 km deep at an epicentral distance of 30 km.

# Parametric study 2  - FS & RSR




The results show that, the local structure beneath the Warth bridge greatly amplifies the frequency components between 3 and 7 Hz, i.e. a frequency range not corresponding to the fundamental transverse mode of oscillation of the bridge (about 0.8 Hz)

Parametric study 2 - DD

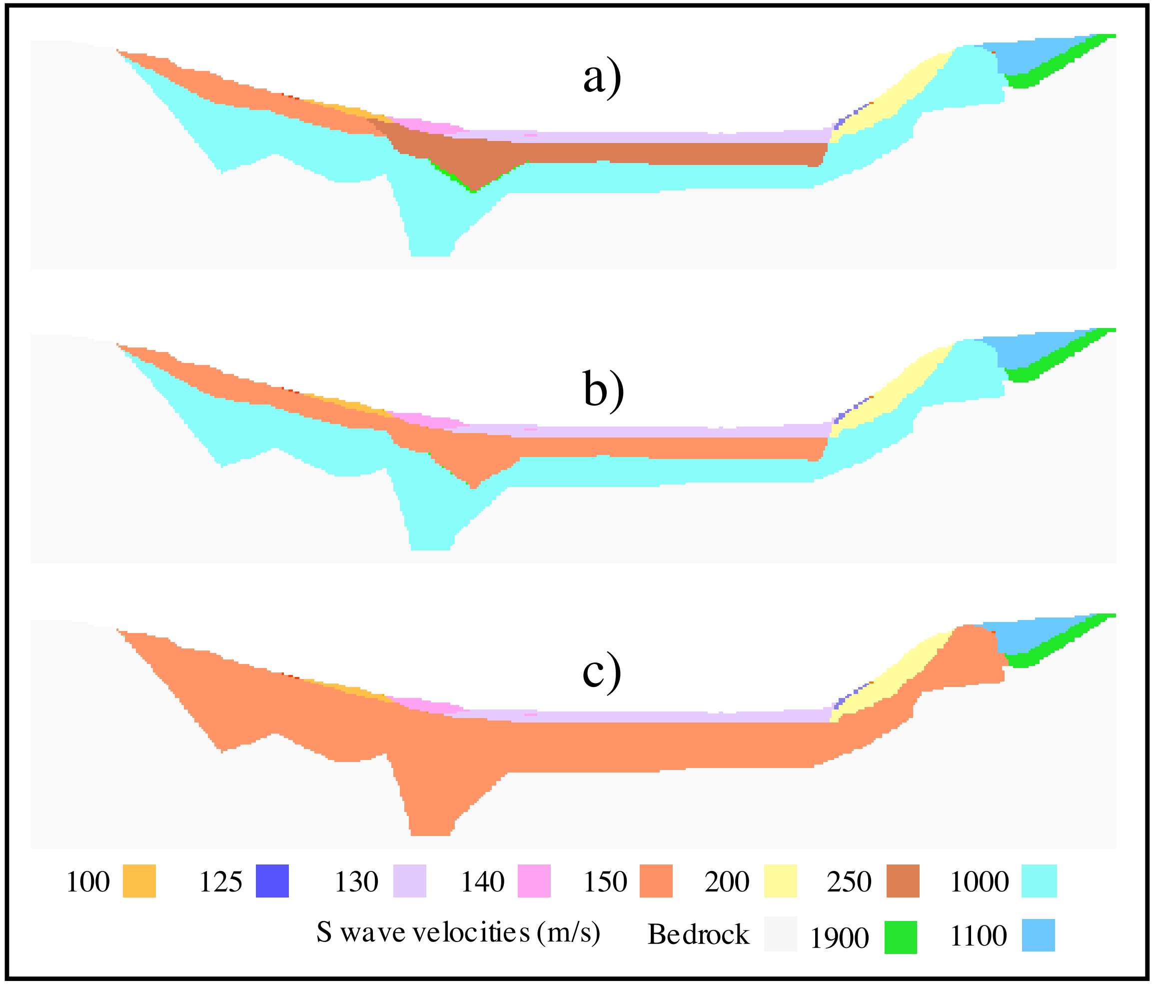
# Outline

**Seismic input for a critical facility**

Parametric studies

- Focal mechanism
- Site effects
- Directivity

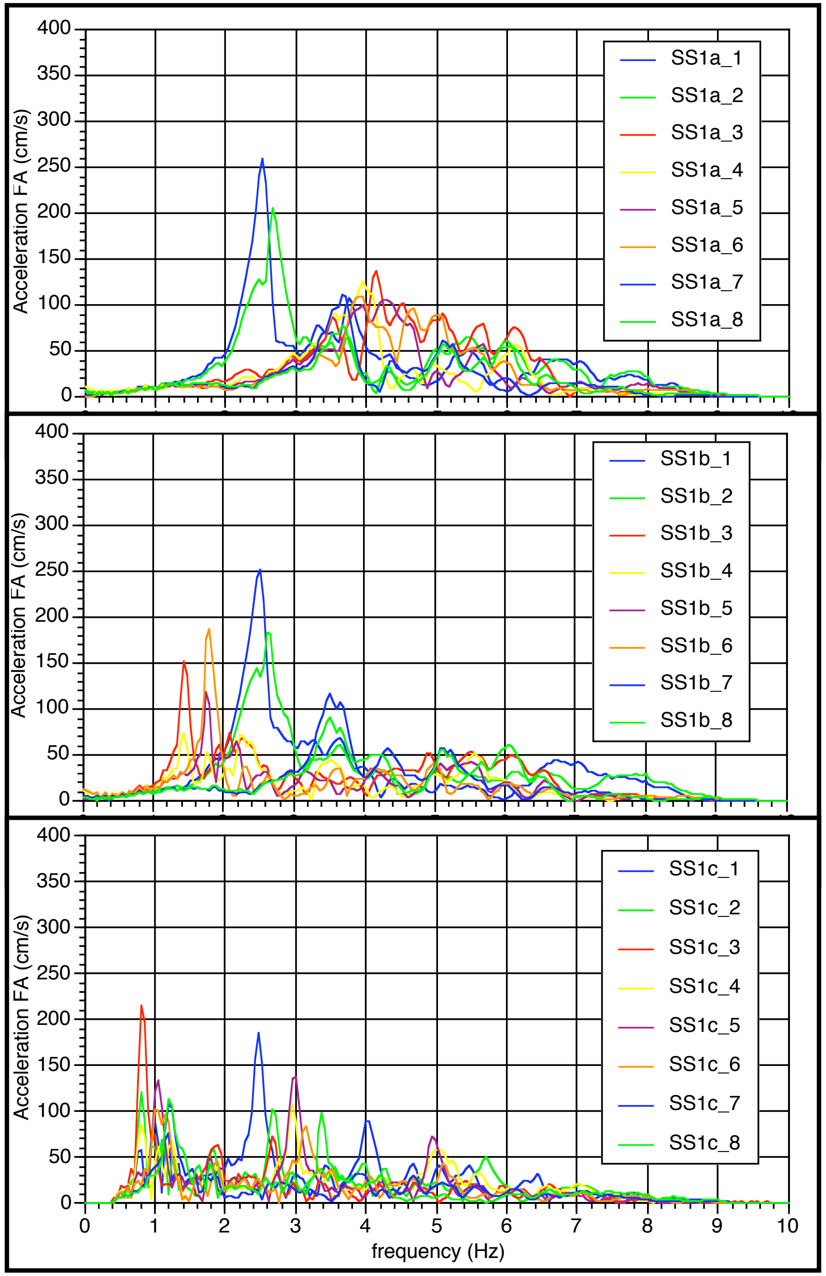
# Parametric study 3 - LMp towards 1Hz



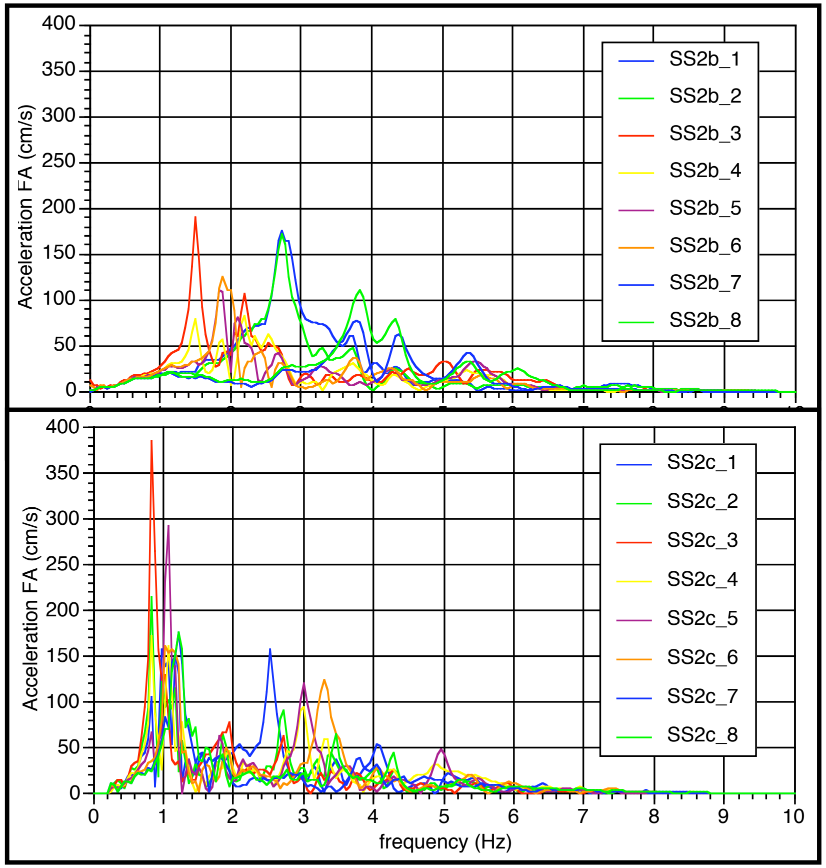

Local geotechnical models of Warth bridge section obtained **lowering successively the S-wave velocities of the uppermost units**

# Fourier Amplitude spectra

## M=5.5; d=8.6km; h=5km

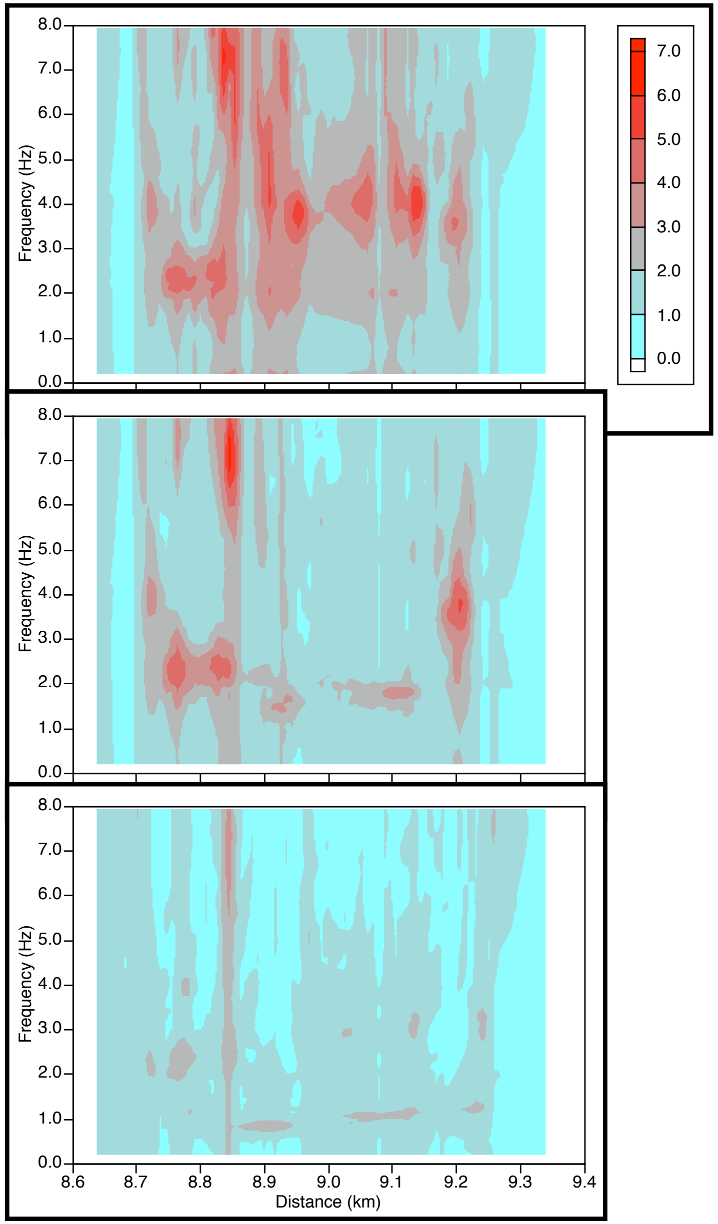



## M=6.5; d=30.0km; h=12km

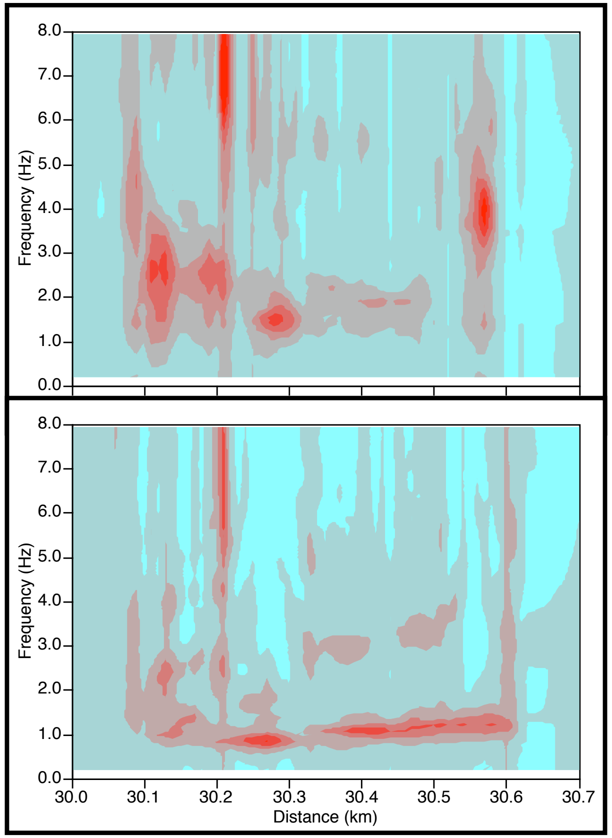


# Site response estimation

## M=5.5; d=8.6km; h=5km

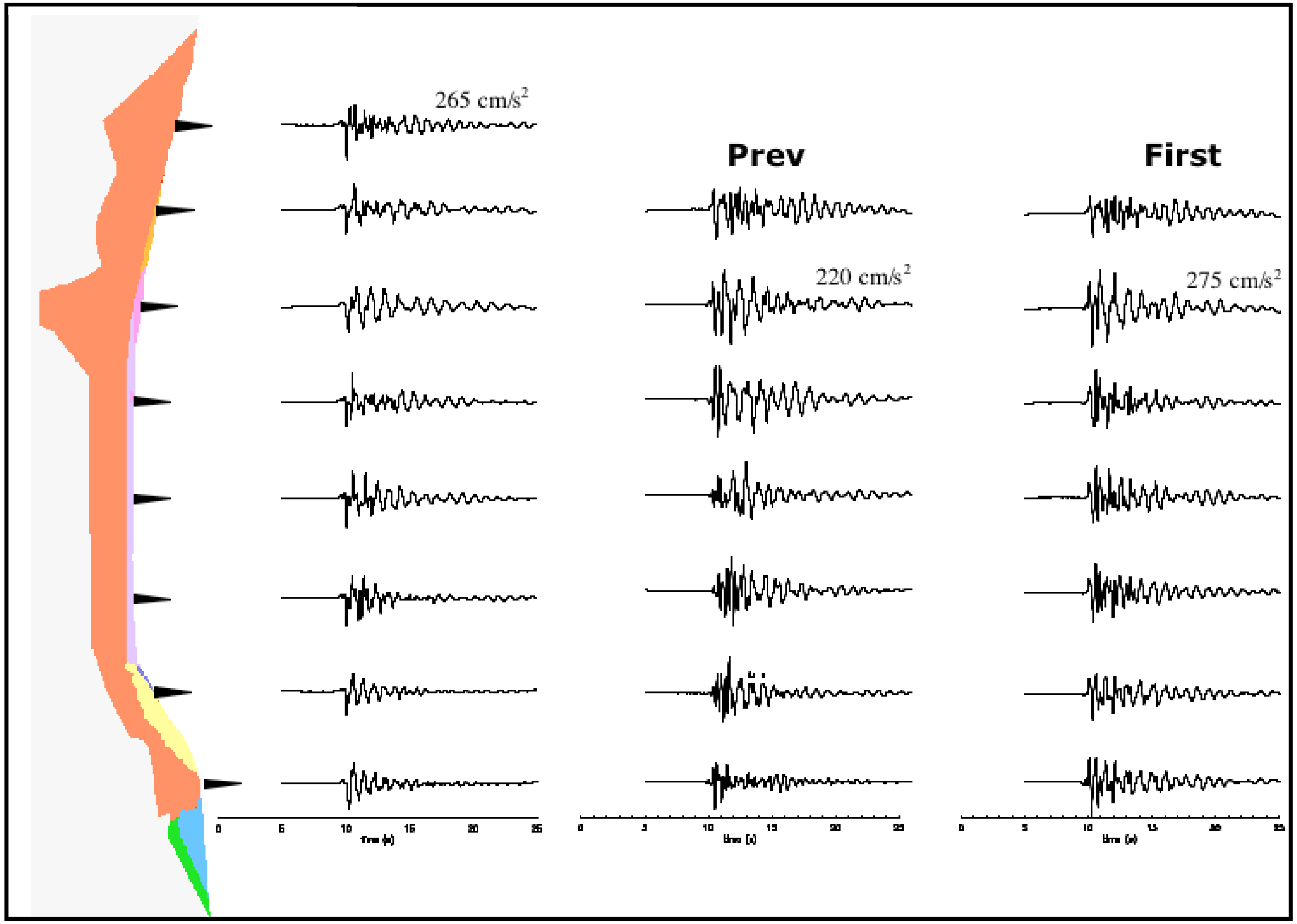



## M=6.5; d=30.0km; h=12km

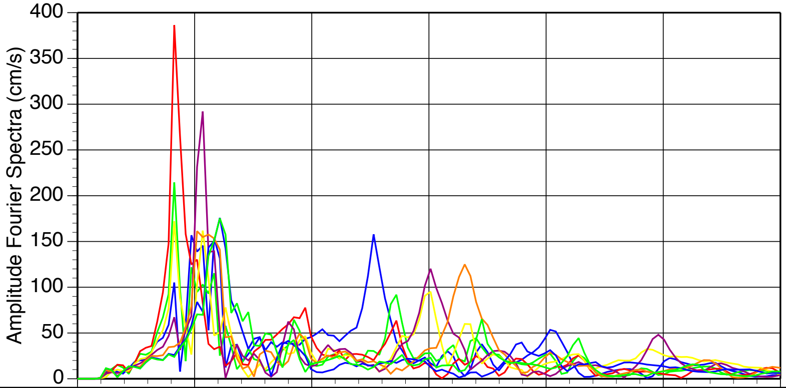


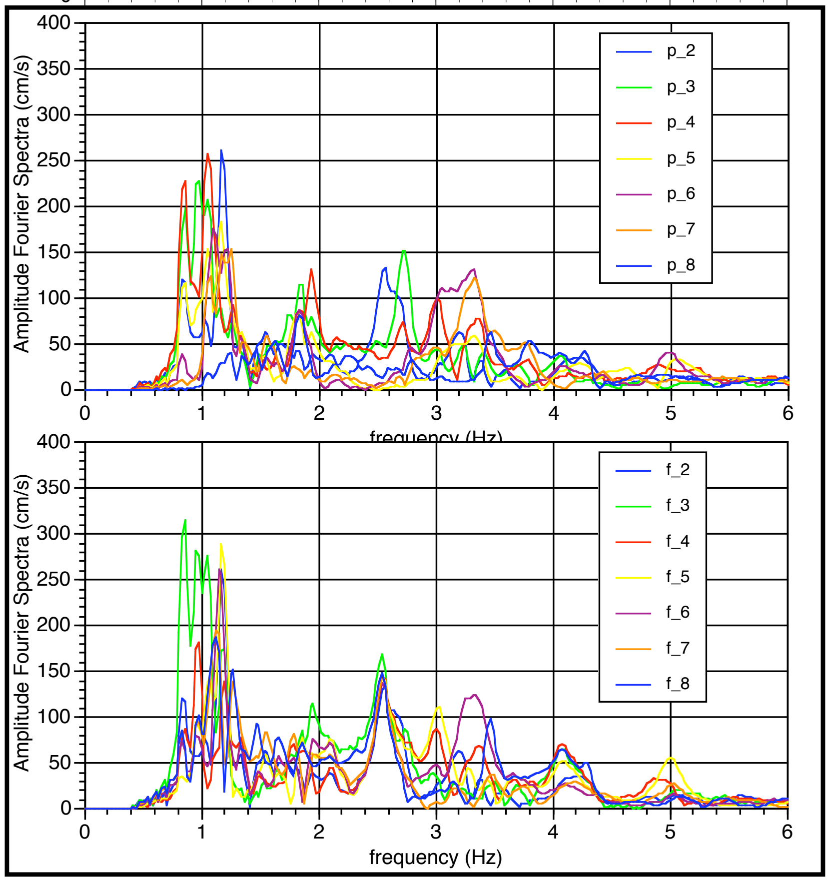

Parametric study 3 - LM

# Synthetic accelerations and diffograms

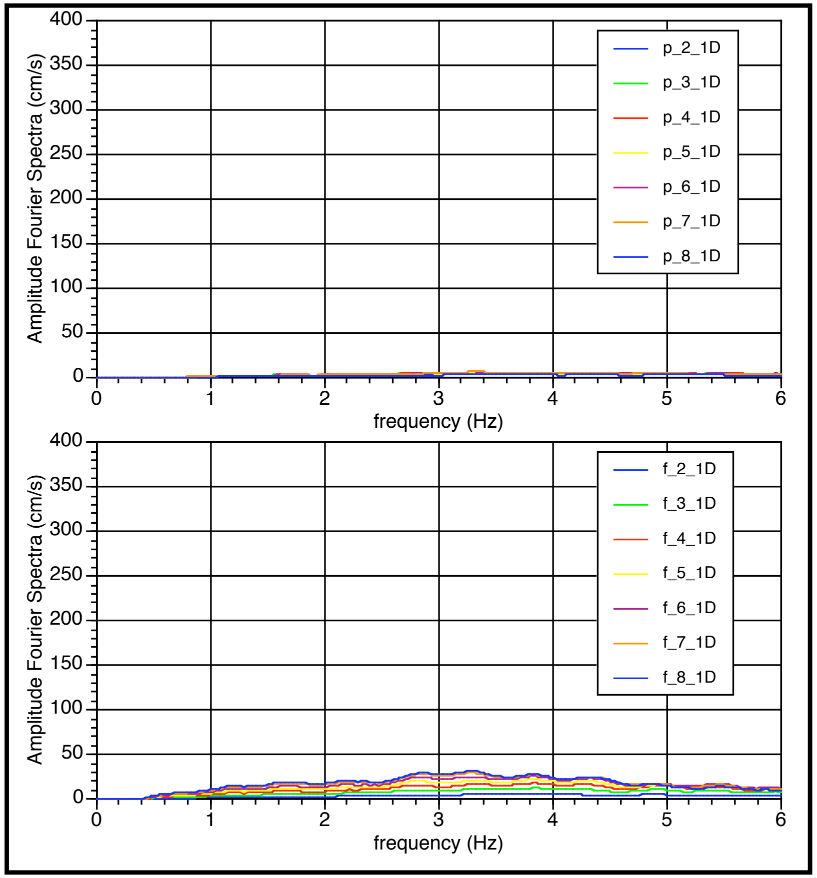


# Fourier AS of diffograms




Bedrock




Case study

# Implementation of PSD tests

Joint Research Centre

## PSD WITH SUBSTRUCTURING

### Application to the Warth Bridge, Austria

Construction of the large-scale bridge piers outside of the ELSA lab

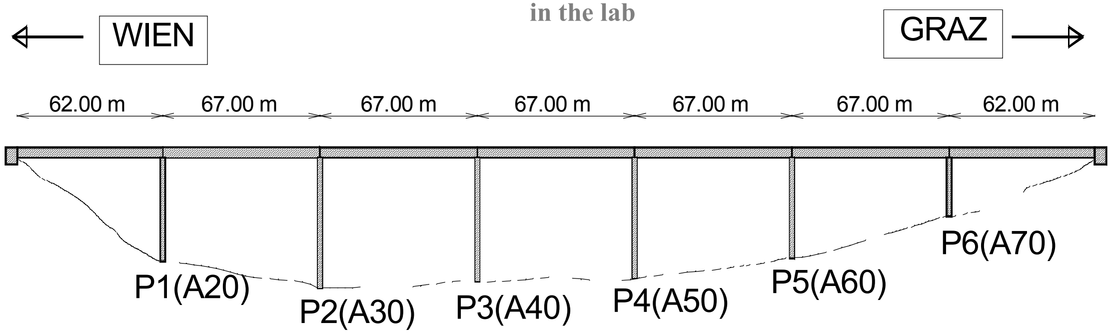
Physical piers A40 & A70 in the lab

Numerical models for the substructured piers A20, A30

Numerical models for the substructured piers A50, A60

Numerical model for the deck and PSD master

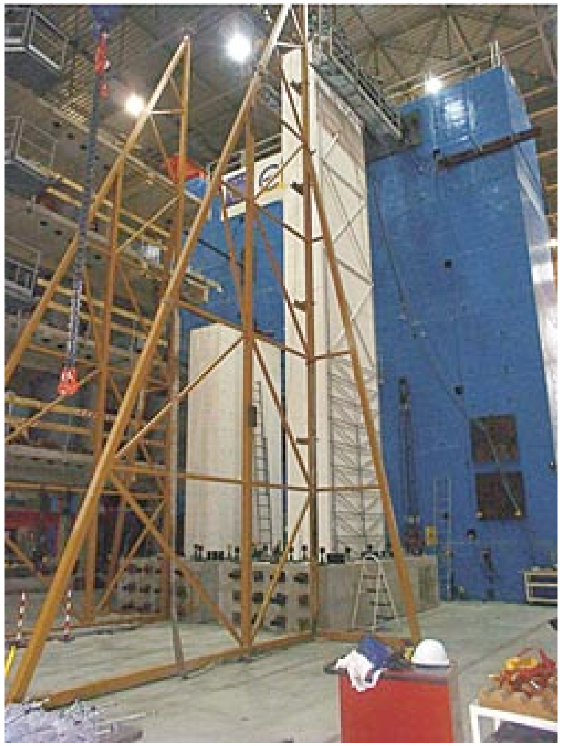
Master experimental process

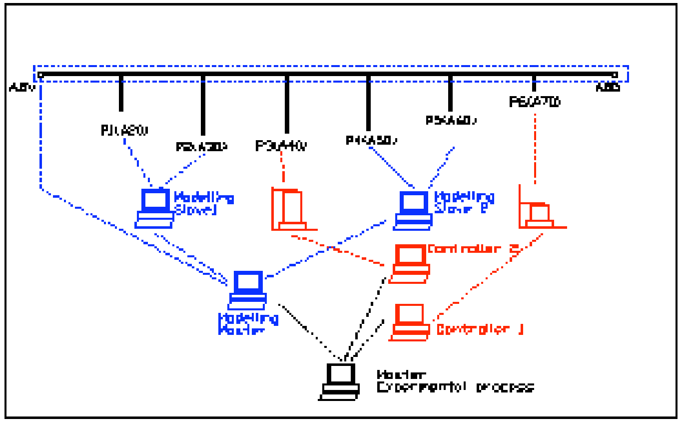



Warth Bridge

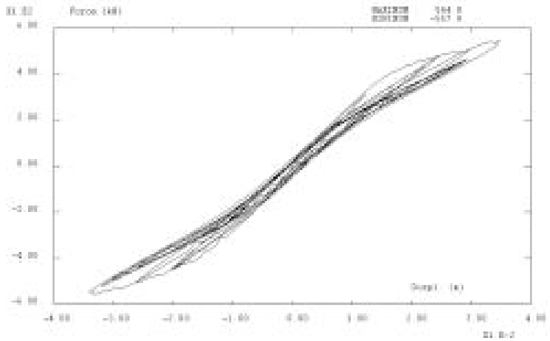
elsa

# Implementation of PSD tests



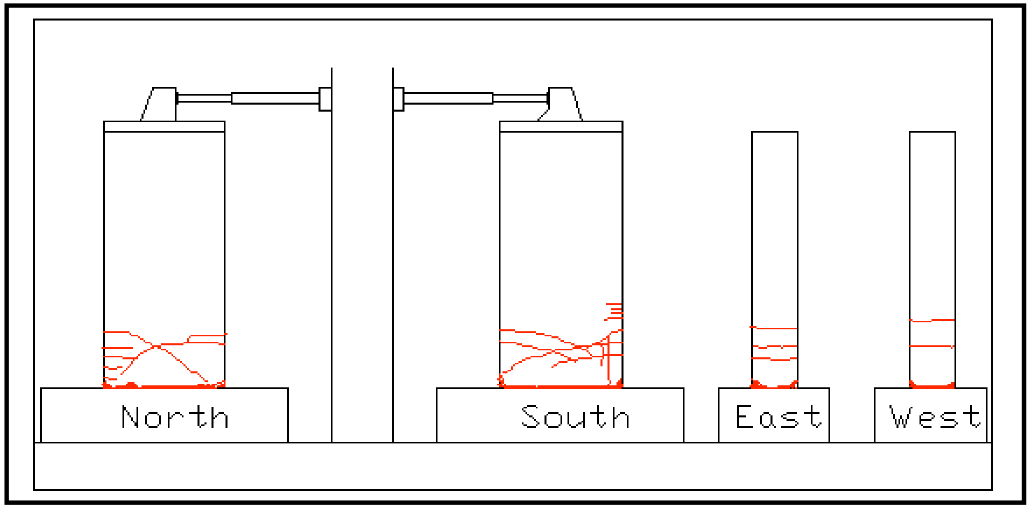



(a) physical piers in the lab, (b), schematic representation
(c) workstations running the PSD algorithm and controlling the test



Force-displacement for Low-level earthquake - experimental results Pier A40

Identification of insufficient seismic detailing. tall pier A40, buckling of longitudinal reinforcement at h = 3.5m




Damage pattern after the end of the High-Level Earthquake PSD test, short pier A70.

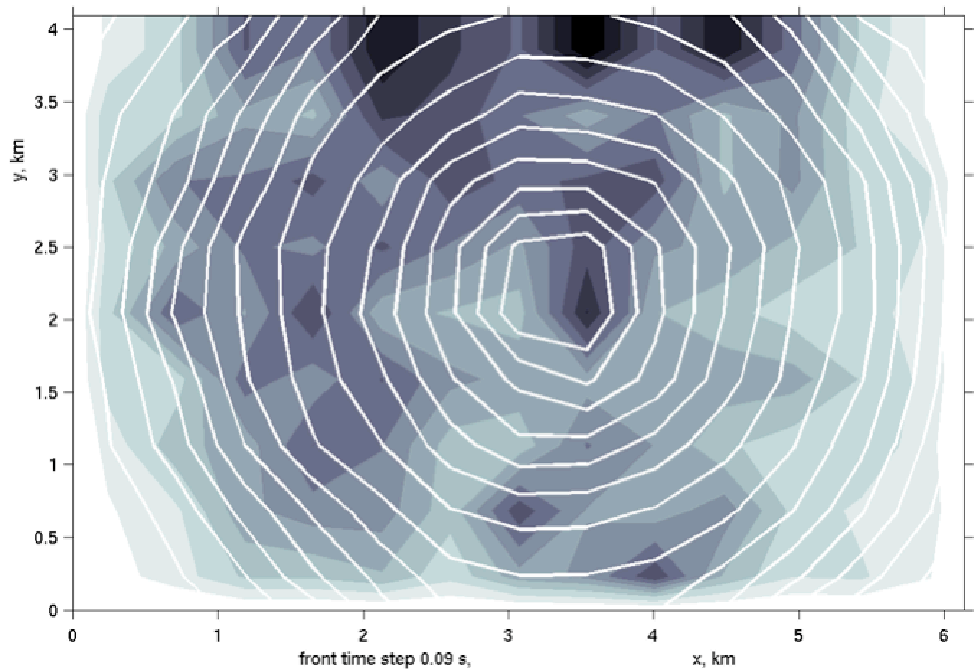
# Outline

**Seismic input for a critical facility**

Parametric studies

- Focal mechanism
- Site effects
- Directivity

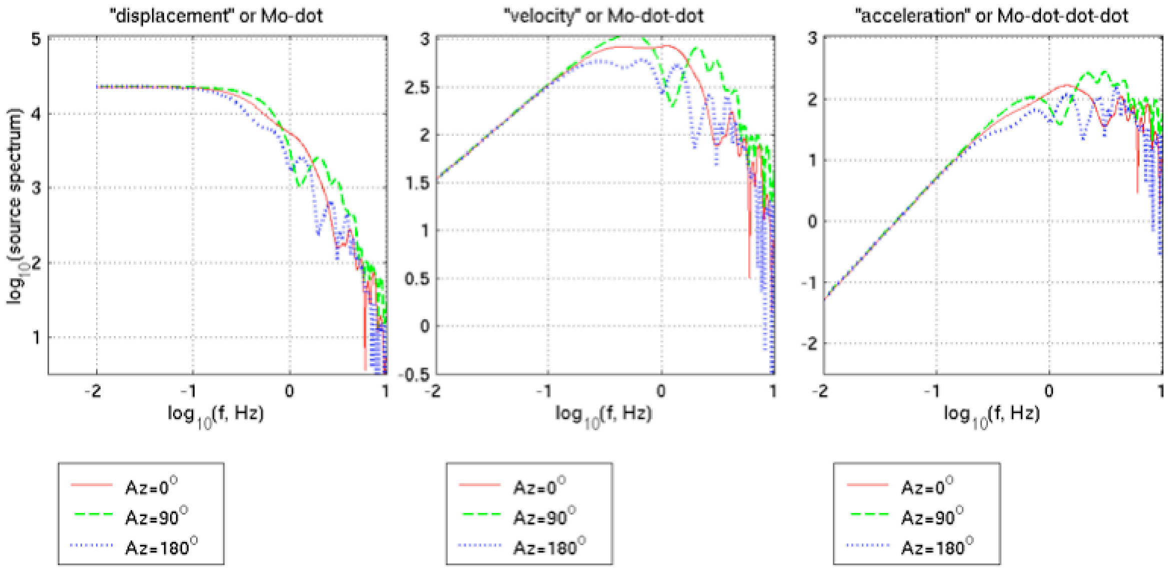
# Parametric study 4 - ESp towards directivity




Parametric study 4 - ES

Rupture model: bilateral at 3 positions

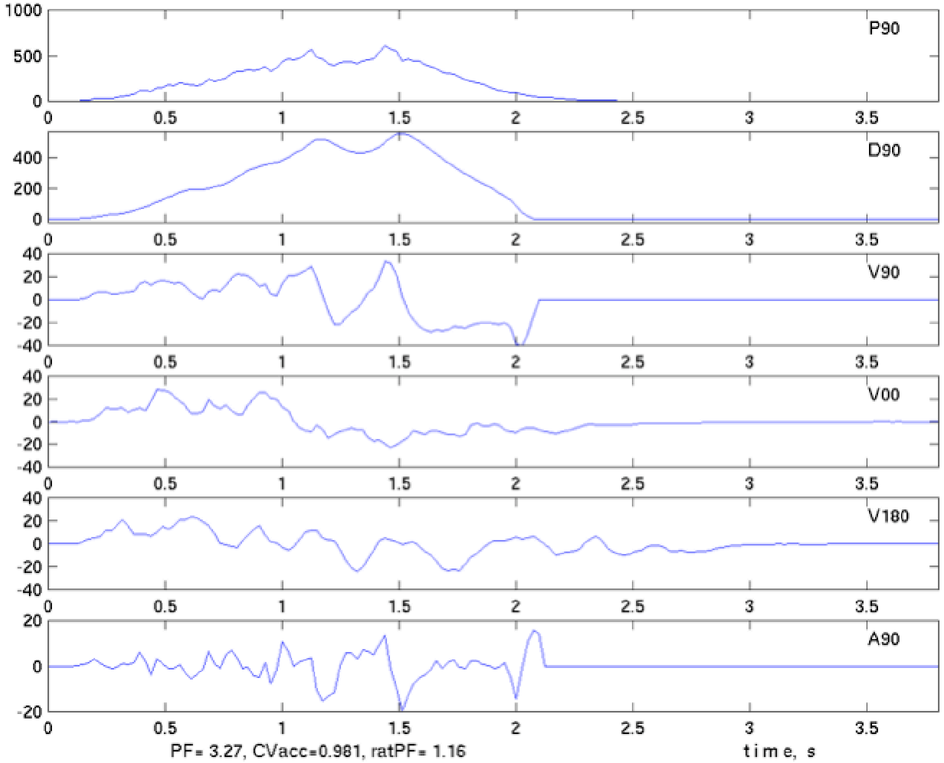
# Parametric study 4 - ESp towards directivity






Rupture model: bilateral at 3 positions

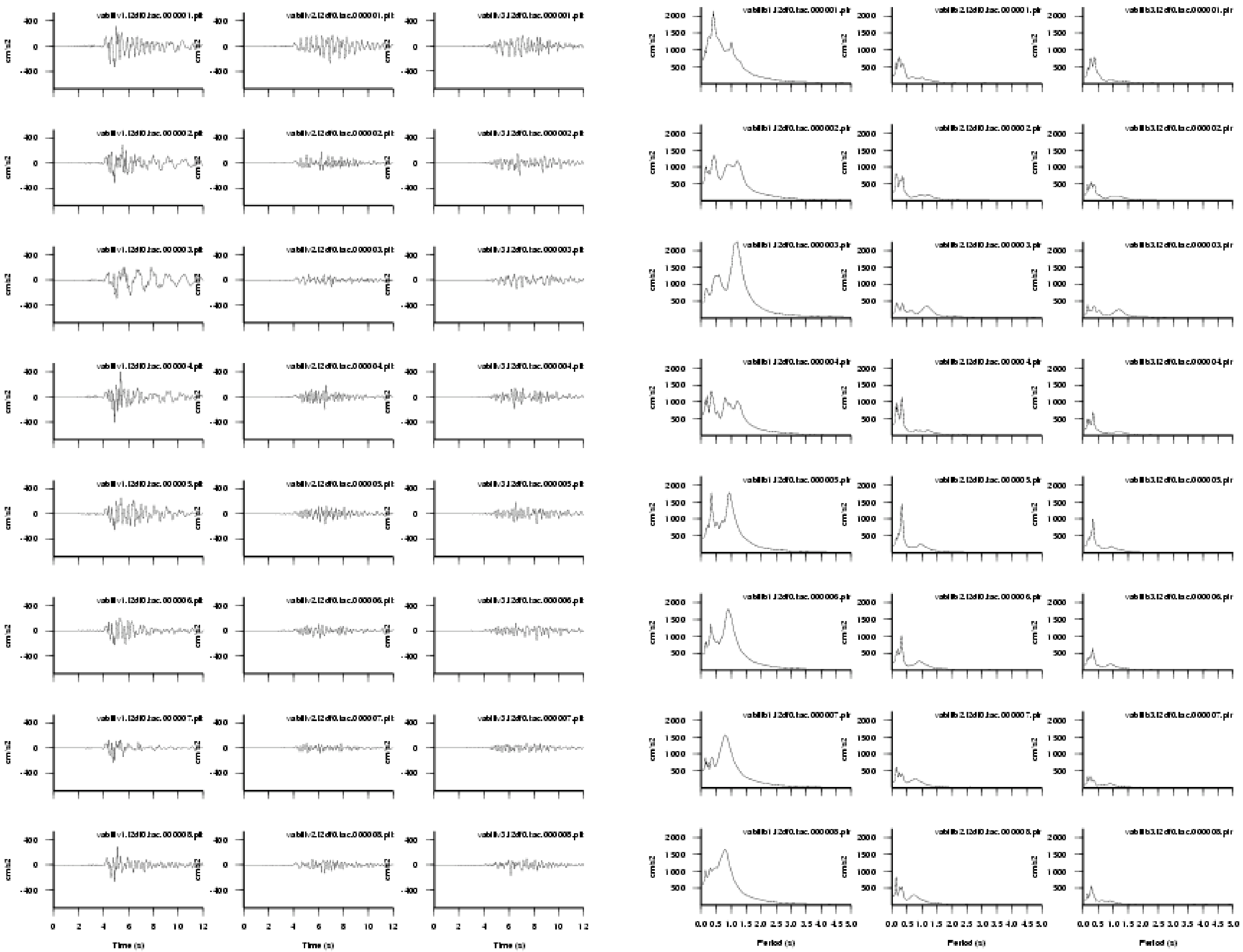
# Parametric study 4 - ESp towards directivity






Rupture model: bilateral at 3 positions

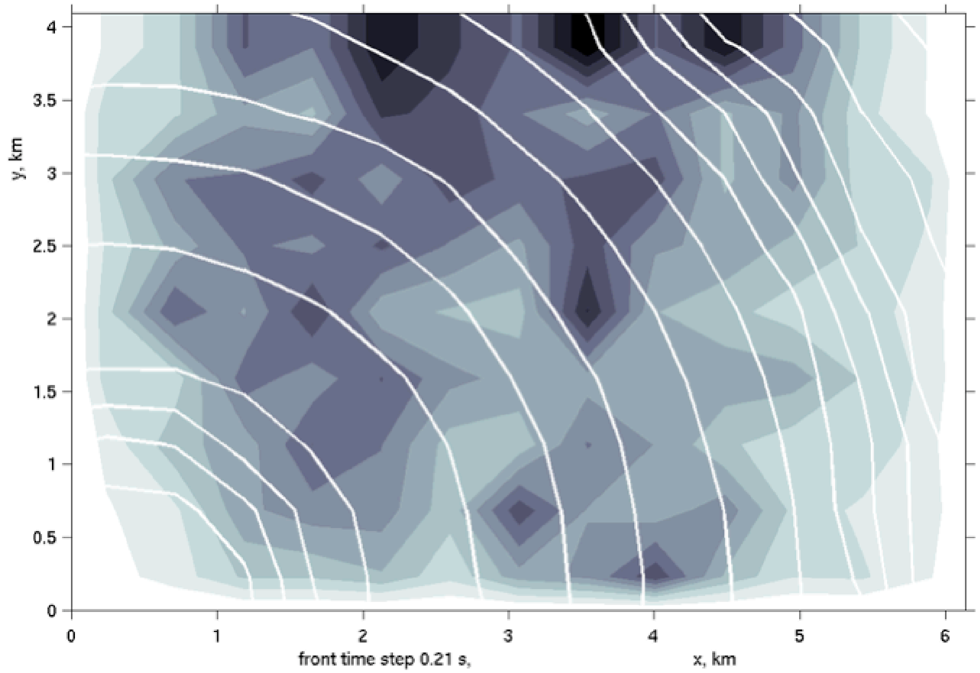
# Parametric study 4 - ESp towards directivity



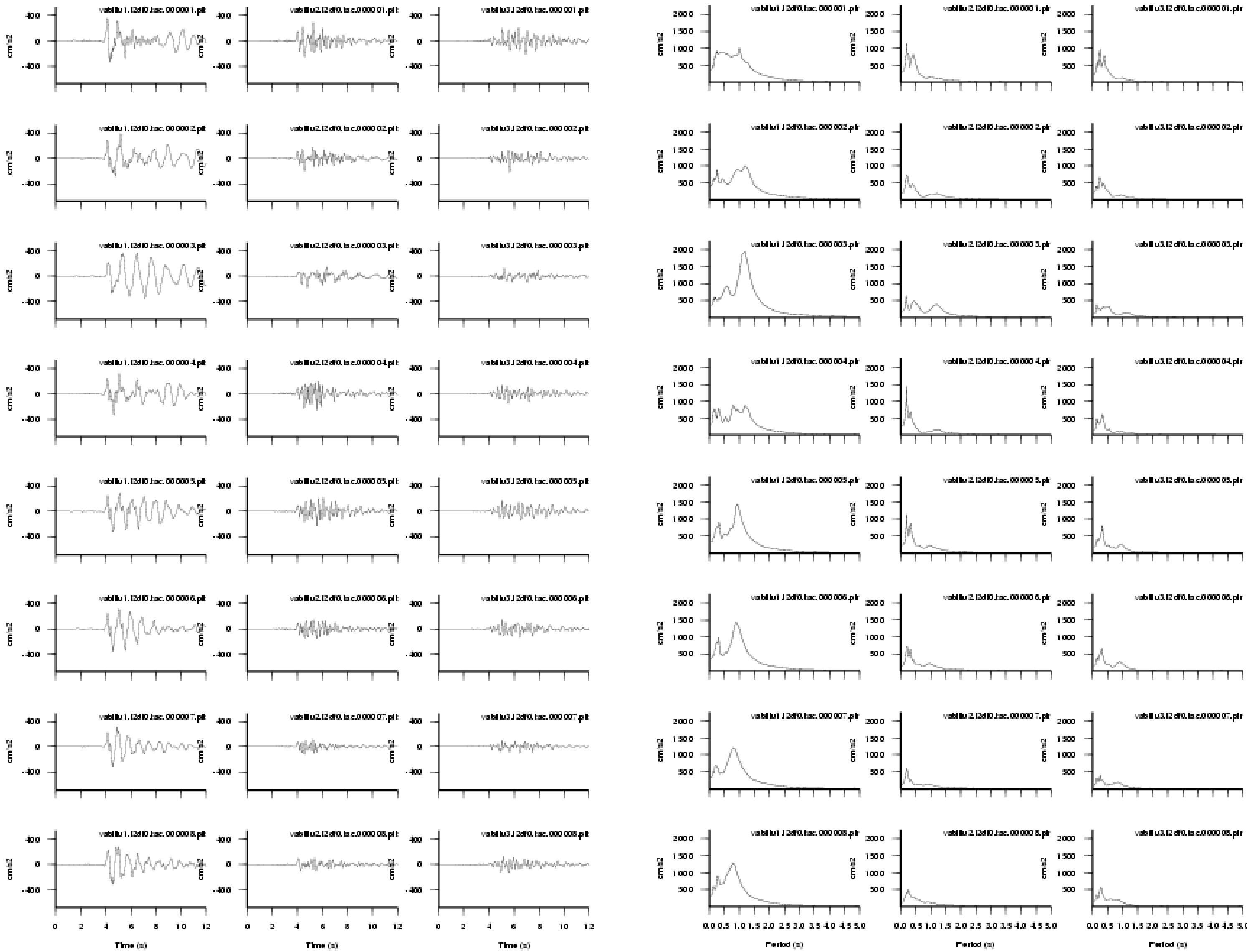
Parametric study 4 - ES

Rupture model: bilateral at 3 positions

# Parametric study - ESp towards directivity



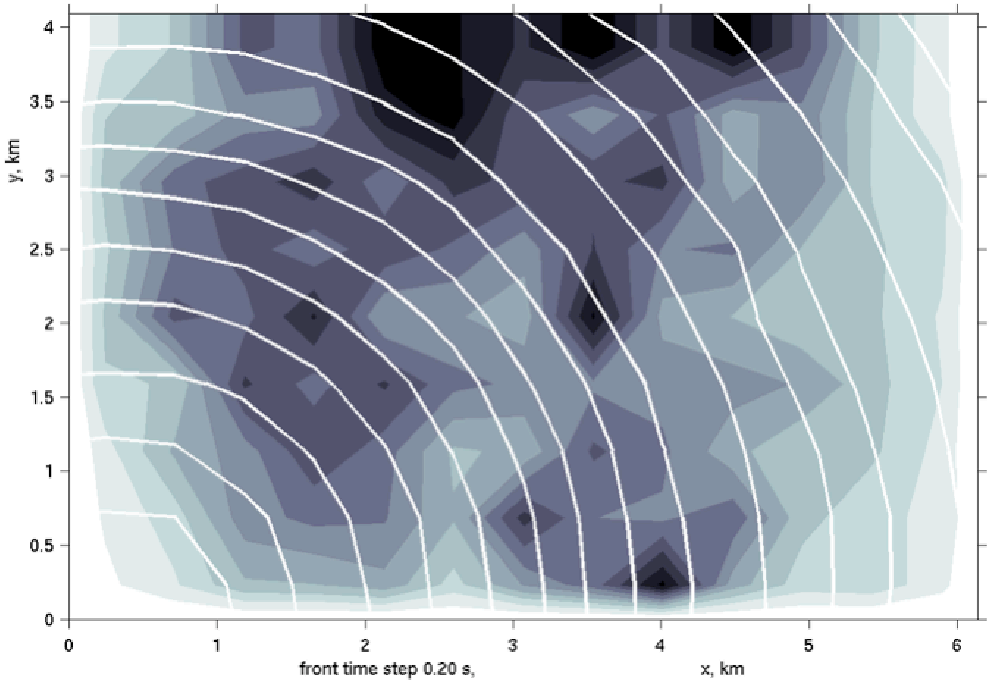
# Parametric study - ESp towards directivity




Parametric study 4 - ES

Rupture model: unilateral at 3 positions

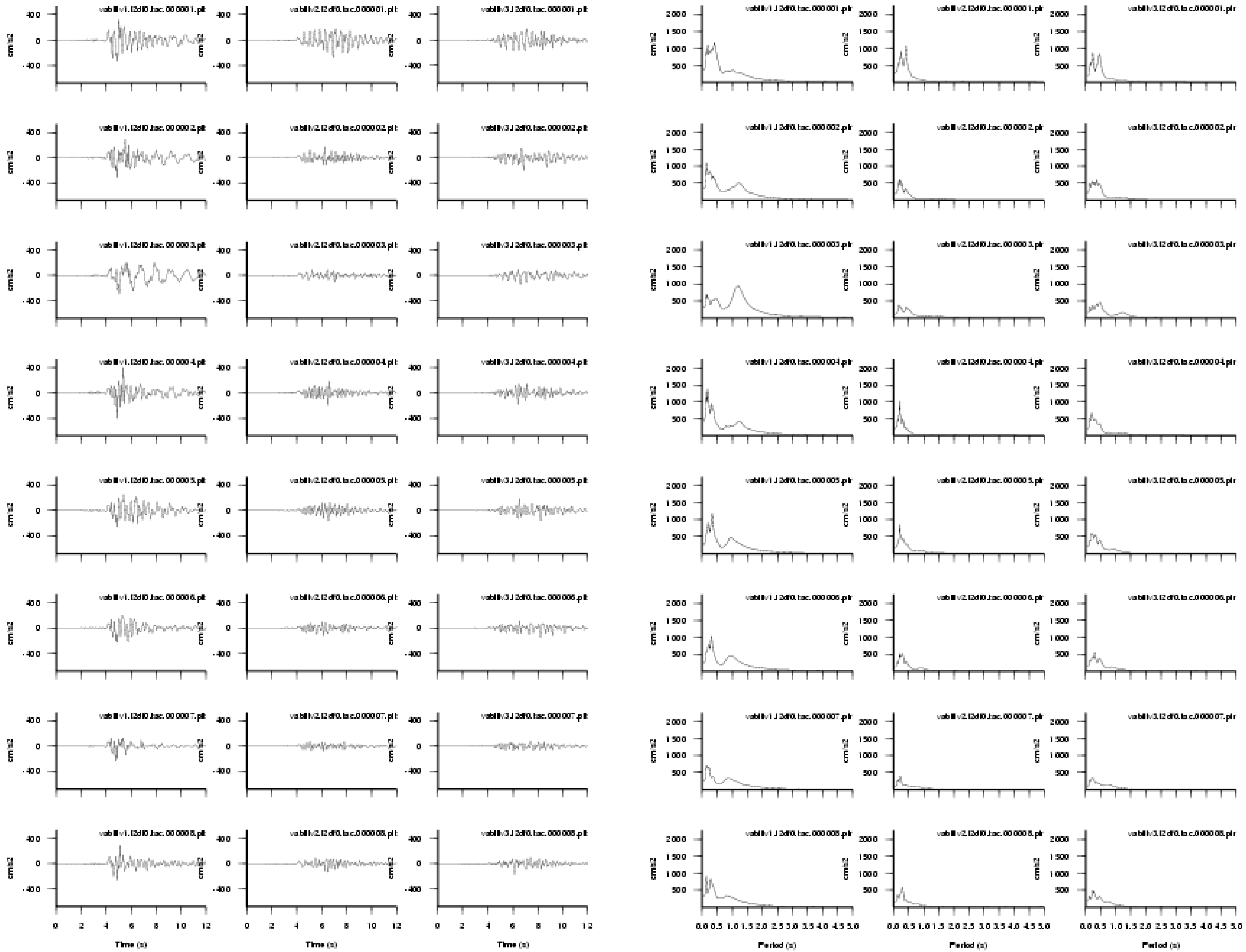
# Parametric study - ESp towards directivity






Rupture model: un. different $v_r$ at 3 positions

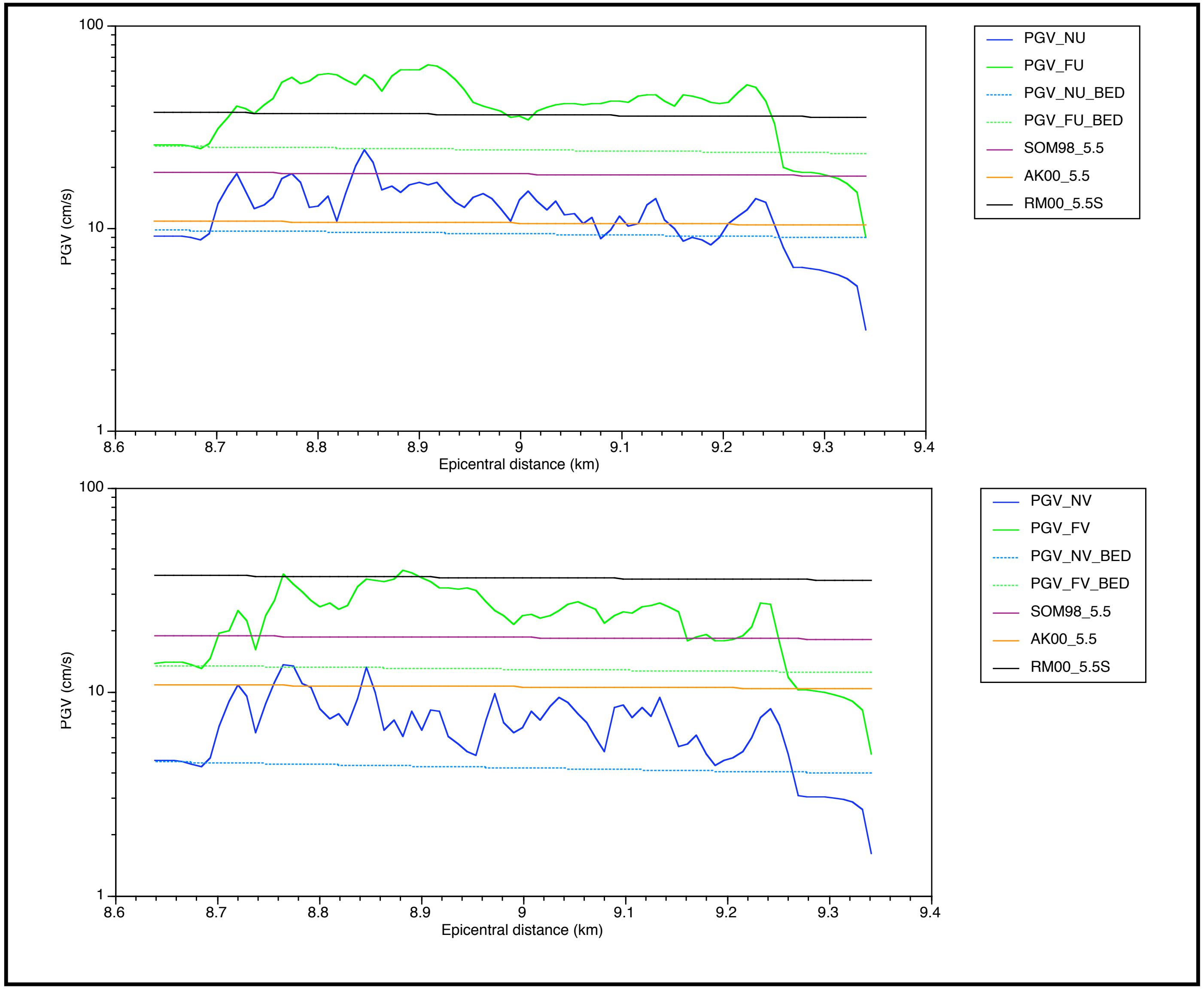
# Parametric study - ESp towards directivity




Parametric study 4 - ES

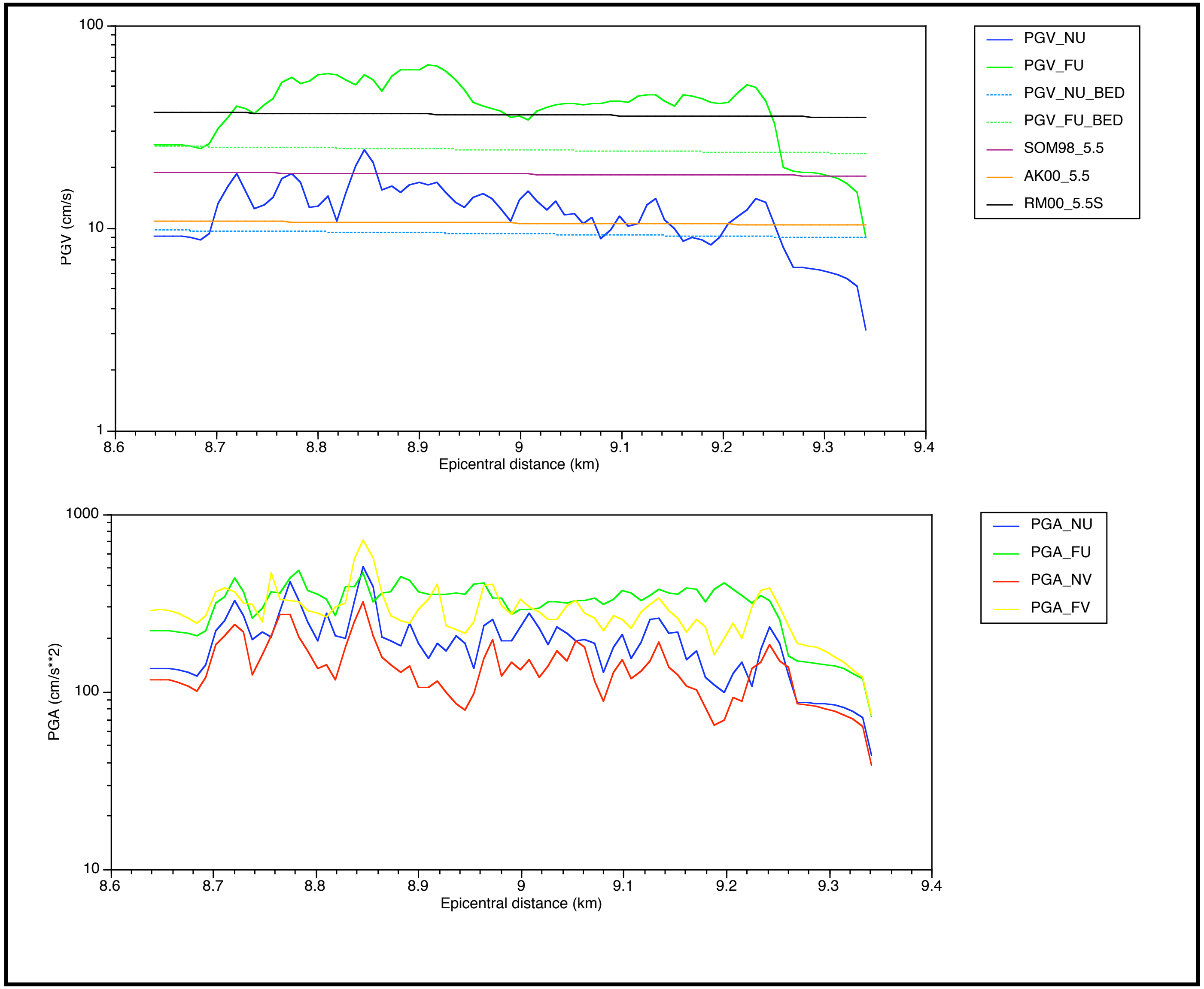
Rupture model: un. different $v_r$ at 3 positions

# PGV - PGA and directivity



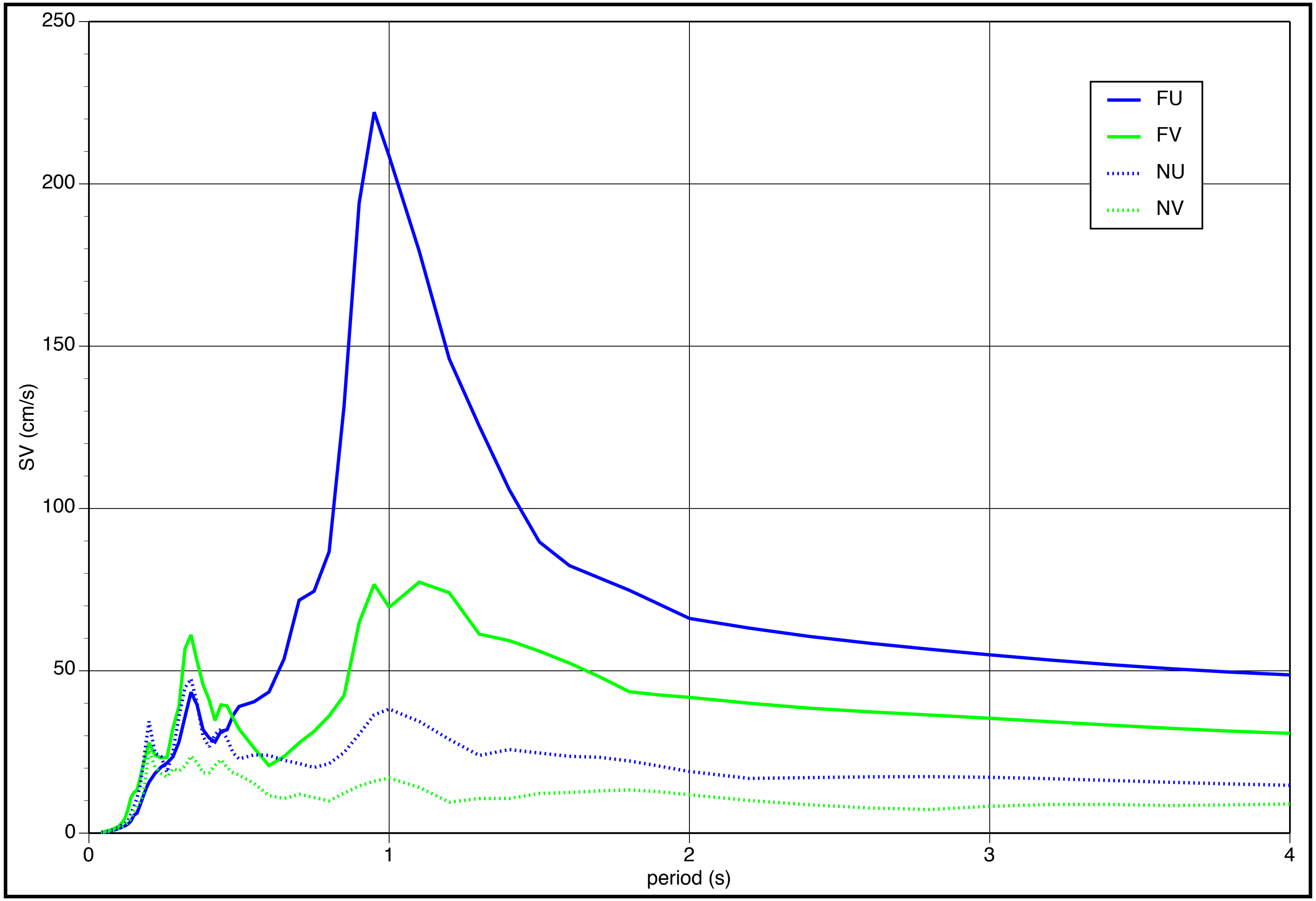

Parametric study 4 - ES

# PGV - PGA and directivity

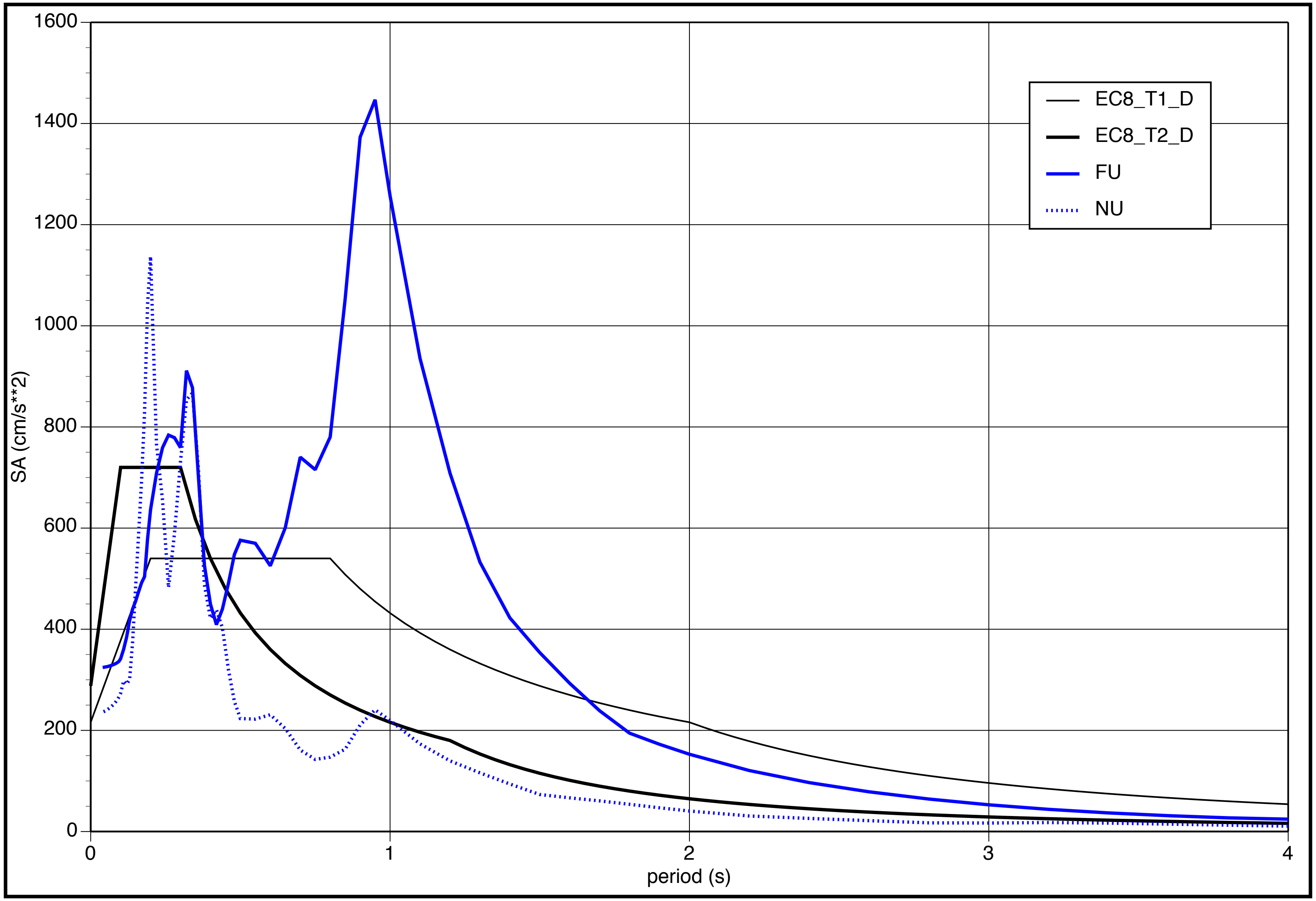



Parametric study 4 - ES

# Parametric study 4 - ESp towards directivity



# Parametric study 4 - ESp towards directivity



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