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Ground motion modelling for seismic hazard assessment

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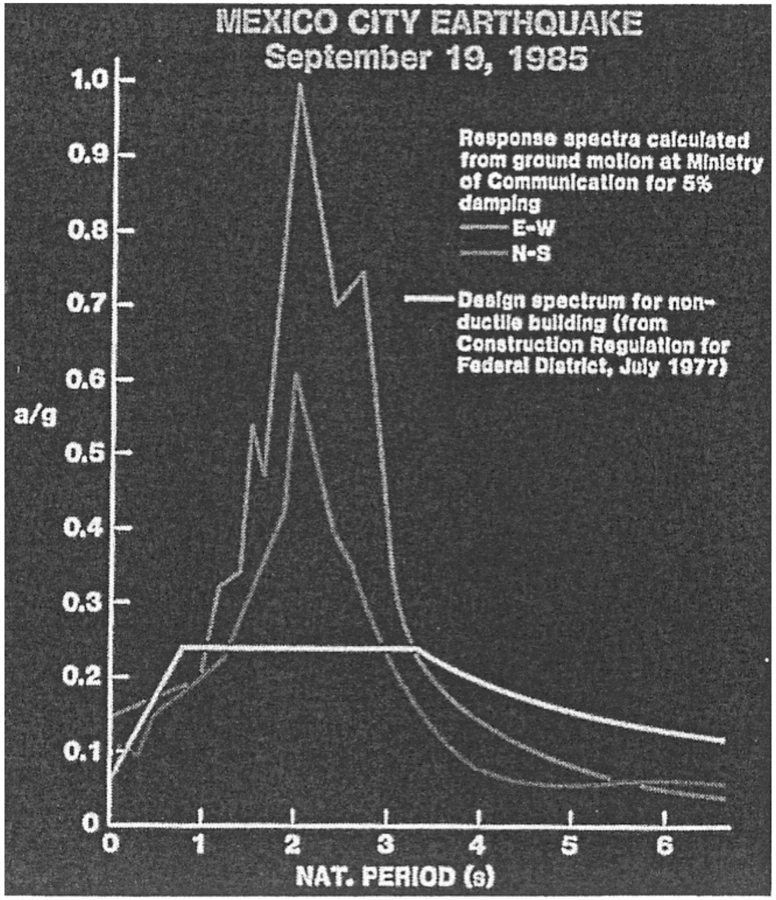
the road to earthquake safety...

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**.

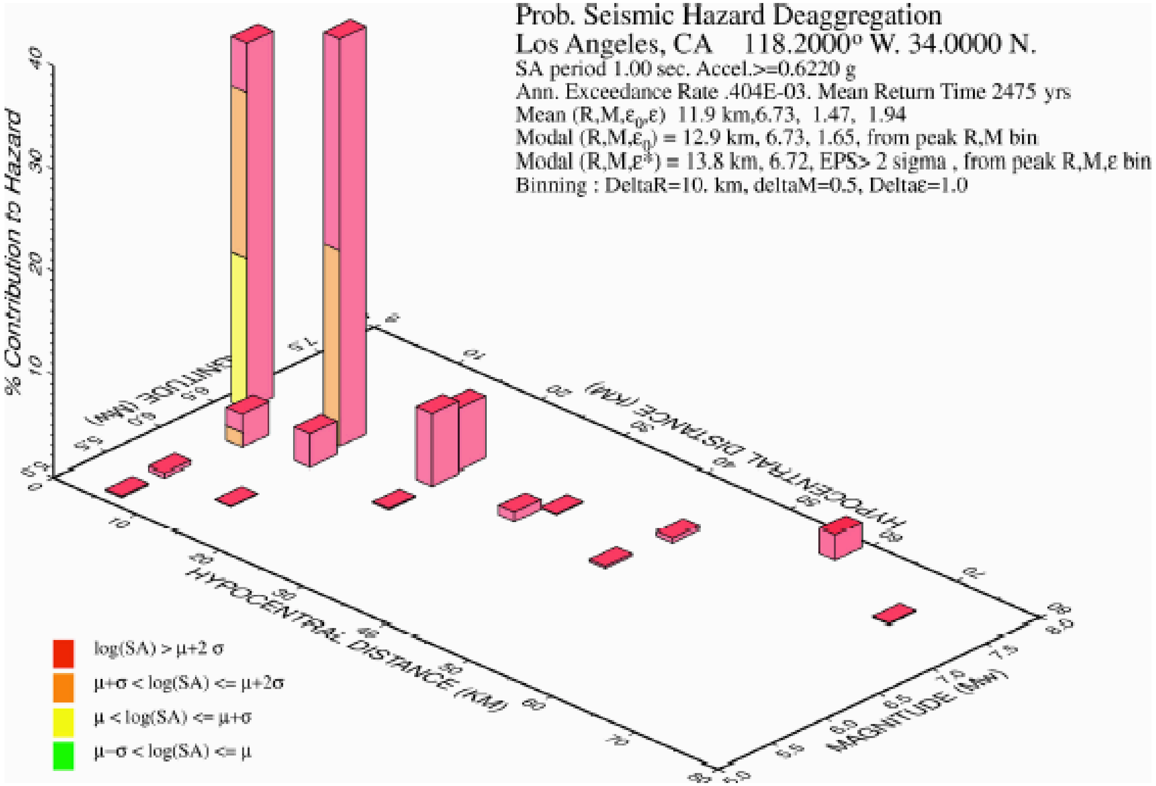
Modern PSHA & DSHA dualism

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)
$f_n=(2n+1)\beta/4H$
$A \approx (\rho_2 v_2)/(\rho_1 v_1)$

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

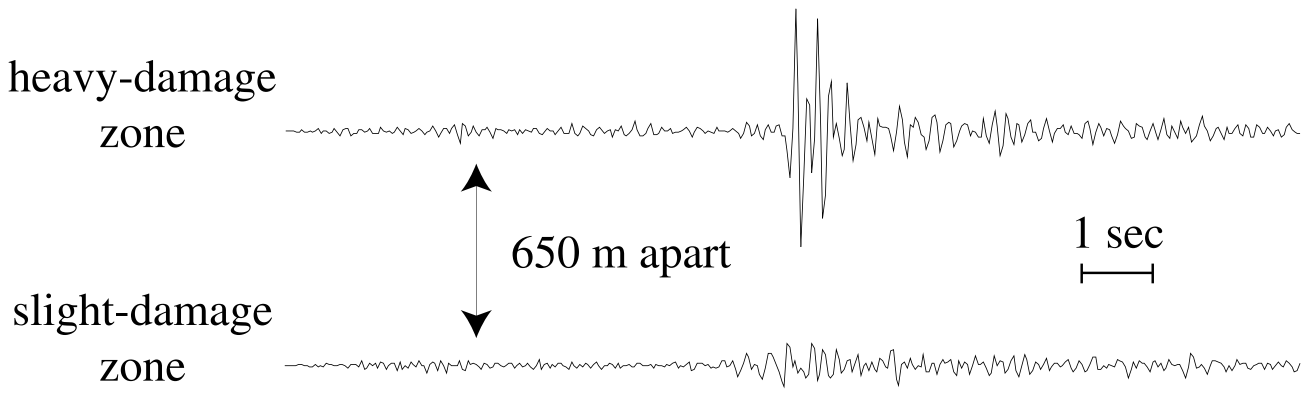
Near surface effects: impedance contrast, velocity

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

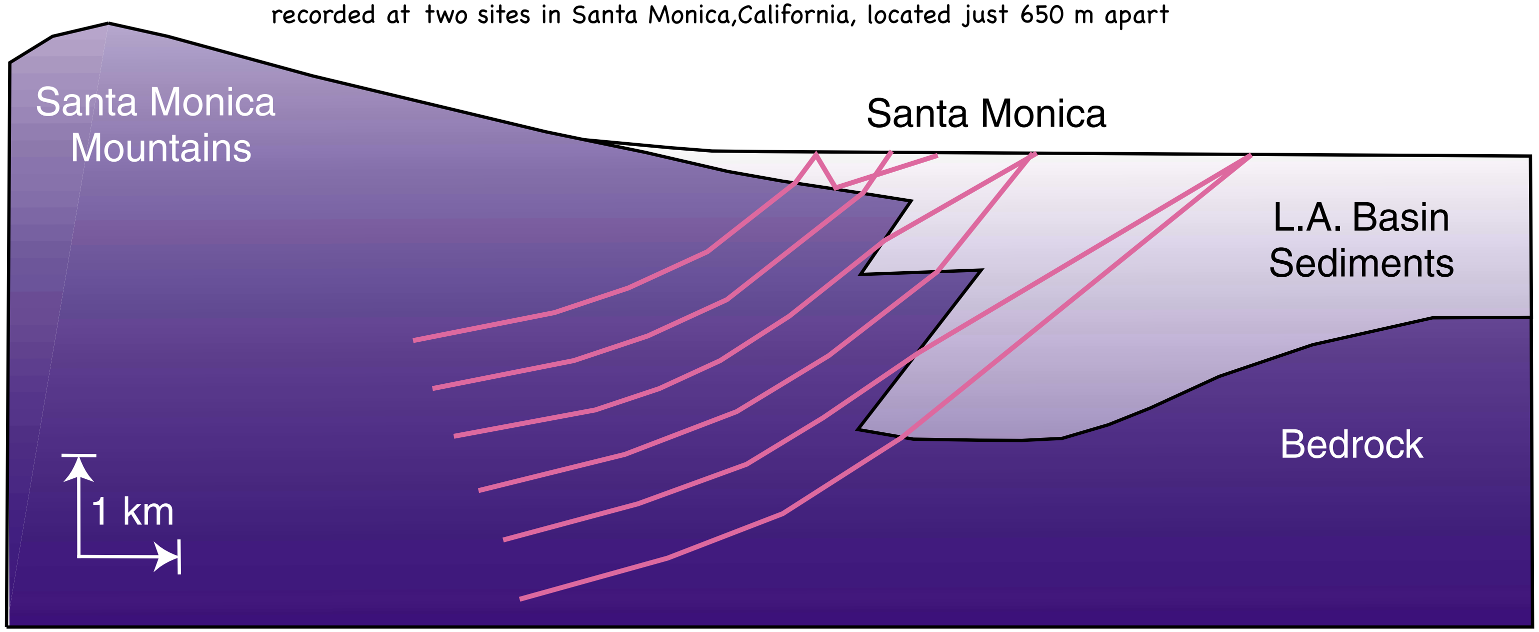
Basin effects

- Basin-edge induced waves
- Subsurface focusing

Important issues in SRE

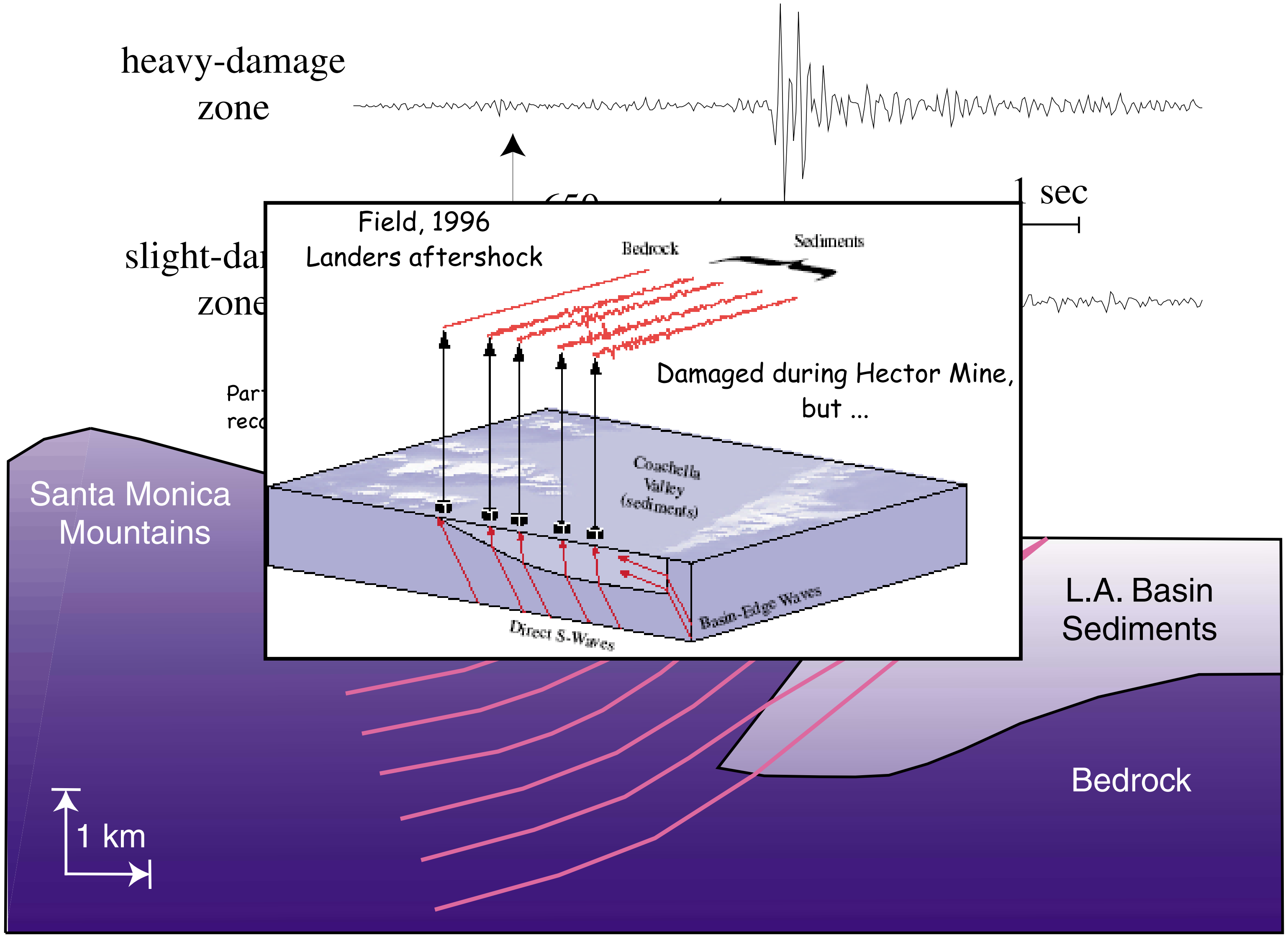


Particle-velocity seismograms of a 1994 Northridge earthquake aftershock recorded at two sites in Santa Monica,California, located just 650 m apart



Problems in SHA-Site effects

Important issues in SRE



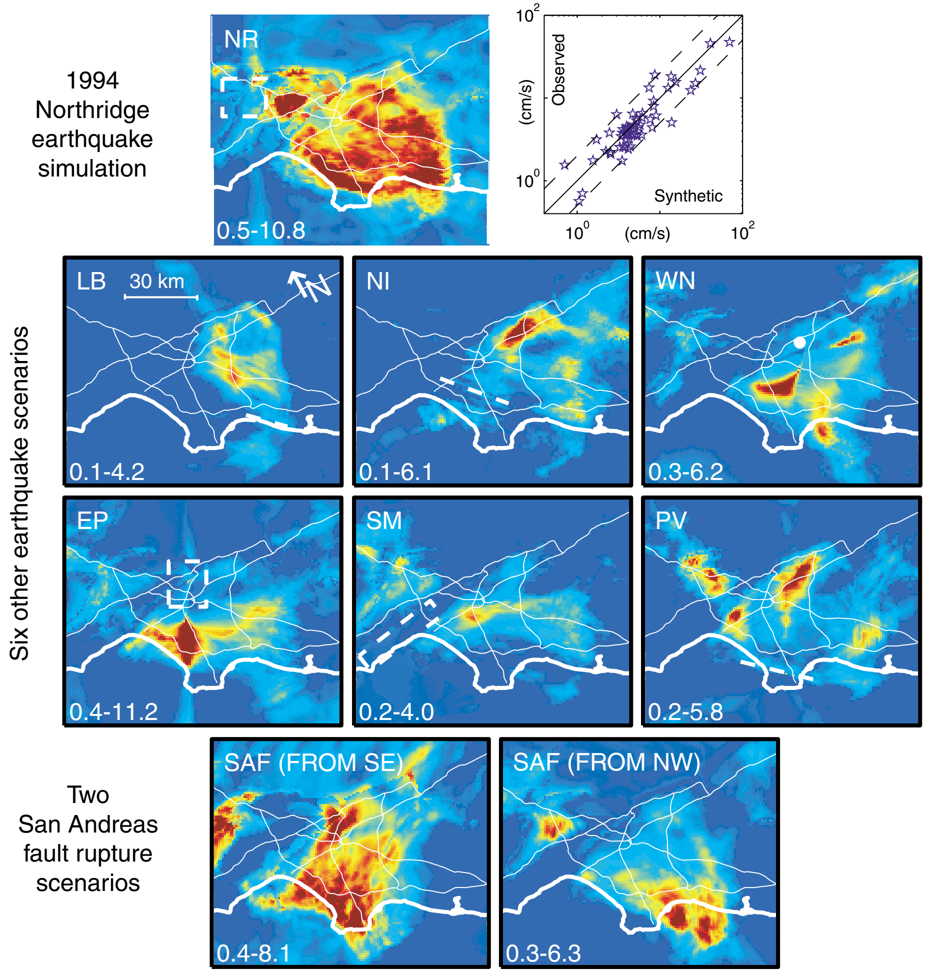
SRE and SHA

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



Problems in SHA-Site effects

SRE and SHA

Amplification patterns may vary greatly among

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

SCEC
Phase 3
Report

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

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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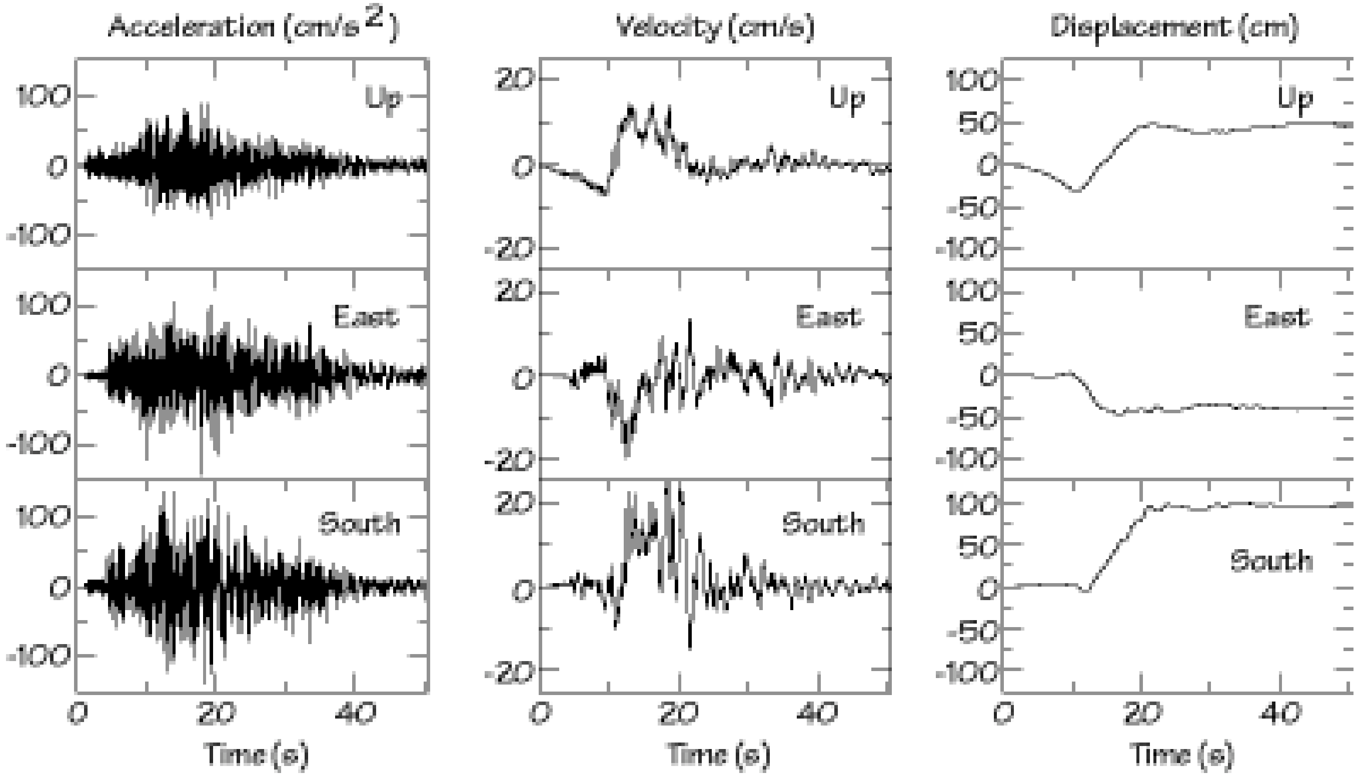
Fling

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

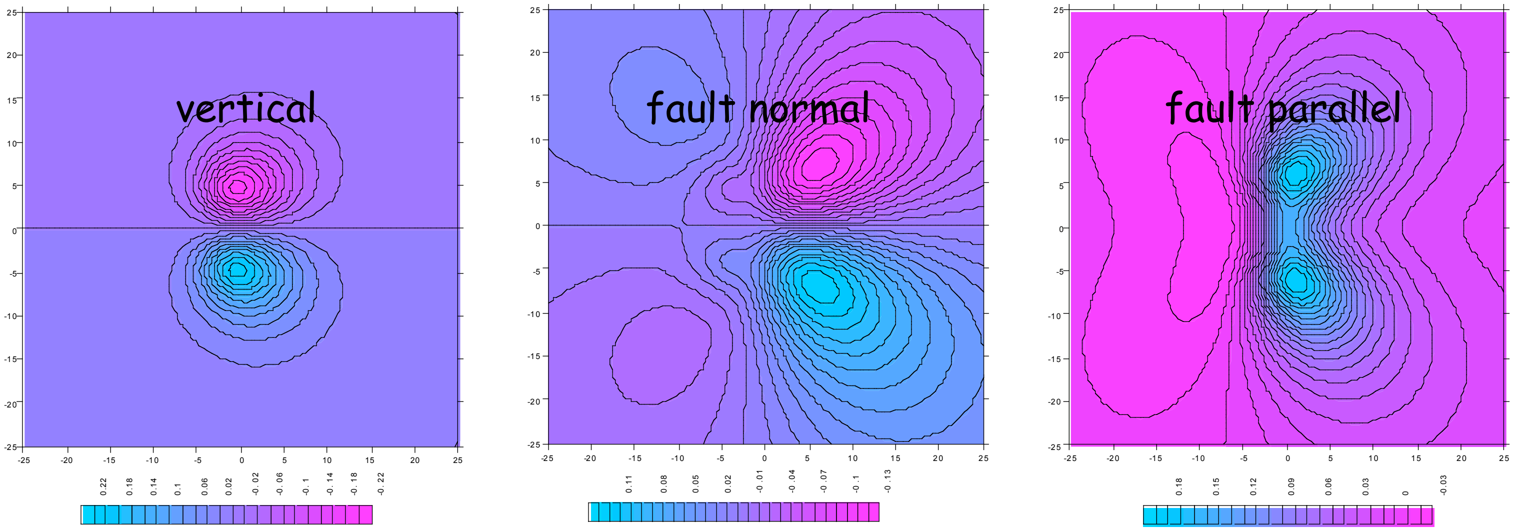


Ground acceleration, velocity and displacement, recorded at a strong-motion seismometer that was located directly above the part of a fault that ruptured during the 1985 Mw = 8.1, Michoacan, Mexico earthquake.

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)

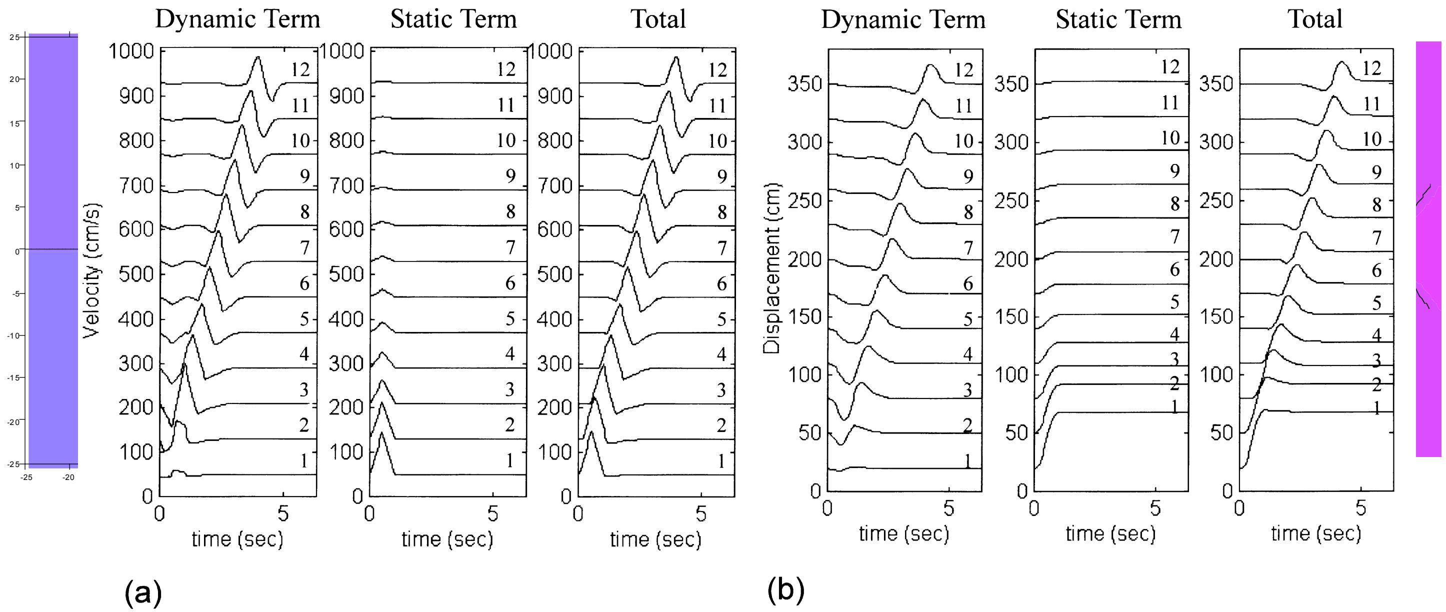
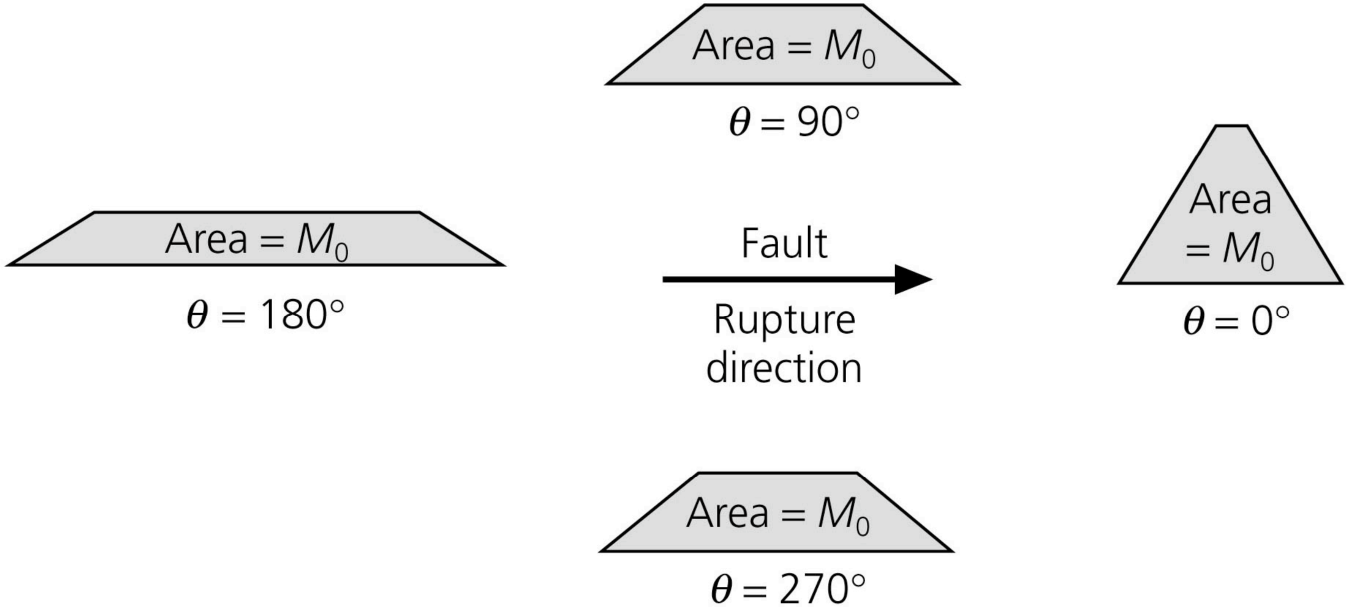


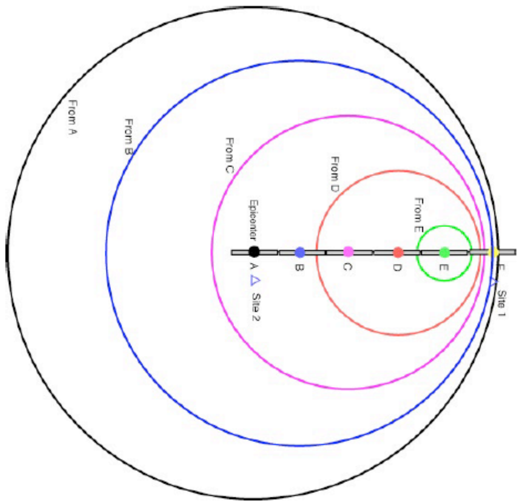
Figure 7. (a) Velocities and (b) displacements of the fault-parallel components at 12 observation points in Figure 6, using the first (dynamic; left), second (static; center), and total (right) integrations of equation (11).

+directivity (Hisada&Bielak, 2003)

Source effect

Directivity (near fault)





Source effect

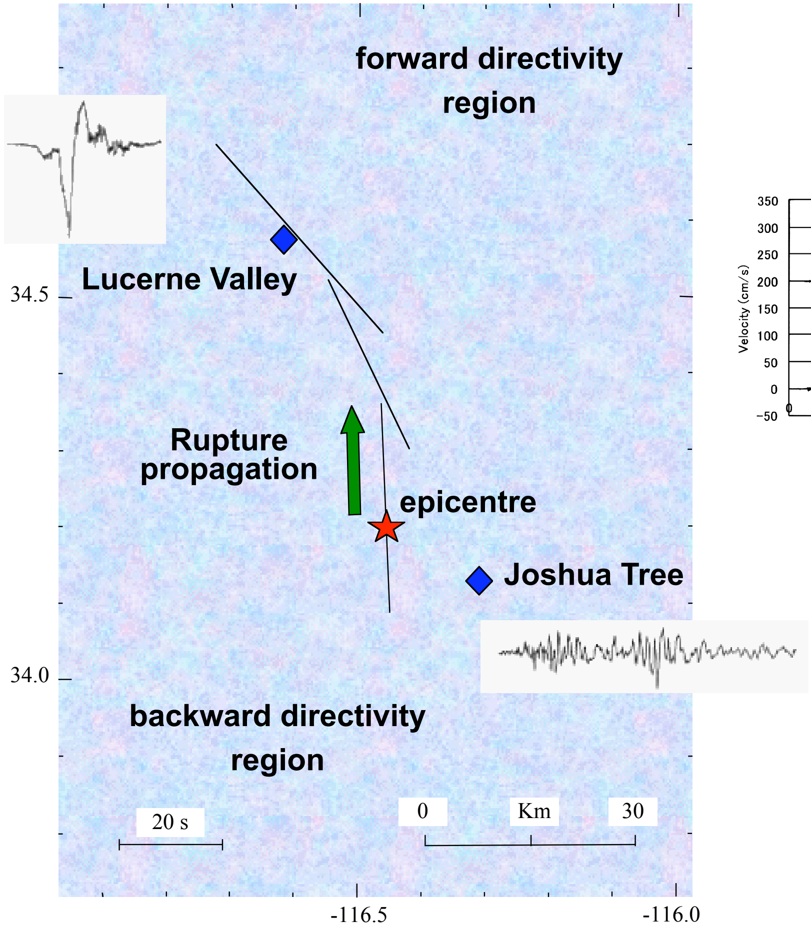
Directivity (near fault)

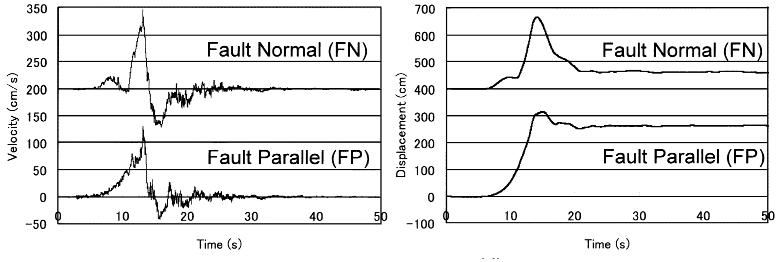
Particularly, in the case of **forward rupture directivity** most of the energy arrives in a single large pulse of motion which may give rise to particularly severe ground motion at sites toward which the fracture propagation progresses.

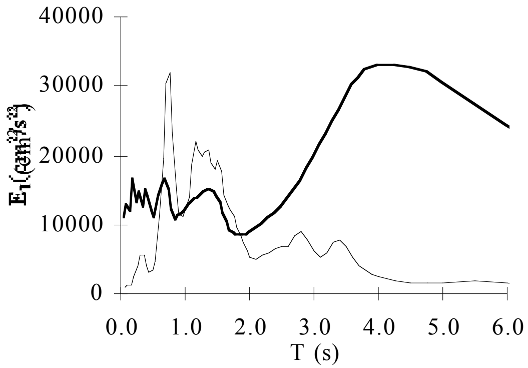
it involves the transmission of large energy amounts to the structures in a very short time.

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

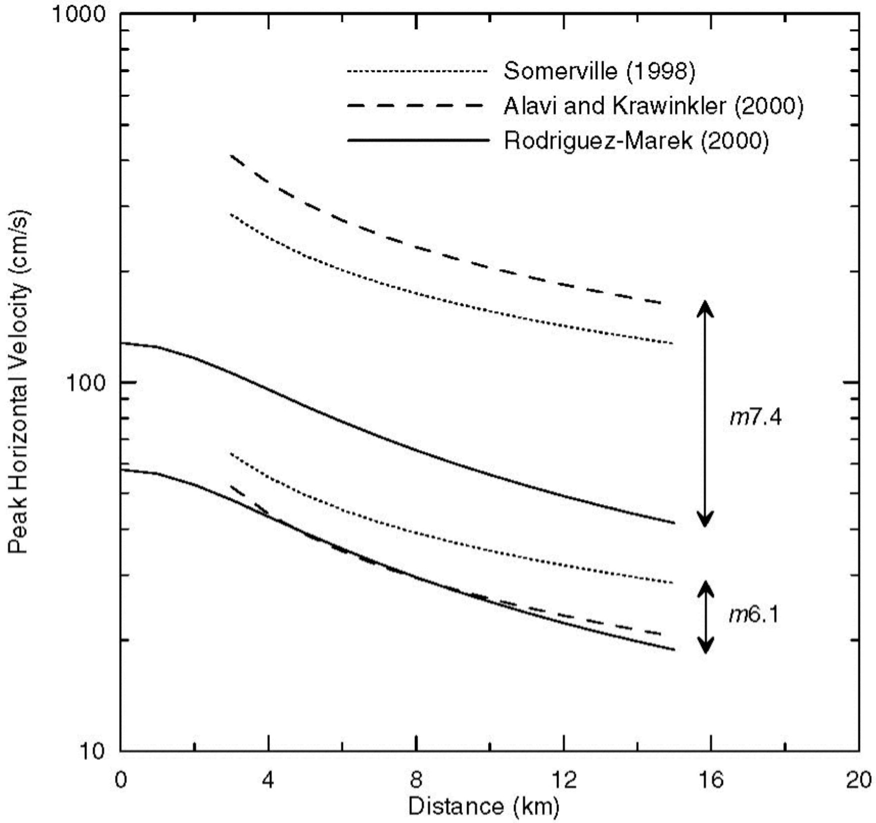






Source effect

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

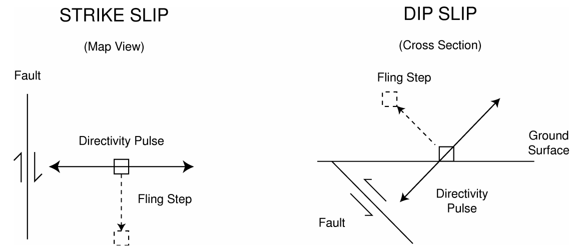


Fig. 4.3. Schematic diagram showing the orientations of fling step and directivity pulse for strike-slip and dip-slip faulting.

Peer report, 2001

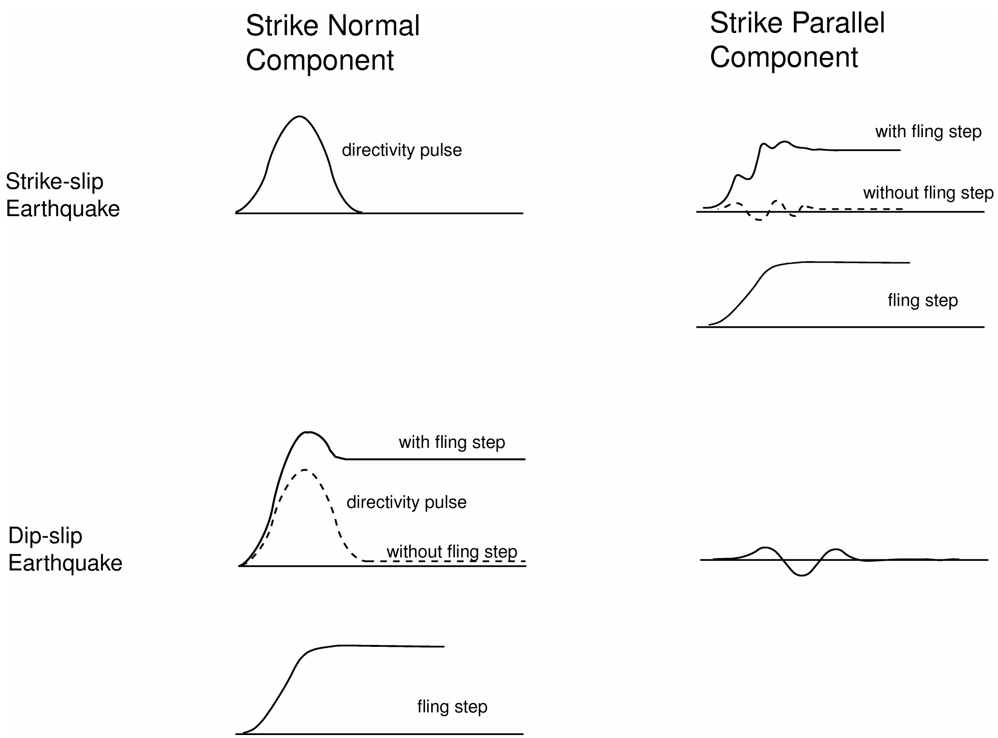


Fig. 4.4. Schematic diagram of time histories for strike-slip and dip-slip faulting in which the fling step and directivity pulse are shown together and separately.

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…

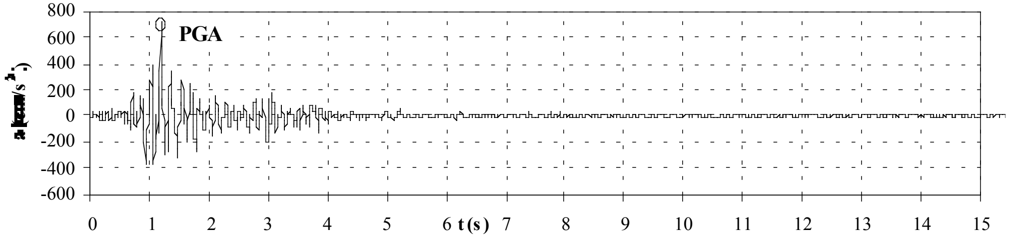


Figure 1 – Acceleration time history. Rocca NS record. 1971 Ancona earthquake (M_L=4.7)

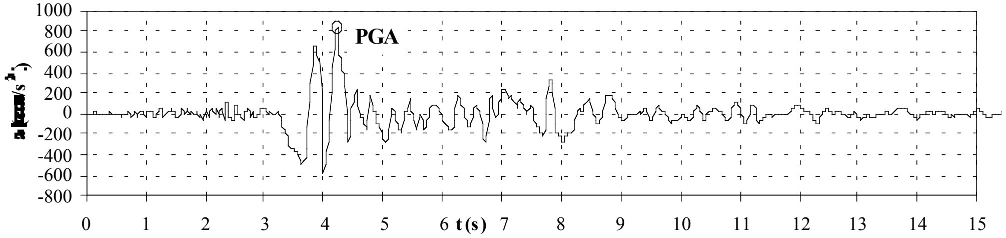


Figure 2 – Acceleration time history. Sylmar N360 record. 1994 Northridge earthquake (M_w=6.7)

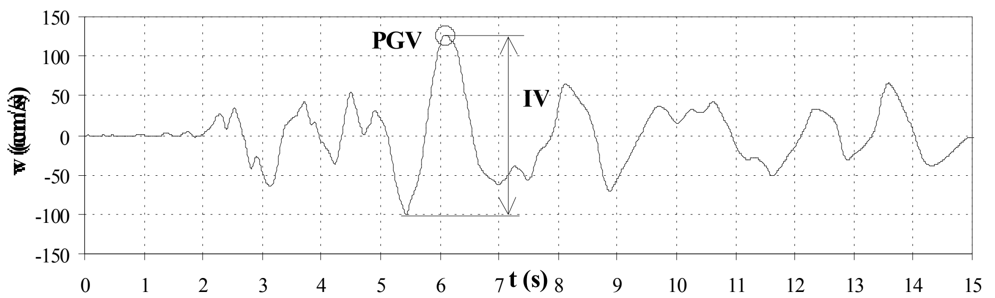


Figure 3 – Velocity time history. Takatori 000 record. 1995 Kobe earthquake (M_w=6.9)

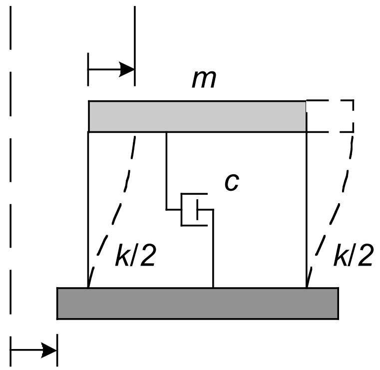
Response spectra

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:

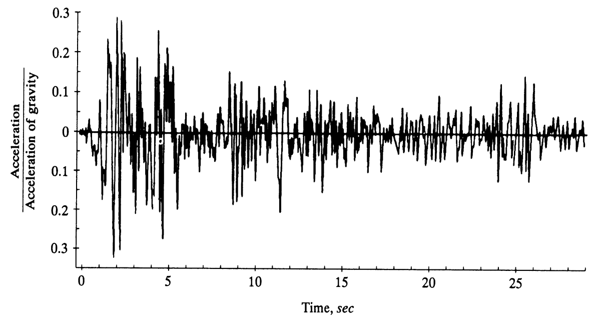
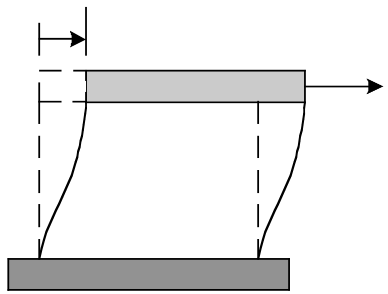


FIGURE 24-15
Accelerogram from El Centro earthquake, May 18, 1940 (*NS* component).

EQUIVALENT STATIC FORCE



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

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

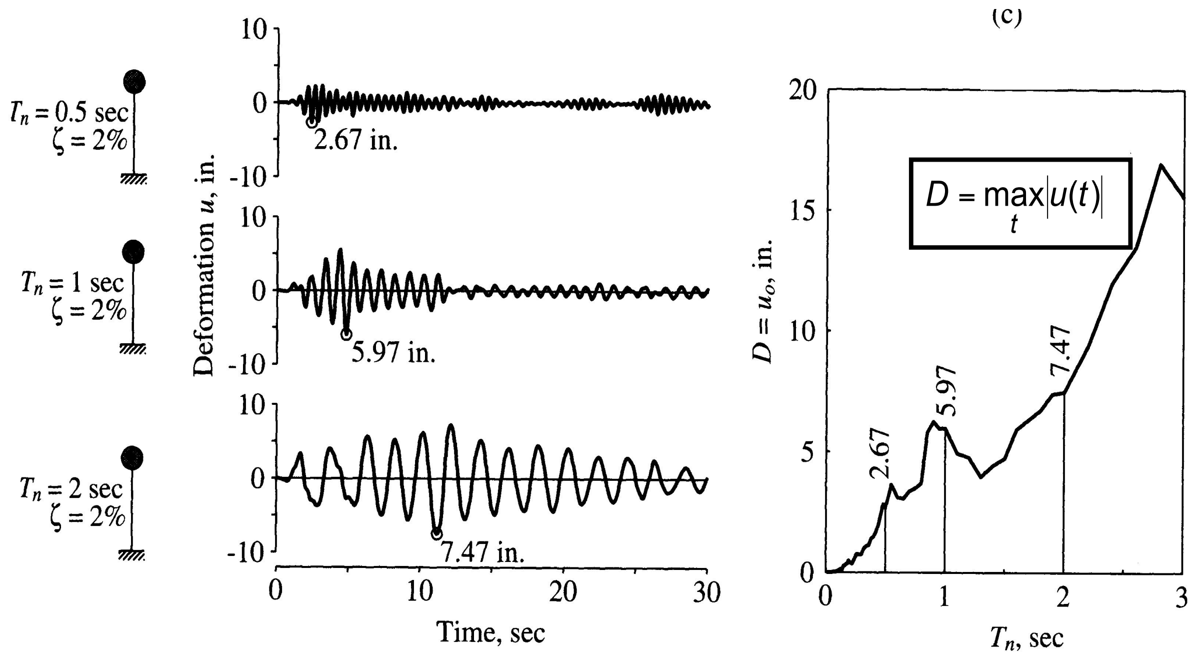
Pseudo acceleration

$f_S(t)$ 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 , ξ).

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 $A = \omega_n^2 D$

ω_n : natural circular frequency of the SDF system.

COMBINED D-V-A SPECTRUM

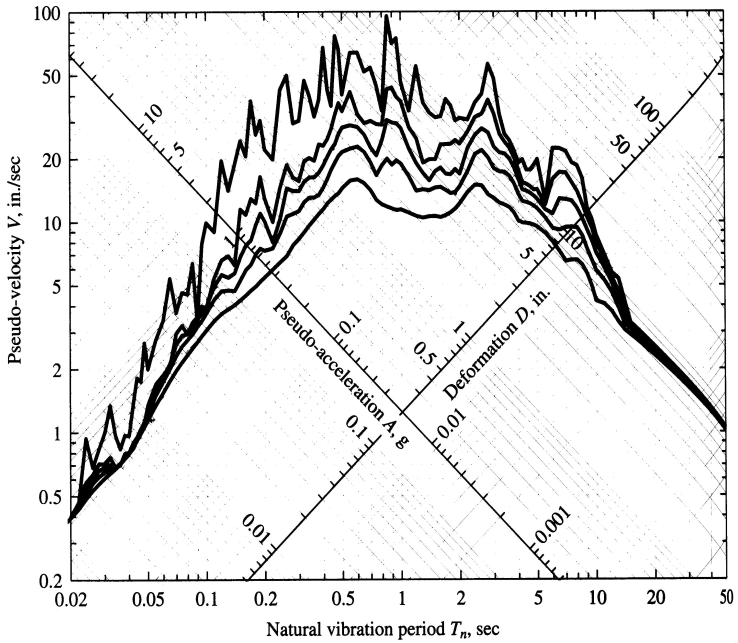
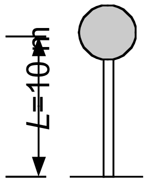


Figure 6.6.4 Combined D–V–A response spectrum for El Centro ground motion; ζ = 0, 2, 5, 10, and 20%.

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

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

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

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

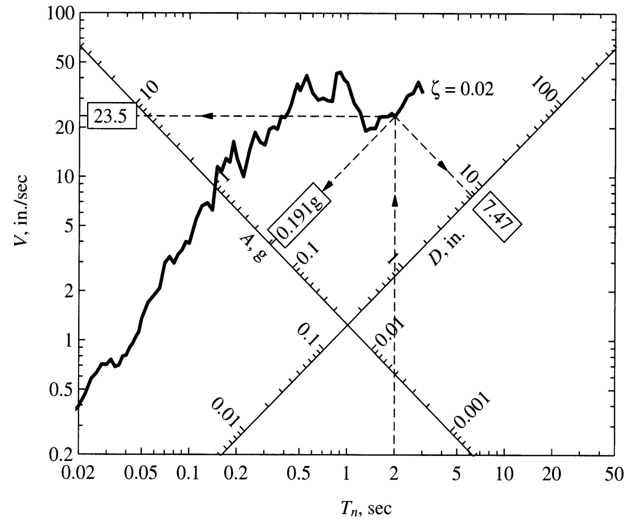
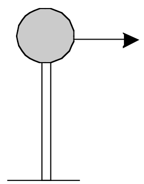
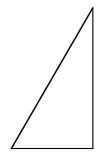


Figure 6.6.3 Combined D–V–A response spectrum for El Centro ground motion; $\zeta = 2\%$.





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.

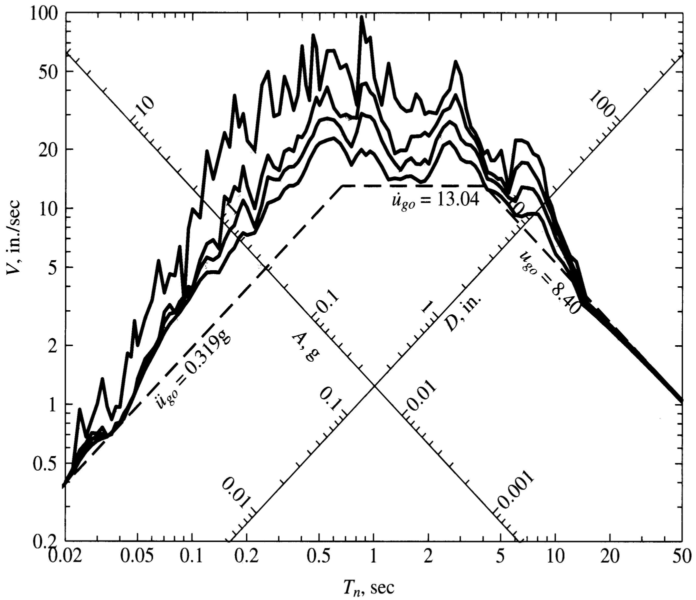


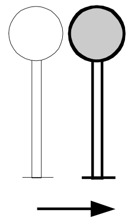
Figure 6.8.1 Response spectrum (ζ = 0, 2, 5, and 10%) and peak values of ground acceleration, ground velocity, and ground displacement for El Centro ground motion.

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

T_n < 0.03 s : rigid system

no deformation

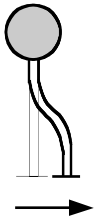
u(t) ≈ 0 → D ≈ 0



T_n > 15 s : flexible system

no total displacement

u(t) = u_g(t) → 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

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

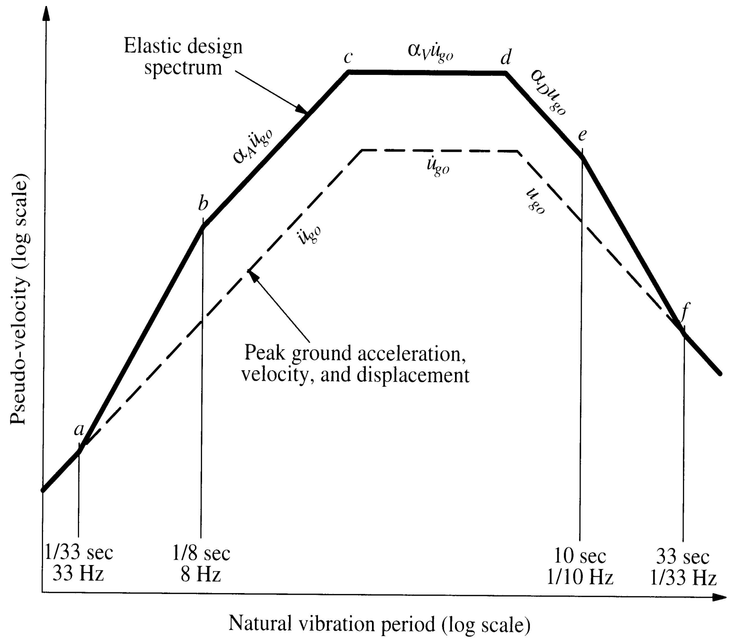


Figure 6.9.3 Construction of elastic design spectrum.

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.

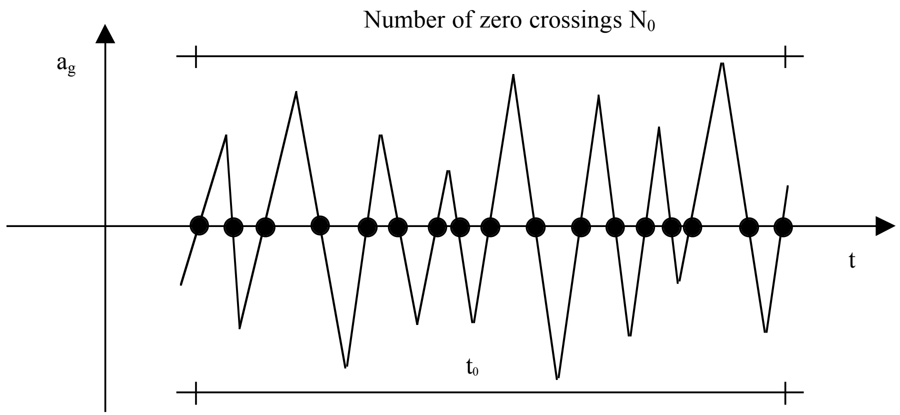
Housner's spectral intensity is the first moment of the area of S_{pa} ($0.1<T<2.5$) about the S_{pa} axis, implying that the Housner spectral intensity is larger for ground motions with a significant amount of low frequency content.
The I_H parameter captures important aspects of the amplitude and frequency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

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:

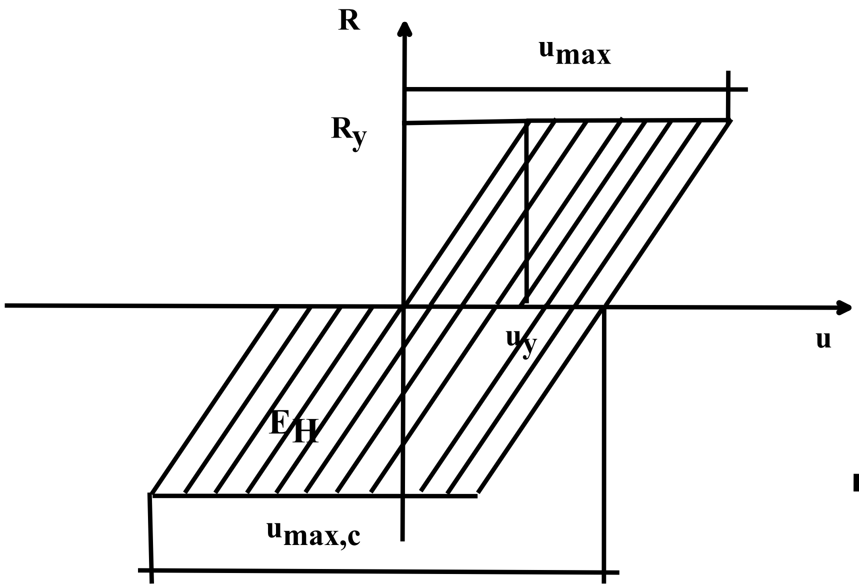
$$C_y = \frac{R_y}{mg} \quad \eta = \frac{R_y}{m\ddot{u}_{g(max)}} = \frac{C_y}{\ddot{u}_{g(max)}/g}$$

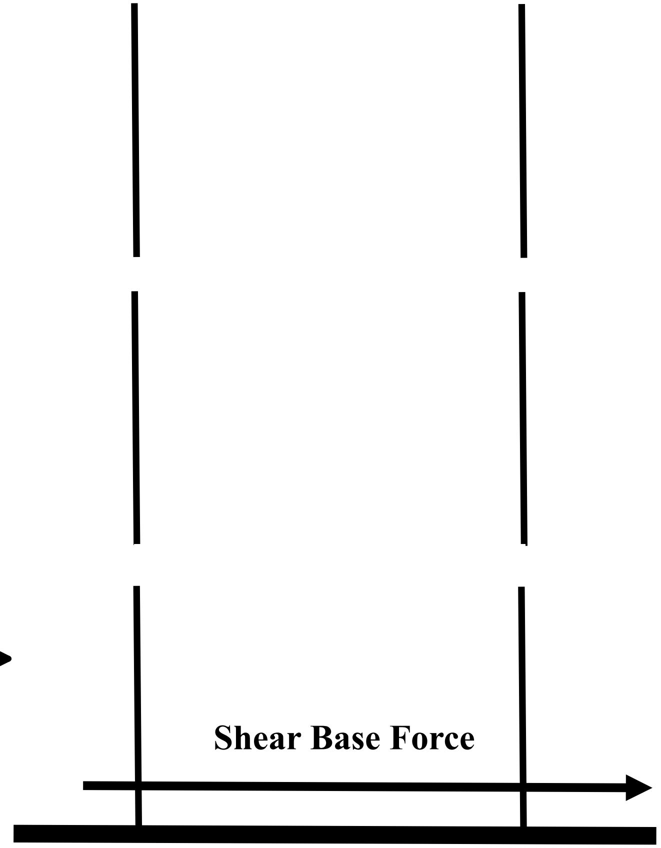
where R_y is the yielding resistance, m is the mass of the system, and $\ddot{u}_{g(max)}$ is the maximum ground acceleration.

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

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

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



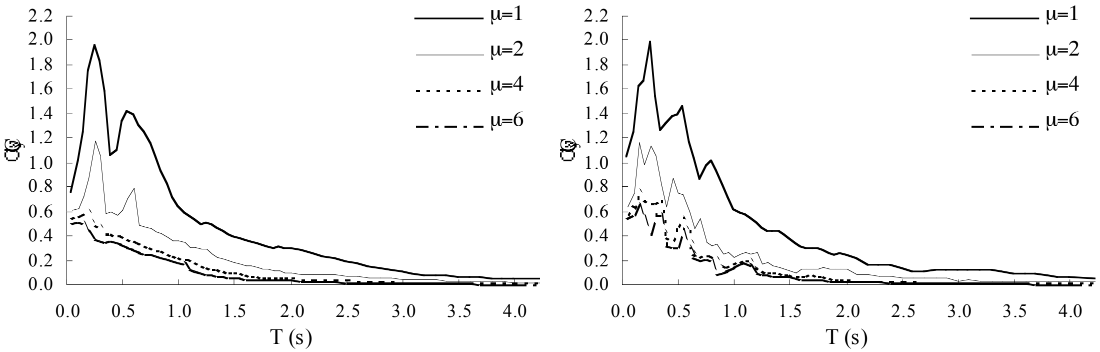


Parameters extraction

Yielding resistance 2

The parameter C_y represents the structure's yielding seismic resistance coefficient and 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):

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

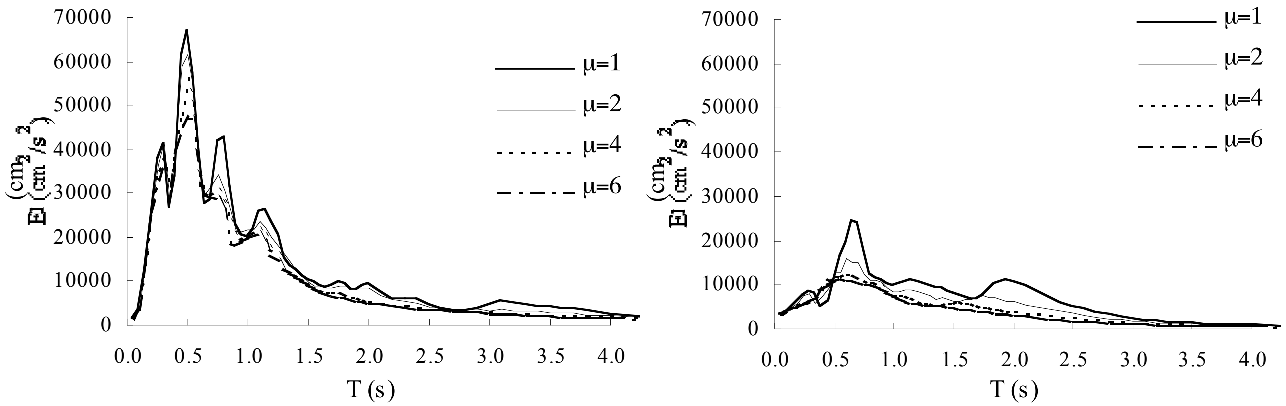
where (E_I) is the input energy, (E_k) is the kinetic energy, (E_ξ) is the damping energy, (E_s) is the elastic strain energy, and (E_H) is the hysteretic energy.

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)

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.

References

Mc Guire, R. K. (2001). "Deterministic vs. probabilistic earthquake hazards and risks", **Soil Dynamics and Earthquake Engineering**, 21, 377-384.

Field, E.H., the SCEC Phase III Working Group (2000). "Accounting for site effects in probabilistic seismic hazard analyses of Southern California: overview of the SCEC Phase III report", **Bull. Seism. Soc. Am.**, 90, 6B, p. S1-S31.

Panza, G.F., Romanelli, F. and Vaccari, F. (2001). "Seismic wave propagation in laterally heterogeneous anelastic media: theory and applications to the seismic zonation", **Advances in Geophysics**, Academic press, 43, 1-95.

Panza, G. F., Romanelli, F.,Vaccari, F., Decanini, L. and Mollaioli, F. (2004). "Seismic ground motion modeling and damage earthquake scenarios: possible bridge between seismologists and seismic engineers", **IUGG Special Volume**, Earthquake Hazard, Risk, and Strong Ground Motion (319).

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

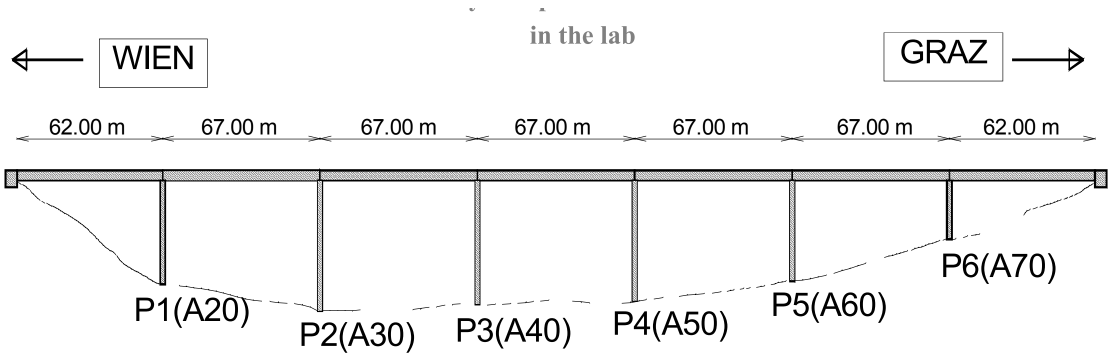
ARSENAL RESEARCH, Vienna, Austria; **ISMES S.P.A**,. Bergamo, Italy;
ICTP, Trieste, Italy; **UPORTO**, Porto, Portugal; **CIMNE**, Barcelona, Spain;
SETRA, Bagneaux, France; **JRC-ISPRA**, EU.

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.



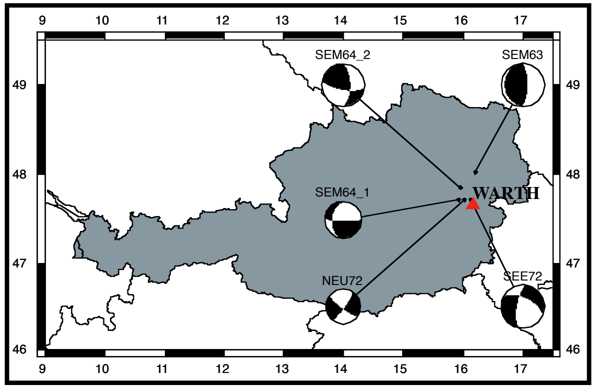
Case study

Examples from EU project

Databank of geological, geophysical and seismotectonic data

SEISMIC SOURCES

1) **Database of focal mechanism**



Maximum Historical Earthquake

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

strike
dip
rake
depth

Maximum Credible Earthquake

Maximum Design Earthquake

Databank of geological, geophysical and seismotectonic data

STRUCTURAL MODELS

Bedrock model

1) EUR-I Data set

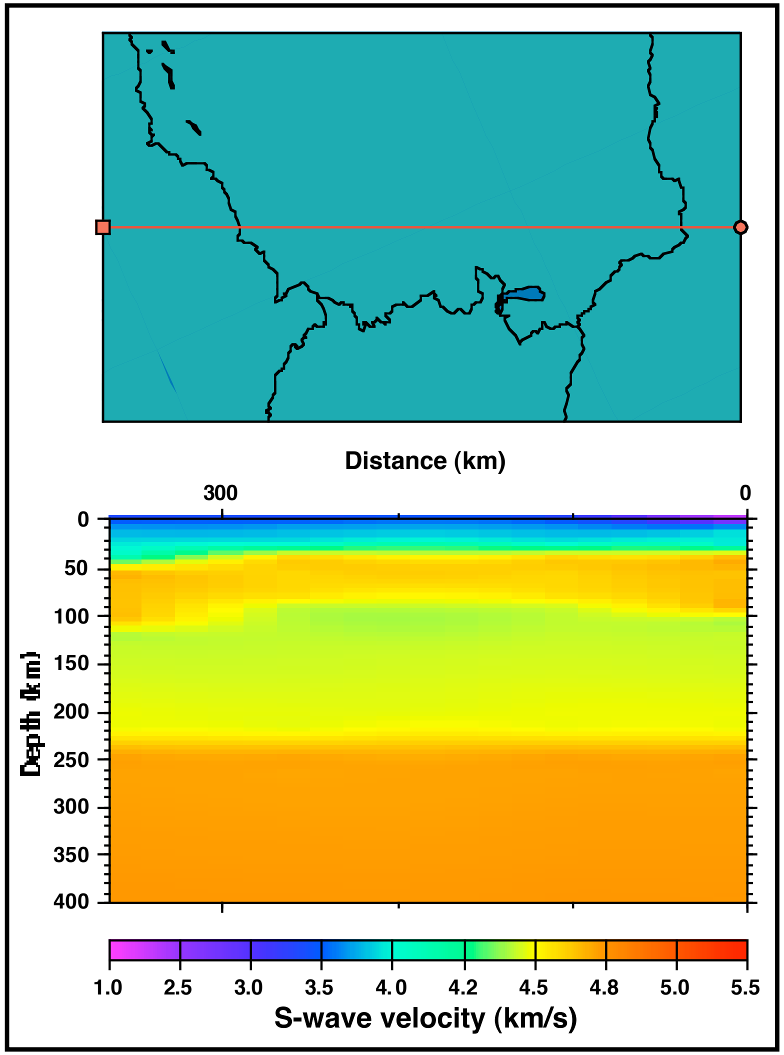
2) updated on the basis of the geological informations collected by CIMG

Local LHET model

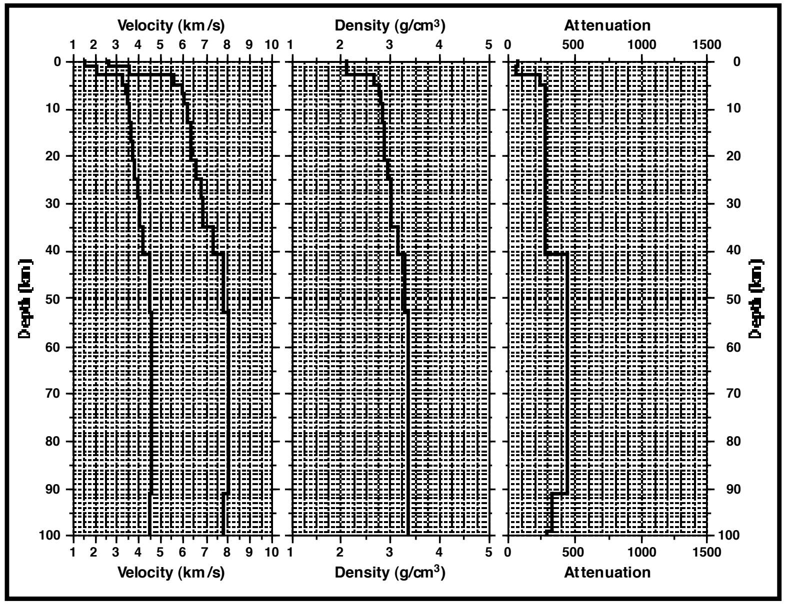
1) available Warth bridge section plan

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

Initial regional model

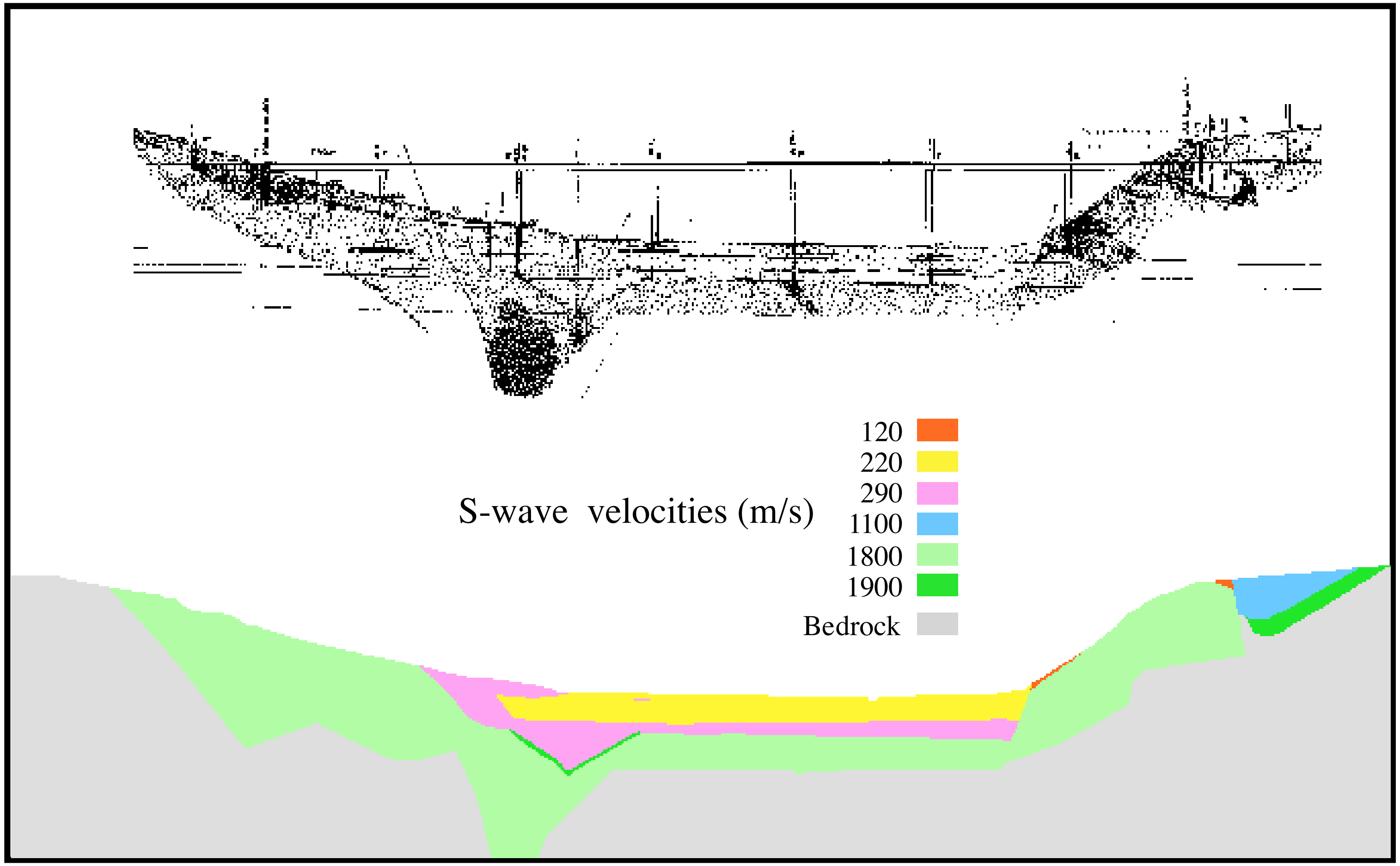


EUR I data set



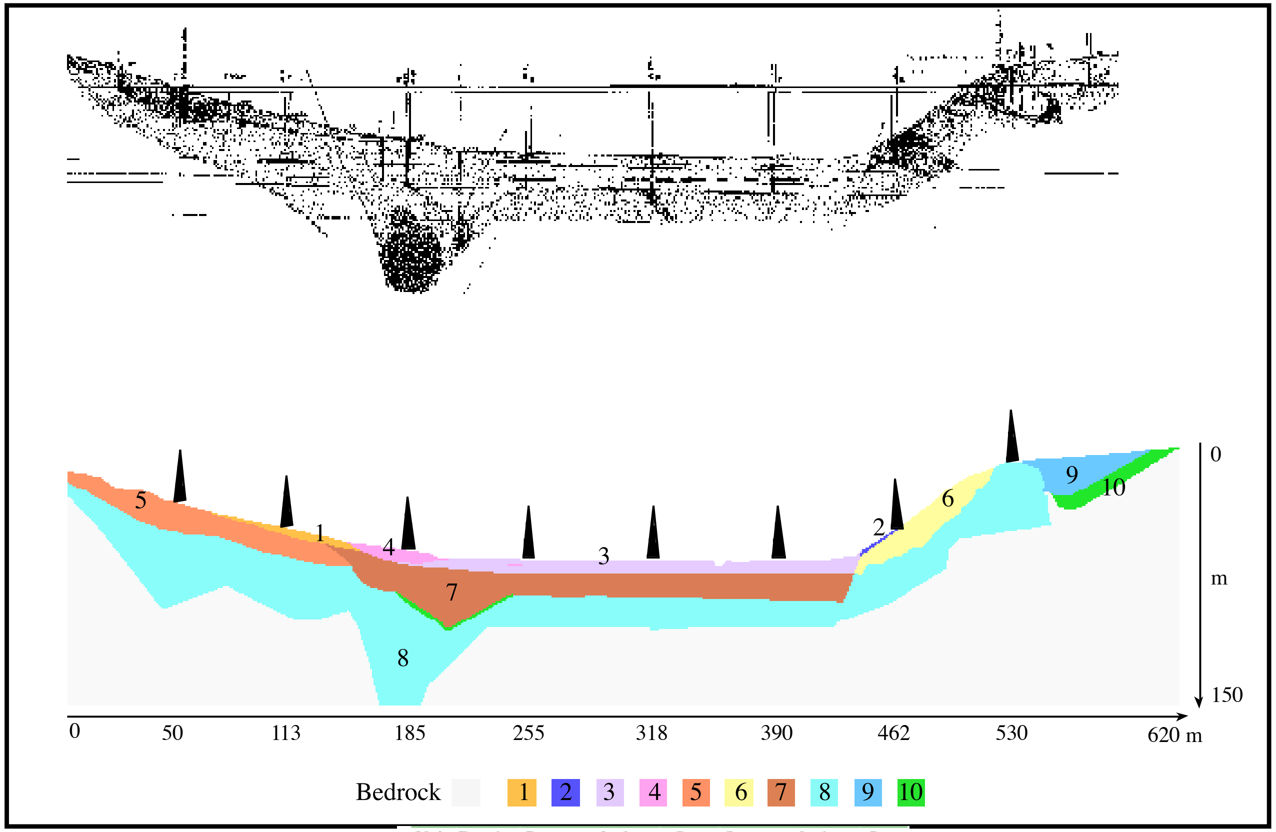
Definition of str. models

Initial LHM - Warth bridge - model



Definition of str. models

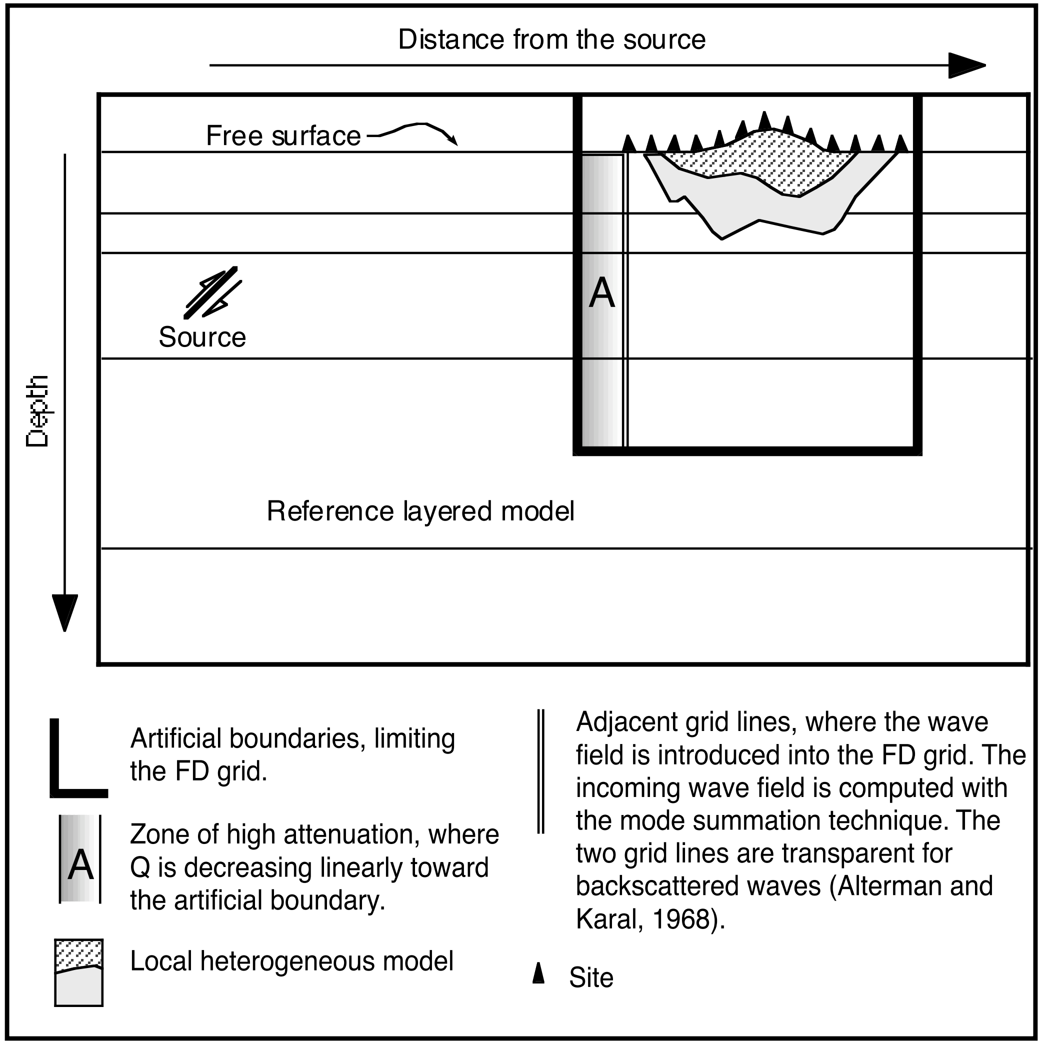
LHM - Warth bridge - model



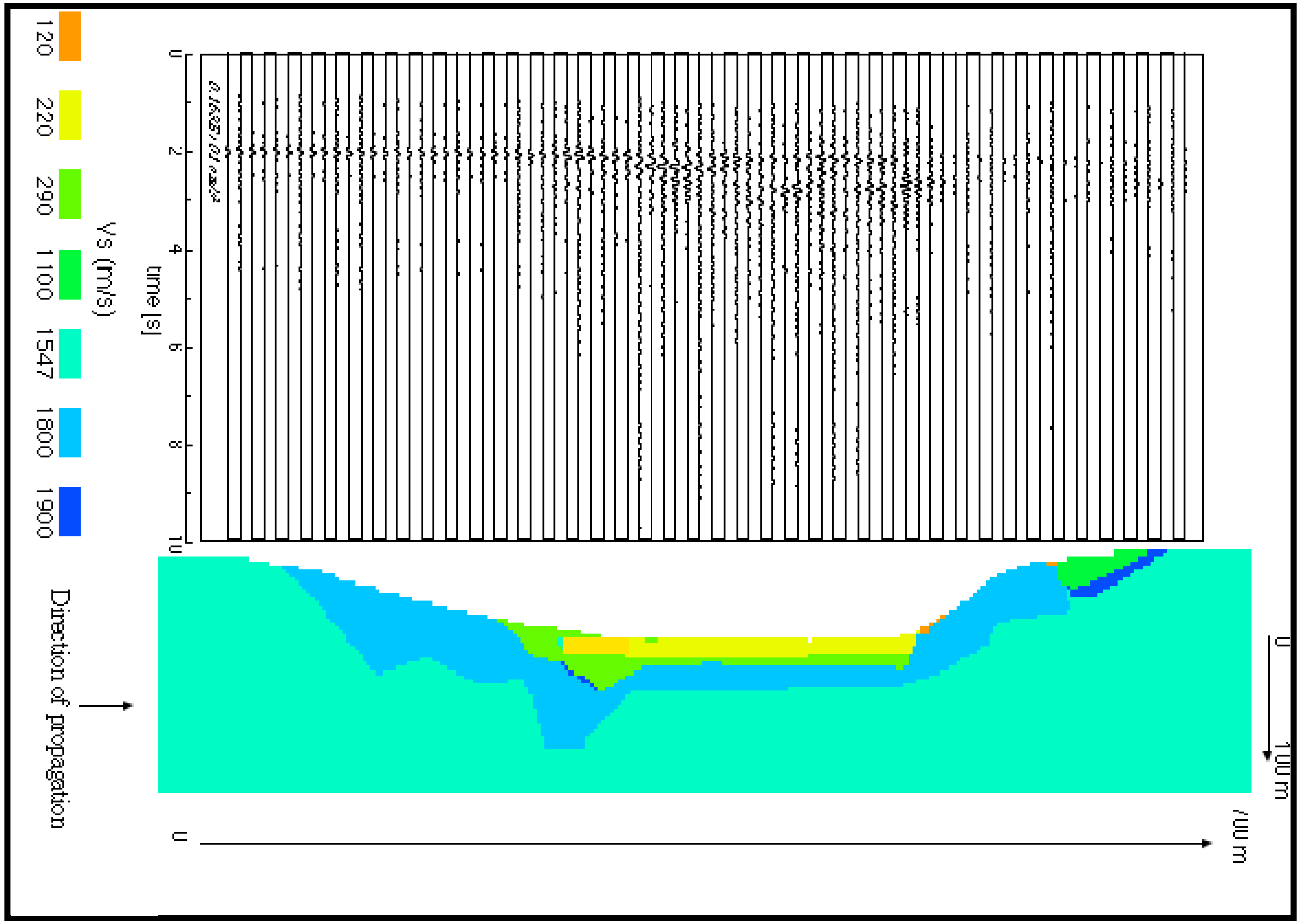
Unit	Density g/cm^3	P-wave velocity km/s	Q_P	S-wave velocity km/s	Q_S
1	1.5	0.30	40.0	0.20	15.0
2	1.7	0.49	40.0	0.25	15.0
3	2.0	0.70	50.0	0.26	20.0
4	1.8	0.70	50.0	0.29	20.0
5	2.3	0.80	50.0	0.30	20.0
6	2.3	0.80	50.0	0.40	20.0
7	1.8	1.70	50.0	0.50	20.0
8	2.3	2.10	150.0	1.00	60.0
9	2.3	3.00	150.0	1.90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

Definition of str. models

Hybrid method: MS-FD

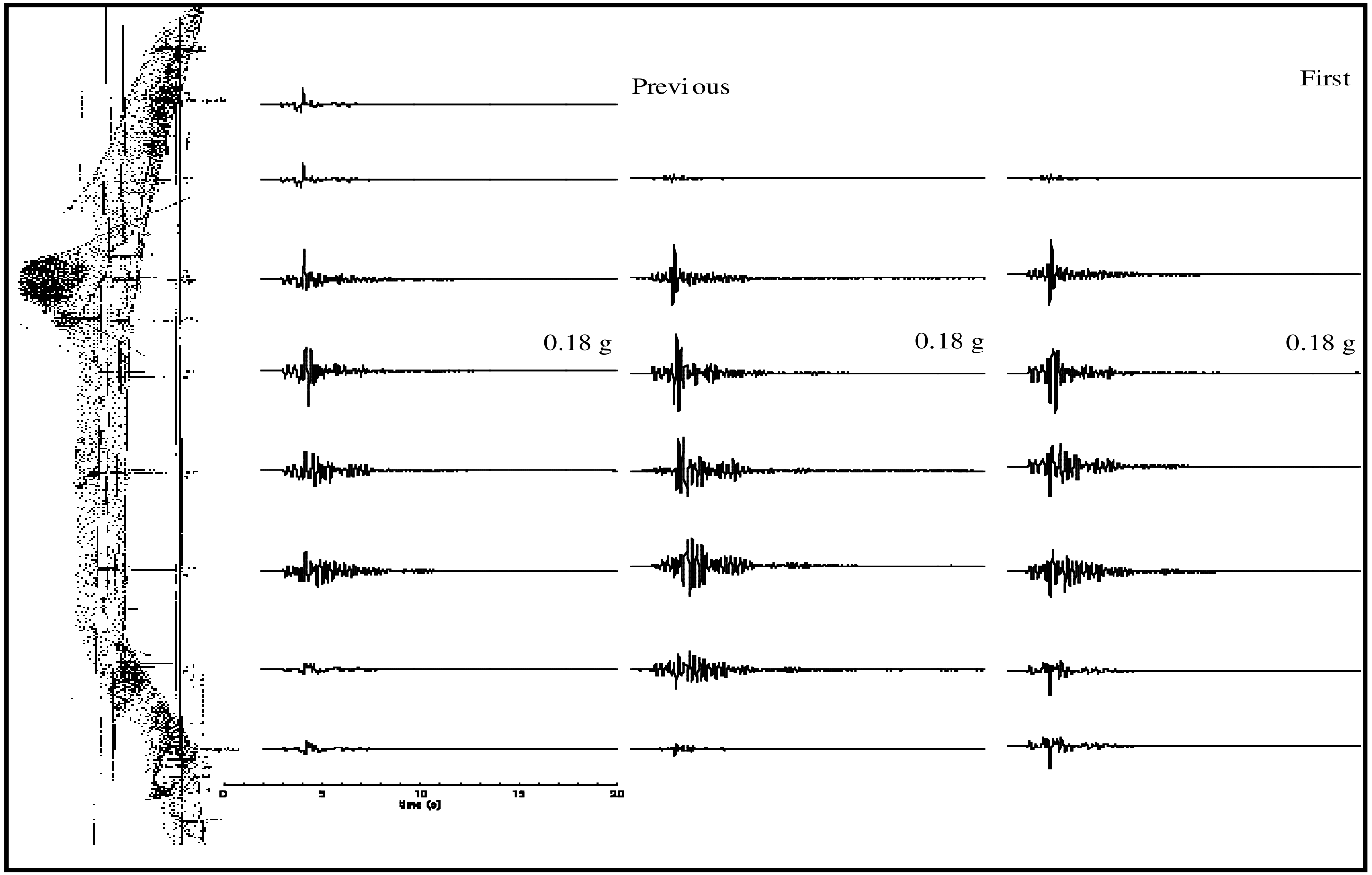


Initial synthesis - radial



Case study: initial scenario

Synthetic accelerations and diffograms



radial

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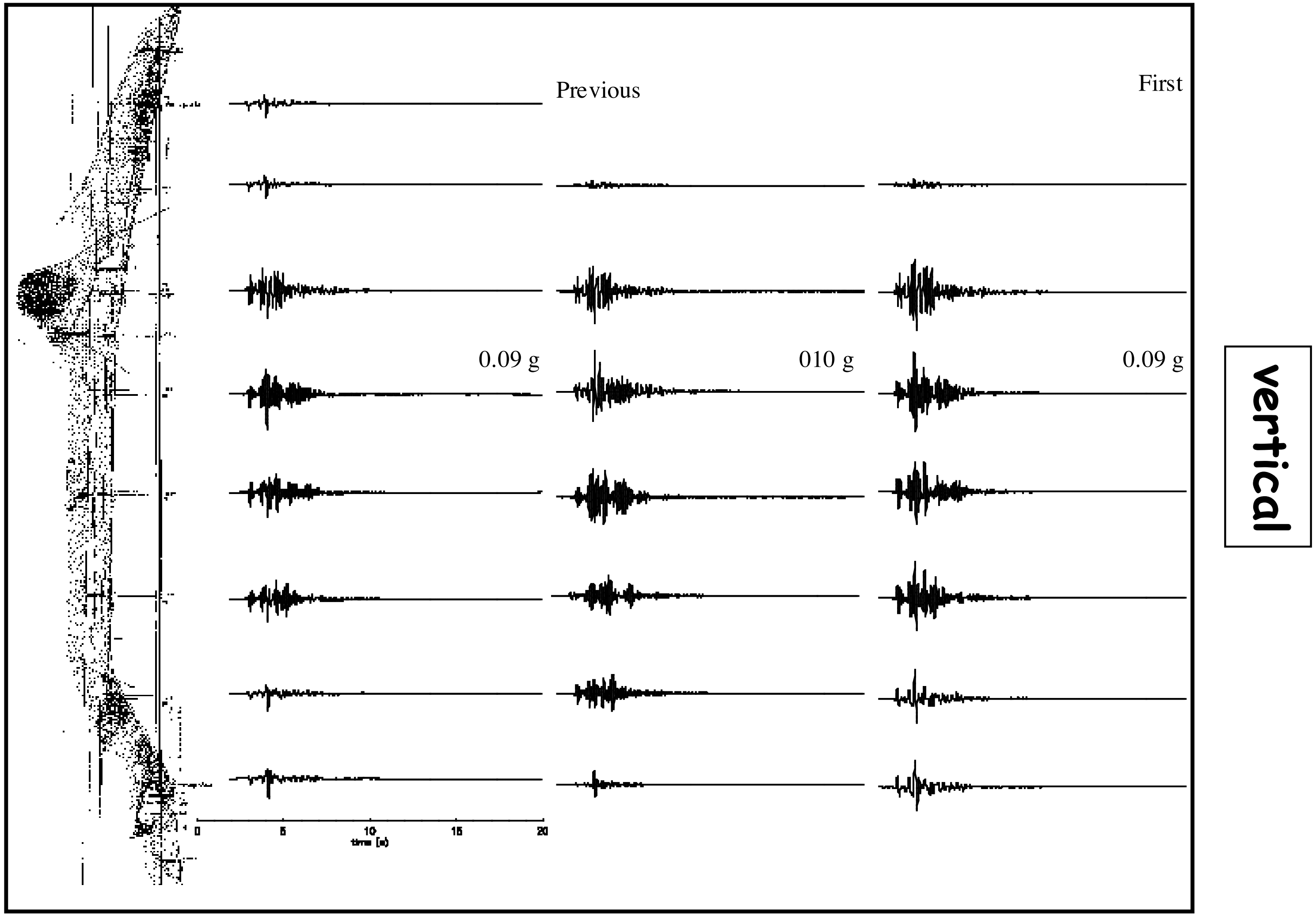
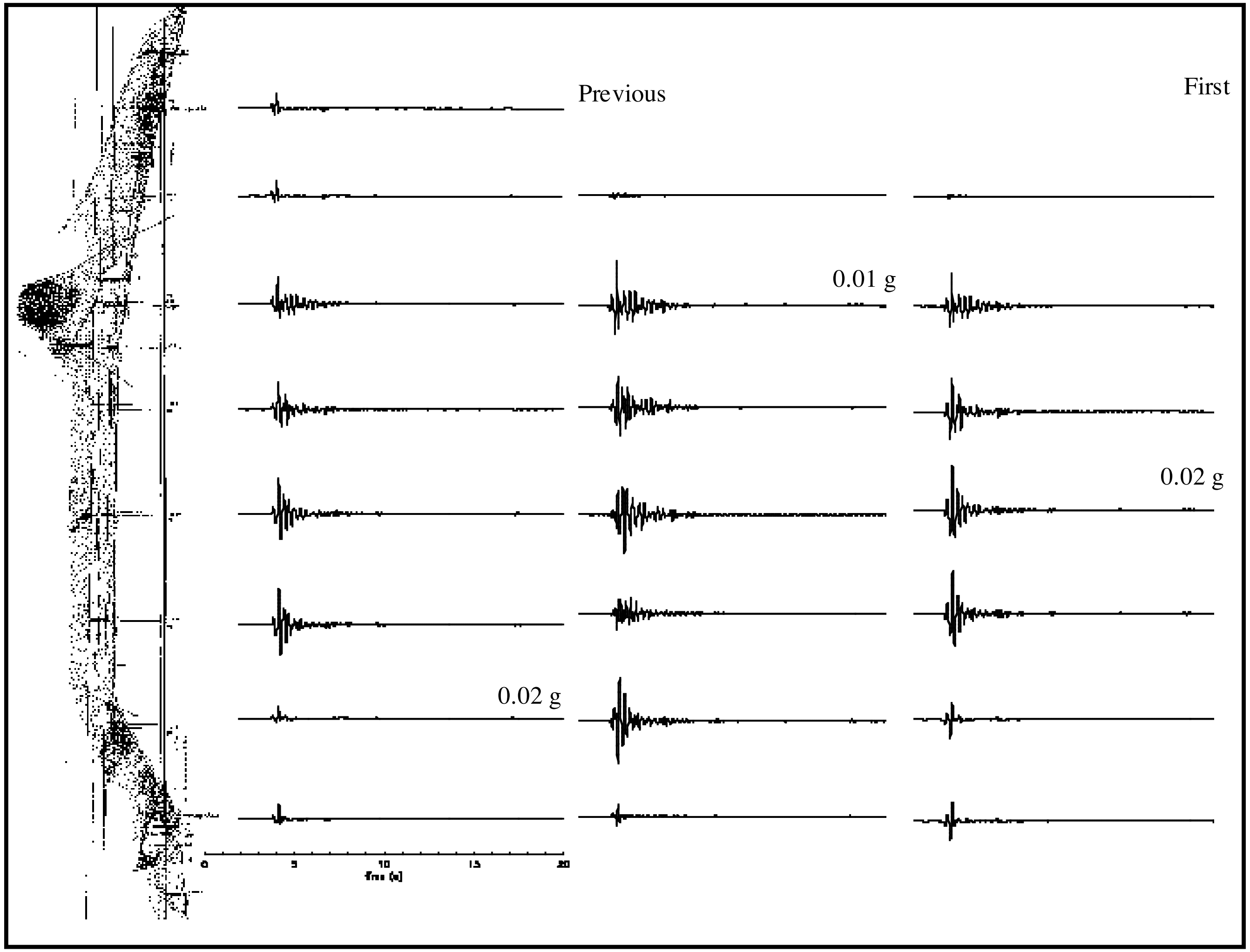


Case study: initial scenario

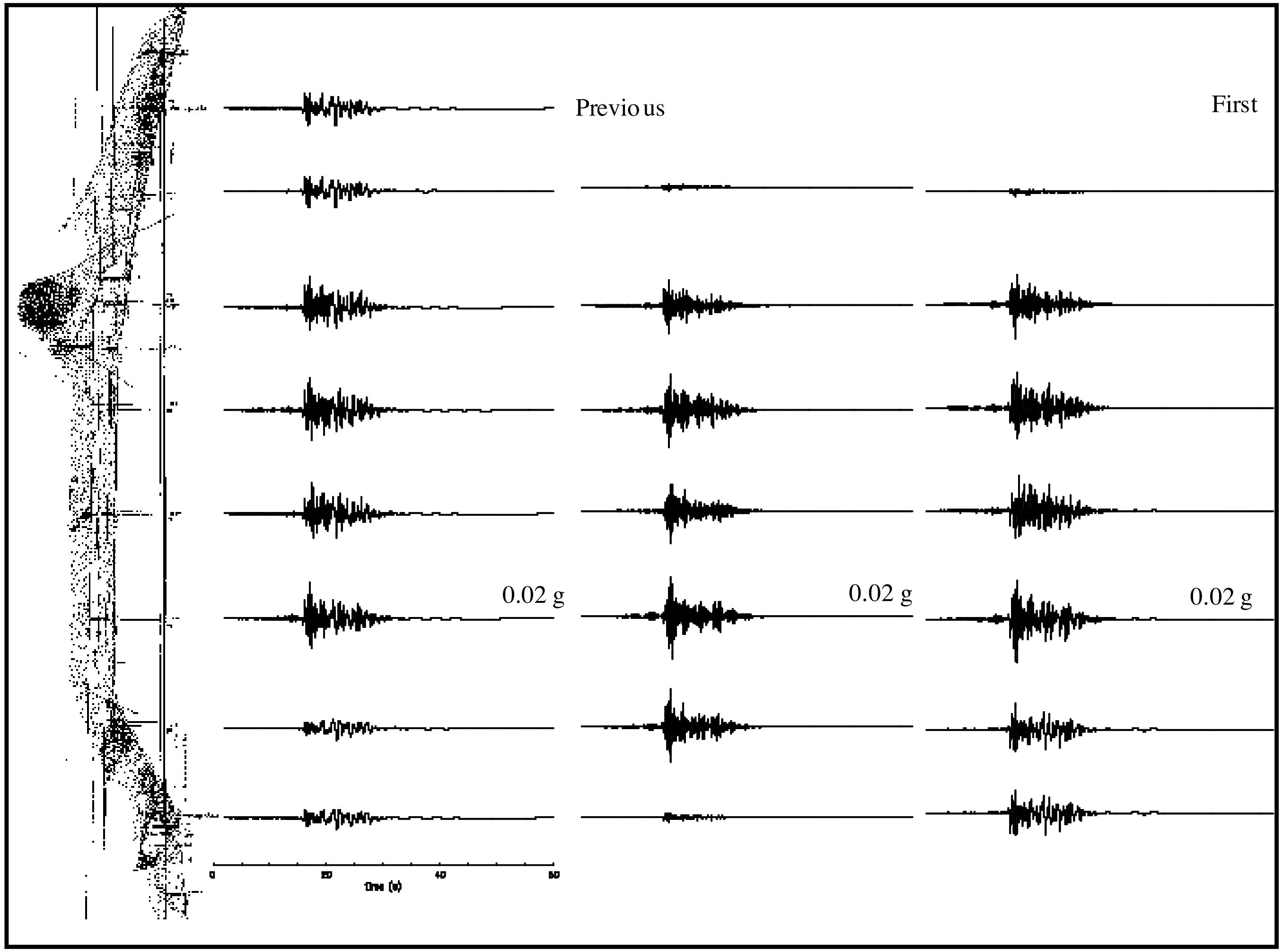
Synthetic accelerations and diffograms



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

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2) Rake a

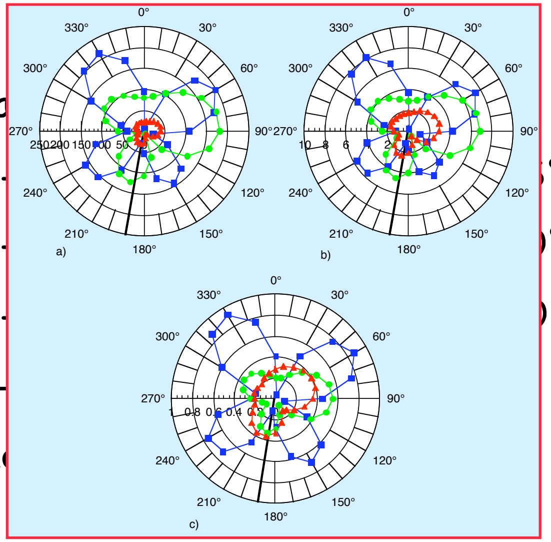
3) Strike- °)

4) Strike- °)

5) Strike- °)

6) Depth-

(Strik



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1) Strik
2) Rake
3) Strik
4) Strik
5) Strik
6) Dept
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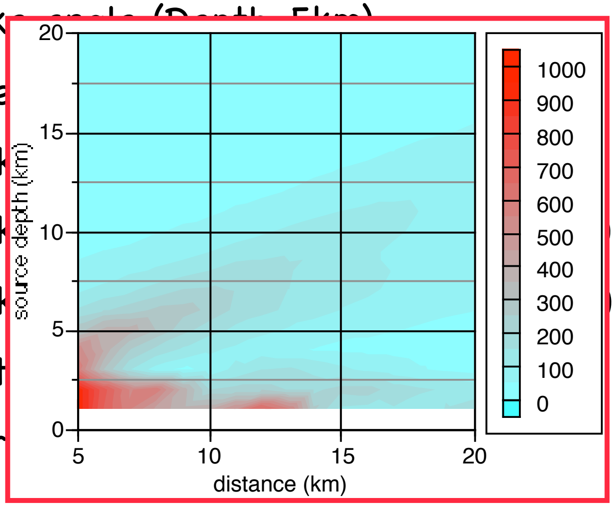
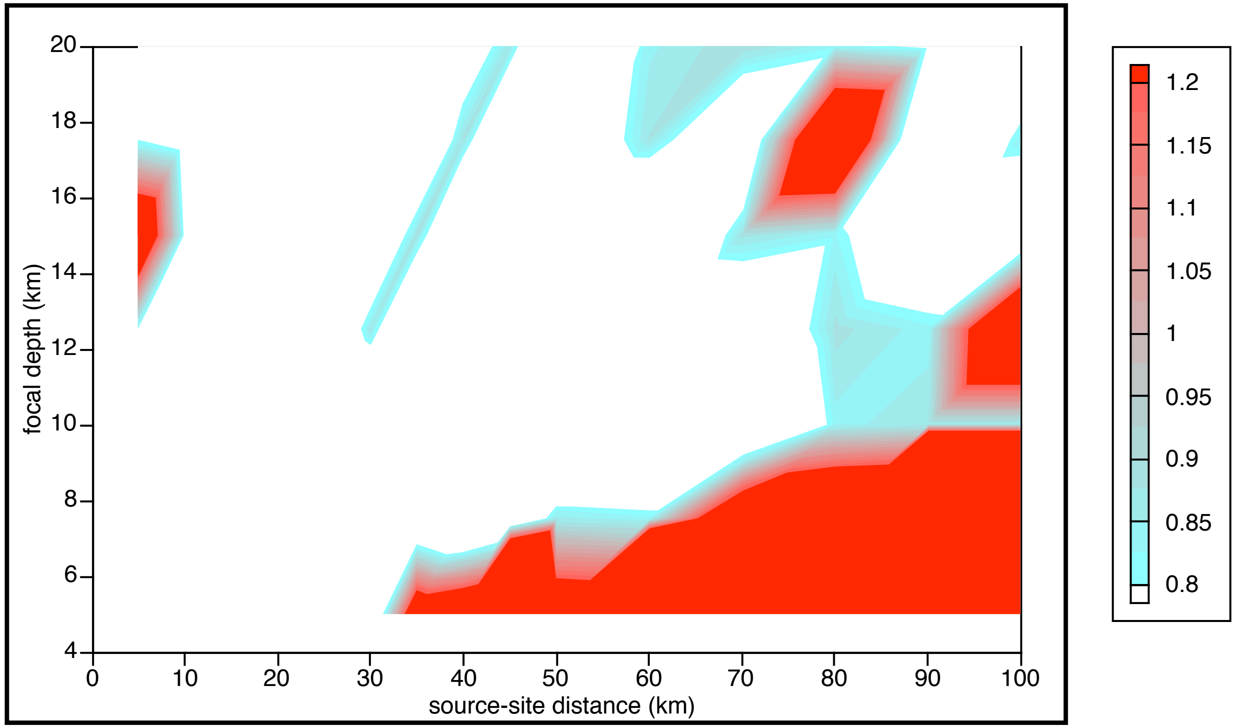


PARAMETRIC STUDY 2 - Fp towards 1Hz

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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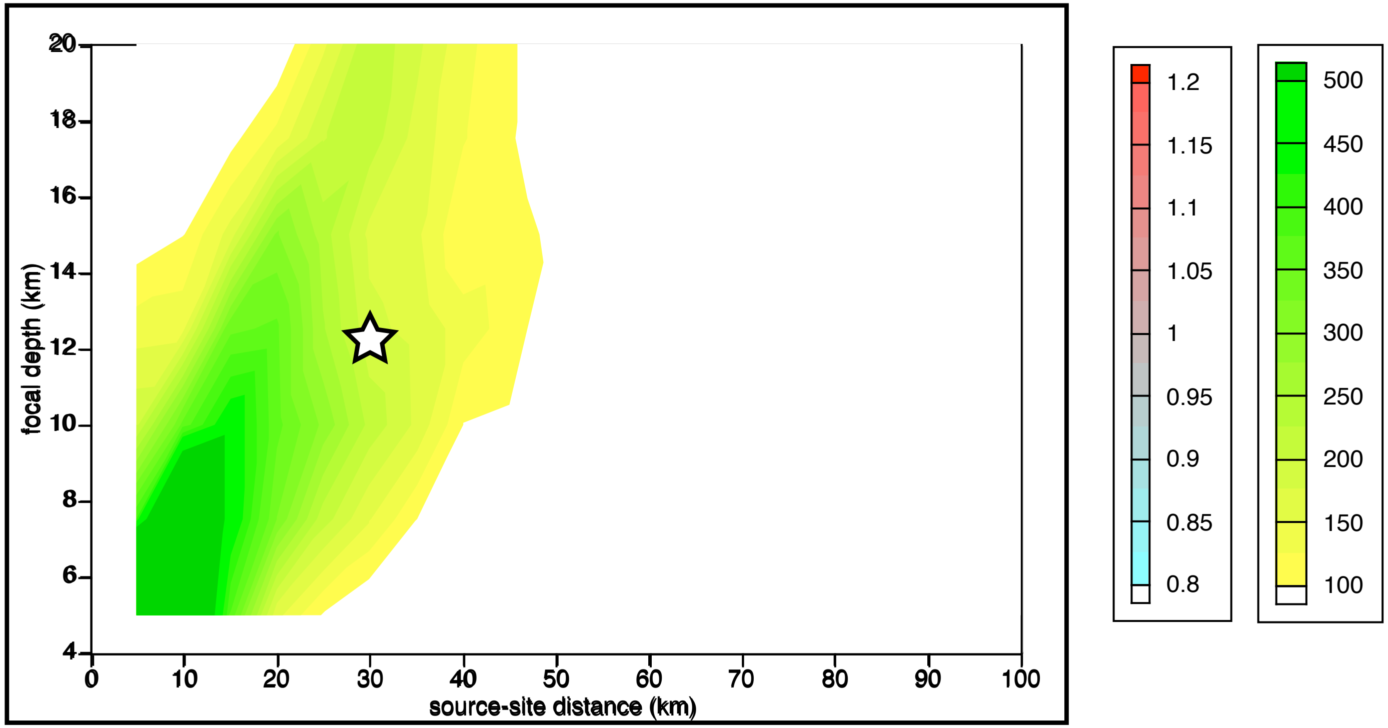
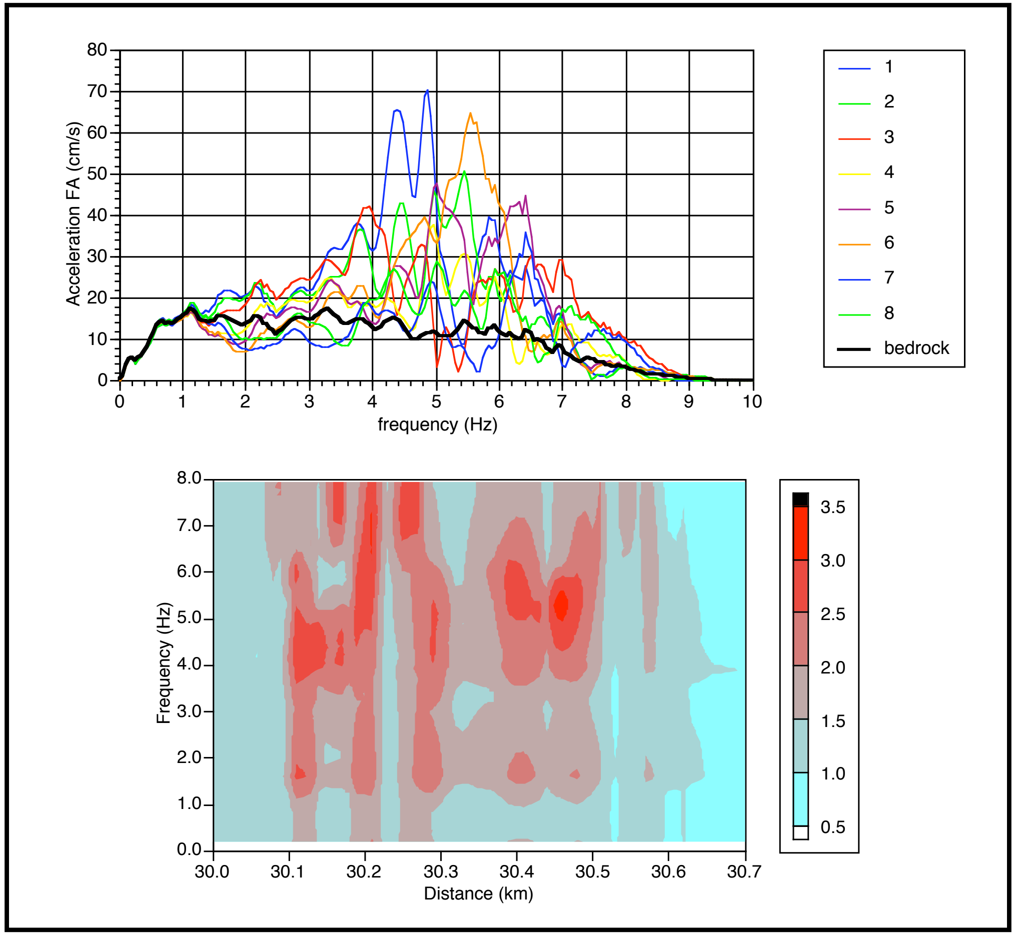


The results show that, in order to reach a relevant value of PGA (e.g. greater than 0.1g) in the desired period range (i.e. 0.8-1.2 s), an alternative and suitable configuration is a source
12 km deep at an epicentral distance of 30 km.

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

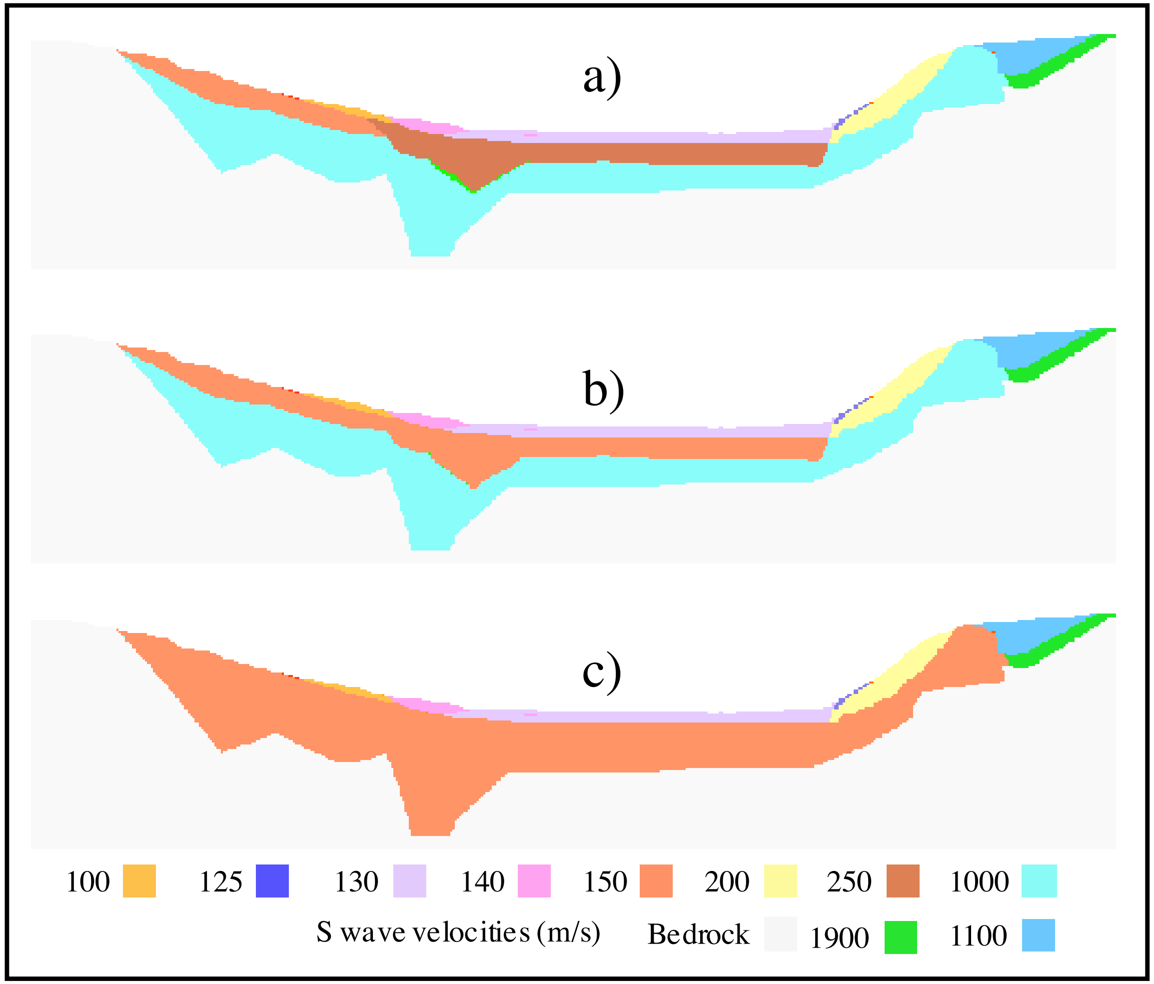
Outline

Seismic input for a critical facility

Parametric studies

- Focal mechanism
- Site effects
- Directivity

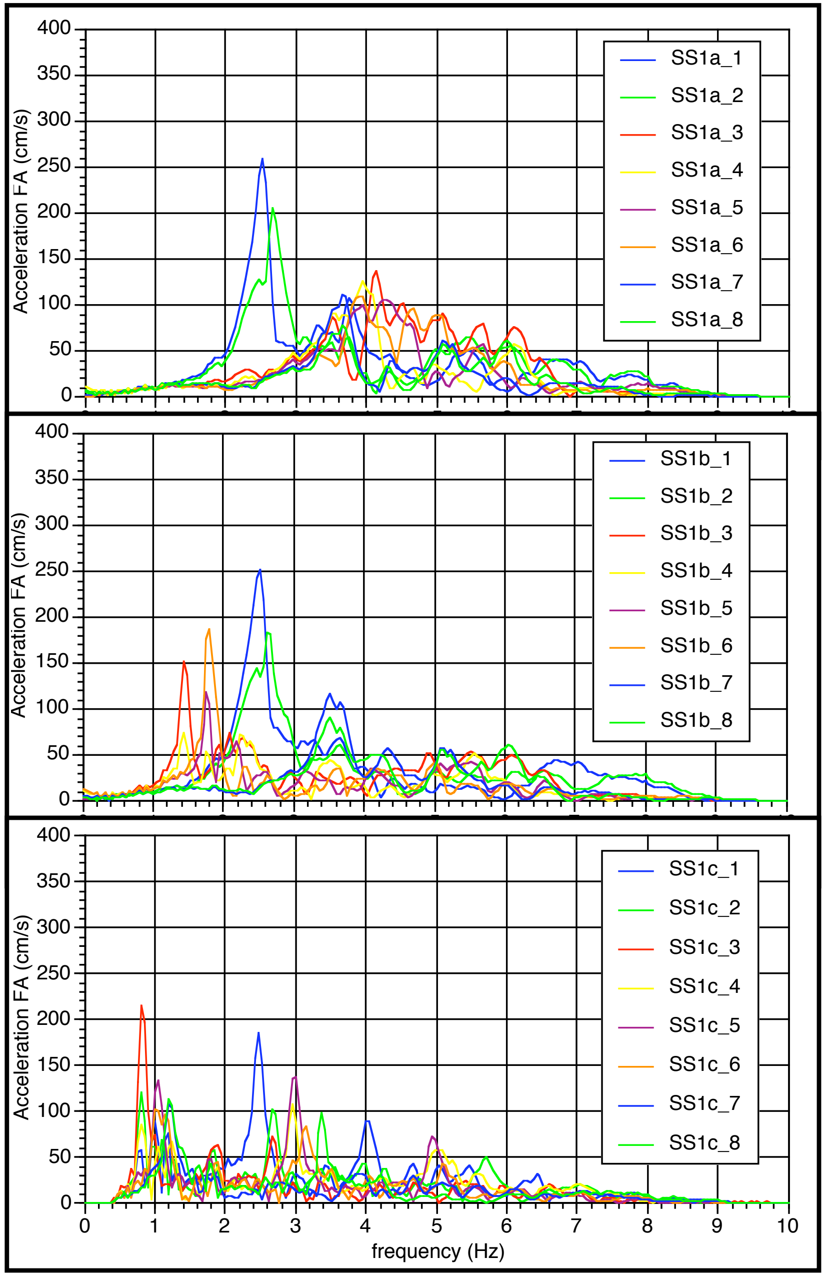
Parametric study 3 - LMp towards 1Hz



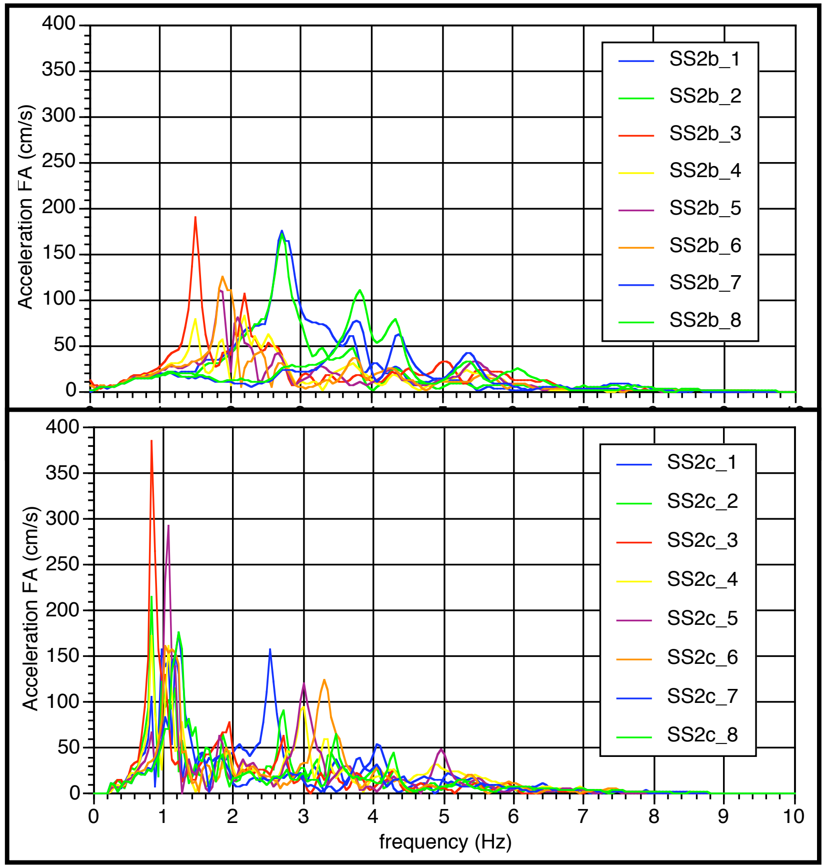
Local geotechnical models of Warth bridge section obtained **lowering successively the S-wave velocities of the uppermost units**

Fourier Amplitude spectra

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



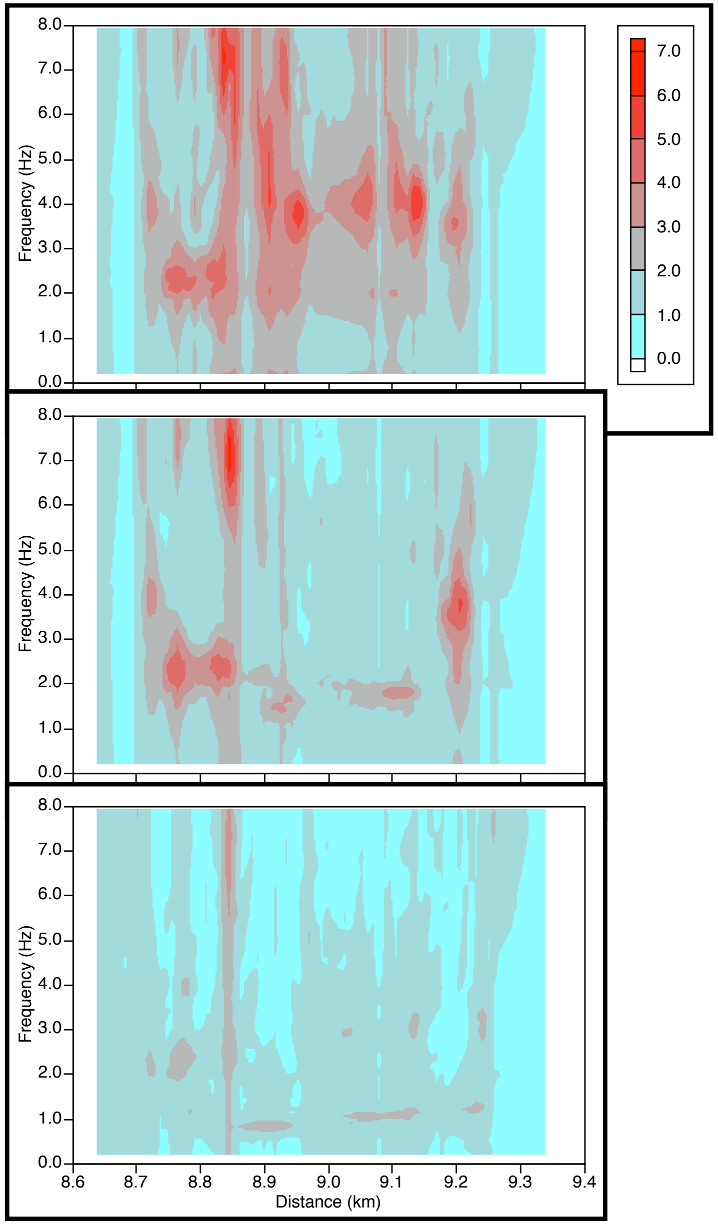
M=6.5; d=30.0km; h=12km



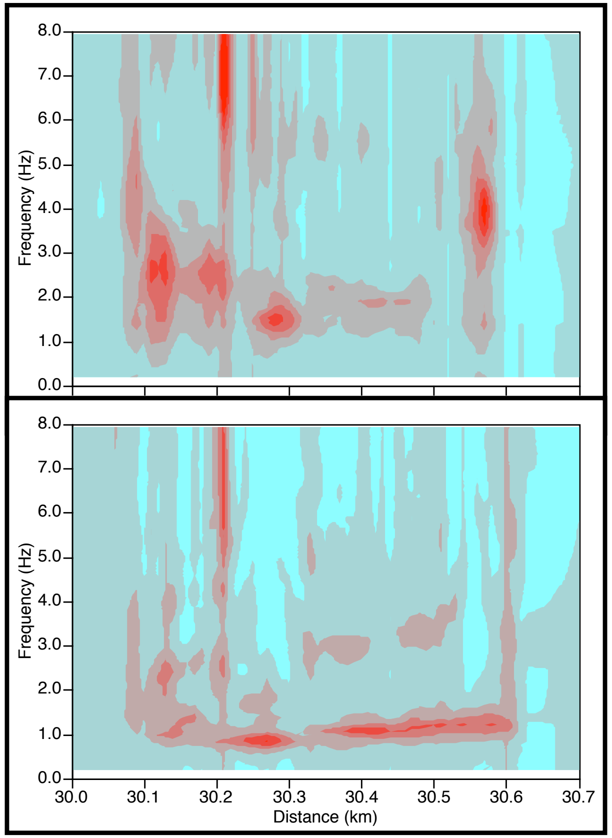
Parametric study 3 - LM

Site response estimation

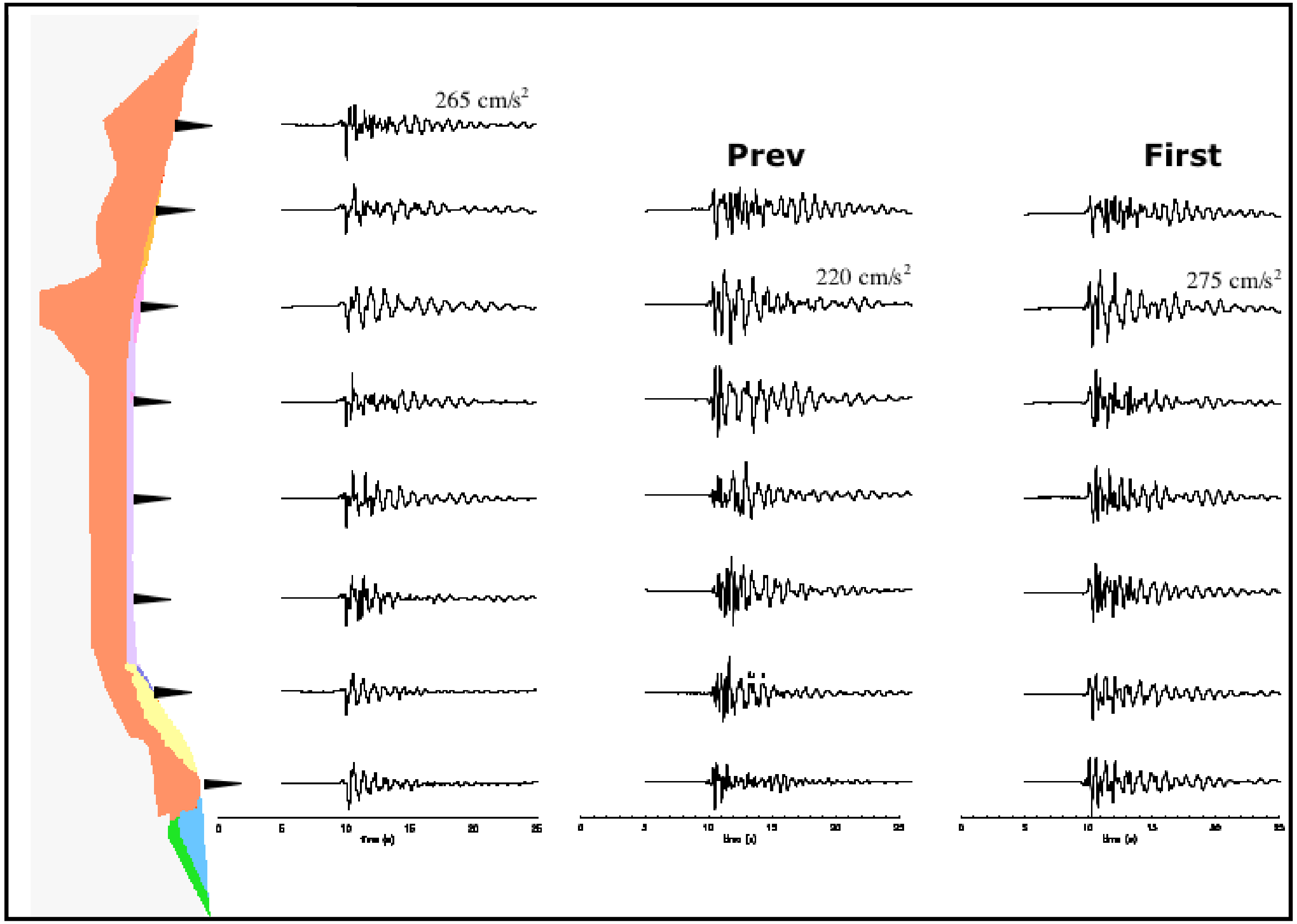
M=5.5; d=8.6km; h=5km



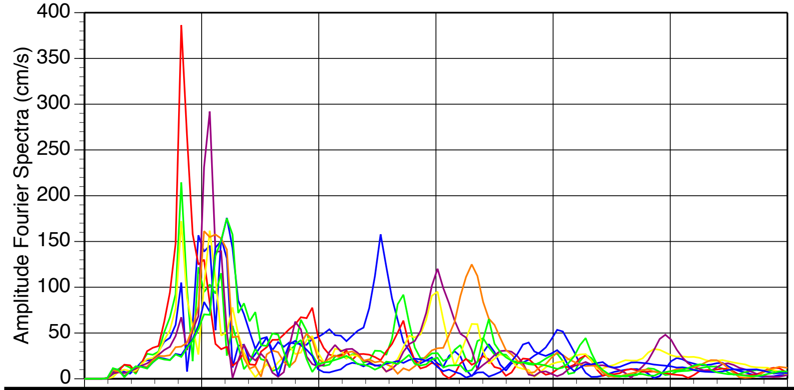
M=6.5; d=30.0km; h=12km

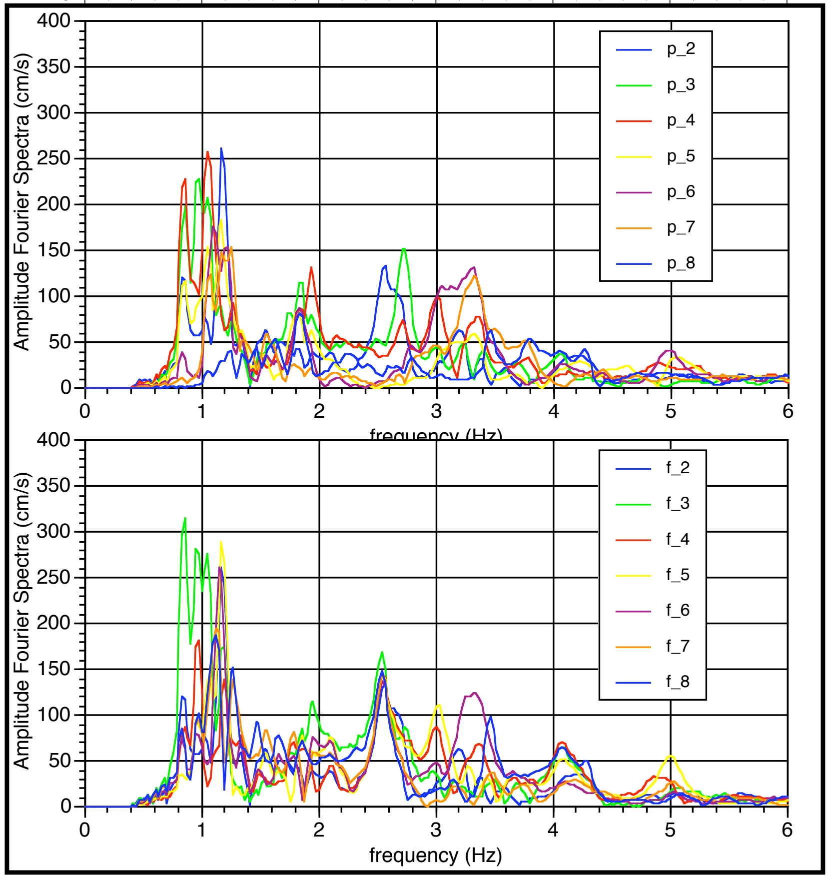


Synthetic accelerations and diffograms

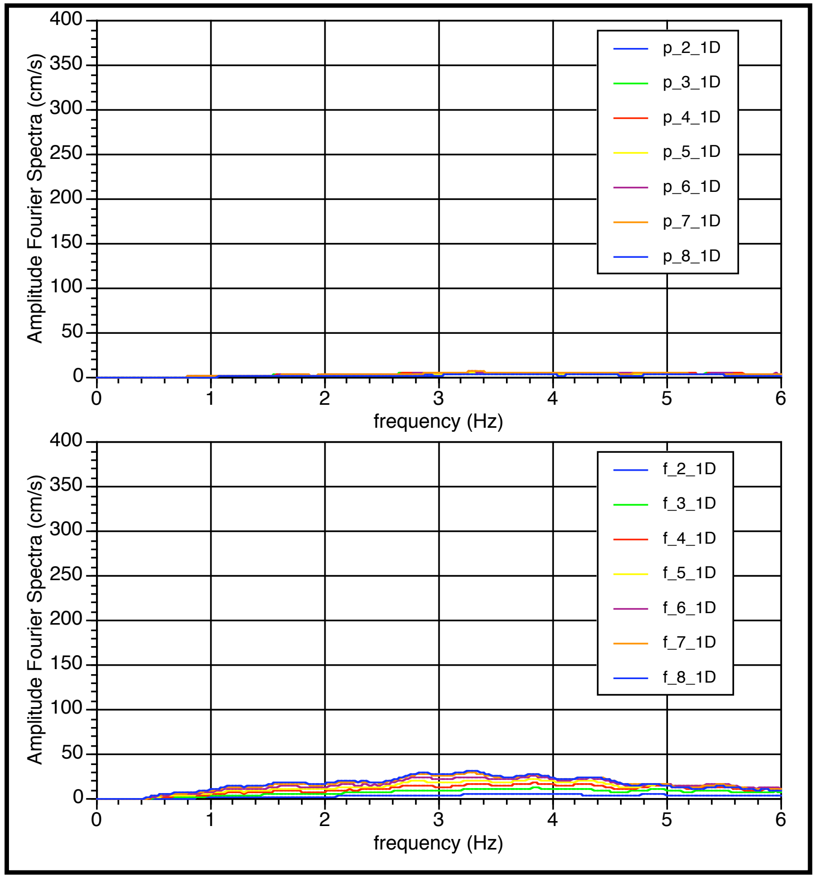


Fourier AS of diffograms





Bedrock



Case study

Implementation of PSD tests

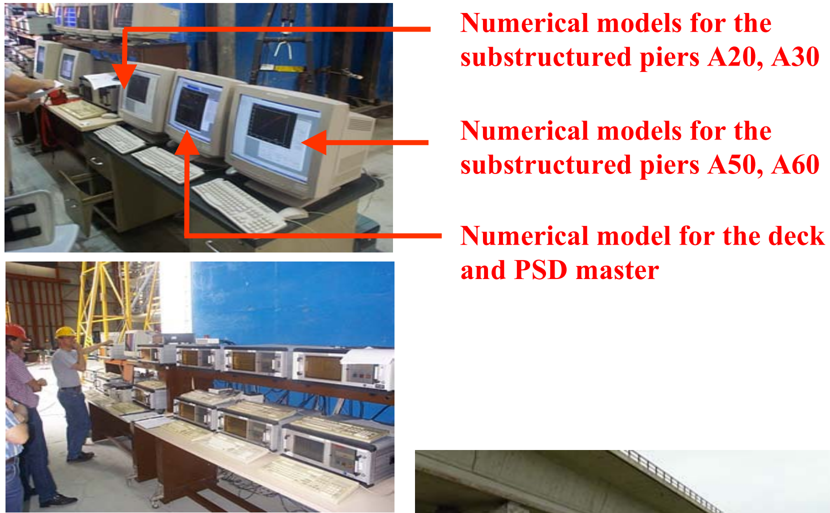
PSD WITH SUBSTRUCTURING

Application to the Warth Bridge, Austria

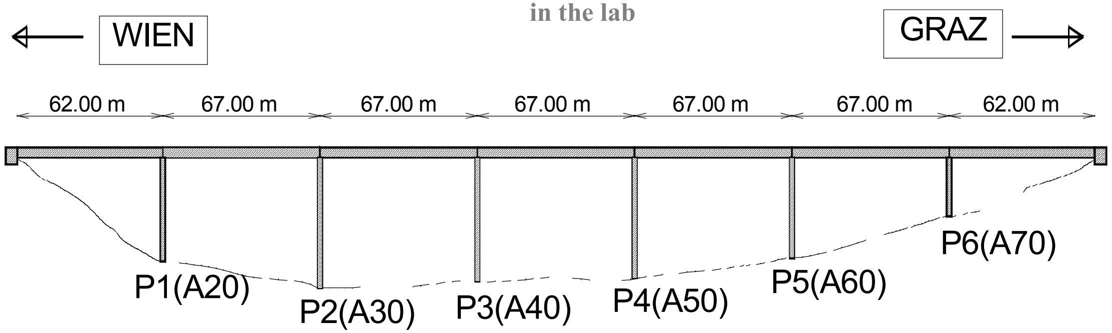
Joint Research Centre

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

Physical piers A40 & A70 in the lab



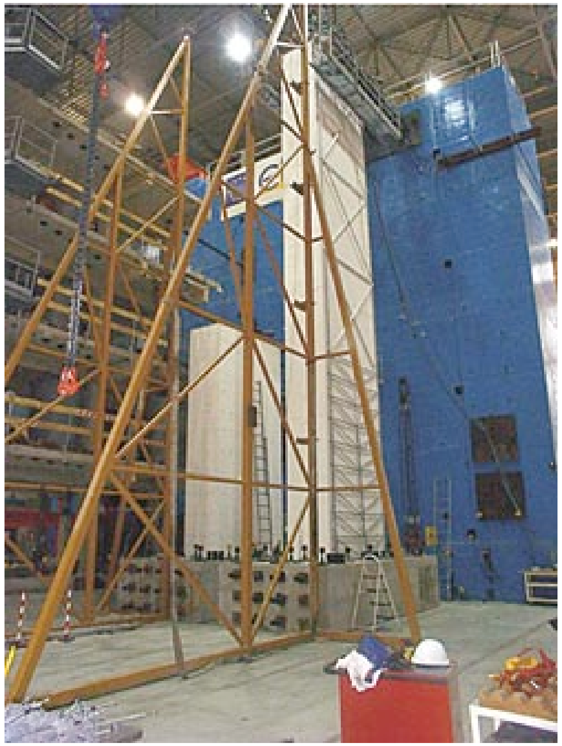
Master experimental process

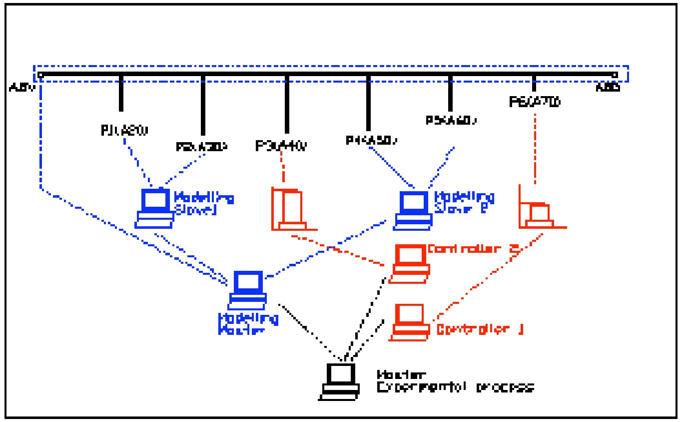


Warth Bridge

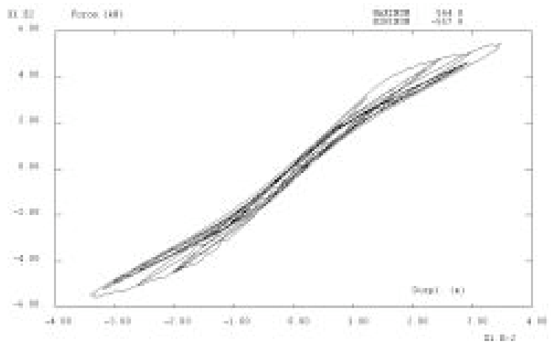
elsa

Implementation of PSD tests



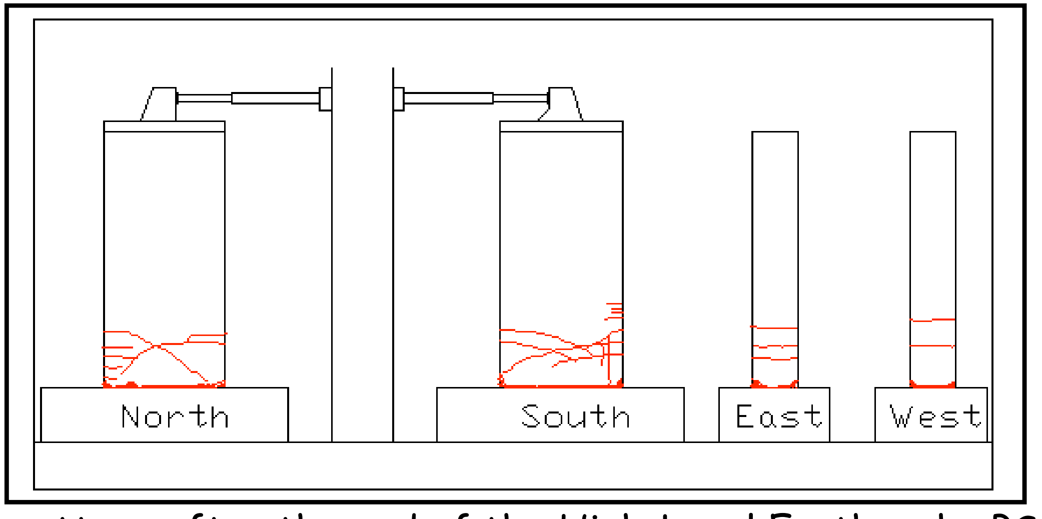


(a) physical piers in the lab, (b), schematic representation
(c) workstations running the PSD algorithm and controlling the test



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.

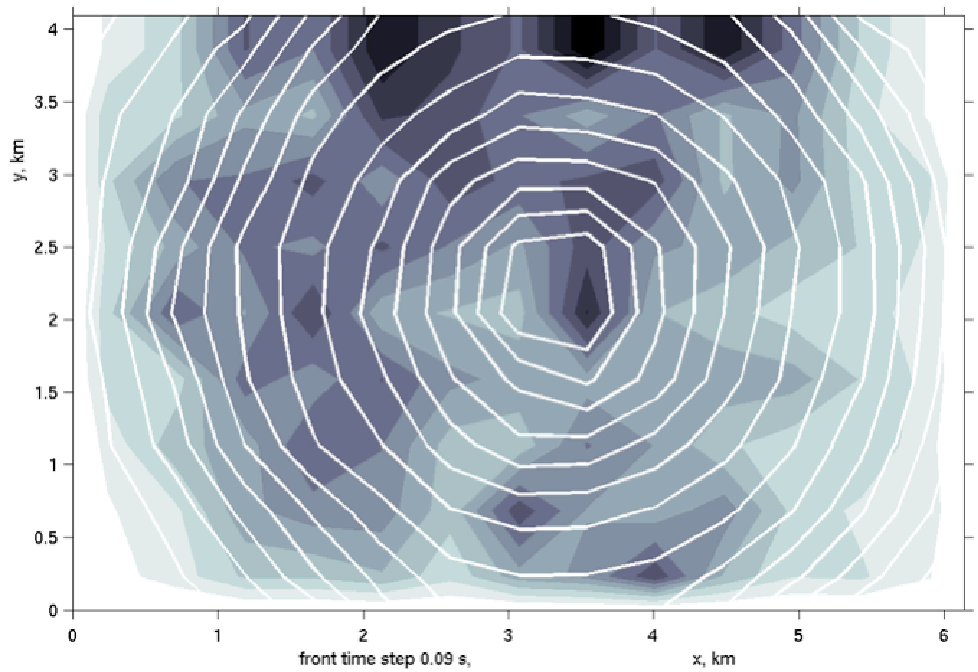
Outline

Seismic input for a critical facility

Parametric studies

- Focal mechanism
- Site effects
- Directivity

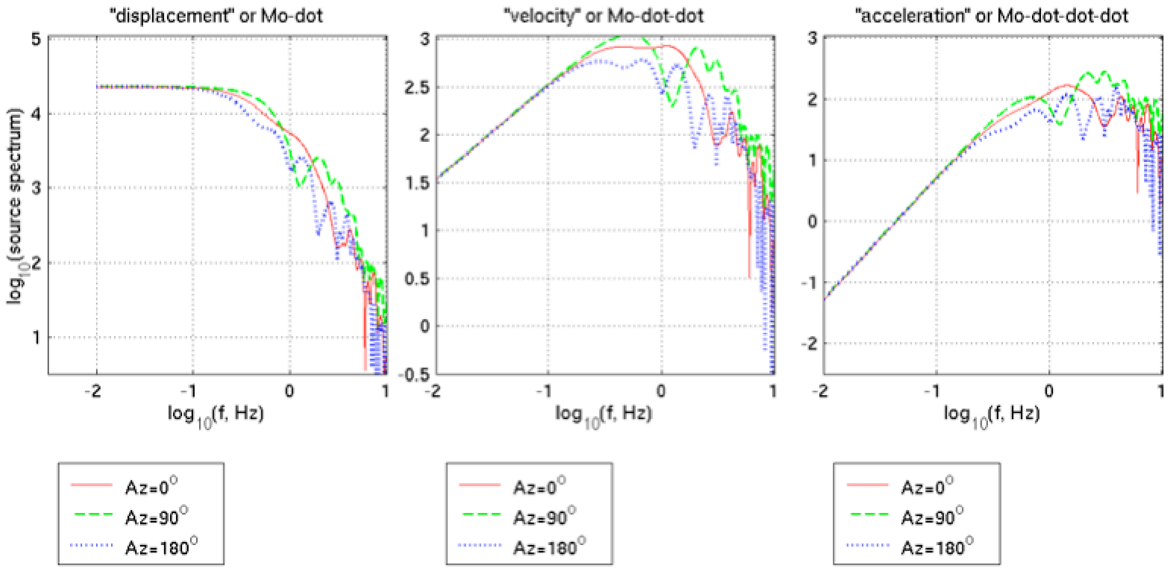
Parametric study 4 - ESp towards directivity



Parametric study 4 - ES

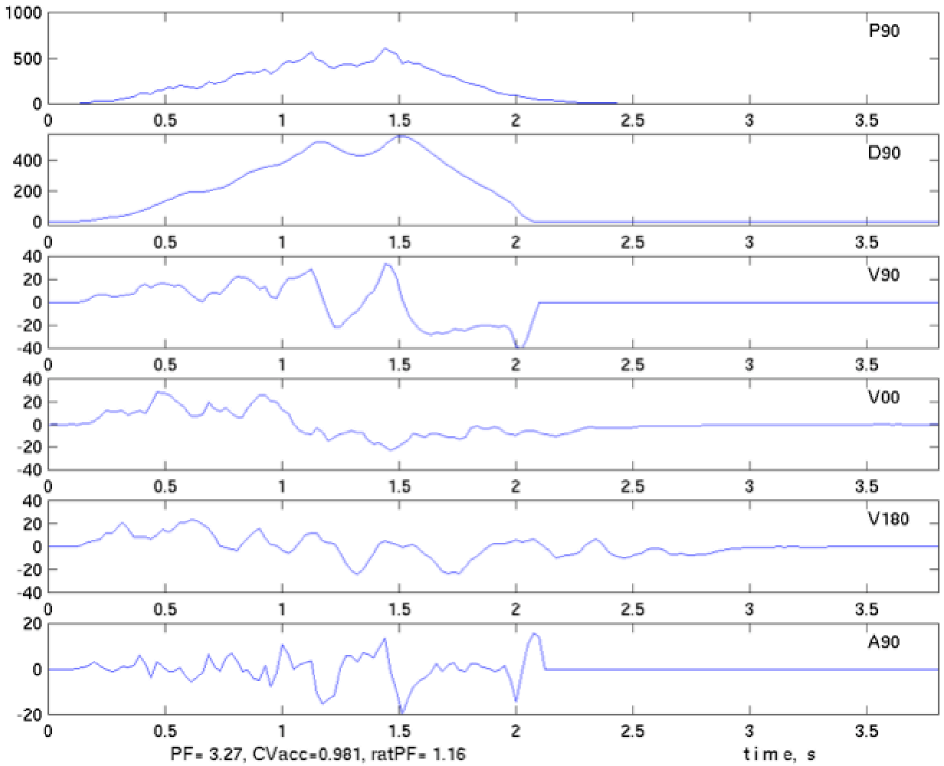
Rupture model: bilateral at 3 positions

Parametric study 4 - ESp towards directivity



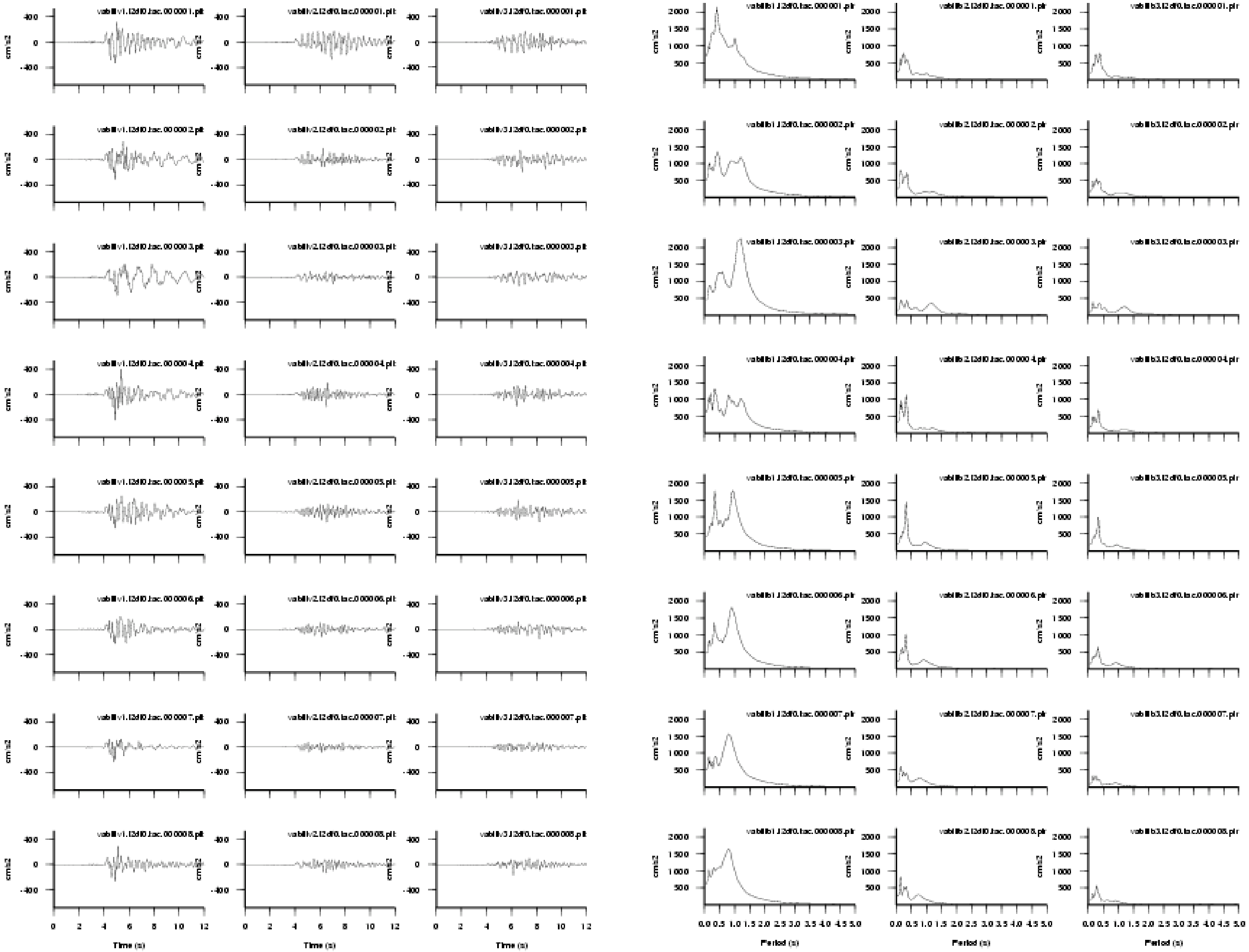
Rupture model: bilateral at 3 positions

Parametric study 4 - ESp towards directivity



Rupture model: bilateral at 3 positions

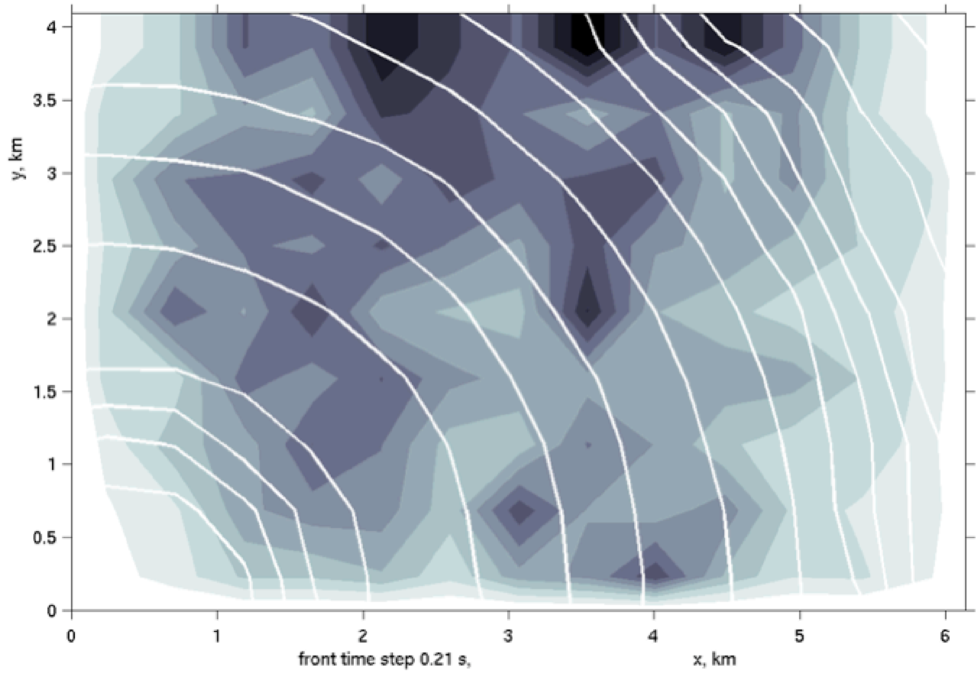
Parametric study 4 - ESp towards directivity



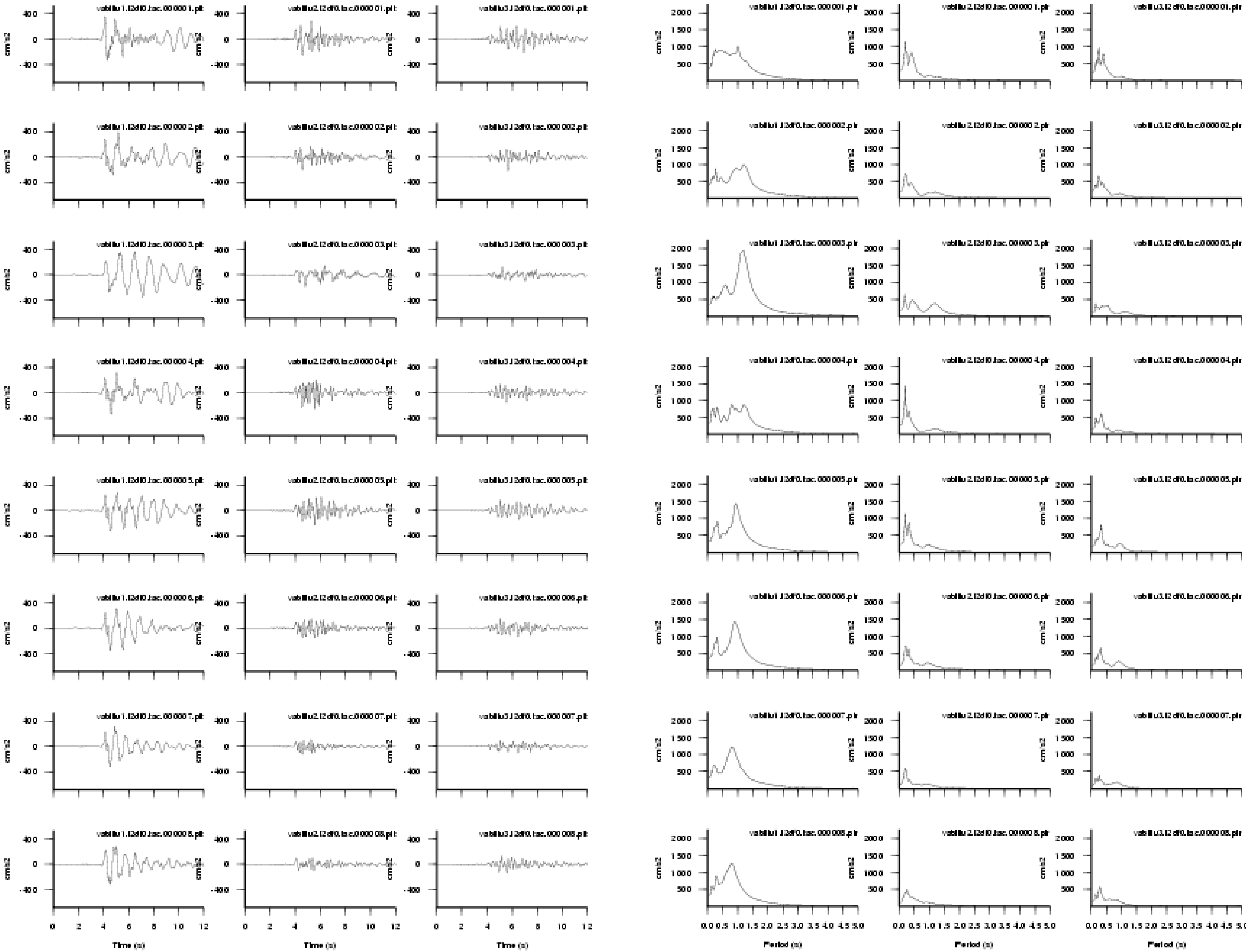
Parametric study 4 - ES

Rupture model: bilateral at 3 positions

Parametric study - ESp towards directivity



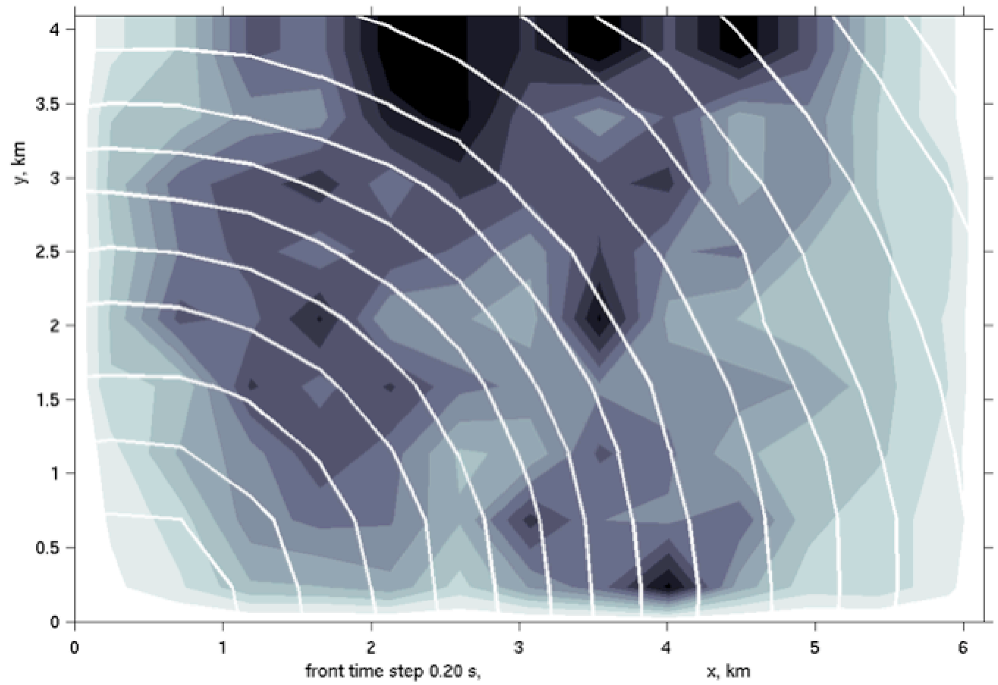
Parametric study - ESp towards directivity



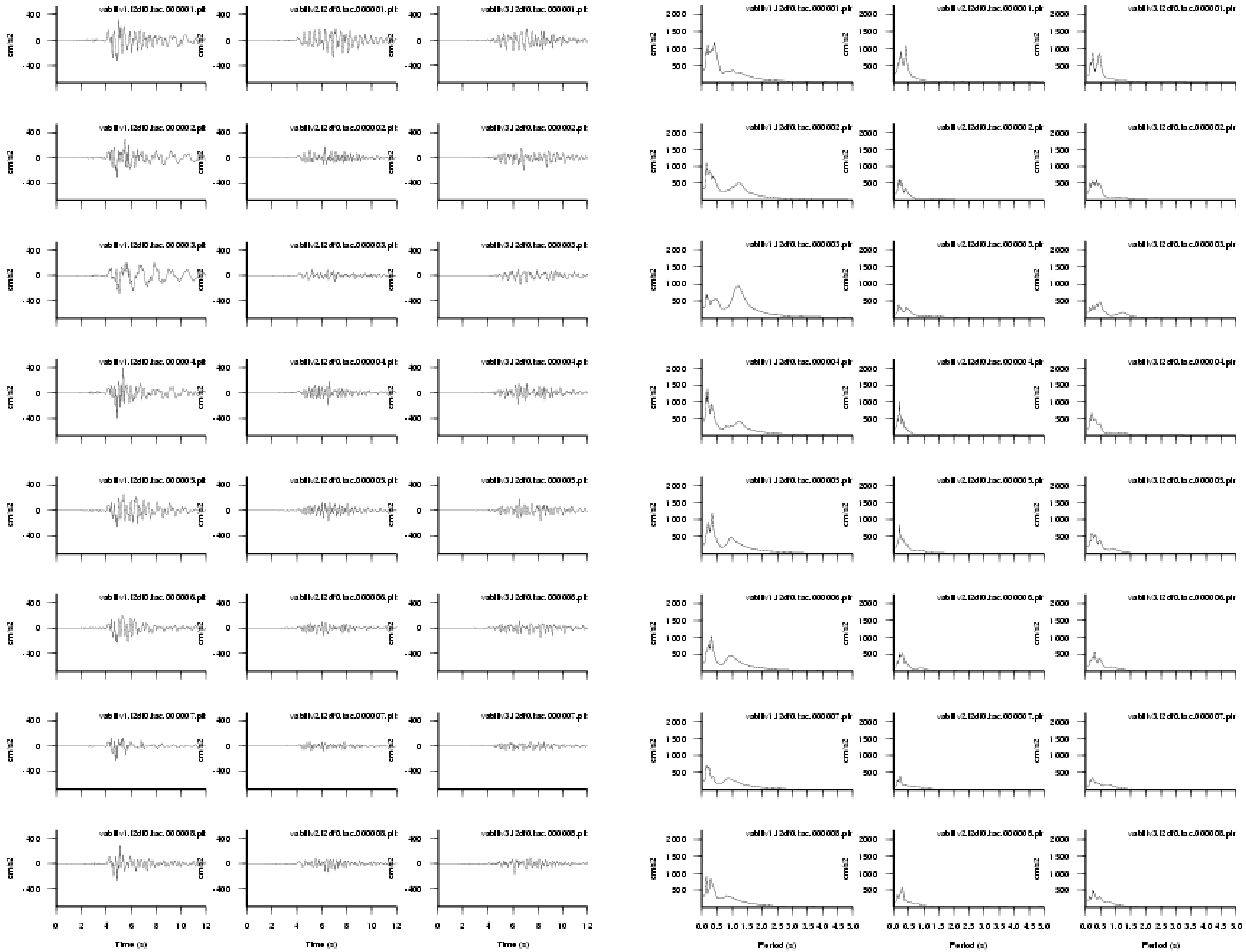
Parametric study 4 - ES

Rupture model: unilateral at 3 positions

Parametric study - ESp towards directivity



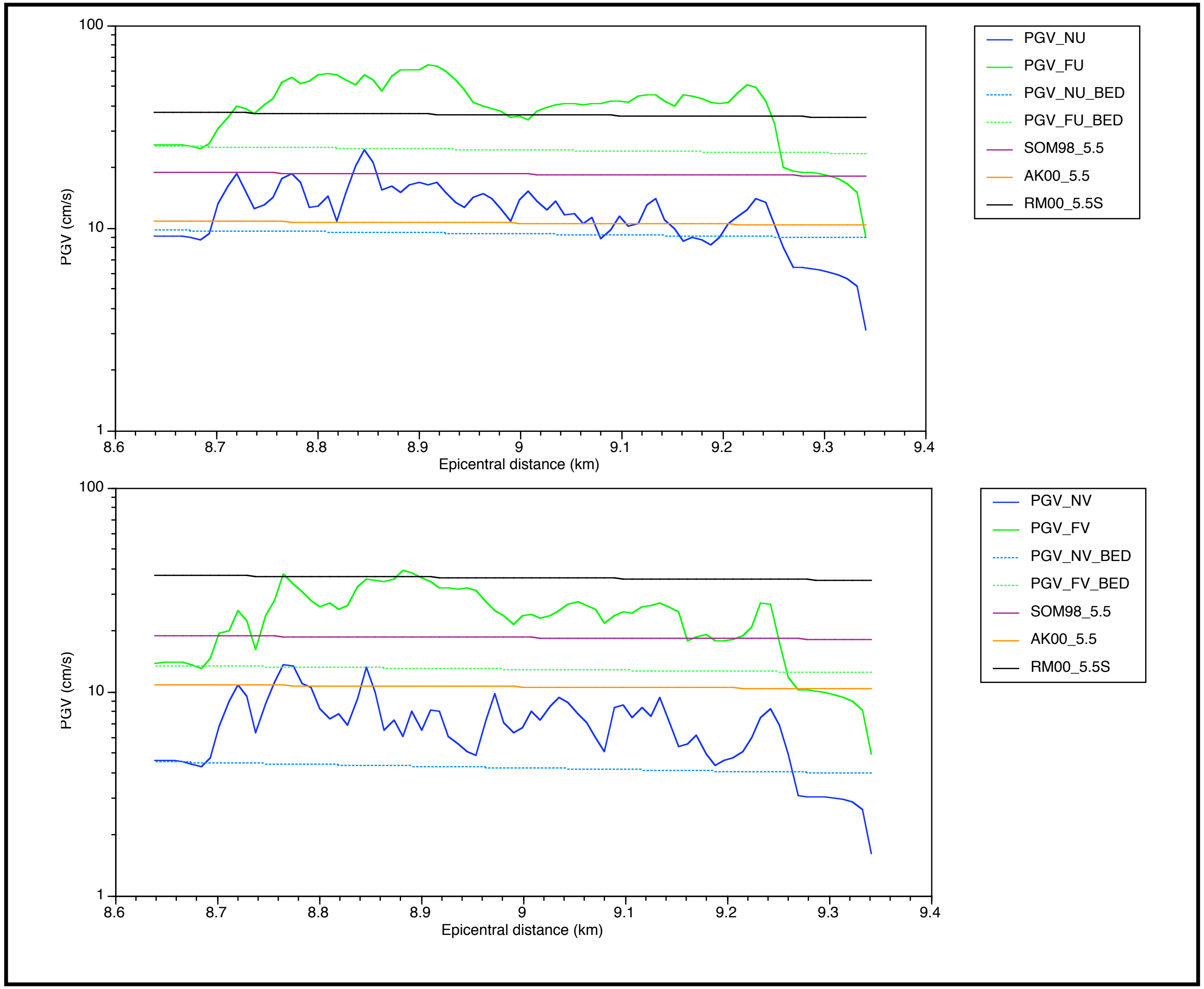
Parametric study - ESp towards directivity



Parametric study 4 - ES

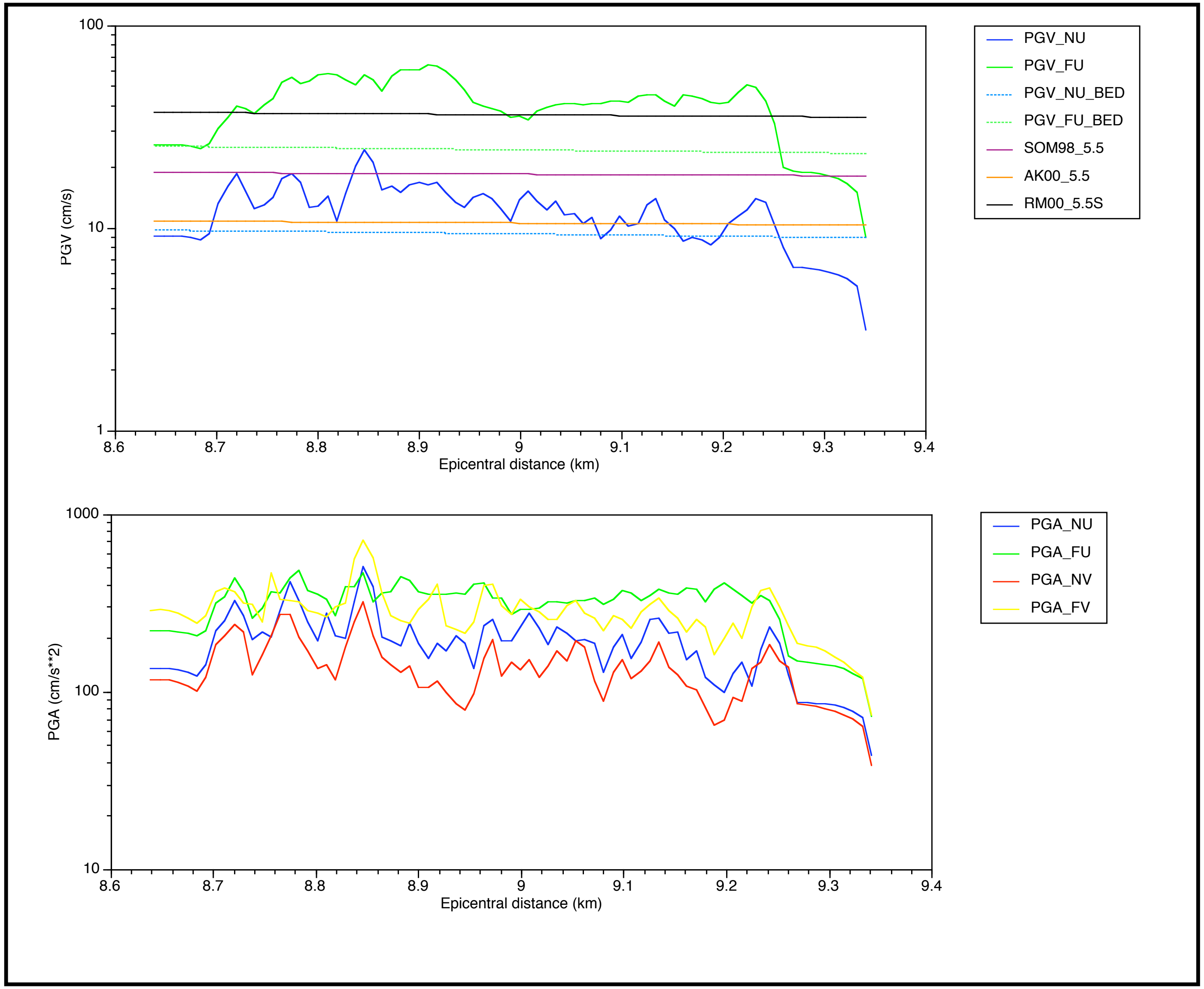
Rupture model: un. different v_r at 3 positions

PGV - PGA and directivity

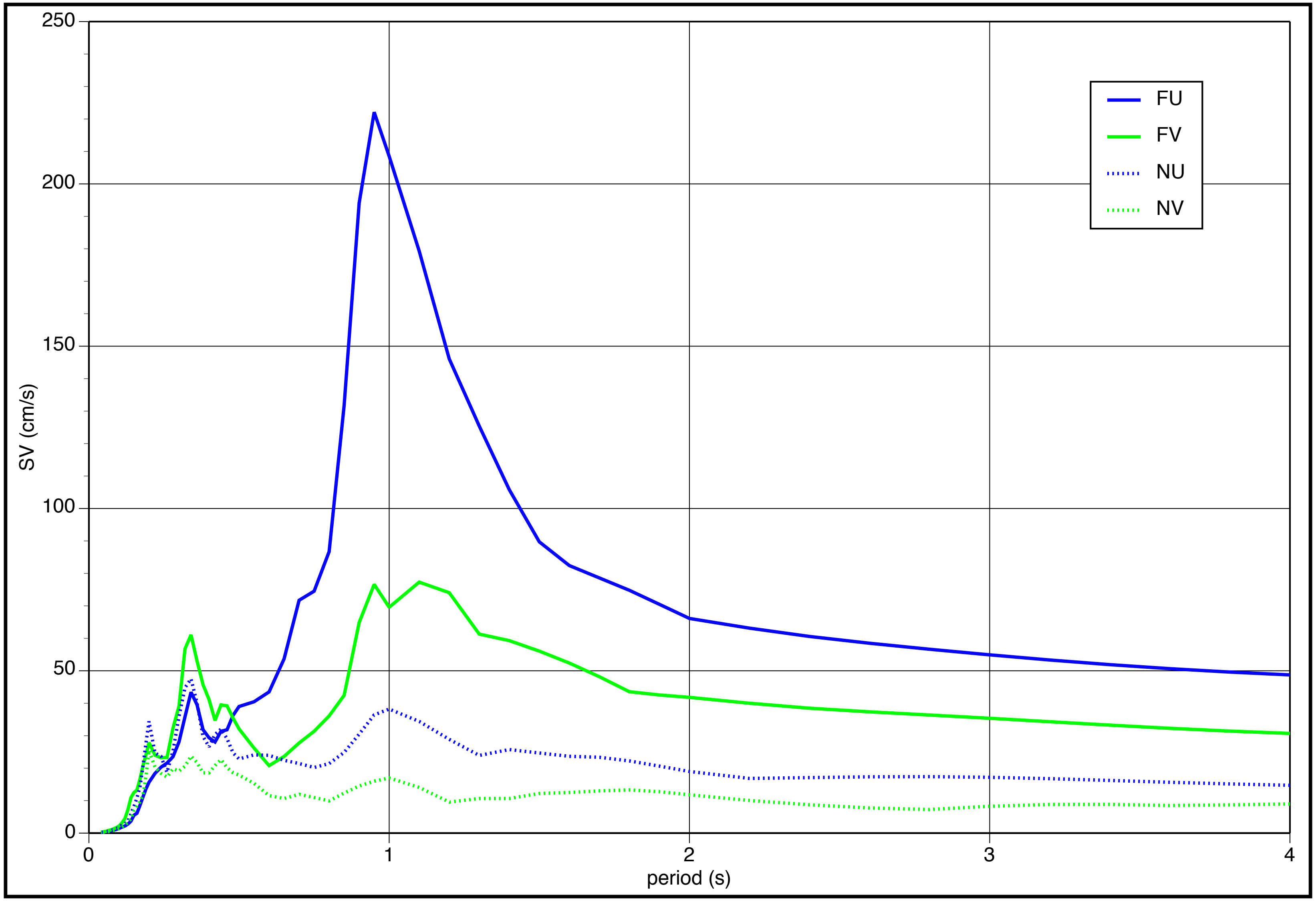


Parametric study 4 - ES

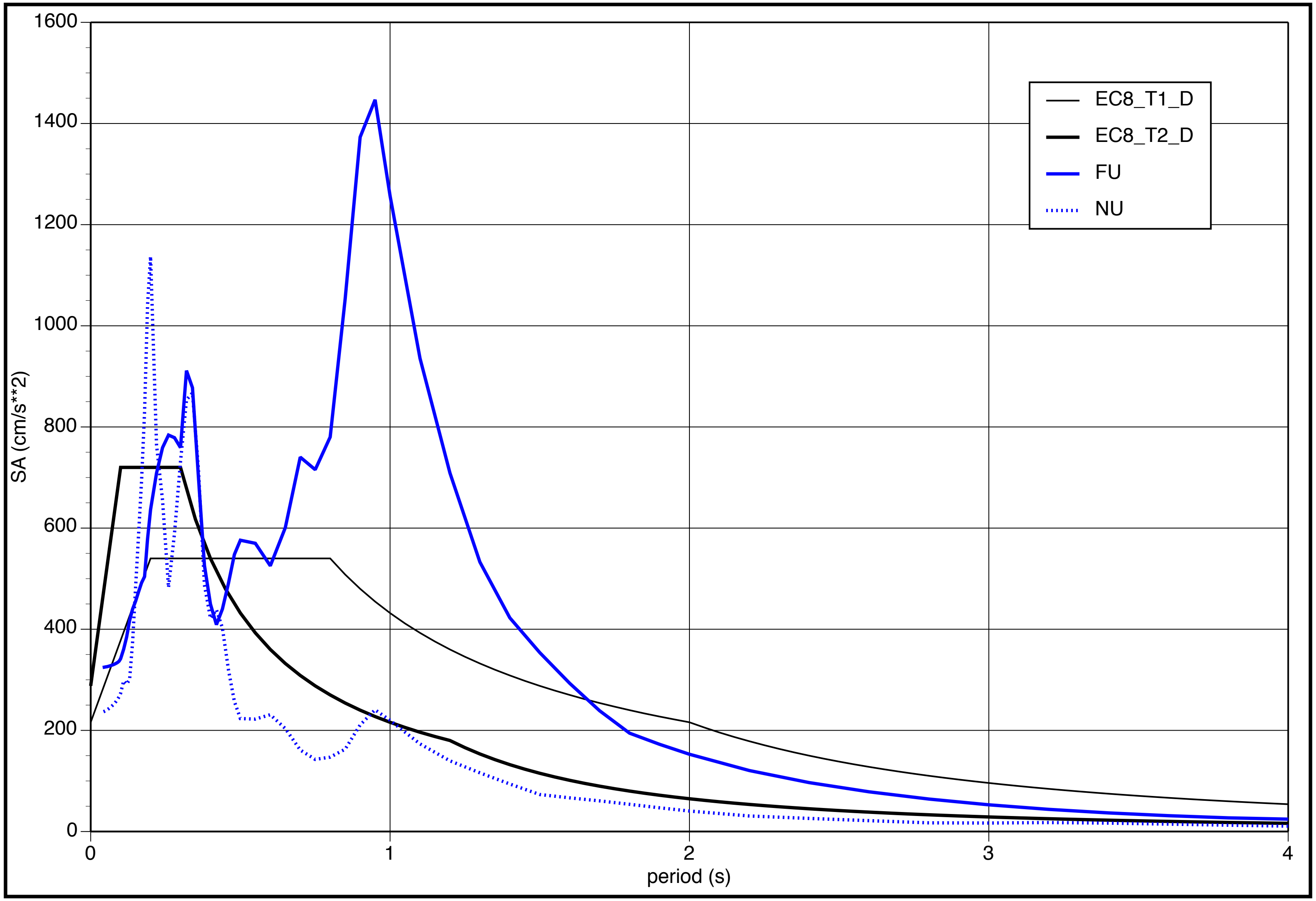
PGV - PGA and directivity



Parametric study 4 - ESp towards directivity



Parametric study 4 - ESp towards directivity



References

Panza, G.F., Romanelli, F. and Vaccari, F. (2001). "Seismic wave propagation in laterally heterogeneous anelastic media: theory and applications to the seismic zonation", **Advances in Geophysics**, Academic press, 43, 1-95.

Romanelli, F., Vaccari, F. and Panza, G.F. (2003). "Realistic modelling of the effects of asynchronous motion at the base of bridge piers", **Journal of Seismology and Earthquake Engineering**, Vol. 6, No. 2, pp. 17-26.

Romanelli, F., Vaccari, F. and Panza, G.F. (2003). "Realistic Modelling of the Seismic Input: Site Effects and Parametric Studies", **Journal of Seismology and Earthquake Engineering**, Vol. 5, No. 3, pp. 27-39.