The Abdus Salam
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"8th Workshop on Three-Dimensional Modelling of
Seismic Waves Generation, Propagation and their Inversion"

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Ground Motion Modelling for Complex Media

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8th Workshop on Three-Dimensional Modelling of Seismic
Waves Generation, Propagation and their Inversion

Seismic waves propagation in complex media

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Introduction - 1

- In many areas of the physical sciences propagation of waves in complex media plays a central role: e.g. acoustics, elastics, environmental sciences, mechanics, marine sciences, medical sciences, microwaves, optics, and seismology.

- The problems that workers in these areas have to overcome to describe, understand, and ultimately predict wave propagation are formidable. Right from the start of this field in the beginning of this century it was clear that new concepts and major approximations had to be introduced.

- The fundamental dilemma with these approximate concepts is that **often length scales of the media inhomogeneities are comparable to the wavelength**. The range of validity of these approximations is confined to situations where these length scales are much larger than the wavelength.

Introduction - 2

- The complexity of the media that support wave propagation can be classified in a number of ways: inhomogeneities can vary from **totally random, via quasi-periodic, and waveguide structures to fully periodic**. A useful criterion for classifying inhomogeneous media is whether this inhomogeneity is of **continuous** nature, or stems from **discrete scatterers**.

- An additional classification basis is whether or not the complexity is confined to the surface or is present all over the media. Many complex materials of acoustic interest are of porous character. They are elastic solids containing fluid-filled pores. These range from natural materials such as soils, rocks, and sediments to manmade materials such as bricks, thermal insulation, and acoustical ceiling tiles.

Introduction - 3

Advances made in understanding waves in complex media has led to a number of practical applications, and is generating new ones at an ever increasing rate:

- ☑ **remote optical sensing** ('looking through a cloud');
- ☑ **inverse optical scattering** ('find the mouse in the milk');
- ☑ **applied optics** (quality control of optical systems by controlling surface roughness);
- ☑ **optical devices** and even (random) lasers;
- ☑ **oil and mineral prospecting** by seismic methods;
- ☑ **ultrasonic imaging and non destructive testing** ('finding hairline cracks in the titanium-aluminium alloy in an airplane wing');
- ☑ **non-invasive medical imaging**;
- ☑ to **microwave propagation and detection** (antennas, mobile phones and radar).

Introduction - 4

- The early 1990s saw many interesting contributions to the field of **seismic wave propagation** from a variety of researchers, even as many wave-propagation specialists shifted their research focus away from new methods for seismogram synthesis toward data acquisition and inversion.

- In part, this shift was a natural consequence of the explosive growth in the amount and availability of **high-quality digital seismic data**, ready to be processed with interpretation tools developed in previous decades.

- As a result, observational seismology has recently made dramatic contributions toward imaging global geodynamics, revealing the great variety of crustal structures.

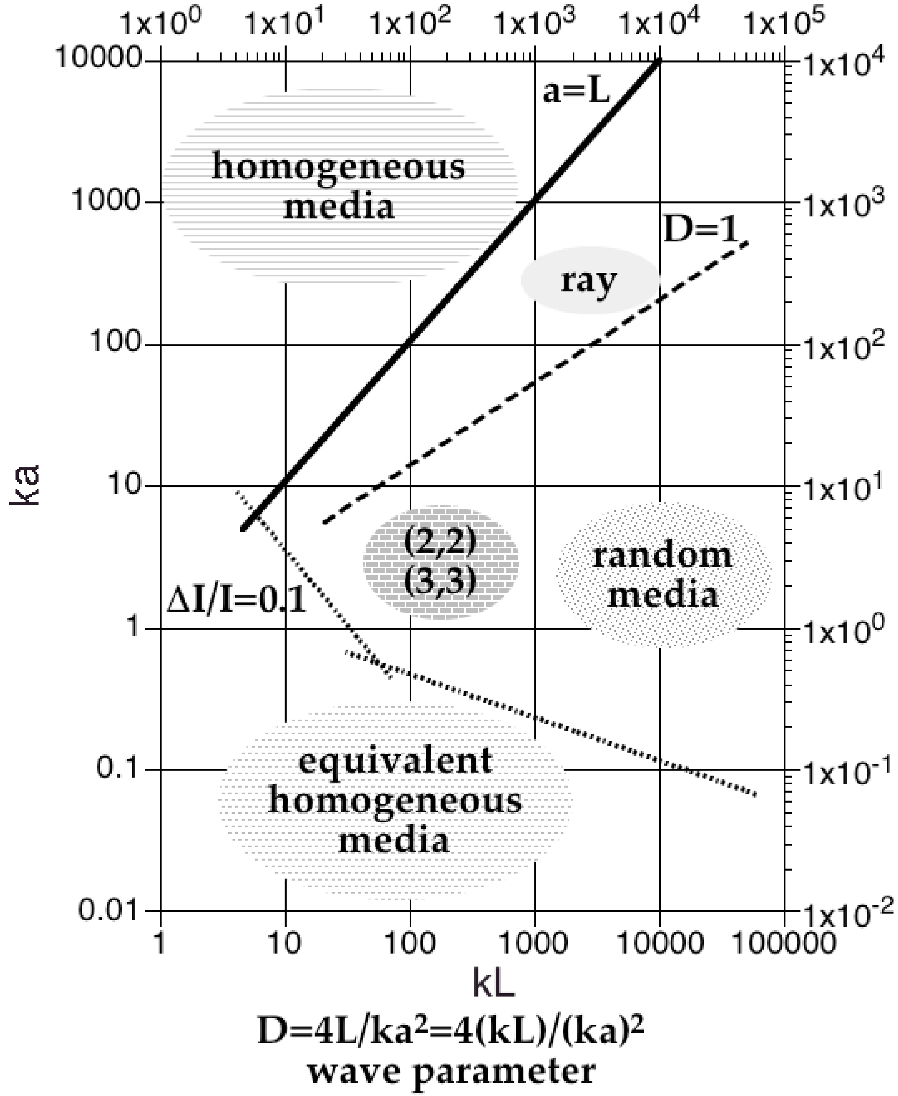
Introduction - 5

Seismic wave propagation studies are defined as investigations of the **seismic forward problem**, i.e. how seismic wave energy travels from source to receiver in an elastic, or anelastic, medium.

Most efforts by researchers have involved improvements in techniques for calculating differential seismograms for use in inverse problems, or studies of wave propagation in complex media. This research sometimes must **sacrifice elegance in order to incorporate realistic seismic velocity structure**.

Even so, **the intellectual gap** between "brute force" solutions in complex media and analytic solutions in simpler media **has often been bridged in innovative ways…**

Seismic Wave Propagation



Seismic wave propagation problems can be classified using some parameters.

This classification is crucial for the choice of technique to calculate synthetic seismograms, but it needs a **deep comprehension of the physical meaning of the problem**.

(Adapted from Aki and Richards, 1980)

(Seismic) wave propagation

Basic physical concepts

What is a wave?

Discrete and continuous models

Born of wave equation

BC: modes and dispersion

PDE: Poisson, diffusion and wave equation

Basic physical concepts 2

EM scattering and diffusion

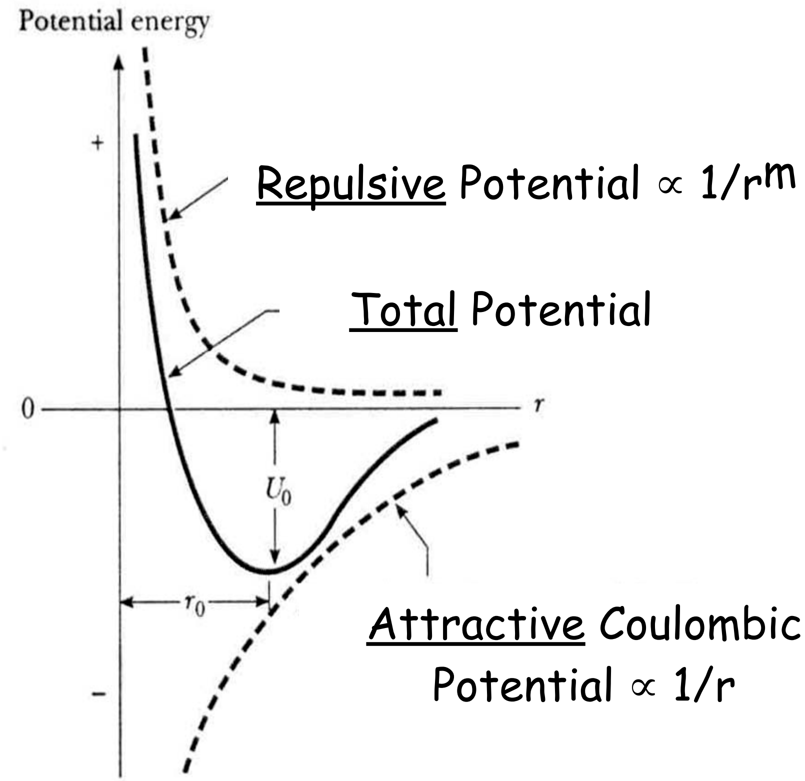
Application to the seismic wavefield

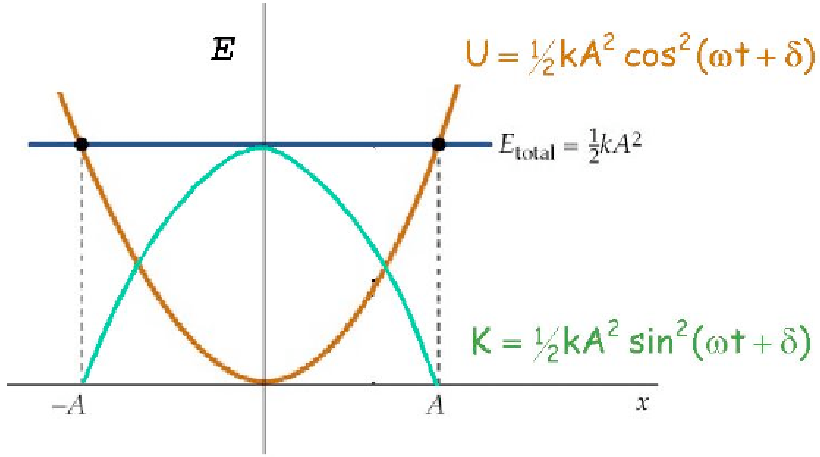
Seismic scattering, diffusion

Methods for laterally heterogenous media

What is a **wave?**

Small perturbations of a **stable** equilibrium point → **Linear restoring force** → **Harmonic Oscillation**

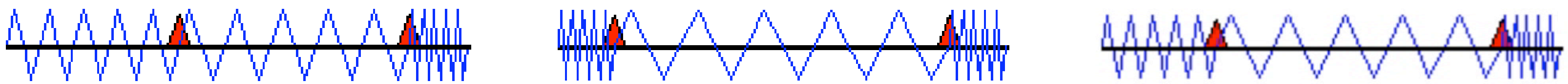




What is a **wave**? - 2

Small perturbations of a **stable** equilibrium point → **Linear restoring force** → **Harmonic Oscillation**

Coupling of harmonic oscillators → the disturbances can propagate, superpose and **stand**

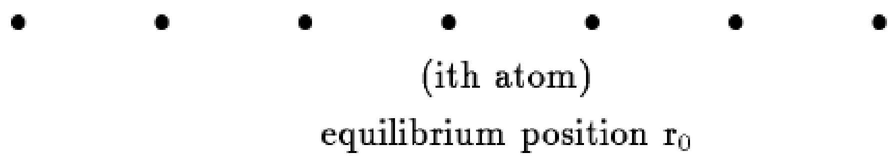


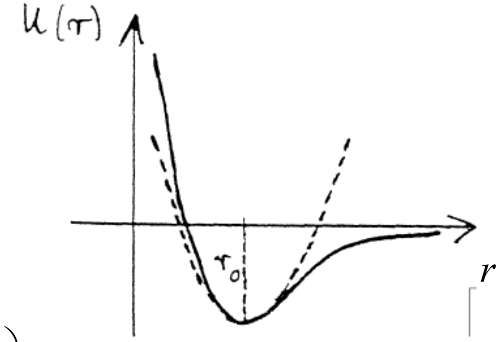
Normal modes of the system

Monoatomic 1D lattice

Interatomic potential

Now we consider a monatomic 1-D lattice in the x-direction. The lattice atoms are very close to eqilibrium. Let us examine a single i-th atom and find the r_i potential as a function of displacement from equilibrium, $U(r_i)$.





We expand this potential into a Taylor's series:

$$U(r_i) = U(r_0) + (r_i - r_0)\left(\frac{dU}{dr_i}\right)_{r_0} + \frac{1}{2}(r_i - r_0)^2\left(\frac{d^2U}{dr_i^2}\right)_{r_0} + \frac{1}{6}(r_i - r_0)^3\left(\frac{d^3U}{dr_i^3}\right)_{r_0} + \ldots$$

The first term of this expansion is just the equilibrium binding energy (≡ const). The second term is the slope of the potential at its minimum (= 0). The fourth and higher terms become increasingly smaller. We are therefore left with the third term as the only significant change in the potential energy for a small displacement $u = r_i - r_o$. This has the form

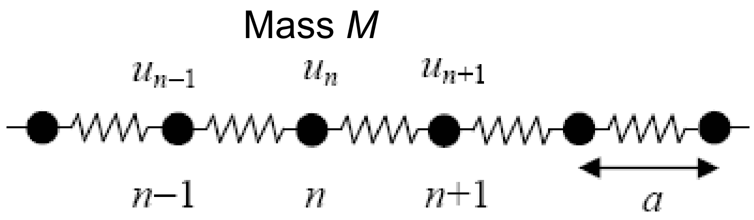
$$\Delta U = \tfrac{1}{2} C u^2 \quad (C = d^2U/dr_i^2 \text{ at } r_i = r_0)$$

representing the *harmonic approximation*, since it is the same as the energy stored in a spring, or the potential energy of a harmonic oscillator. Our simple model of the dynamic crystal structure should therefore be a “ball and spring” model, with the lengths of the springs equivalent to the equilibrium separations of the ion cores.

Monatomic 1D lattice

Let us examine the simplest periodic system within the context of harmonic approximation ($F = dU/du = Cu$) - a one-dimensional crystal lattice, which is a sequence of masses m connected with springs of force constant C and separation a.

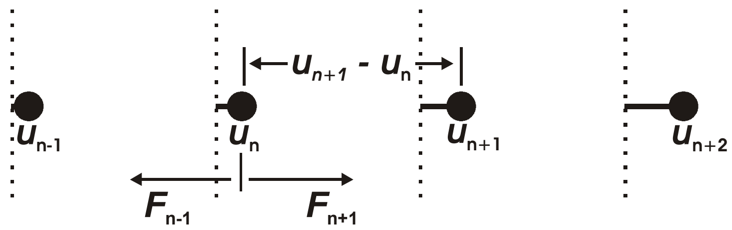
The collective motion of these springs will correspond to solutions of a wave equation.
Note: by construction we can see that 3 types of wave motion are possible,
2 transverse, 1 longitudinal (or compressional)



How does the system appear with a longitudinal wave?:

The force exerted on the n-th atom in the lattice is given by

$F_n = F_{n+1,n} - F_{n-1,n} = C[(u_{n+1} - u_n) - (u_n - u_{n-1})]$.

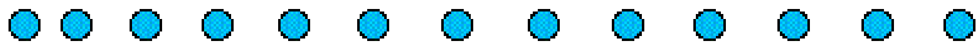


Applying Newton's second law to the motion of the n-th atom we obtain

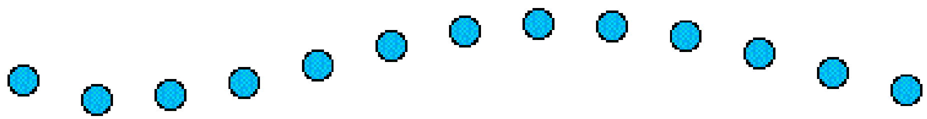
$$M\frac{d^2u_n}{dt^2} = F_n = -C(2u_n - u_{n+1} - u_{n-1})$$

Note that we neglected hereby the interaction of the n-th atom with all but its nearest neighbors. A similar equation should be written for each atom in the lattice, resulting in N coupled differential equations, which should be solved simultaneously (N - total number of atoms in the lattice). In addition the boundary conditions applied to end atoms in the lattice should be taken into account.

Acoustic and optical modes



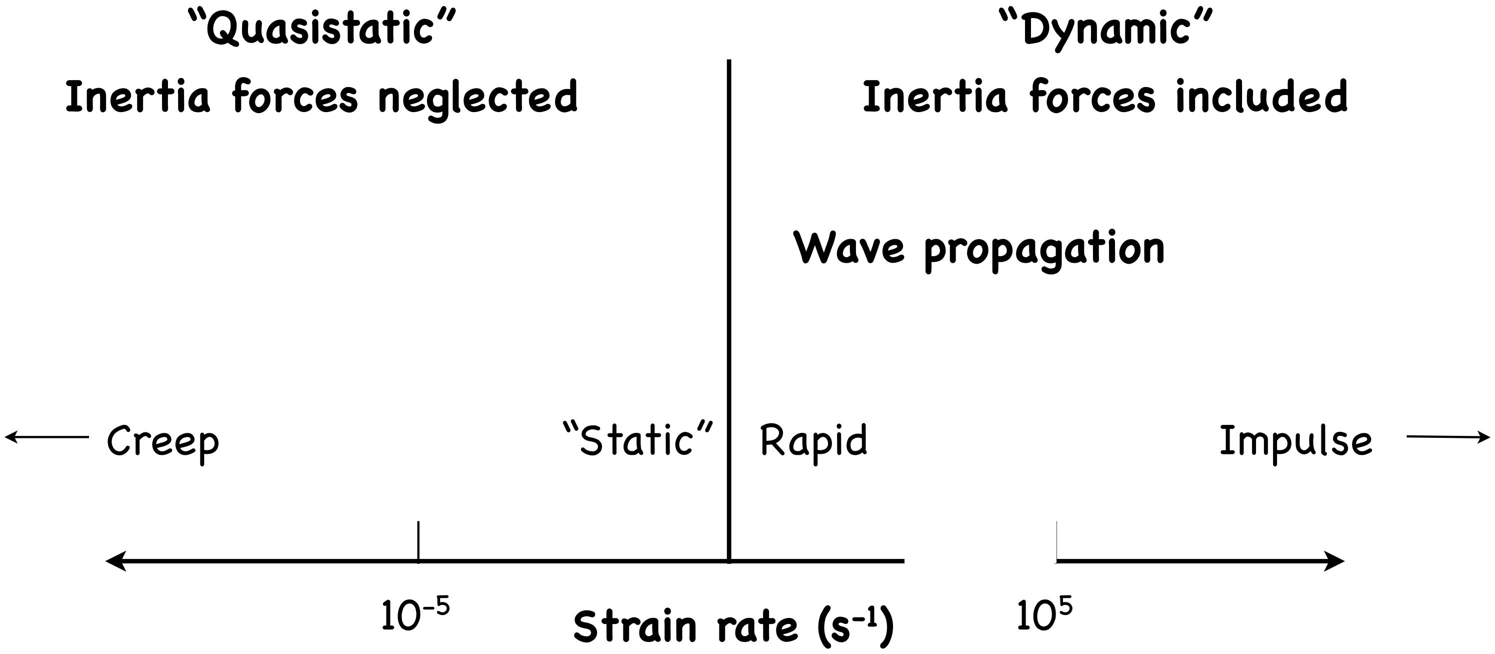
Monoatomic chain
acoustic longitudinal mode



Monoatomic chain
acoustic transverse mode

Elasticity...

☑ the study and determination of the response of **continuous, perfectly elastic** solids subjected to applications of forces



Towards sound wave

The gas moves and causes density variations

$$\Delta\rho = -\rho_0 \frac{\partial s}{\partial x}$$

Density variations cause pressure variations

$$\Delta P = \kappa \Delta\rho$$

Pressure variations generate gas motion

$$\rho_0 \frac{\partial^2 s}{\partial t^2} = -\frac{\partial \Delta P}{\partial x}$$

$$\boxed{\frac{1}{\kappa}\frac{\partial^2 s}{\partial t^2} = \frac{\partial^2 s}{\partial x^2}}$$

$$v = \sqrt{\left(\frac{dP}{d\rho}\right)_0} = \sqrt{\left(\frac{\gamma}{\rho} \mathrm{constant}\,\rho^{\gamma}\right)_0} = \sqrt{\gamma\left(\frac{P}{\rho}\right)_0}$$

$v = 331.4 + 0.6T_c$ m/s

If the medium has a bulk modulus B and density at the equilibrium is ρ, **$v = (B/\rho)^{1/2}$**

Thus, velocity depends on the elastic properties of the medium (B or F) and on inertial (ρ or μ) ones

What is a **wave**? - 3

Small perturbations of a **stable** equilibrium point → **Linear restoring force** → **Harmonic Oscillation**

Coupling of harmonic oscillators → the disturbances can **propagate**, superpose and stand

WAVE: organized **propagating imbalance**, satisfying differential equations of motion

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2}$$

General form of LWE

(Seismic) wave propagation

Basic physical concepts

What is a wave?

Discrete and continuous models

Born of wave equation

BC: modes and dispersion

- discreteness
- stiffness
- geometry
- boundaries

Dispersion relation

- In physics, the dispersion relation is the relation between the energy of a system and its corresponding momentum. For example, for massive particles in free space, the dispersion relation can easily be calculated from the definition of kinetic energy: $$E = \frac{1}{2}mv^2 = \frac{p^2}{2m}$$
- For electromagnetic waves, the energy is proportional to the frequency of the wave and the momentum to the wavenumber. In this case, Maxwell's equations tell us that the dispersion relation for vacuum is linear: ω**=ck.**
- The name "**dispersion relation**" originally comes from optics. It is possible to make the effective speed of light dependent on wavelength by making light pass through a material which has a non-constant index of refraction, or by using light in a non-uniform medium such as a waveguide. In this case, the waveform will spread over time, such that a narrow pulse will become an extended pulse, i.e. be dispersed.

Dispersion...

- In optics, dispersion is a phenomenon that causes the separation of a wave into spectral components with different wavelengths, due to a dependence of the wave's speed on its wavelength. It is most often described in light waves, but it may happen to any kind of wave that interacts with a medium or can be confined to a waveguide, such as sound waves. There are generally two sources of dispersion: **material dispersion**, which comes from a frequency-dependent response of a material to waves; and **waveguide dispersion**, which occurs when the speed of a wave in a waveguide depends on its frequency.

- In optics, the phase velocity of a wave v in a given uniform medium is given by: **$v=c/n$**, where c is the speed of light in a vacuum and n is the refractive index of the medium. In general, the refractive index is some function of the frequency of the light, thus $n = n(f)$, or alternately, with respect to the wave's wavelength $n = n(\lambda)$. For visible light, most transparent materials (e.g. glasses) have a refractive index n decreases with increasing wavelength λ (**$dn/d\lambda<0$**, i.e. **$dv/d\lambda>0$**). In this case, the medium is said to have **normal dispersion** and if the index increases with increasing wavelength the medium has **anomalous dispersion**.

Group velocity

- Another consequence of dispersion manifests itself as a temporal effect. The phase velocity is the velocity at which the phase of any one frequency component of the wave will propagate. This is not the same as the **group velocity of the wave, which is the rate that changes in amplitude** (known as the envelope of the wave) will propagate. The group velocity v_g is related to the phase velocity by, for a homogeneous medium (here λ is the wavelength in vacuum, not in the medium):

$$v_g = c\left(n - \lambda \frac{dn}{d\lambda}\right)^{-1} = v - \lambda \frac{dv}{d\lambda}$$

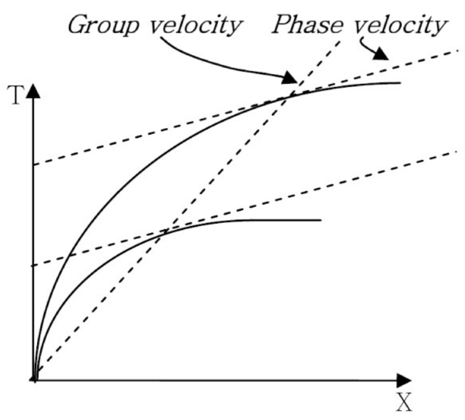
and thus in the normal dispersion case

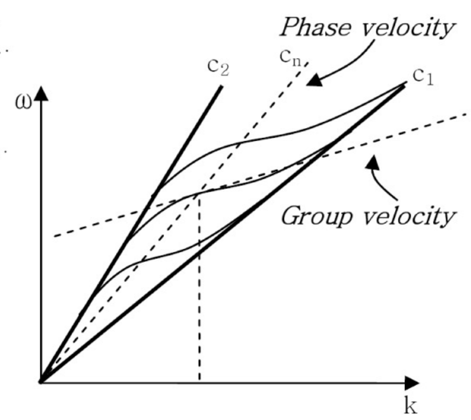
v_g is always < v !

Dispersion...

The group velocity itself is usually a function of the wave's frequency. This results in group velocity dispersion (GVD),that is often quantified as the group delay dispersion parameter (again, this formula is for a uniform medium only): If D is less than zero, the medium is said to have **positive dispersion**. If D is greater than zero, the medium has **negative dispersion**.

$$D = -\frac{\lambda}{c}\left(\frac{d^2 n}{d\lambda^2}\right)$$





Airy Phase –
wave that arises if the phase and the change in group velocity are stationary and gives the highest amplitude in terms of group velocity and are prominent on the seismogram.

Dispersion relation

- In classical mechanics, the Hamilton's principle the perturbation scheme applied to an averaged Lagrangian for an harmonic wave field gives a characteristic equation: $\Delta(\omega, k_i)=0$

Transverse wave in a string

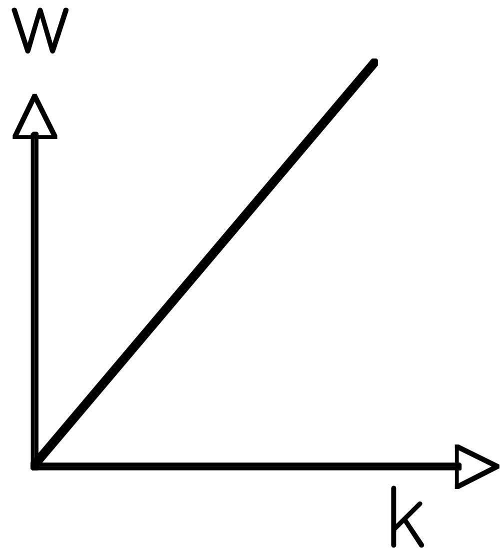
$$\left(\frac{\partial^2}{\partial x^2} - \frac{\mu}{F}\frac{\partial^2}{\partial t^2}\right)\phi = 0 \Rightarrow \quad \omega = \pm kc$$

Acoustic wave

$$\left(\frac{\partial^2}{\partial x^2} - \frac{\rho}{B}\frac{\partial^2}{\partial t^2}\right)\phi = 0 \Rightarrow \quad \omega = \pm kc$$

Longitudinal wave in a rod

$$\left(\frac{\partial^2}{\partial x^2} - \frac{\rho}{E}\frac{\partial^2}{\partial t^2}\right)\phi = 0 \Rightarrow \quad \omega = \pm kc$$



Dispersion examples

- Discrete systems: lattices
- Stiff systems: rods and thin plates
- Boundary waves: plates and rods

  Discontinuity interfaces are intrinsic in their propagation since they allow to store energy (not like body waves)!

Monatomic 1D lattice - continued

Now let us attempt a solution of the form: $u_n = Ae^{i(kx_n - \omega t)}$,

where x_n is the equilibrium position of the *n*-th atom so that $x_n = na$. This equation represents a traveling wave, in which all atoms oscillate with the same frequency ω and the same amplitude *A* and have a wavevector *k*. Now substituting the guess solution into the equation and canceling the common quantities (the amplitude and the time-dependent factor) we obtain

$$M(-\omega^2)e^{ikna} = -C[2e^{ikna} - e^{ik(n+1)a} - e^{ik(n-1)a}].$$

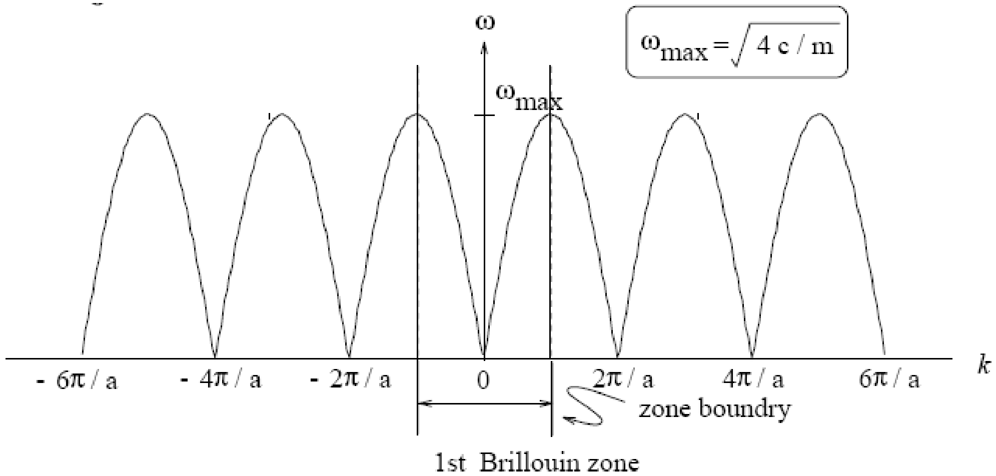
This equation can be further simplified by canceling the common factor e^{ikna} , which leads to

$$M\omega^2 = C\left(2 - e^{ika} - e^{-ika}\right) = 2C(1 - \cos ka) = 4C\sin^2\frac{ka}{2}.$$

We find thus the dispersion relation for the frequency:

$$\omega = \sqrt{\frac{4C}{M}}\left|\sin\frac{ka}{2}\right|$$

which is the relationship between the frequency of vibrations and the wavevector *k*. The dispersion relation has a number of important properties.



Diatomic 1D lattice

We can treat the motion of this lattice in a similar fashion as for the monatomic lattice. However, in this case, because we have two different kinds of atoms, we should write two equations of motion:

$$M_1 \frac{d^2 u_n}{dt^2} = -C(2u_n - u_{n+1} - u_{n-1})$$

$$M_2 \frac{d^2 u_{n+1}}{dt^2} = -C(2u_{n+1} - u_{n+2} - u_n)$$

In analogy with the monatomic lattice we are looking for the solution in the form of traveling mode for the two atoms:

$$\begin{bmatrix} u_n \\ u_{n+1} \end{bmatrix} = \begin{bmatrix} A_1 e^{ikna} \\ A_2 e^{ik(n+1)a} \end{bmatrix} e^{-i\omega t}$$ in matrix form.

Substituting this solution into the equations of the previous slide we obtain:

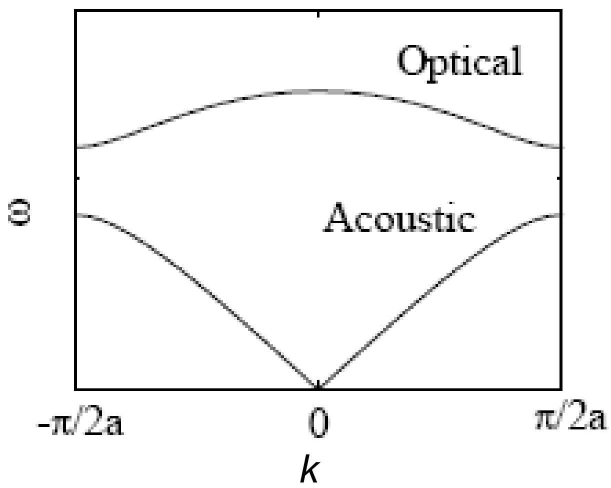
$$\begin{bmatrix} 2C - M_1\omega^2 & -2C\cos ka \\ -2C\cos ka & 2C - M_2\omega^2 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = 0.$$

This is a system of linear homogeneous equations for the unknowns A_1 and A_2. A nontrivial solution exists only if the determinant of the matrix is zero. This leads to the secular equation

$$\left(2C - M_1\omega^2\right)\left(2C - M_2\omega^2\right) - 4C\cos^2 ka = 0.$$

This is a quadratic equation, which can be readily solved:

$$\omega^2 = C\left(\frac{1}{M_1}+\frac{1}{M_2}\right) \pm C\sqrt{\left(\frac{1}{M_1}+\frac{1}{M_2}\right)^2 - \frac{4\sin^2 ka}{M_1 M_2}}$$



Depending on sign in this formula there are two different solutions corresponding to two different dispersion curves, as is shown in the figure:

The lower curve is called the ***acoustic*** *branch*, while the upper curve is called the ***optical*** *branch*.

The acoustic branch begins at $k = 0$ and $\omega = 0$, and as k $\Rightarrow$ 0:

$$\omega_a(0) = \sqrt{\frac{C}{2(M_1+M_2)}} \cdot ka$$

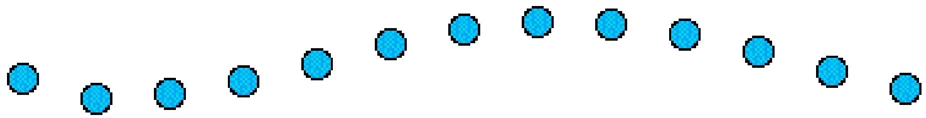
With increasing *k* the frequency increases in a linear fashion. This is why this branch is called *acoustic*: it corresponds to elastic waves, or sound. Eventually, this curve saturates at the edge of the Brillouin zone. On the other hand, the optical branch Has a nonzero frequency at zero *k*,

$$\omega_o = \sqrt{2C\left(\frac{1}{M_1}+\frac{1}{M_2}\right)}$$

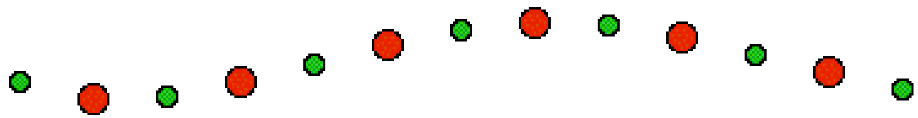
and it does not change much with *k*.

Acoustic and optical modes

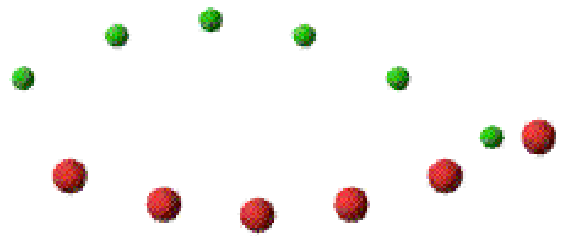
Monoatomic chain
acoustic longitudinal mode



Monoatomic chain
acoustic transverse mode

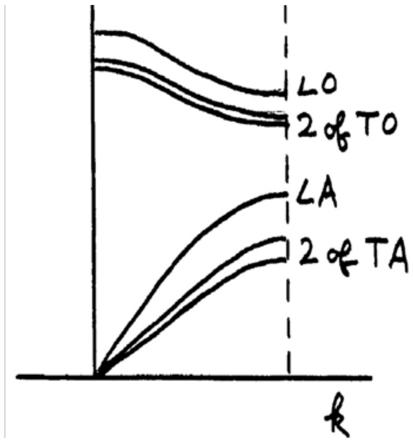


Diatomic chain
acoustic transverse mode

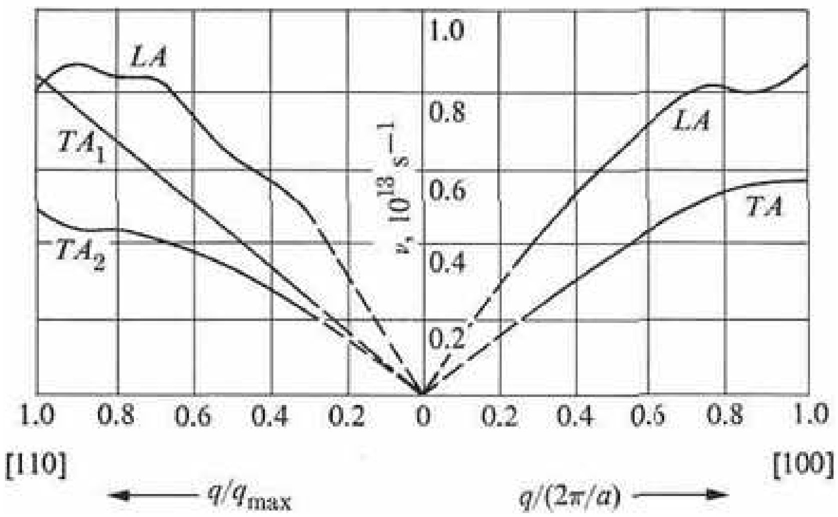


Diatomic chain
optical transverse mode

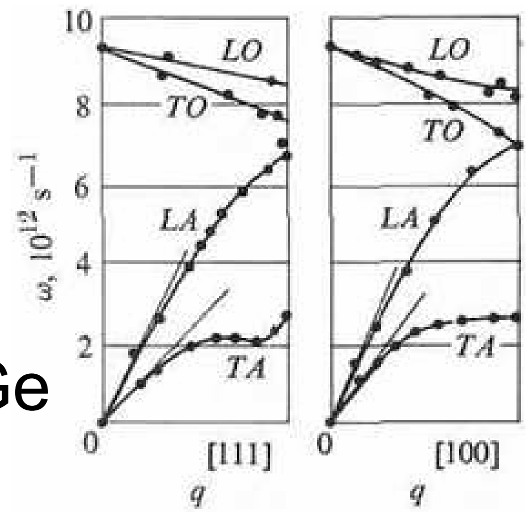
- If the lattice has a basis, things are more complex...
- Again, same physical arguments apply as in 1-D theory.
- If the basis has 2 atoms, results are typically – as shown in the figure.
- If the basis has many atoms, optical modes are *very* complicated.
- But chemically different atoms are *not* needed for optical modes – just need a basis with ≥ 2 atoms, so they can vibrate *either* mutually in phase *or* in antiphase.
- E.g. diamond has optical modes, despite being entirely composed of C.



Al

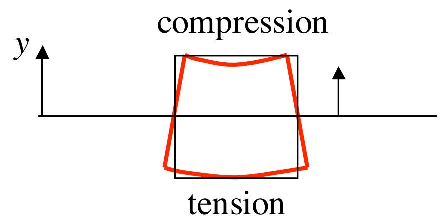


Ge



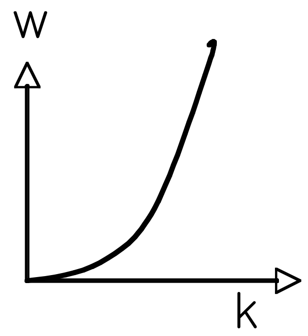
Stiffness...

- How "**stiff**" or "flexible" is a material? It depends on whether we pull on it, twist it, bend it, or simply compress it. In the simplest case the material is characterized by two independent "stiffness constants" and that different combinations of these constants determine the response to a pull, twist, bend, or pressure.



Euler Bernoulli equation

$$\left(\frac{\partial^4}{\partial x^4} - \frac{\rho A}{EI} \frac{\partial^2}{\partial t^2} \right) w = 0 \Rightarrow \quad \omega = \pm k^2 \sqrt{\frac{EI}{\rho A}}$$

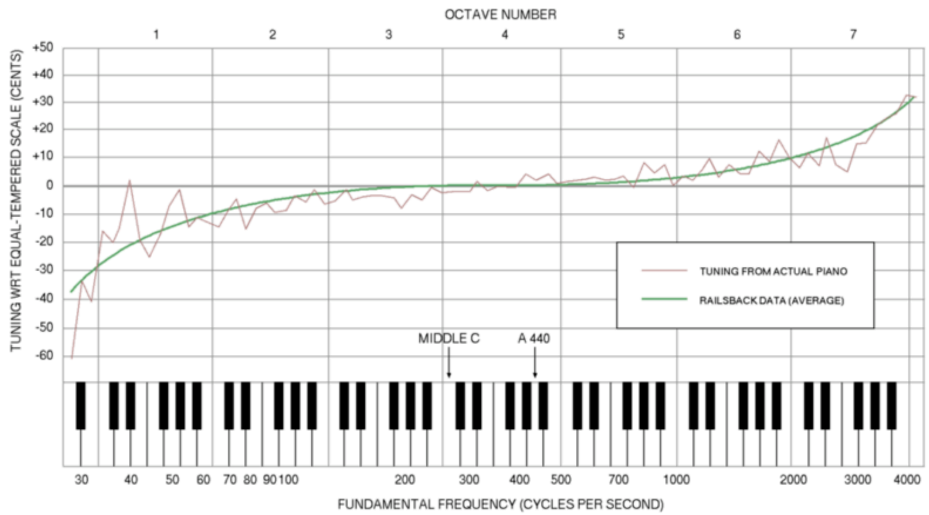


Stiffness...

- Stiffness in a vibrating string introduces a restoring force proportional to the bending angle of the string and the usual stiffness term added to the wave equation for the ideal string. Stiff-string models are commonly used in piano synthesis and they have to be included in tuning of piano strings due to inharmonic effects.

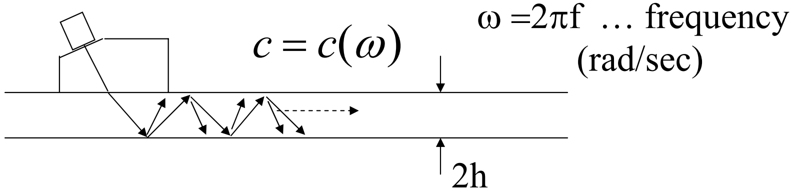
$$\left(\frac{\partial^4}{\partial x^4} + \frac{E}{\rho}\frac{\partial^2}{\partial x^2} - \frac{\rho A}{EI}\frac{\partial^2}{\partial t^2}\right)w = 0 \Rightarrow \quad \omega = \pm k\sqrt{\frac{E}{\rho}}\left(1 + k^2\sqrt{\frac{I}{A}}\right)^{1/2}$$

$$\Rightarrow \quad \omega \approx \pm k\sqrt{\frac{E}{\rho}}\left(1 + \frac{1}{2}k^2\sqrt{\frac{I}{A}}\right)$$



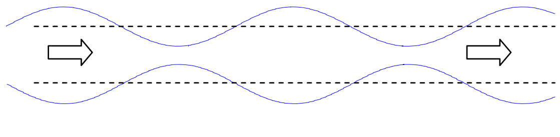
Waves in plates

In low frequency plate waves, there are two distinct type of harmonic motion. These are called symmetric or **extensional** waves and antisymmetric or **flexural** waves.



$$\phi = f(y)\exp[ik(x-ct)]$$

$$\psi = g(y)\exp[ik(x-ct)]$$

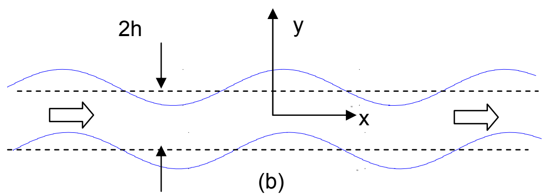


(a)

extensional waves

$$f = A\cosh(\alpha y)$$

$$g = B\sinh(\beta y)$$



(b)

flexural waves

$$f = A'\sinh(\alpha y)$$

$$g = B'\cosh(\beta y)$$

satisfying the boundary conditions $\tau_{yy} = \tau_{xy} = 0$

on $y = \pm h$ gives the Rayleigh-Lamb equations:

$$\frac{\tanh(\beta h)}{\tanh(\alpha h)} = \left[\frac{4\omega^2 \alpha\beta}{c^2 \left(\omega^2 / c^2 + \beta^2\right)^2} \right]^{\pm 1}$$

\+ … extensional waves

\- … flexural waves

$$\alpha = \left|\frac{\omega}{c}\right| \sqrt{1 - \frac{c^2}{c_p^2}} \quad , \beta = \left|\frac{\omega}{c}\right| \sqrt{1 - \frac{c^2}{c_s^2}}$$

consider the extensional waves

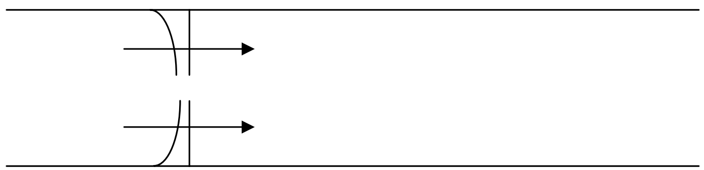
$$\frac{\tanh\left[2\pi fh\sqrt{1/c^2-1/c_s^2}\right]}{\tanh\left[2\pi fh\sqrt{1/c^2-1/c_p^2}\right]}=\frac{4\sqrt{1-c^2/c_s^2}\sqrt{1-c^2/c_p^2}}{\left(2-c^2/c_s^2\right)^2}$$

If we let $kh=\dfrac{2\pi fh}{c}>>1$ (high frequency)

then both tanh functions are $\cong 1$

and we find $\left(2-c^2/c_s^2\right)^2=4\sqrt{1-c^2/c_s^2}\sqrt{1-c^2/c_p^2}$

so we just have Rayleigh waves on both stress-free surfaces:



In contrast for $kh \ll 1$ (low frequency)

we find
$$\tanh(\alpha h) \cong \alpha h$$
$$\tanh(\beta h) \cong \beta h$$

and the Rayleigh-Lamb equation reduces to

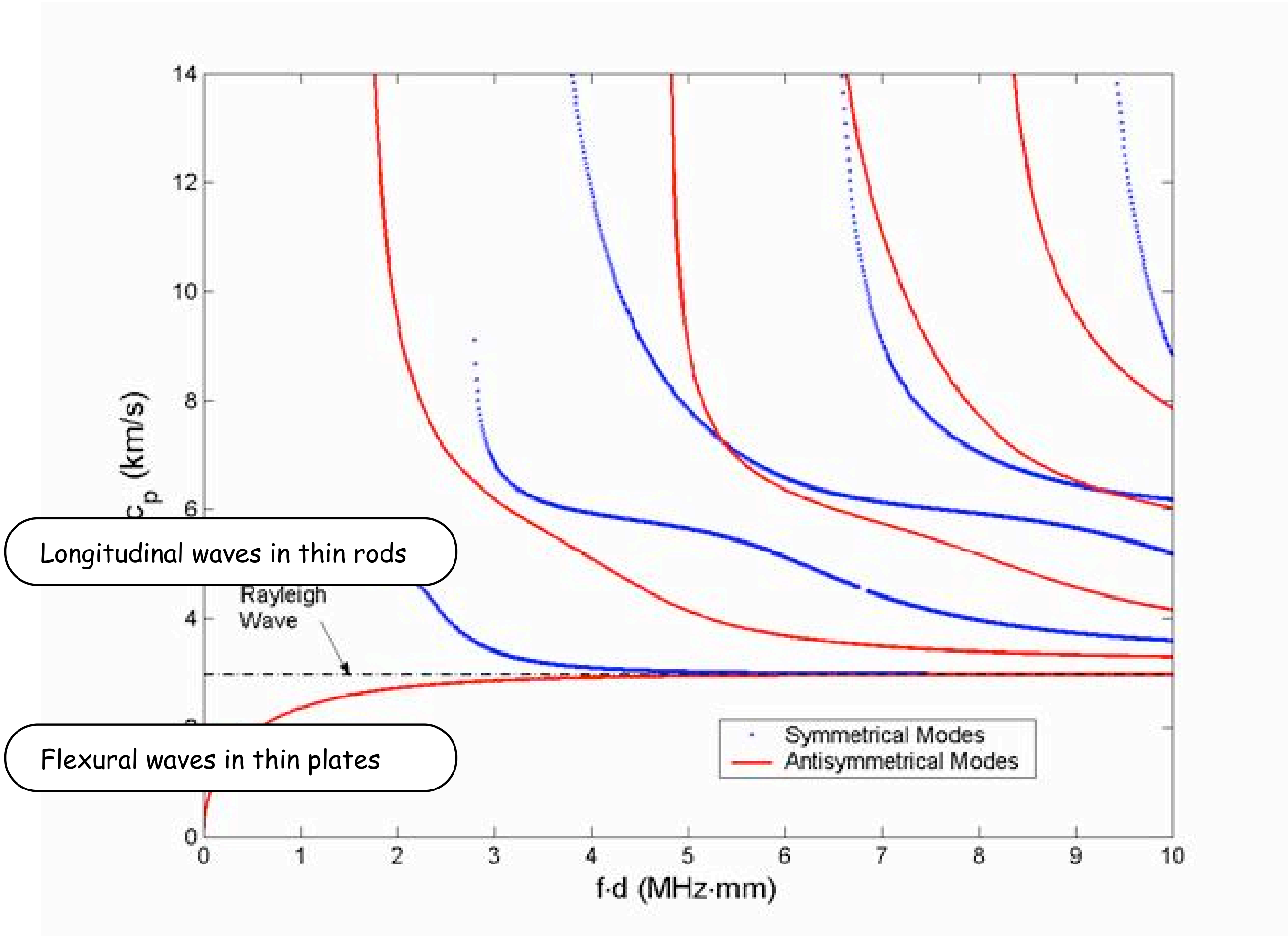
$$\left(2 - c^2 / c_s^2\right)^2 = 4\left(1 - c^2 / c_p^2\right)$$

which can be solved for c to give

$$c = c_{plate} = \sqrt{\frac{E}{\rho\left(1 - \nu^2\right)}}$$

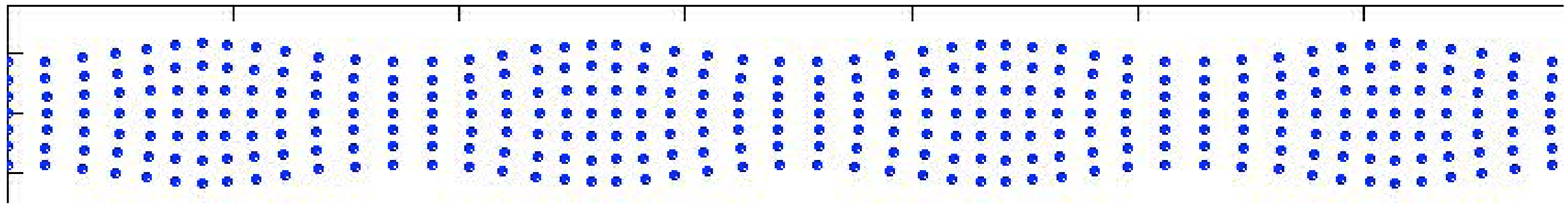
Waves in plates

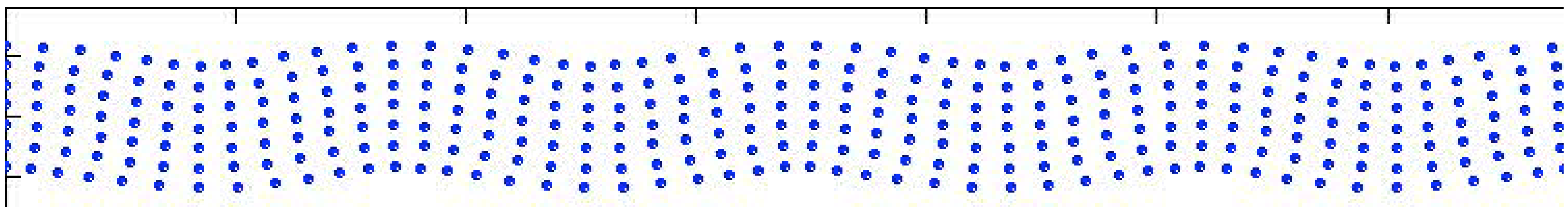
In low frequency plate waves, there are two distinct type of harmonic motion. These are called symmetric or **extensional** waves and antisymmetric or **flexural** waves.



Lamb waves

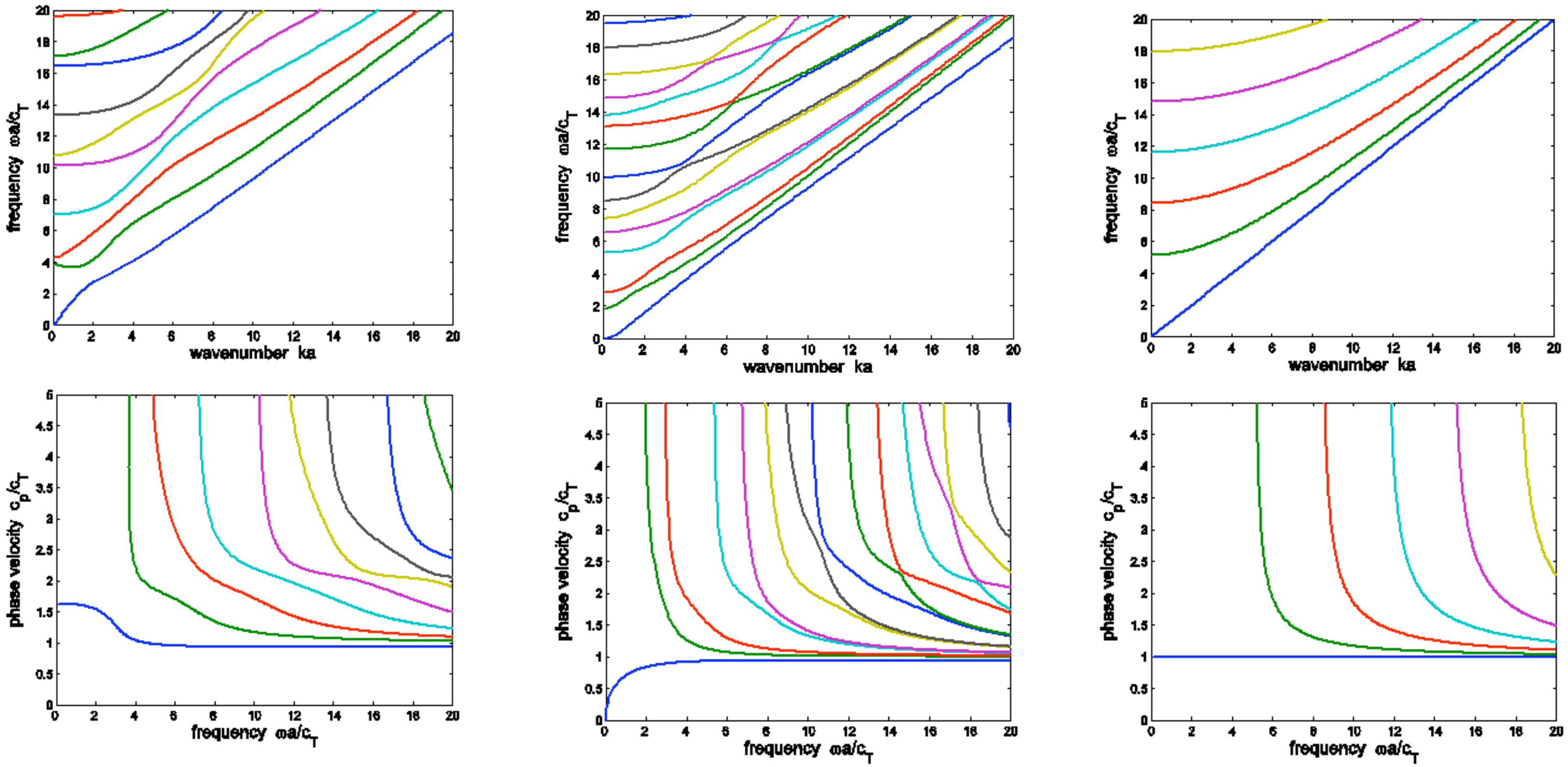
Lamb waves are waves of plane strain that occur in a free plate, and the traction force must vanish on the upper and lower surface of the plate. In a free plate, a line source along y axis and all wave vectors must lie in the x-z plane. This requirement implies that response of the plate will be independent of the in-plane coordinate normal to the propagation direction.



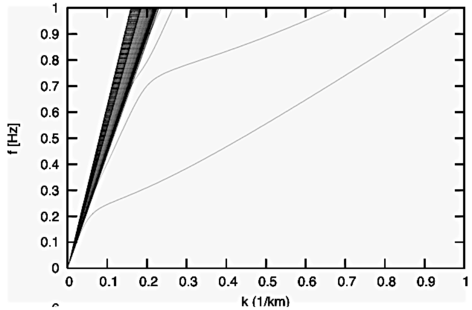


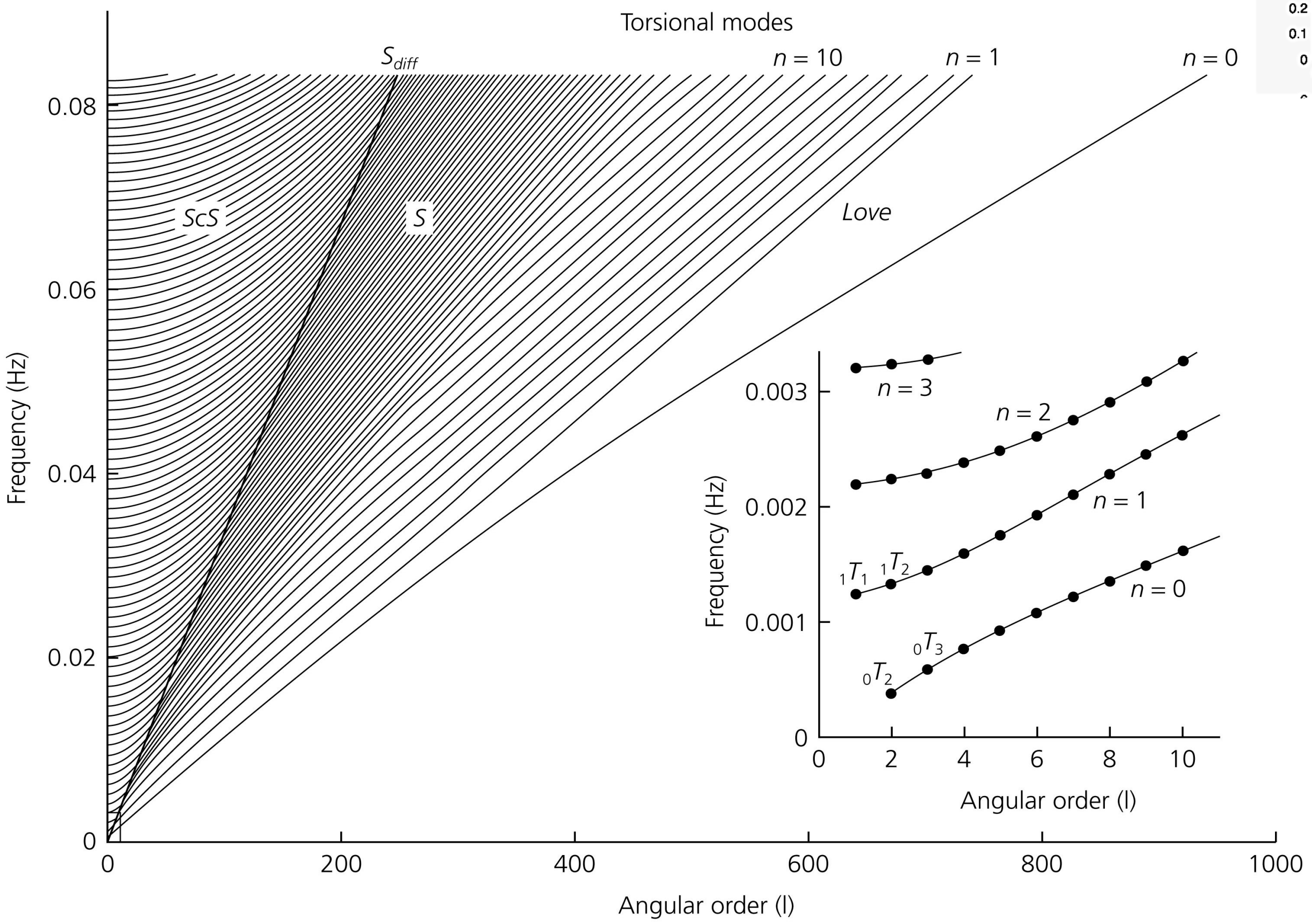
Elastic waves in rods

Three types of elastic waves can propagate in rods: (1) **longitudinal waves**, (2) **flexural waves**, and (3) **torsional waves**. Longitudinal waves are similar to the symmetric Lamb waves, flexural waves are similar to antisymmetric Lamb waves, and torsional waves are similar to horizontal shear (SH) waves in plates.



Torsional modes dispersion





What is a **wave**? - 3

Small perturbations of a **stable** equilibrium point → **Linear restoring force** → **Harmonic Oscillation**

Coupling of harmonic oscillators → the disturbances can propagate, superpose, stand, and **be dispersed**

WAVE: organized **propagating imbalance**, satisfying differential equations of motion

Organization can be destroyed, when interference is destructive

non linearity — **Turbulence**

strong scattering — **Diffusion**

Exceptions

Solitons

Phonons

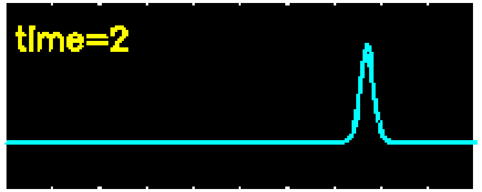
Dispersion & Non linearity

The dynamics of water waves in shallow water is described mathematically by the Korteveg - de Vries (KdV) equation

u=u(x,t) measures the elevation at time t and position x, i.e. the height of the water above the equilibrium level

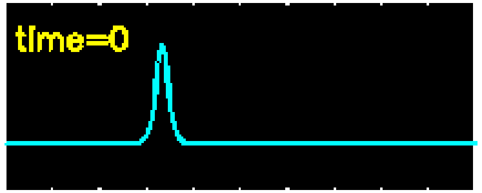
Dispersive term

$$u_t + u_{xxx} = 0$$



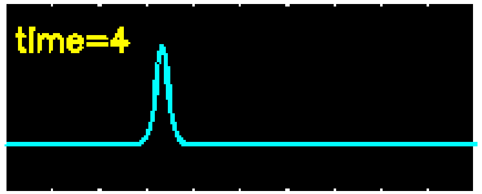
Nonlinearity

$$u_t + u\,u_x = 0$$



KdV

$$u_t + u_{xxx} + u\,u_x = 0$$



(Seismic) wave propagation

Basic physical concepts

- What is a wave?
- Discrete and continuous models
- Born of wave equation
- BC: modes and dispersion
- PDE: Poisson, diffusion and wave equation

Basic physical concepts 2

- EM scattering and diffusion

Application to the seismic wavefield

- Seismic scattering, diffusion
- Methods for laterally heterogenous media

Classification of Partial Differential Equations (PDE)

Second-order PDEs of two variables are of the form:

$$a\frac{\partial^2 f(x,y)}{\partial x^2} + b\frac{\partial^2 f(x,y)}{\partial x \partial y} + c\frac{\partial^2 f(x,y)}{\partial y^2} + d\frac{\partial f(x,y)}{\partial x} + e\frac{\partial f(x,y)}{\partial y} = F(x,y)$$

$b^2 - 4ac < 0$	elliptic	LAPLACE equation
$b^2 - 4ac = 0$	parabolic	DIFFUSION equation
$b^2 - 4ac > 0$	hyperbolic	WAVE equation

Elliptic equations produce **stationary and energy-minimizing** solutions

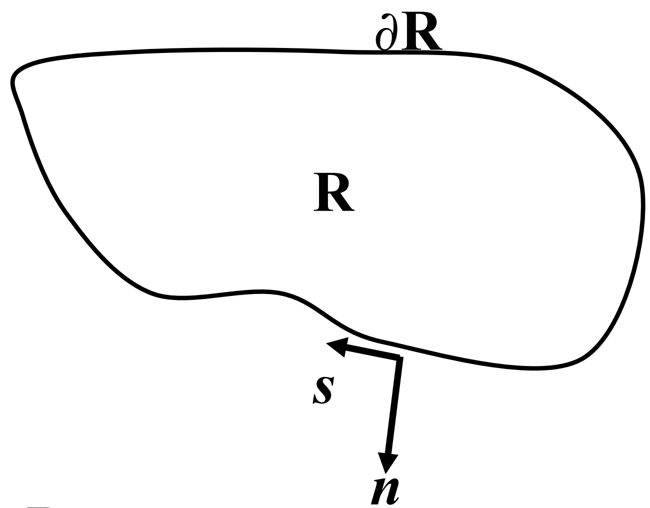
Parabolic equations a **smooth-spreading flow** of an initial disturbance

Hyperbolic equations a **propagating disturbance**

Boundary and **Initial** conditions

Initial conditions: starting point for propagation problems

Boundary conditions: specified on domain boundaries to provide the interior solution in computational domain



$$\begin{cases} \text{(i) Dirichlet condition}: u = f \text{ on } \partial R \\ \text{(ii) Neumann condition}: \dfrac{\partial u}{\partial n} = f \text{ or } \dfrac{\partial u}{\partial s} = g \text{ on } \partial R \\ \text{(iii) Robin (mixed) condition}: \dfrac{\partial u}{\partial n} + ku = f \text{ on } \partial R \end{cases}$$

Elliptic PDEs

Steady-state two-dimensional heat conduction equation is prototypical elliptic PDE

Laplace equation - no heat generation

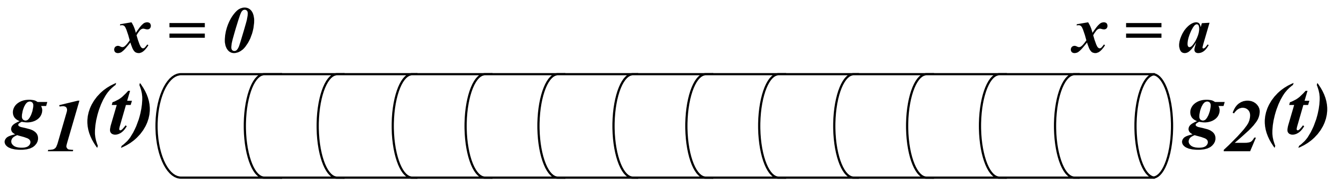
$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

Poisson equation - with heat source

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = f(x,y)$$

Heat Equation: Parabolic PDE

Heat transfer in a one-dimensional rod



$$\boxed{\frac{\partial u}{\partial t} = d\,\frac{\partial^2 u}{\partial x^2},}\quad 0 \le x \le a,\quad 0 \le t \le T$$

$$\text{I.C.s}\qquad u(x,0) = f(x) \qquad 0 \le x \le a$$

$$\text{B.C.s}\quad \begin{cases} u(0,t) = g_1(t) \\ u(a,t) = g_2(t) \end{cases} \qquad 0 \le t \le T$$

Wave Equation

Hyperbolic Equation

b2 - 4ac = 0 - 4(1)(-c2) > 0 : Hyperbolic

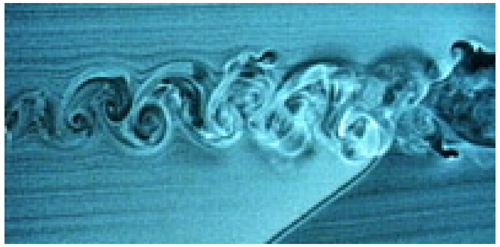
$$\boxed{\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2}}, \quad 0 \le x \le a, \quad 0 \le t$$

$$\text{I.C.s} \quad \begin{cases} u(x,0) = f_1(x) \\ u_t(x,0) = f_2(x) \end{cases} \qquad 0 \le x \le a$$

$$\text{B.C.s} \quad \begin{cases} u(0,t) = g_1(t) \\ u(a,t) = g_2(t) \end{cases} \qquad t > 0$$

Coupled PDE

Navier-Stokes Equations



$$
\begin{cases}
\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} = 0 \\[2ex]
\dfrac{\partial u}{\partial t} + u\dfrac{\partial u}{\partial x} + v\dfrac{\partial u}{\partial y} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} + \nu\left(\dfrac{\partial^2 u}{\partial x^2} + \dfrac{\partial^2 u}{\partial y^2}\right) \\[2ex]
\dfrac{\partial v}{\partial t} + u\dfrac{\partial v}{\partial x} + v\dfrac{\partial v}{\partial y} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial y} + \nu\left(\dfrac{\partial^2 v}{\partial x^2} + \dfrac{\partial^2 v}{\partial y^2}\right)
\end{cases}
$$

Numerical Methods

- **Complex geometry**
- **Complex equations (nonlinear, coupled)**
- **Complex initial / boundary conditions**

- **No analytic solutions**
- **Numerical methods needed !!**

(Seismic) wave propagation in complex media

Basic physical concepts

What is a wave?

Discrete and continuous models

Born of wave equation

BC: modes and dispersion

PDE: Poisson, diffusion and wave equation

Basic physical concepts 2

EM scattering and diffusion

Application to the seismic wavefield

Seismic scattering, diffusion

Methods for laterally heterogenous media

Basic concepts of EM wavefield

Extinction and **emission** are two main types of the interactions between an electromagnetic radiation field and a medium (e.g., the atmosphere).
Extinction is due to **absorption** and **scattering**.

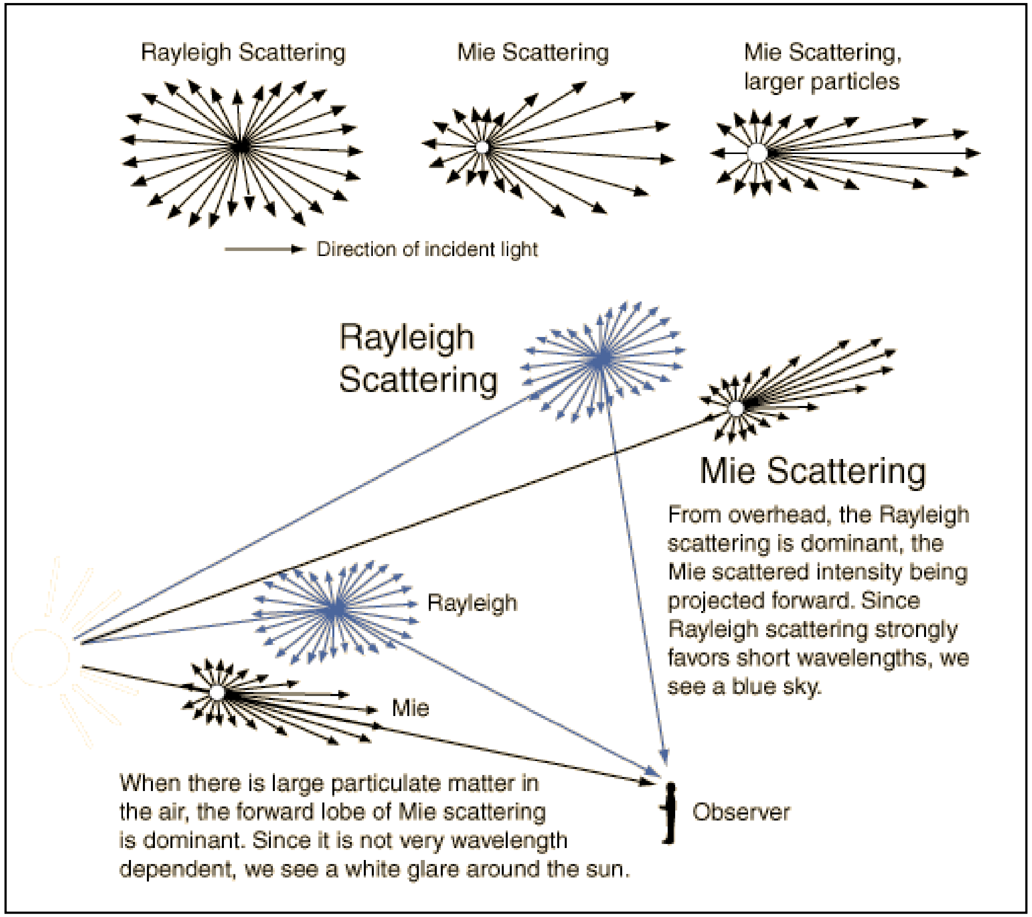
Absorption is a process that removes the radiant energy from an electromagnetic field and transfers it to other forms of energy.
Scattering is a process that does not remove energy from the radiation field, but **redirect** it. Scattering can be thought of as absorption of radiant energy followed by re-emission back to the electromagnetic field with negligible conversion of energy, i.e.can be a "source" of radiant energy for the light beams traveling in other directions.
Scattering **occurs at all wavelengths** (spectrally not selective) in the electromagnetic spectrum, for any material whose refractive index is different from that of the surrounding medium (**optically inhomogeneous**).

Scattering of EM wavefield (1)

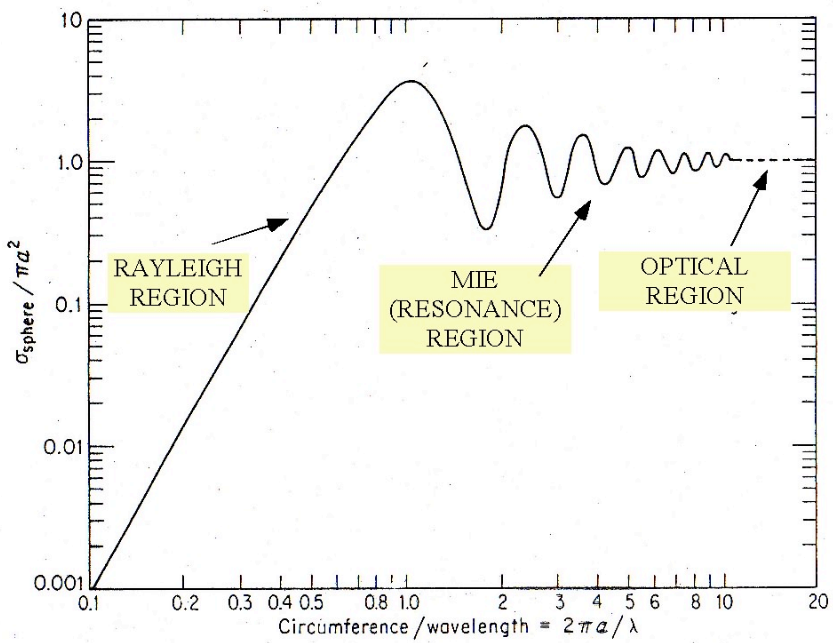
The amount of scattered energy depends strongly on the ratio of: particle size (a) to wavelength (λ) of the incident wave

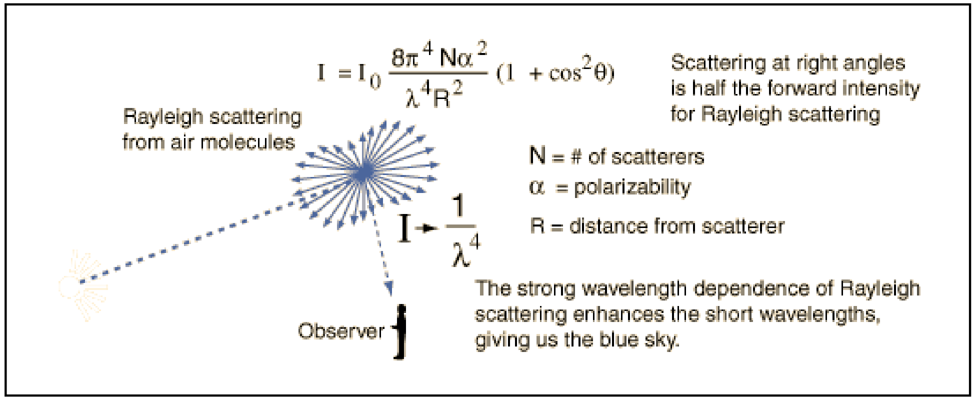
When **(a < λ/10)**, the scattered intensity on both forward and backward directions are equal. This type of scattering is called **Rayleigh scattering**.

For **(a > λ)**, the angular distribution of scattered intensity becomes more complex with more energy scattered in the forward direction. This type of scattering is called **Mie scattering**



Scattering of EM wavefield (2)





Single Scattering

$\chi = 2\pi \mathbf{a}/\lambda$

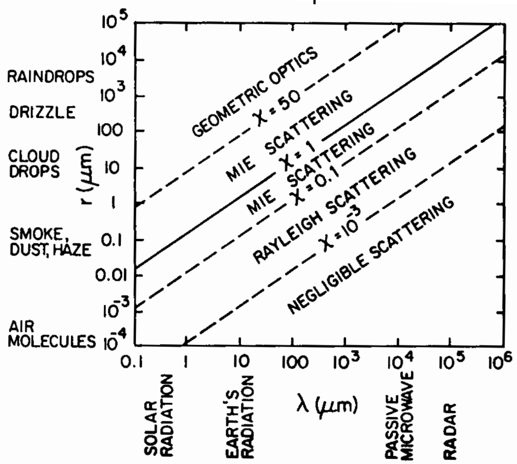
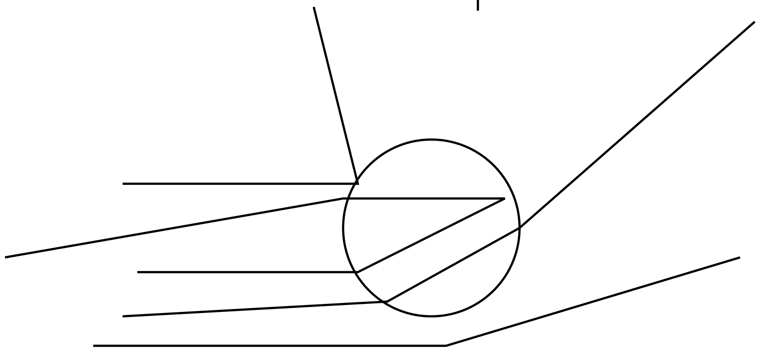


FIGURE 3.18. Scattering regimes. [Adapted from Wallace and Hobbs (1977). Reprinted by permission of Academic Press.]



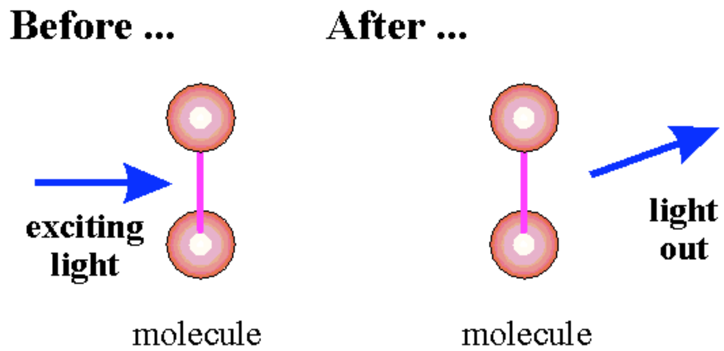
For **(a >> λ)**, the Scattering characteristics are determined from explicit Reflection, Refraction and Diffraction: **Geometric "Ray" Optics**

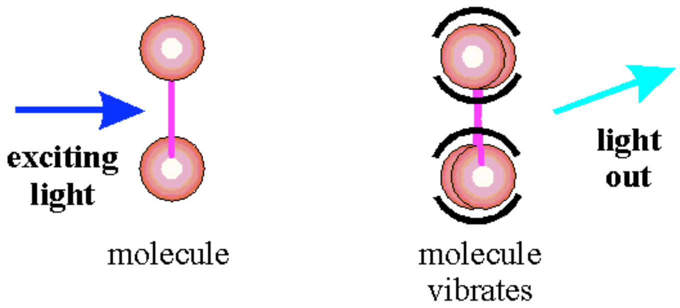
Scattering of EM wavefield (3)

Composition of the scatterer (n) is important!

The interaction (and its redirection) of electromagnetic radiation with matter May or may not occur with **transfer of energy**, i.e., the scattered radiation has a slightly different or the same wavelength.

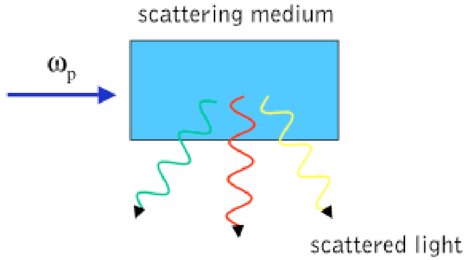
Rayleigh scattering - Light out has same frequency as light in, with scattering at many different angles.



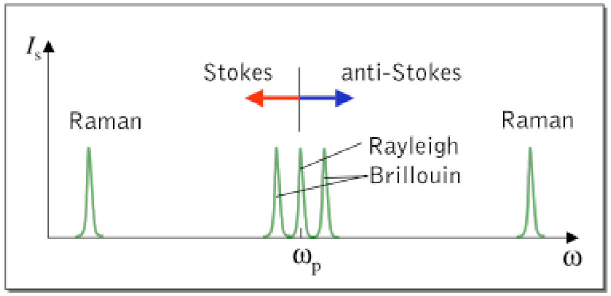


Raman scattering - Light is scattered due to vibrations in molecules or optical phonons in solids. Light is shifted by as much as 4000 wavenumbers and exchanges energy with a molecular vibration.

Scattering of EM wavefield (4)



spectrally resolved detection



Rayleigh scattering
scattering from *nonpropagating* density fluctuations (elastic)
Brillouin scattering
scattering from *propagating* pressure waves (sound waves, acoustic phonons)
Raman scattering
interaction of light with vibrational modes of molecules or lattice vibrations of crystals (scattering from optical phonons)

Raman scattering

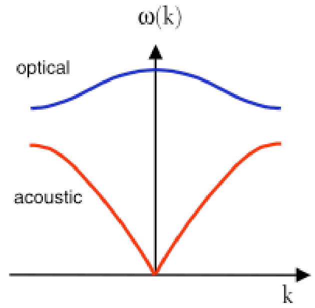
✓ optical phonon

Brillouin scattering

✓ acoustic phonon

Phonons
quanta of the ionic displacement field in a solid

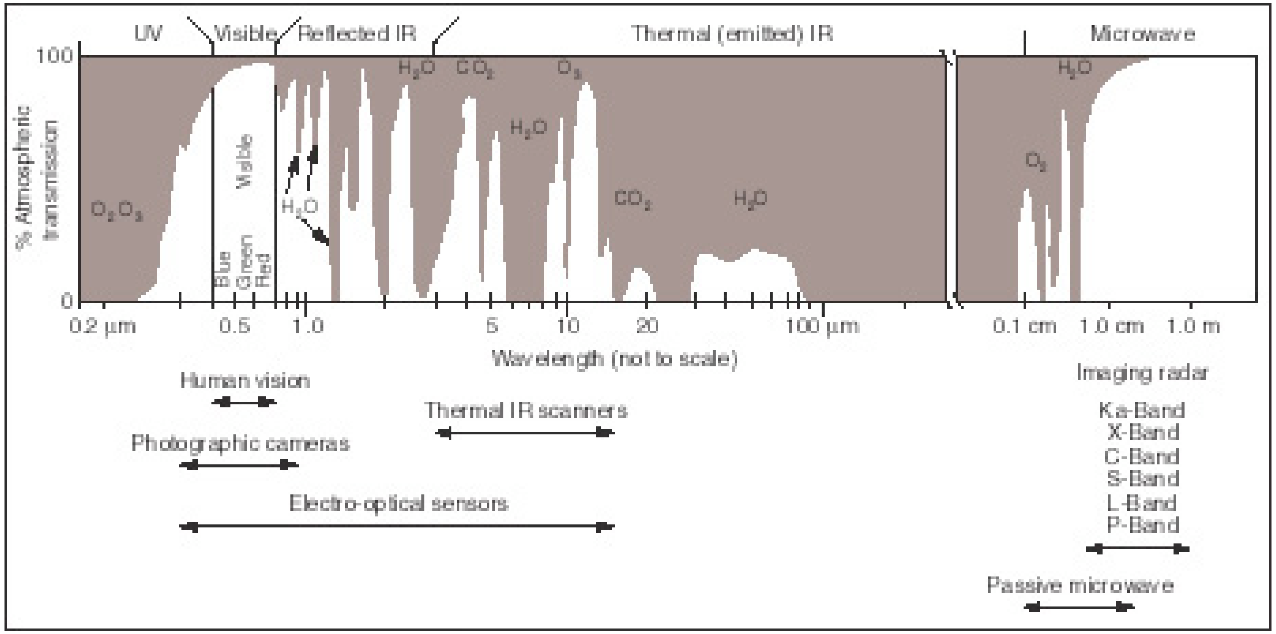
phonon dispersion curve



Scattering and **Absorption**

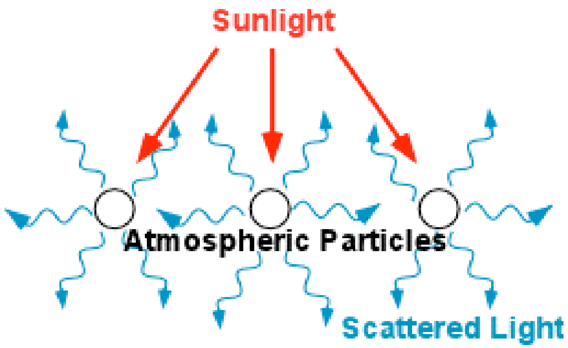
When the photon is absorbed and re-emitted at a different wavelength, this is absorption.

Transmissivity of the Earth's atmosphere



Scattering and **Diffusion**

In single scattering, the properties of the scatterer are important , but multiple scattering erases these effects - eventually **all** wavelengths are scattered in **all** directions.



Works for turbid media: clouds, beer foam, milk, etc...

Example: when a solid has a very low temperature, phonons behave like waves (long mean free paths) and heat propagate following ballistic term.
At higher temperatures, the phonons are in a diffusive regime and heat propagate following Maxwell law.

(Seismic) wave propagation in complex media

Basic physical concepts

What is a wave?

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BC: modes and dispersion

PDE: Poisson, diffusion and wave equation

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Seismic scattering, diffusion

Methods for laterally heterogenous media

Basic parameters for **seismic wavefield**

The governing parameters for the seismic scattering are:

wavelength of the wavefield (or wavenumber k)

λ **(10^0-10^5 m)**

correlation length, or dimension, of the heterogeneity

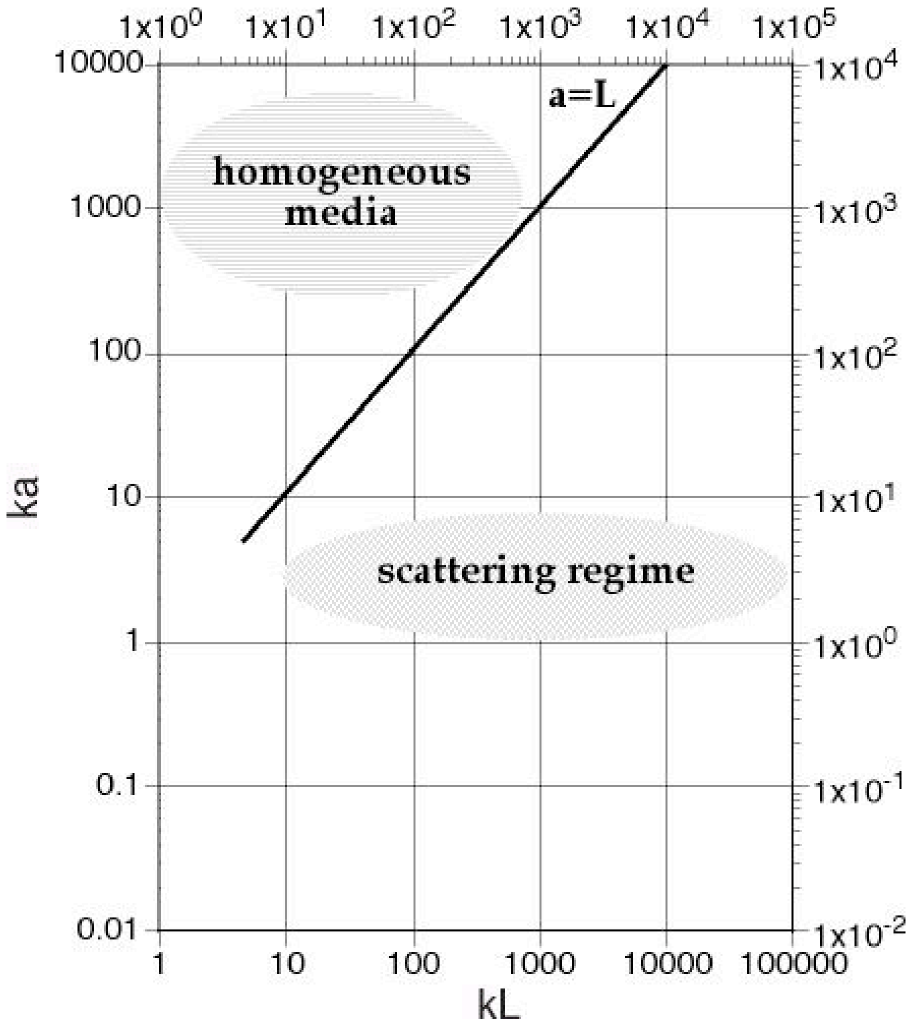
a ($10^?$-10^4 m)

distance travelled in the heterogeneity

L (10^0-10^5 m)

With special cases:
- a = L   homogeneous region
- $a \gg \lambda$ ray theory is valid
- $a \approx \lambda$ strong scattering effects

Seismic Scattering (1)



Wave propagation problems can be classified using the parameters just introduced.

This classification is crucial for the choice of technique to calculate synthetic seismograms

(Adapted from Aki and Richards, 1980)

Scattering in a **perturbed** model

Let us consider a **perturbed** model:
reference+perturbation (in elastic parameters)

$$\rho = \rho_0 + \varepsilon\delta\rho \quad \lambda = \lambda_0 + \varepsilon\delta\lambda \quad \mu = \mu_0 + \varepsilon\delta\mu$$

resulting in a velocity perturbation

$$c = c_0 + \varepsilon\delta c$$

solution: **Primary** field + **Scattered** field

$$\mathbf{u} = \mathbf{u}_0 + \mathbf{u}_1(\delta\rho, \delta\lambda, \delta\mu)$$

satisfying equations of motion:

$$\rho_0 \ddot{u}_i^0 - (\lambda_0 + \mu_0)\left(\nabla \cdot \mathbf{u}^0\right)_{,i} - \mu_0 \nabla^2 \mathbf{u}_i^0 = 0$$

$$\rho_0 \ddot{u}_i - (\lambda \nabla \cdot \mathbf{u})_{,i} - \left[\mu\left(u_{i,j} + u_{j,i}\right)\right]_{,j} = 0$$

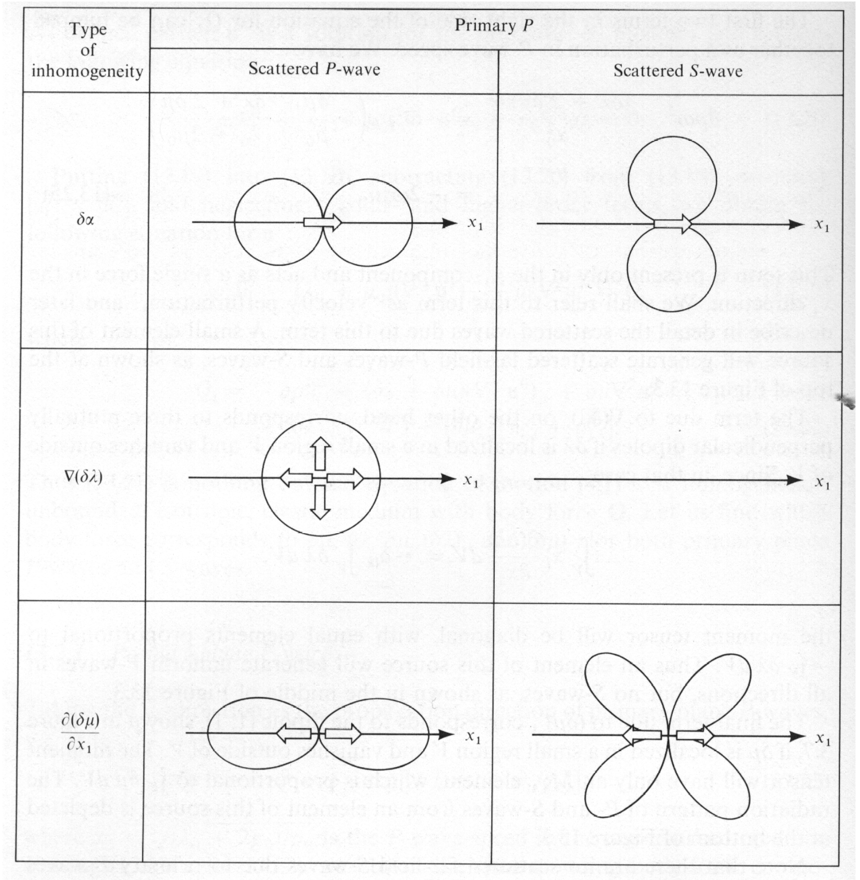
$$\rho_0 \ddot{u}_i^1 - (\lambda_0 + \mu_0)\left(\nabla \cdot \mathbf{u}^1\right)_{,i} - \mu_0 \nabla^2 \mathbf{u}_i^1 = Q_i$$

Point Scatterers

How does a point-like perturbation of the elastic parameters affect the wavefield?

Perturbation of the different elastic parameters produce characteristic radiation patterns. These effects are used in diffraction tomography to recover the perturbations from the recorded wavefield.

(Figure from Aki and Richards, 1980)



Correlation distance

When velocity varies in all directions with a finite scale length, it is more convenient to consider spatial fluctuations

Autocorrelation function (a is the **correlation distance)**:

$$N(\mathbf{r}_1) = \frac{\left\langle \dfrac{\delta c(\mathbf{r})}{c_0(\mathbf{r})} \dfrac{\delta c(\mathbf{r}+\mathbf{r}_1)}{c_0(\mathbf{r}+\mathbf{r}_1)} \right\rangle}{\left\langle \left(\dfrac{\delta c(\mathbf{r})}{c_0(\mathbf{r})} \right)^2 \right\rangle} = \begin{cases} e^{-|r_1|/a} \\ e^{-(|r_1|/a)^2} \end{cases}$$

Power Spectra of scattered waves

$$\left\langle |\mathbf{u}_1|^2 \right\rangle \propto \begin{cases} k^4 \left(1 + 4k^2 a^2 \sin^2 \dfrac{\theta}{2}\right)^{-2} \\ k^4 \exp\left(-k^2 a^2 \sin^2 \dfrac{\theta}{2}\right) \end{cases}$$

$\propto k^4$ if $ka << 1$ (Rayleigh scattering)
if ka is large (forward scattering)

Wave parameter

Energy loss through a cube of size L (Born approximation)

$$\frac{\Delta I}{I} \propto \begin{cases} k^4 a^3 L\left(1+4k^2a^2\right)^{-1} \\ k^2 a L\left(1-e^{k^2a^2}\right)^{-1} \end{cases}$$

but violates the energy conservation law and it is valid if **(<0.1)**

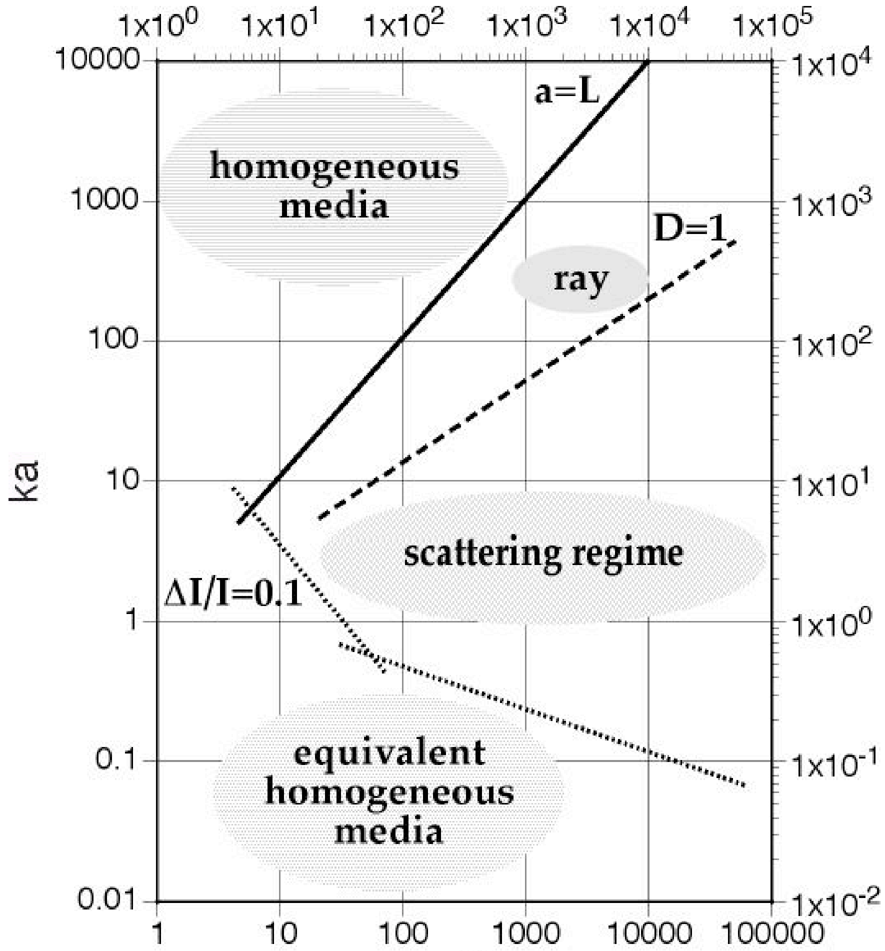
the **perturbations** (P &A) are function of the **wave parameter**:

$$D = \frac{4L}{ka^2}$$

$$D = \begin{cases} 0 & \text{phase perturbation} \\ \infty & \text{phase = amplitude} \end{cases}$$

when D<1, geometric ray theory is valid

Seismic Scattering (2)



$D = 4L/ka^2 = 4(kL)/(ka)^2$
wave parameter

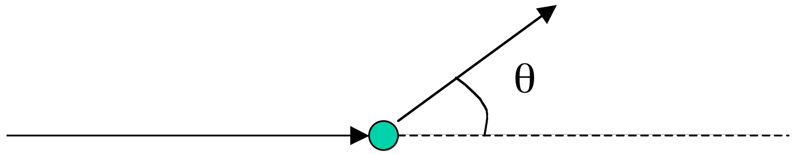
Wave propagation problems can be classified using the parameters just introduced.

This classification is crucial for the choice of technique to calculate synthetic seismograms

(Adapted from Aki and Richards, 1980)

From scattering....

Multiple scattering process leads to **attenuation** (spatial loss non a true dissipative one) and **energy mean free path**



σ(θ) is the **differential scattering cross-section** and after a wave has travelled a distance x, the energy is reduced by an amount of

$$e^{-\Sigma x} \qquad \Sigma = \int_{-1}^{+1} \sigma(\cos\theta)\, d\cos\theta$$

and the **average path length** between scattering events is

$$l = \int_0^\infty e^{-\Sigma x} dx = \frac{1}{\Sigma}$$

Towards **random** media

forward scattering tendency

$$\Sigma' = \int_{-1}^{+1} (\cos\theta)\sigma(\cos\theta)d\cos\theta \begin{cases} > 0 \text{ forward} \\ \approx 0 \text{ isotropic} \\ < 0 \text{ backward} \end{cases}$$

Multiple scattering randomizes the phases of the waves adding a diffuse (incoherent) component to the average wavefield.
Statistical approaches can be used to derive **elastic radiative transfer equations**

Diffusion constants
use the definition of a diffusion (transport) mean free path

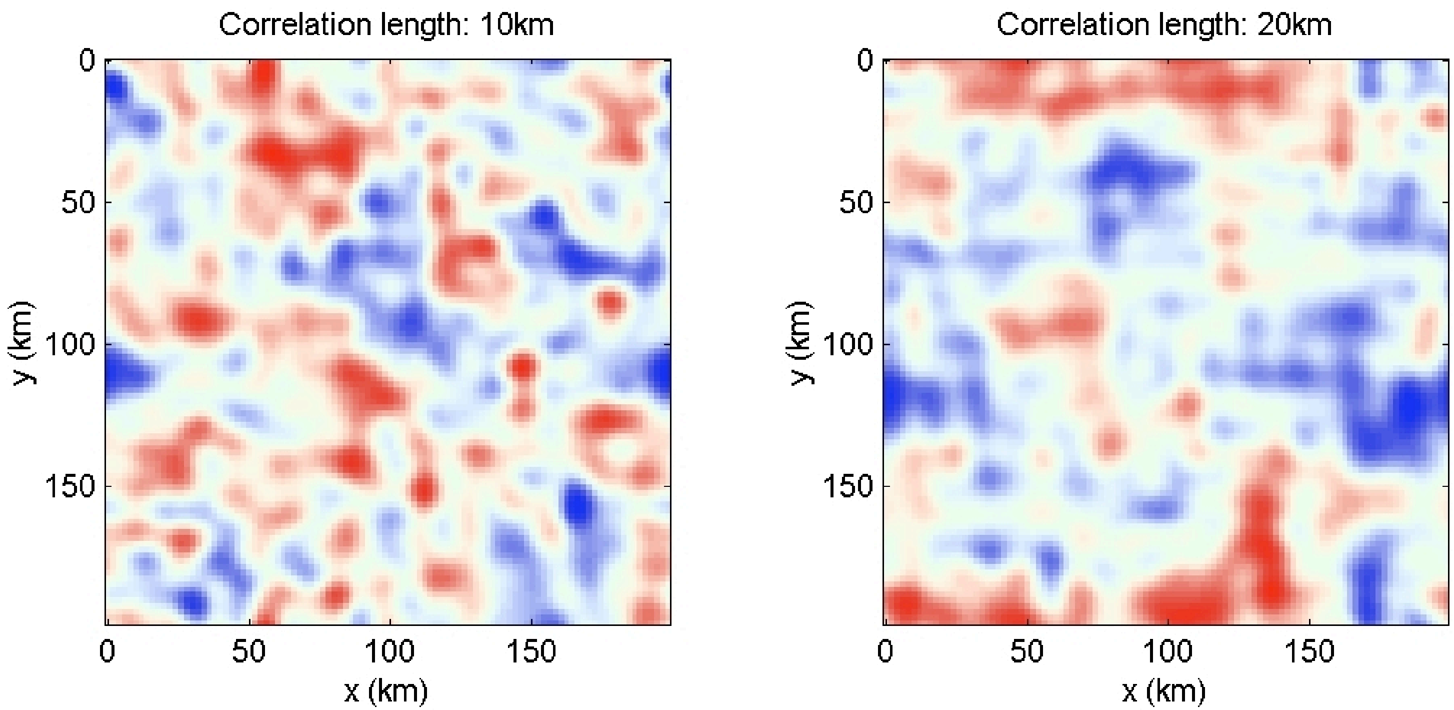
$$d = \frac{cl^*}{3} \quad l^* = \frac{1}{\Sigma - \Sigma'} \text{ (acoustic)}$$

$$d = \frac{1}{1 + 2K^3}\left(\frac{c_P l_P^*}{3} + 2K^2 \frac{c_S l_S^*}{3} \right) \text{ (elastic)}$$

for non-preferential scattering l^* coincides with energy mean free path, l
for enhanced forward scattering $l^*>l$

Experiments for ultrasound in materials can be applied to seismological problems…

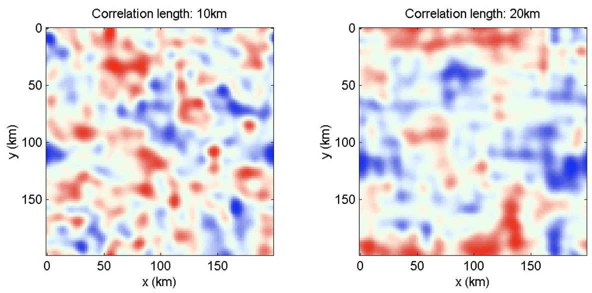
Scattering in random media

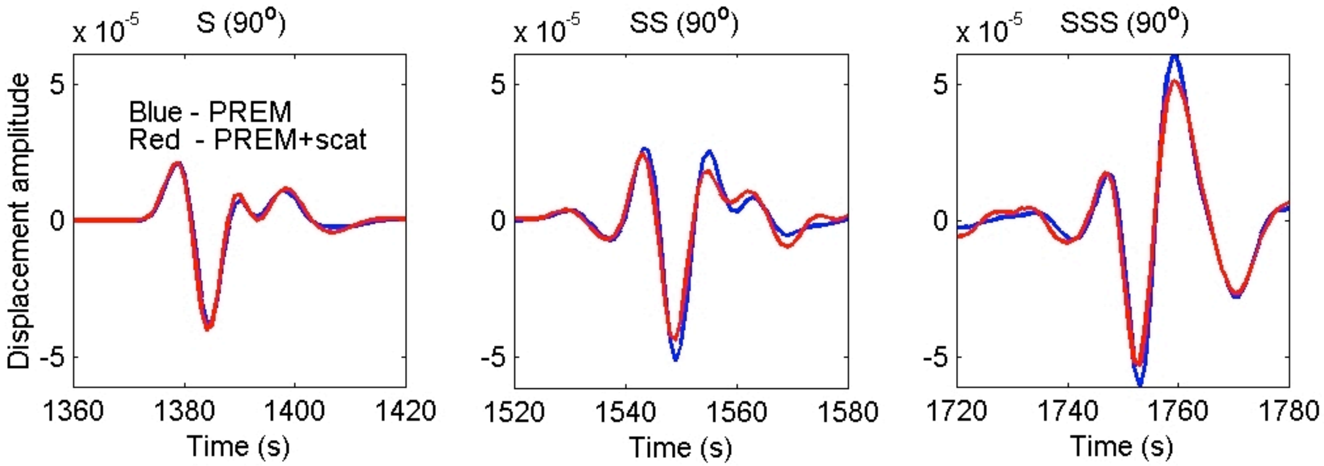


How is a propagating wavefield affected by random heterogeneities?

Synthetic seismograms

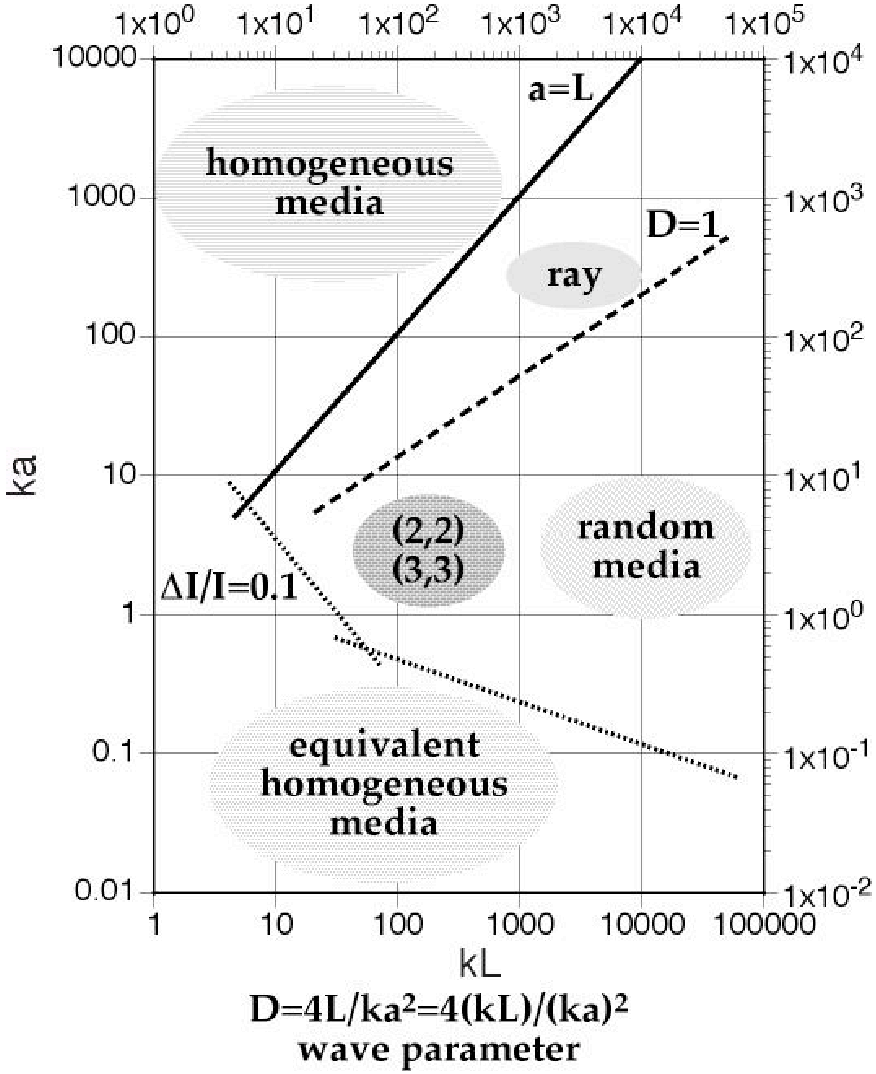
Synthetic seismograms for a global model with random velocity perturbations.





When the wavelength is long compared to the correlation length, scattering effects are difficult to distinguish from intrinsic attenuation.

Seismic Scattering Classification

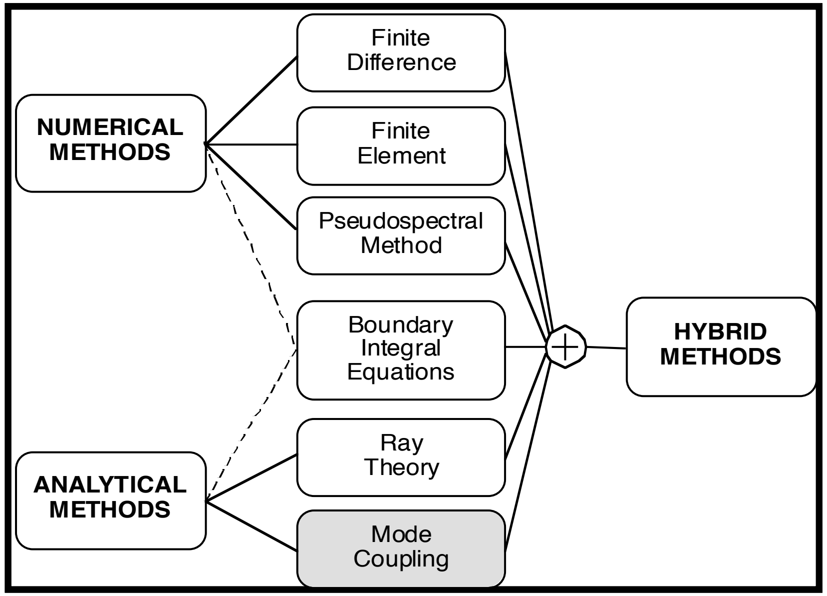


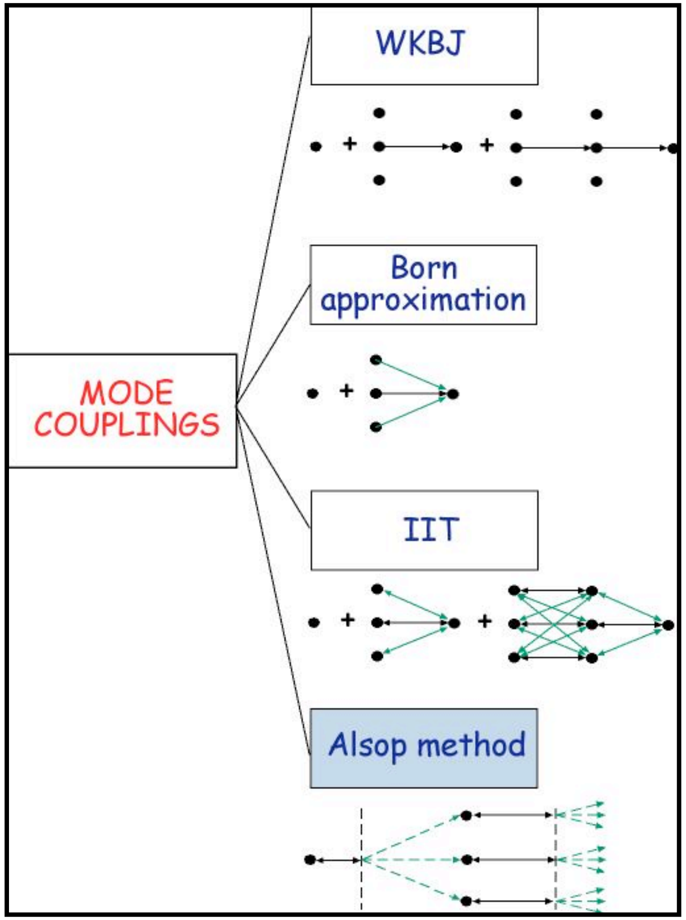
Wave propagation problems can be classified using the parameters just introduced.

This classification is crucial for the choice of technique to calculate synthetic seismograms

(Adapted from Aki and Richards, 1980)

Synthetic seismograms





Selected References - 1

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Scales, J., and Snieder, R., 1999. What is a wave?, Nature, 401, 739-740.

Snieder, R., 2002. General theory of elastic wave scattering , in Scattering and Inverse Scattering in Pure and Applied Science, Eds. Pike, R. and P. Sabatier, Academic Press, San Diego, 528-542.

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The Abdus Salam
International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

International Atomic Energy Agency

8th Workshop on Three-Dimensional Modelling of Seismic Waves Generation, Propagation and their Inversion

Site specific SH assessment: source & site effects

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Università degli studi di Trieste
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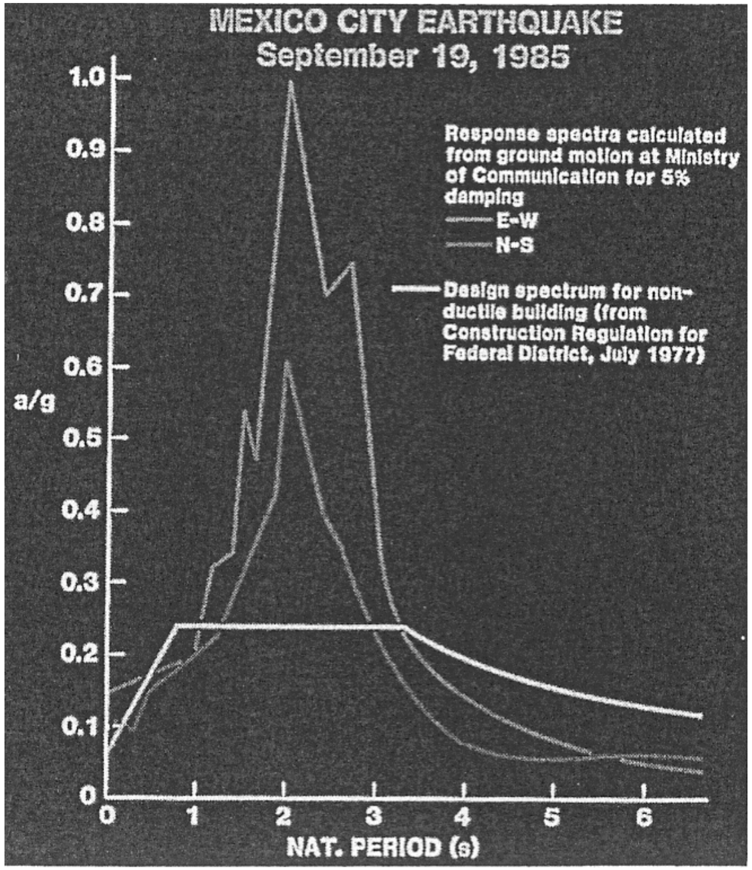
&
ESP Group of ICTP

the road to earthquake safety...

Know the input - Bound the output...



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**.

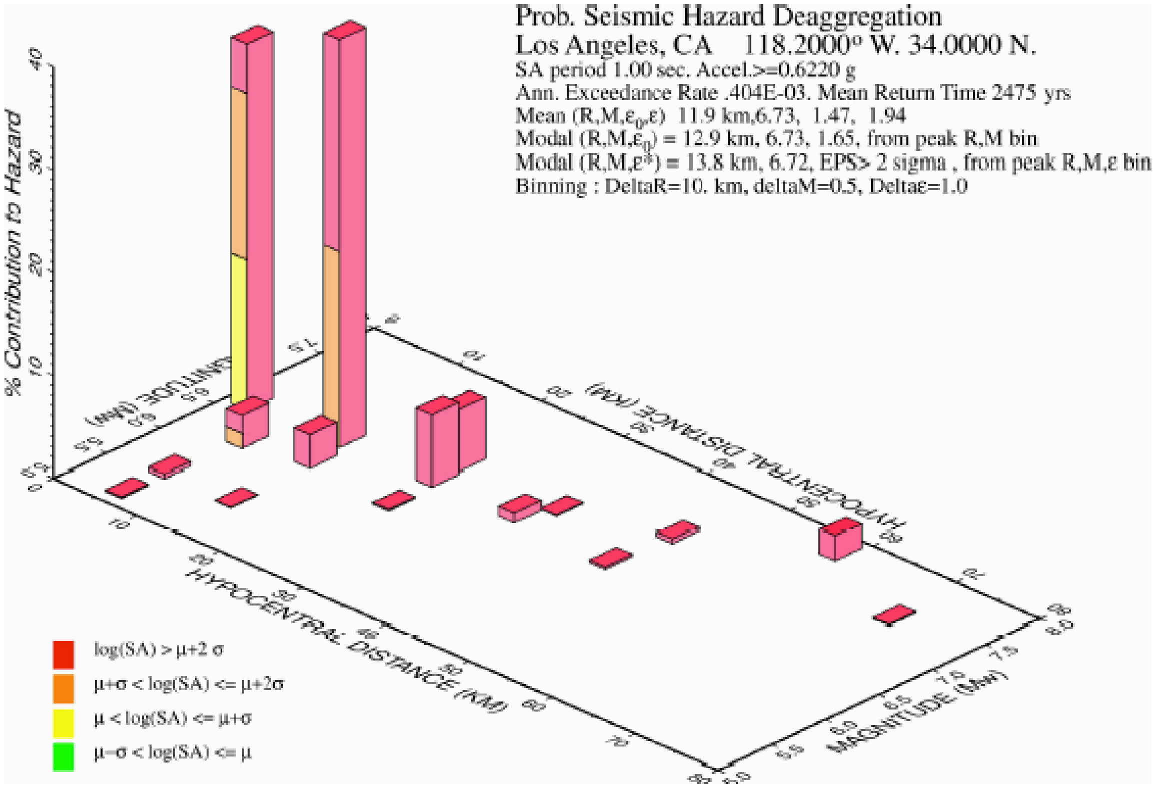
Modern PSHA & DSHA dualism

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. (see Dr. Klugel's notes)

PEER Report



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SITE EFFECTS

Surface topography effects (convexity)

sensitivity to:

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

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

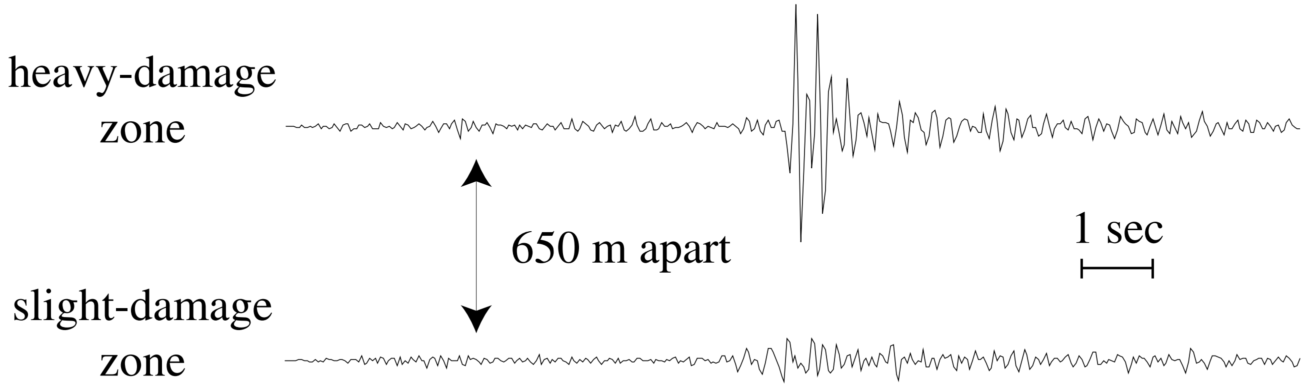
Near surface effects: impedance contrast, velocity

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

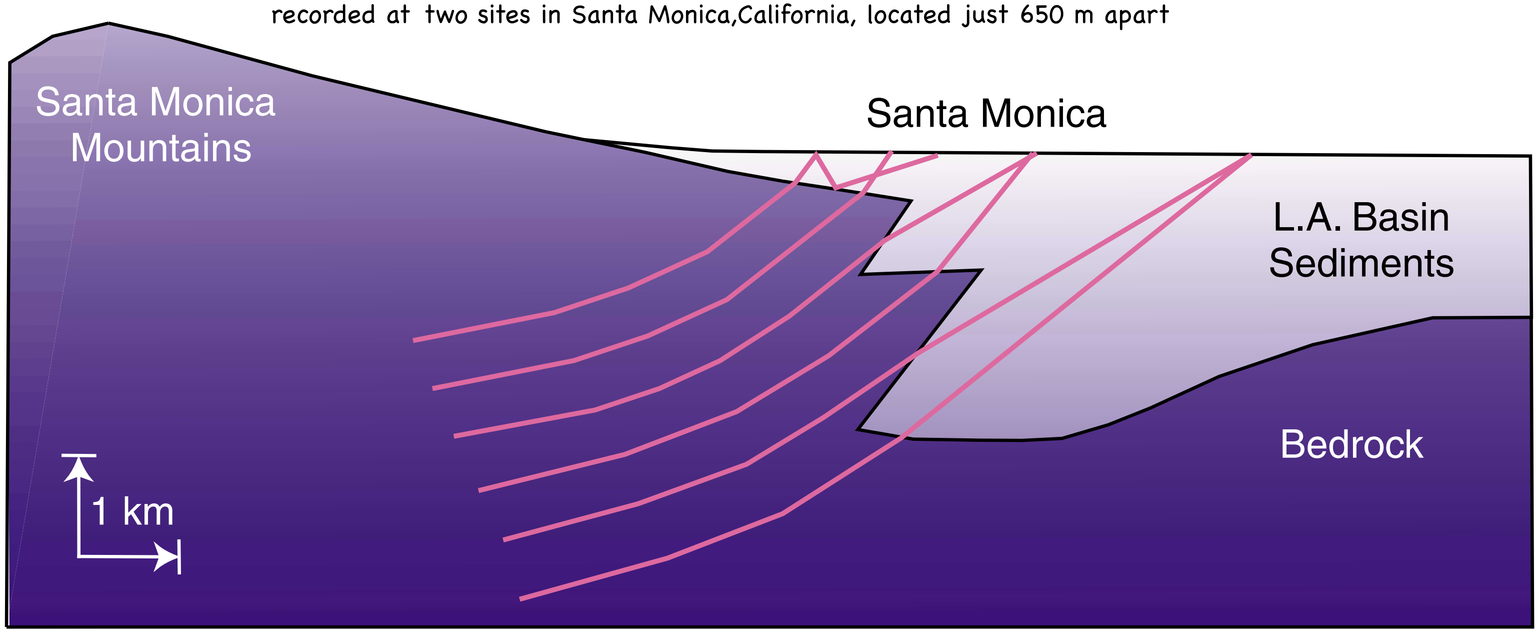
Basin effects

- Basin-edge induced waves
- Subsurface focusing

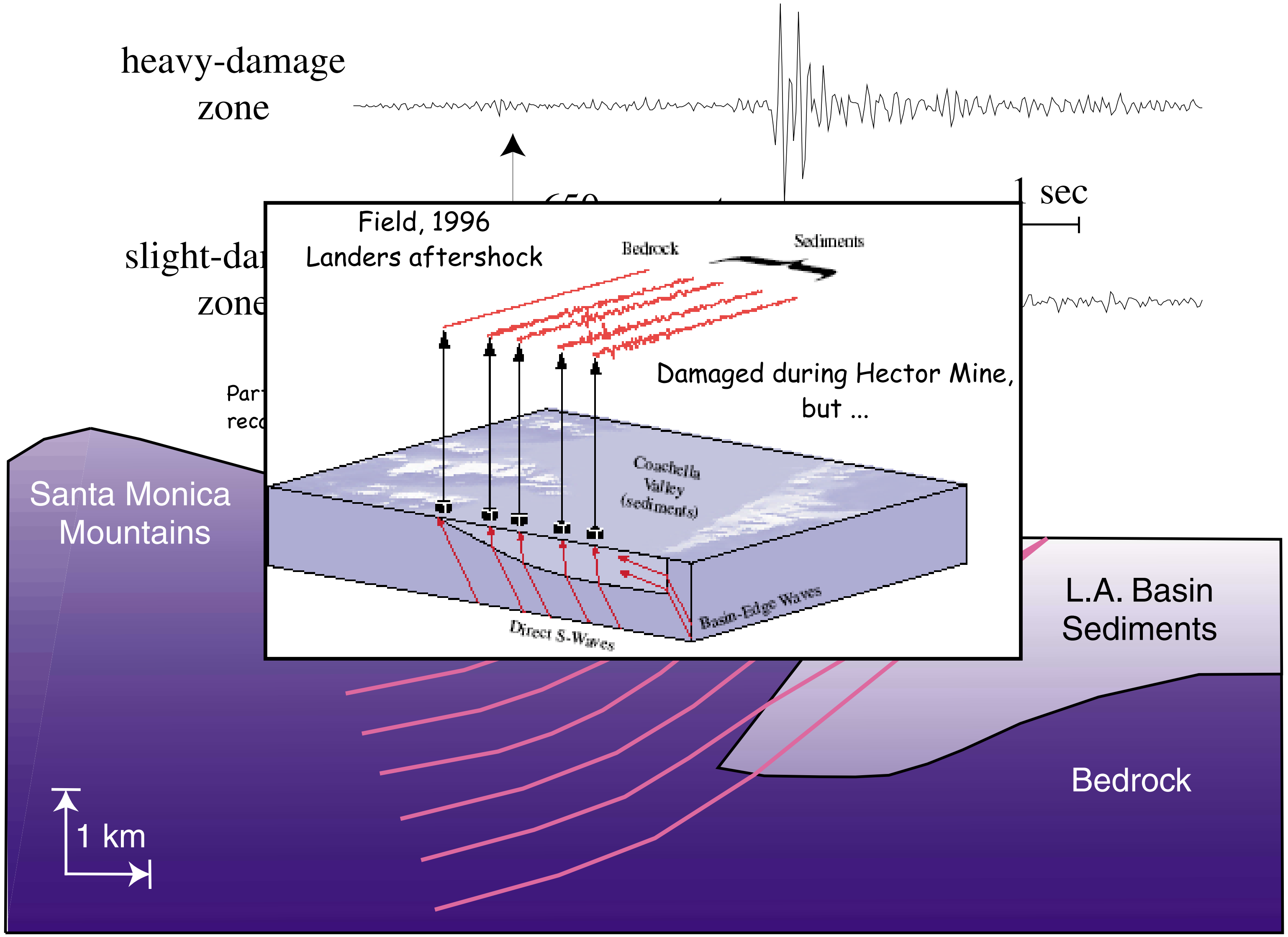
Important issues in SRE



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



Important issues in SRE

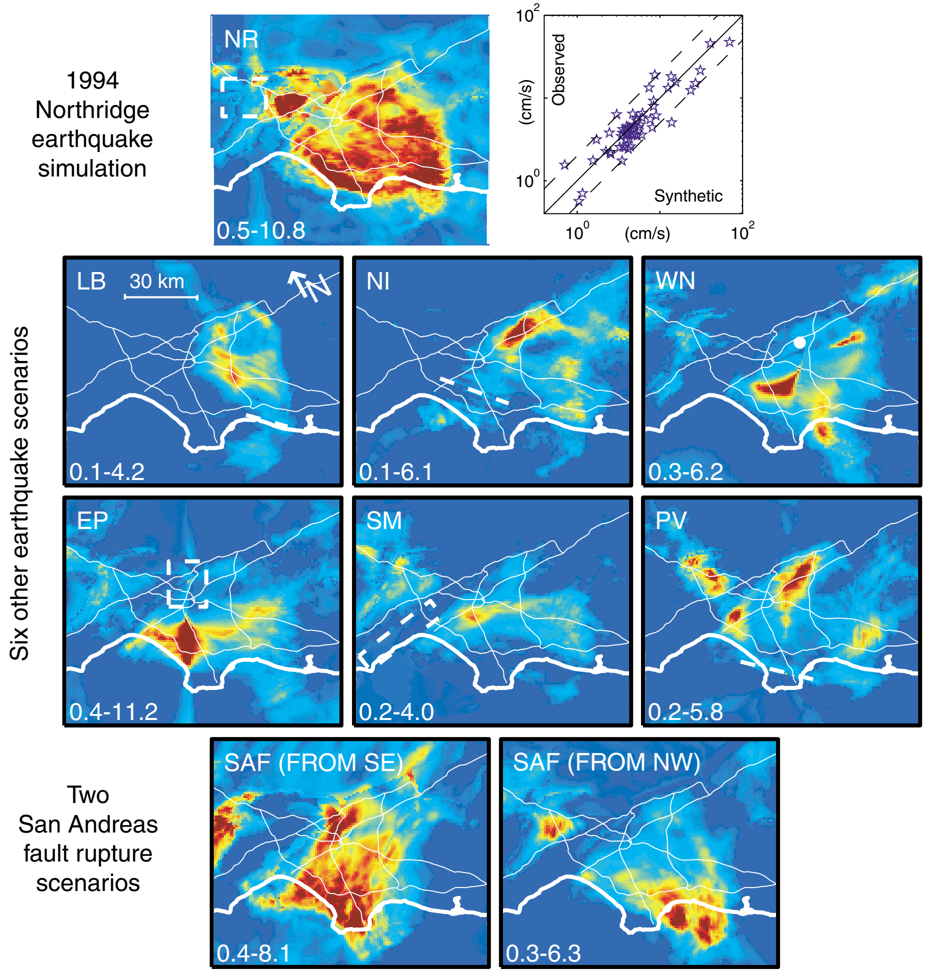


SRE and SHA

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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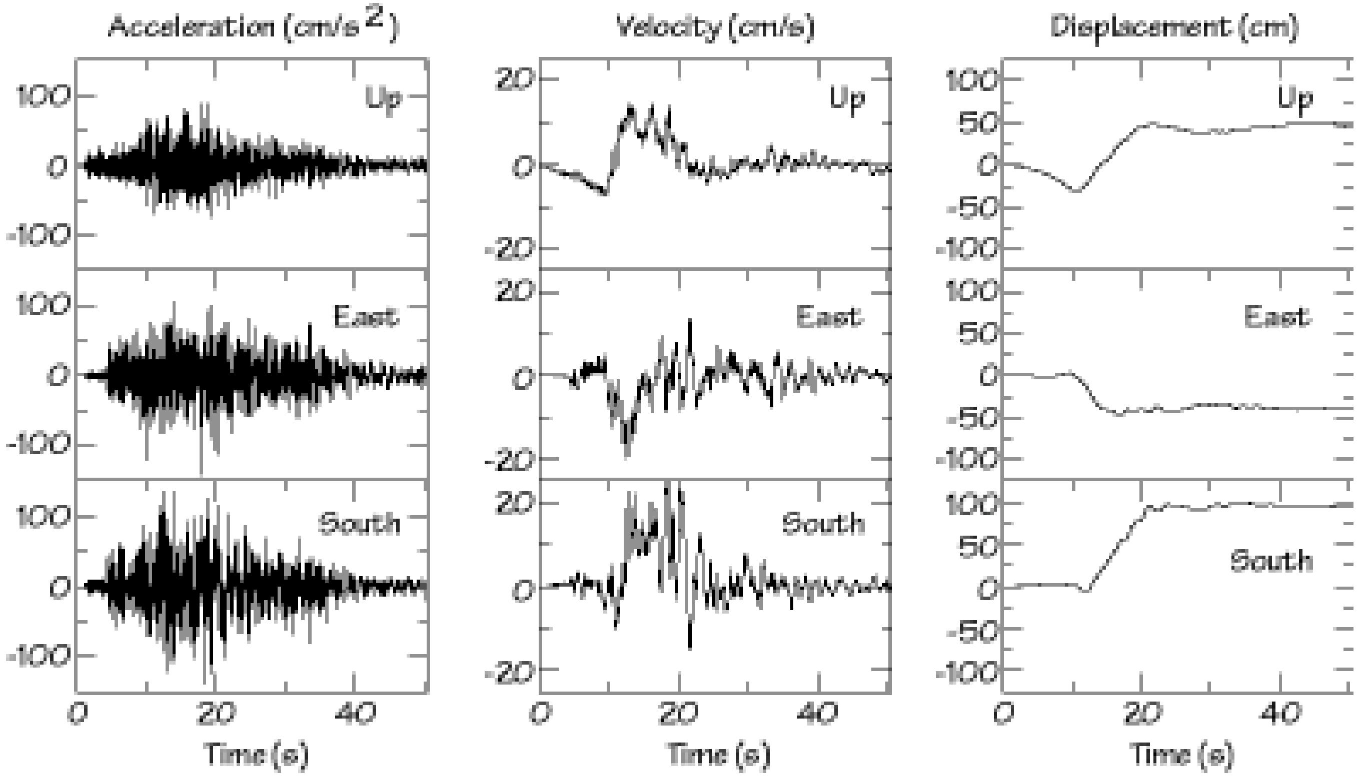
  - Directivity

Fling

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

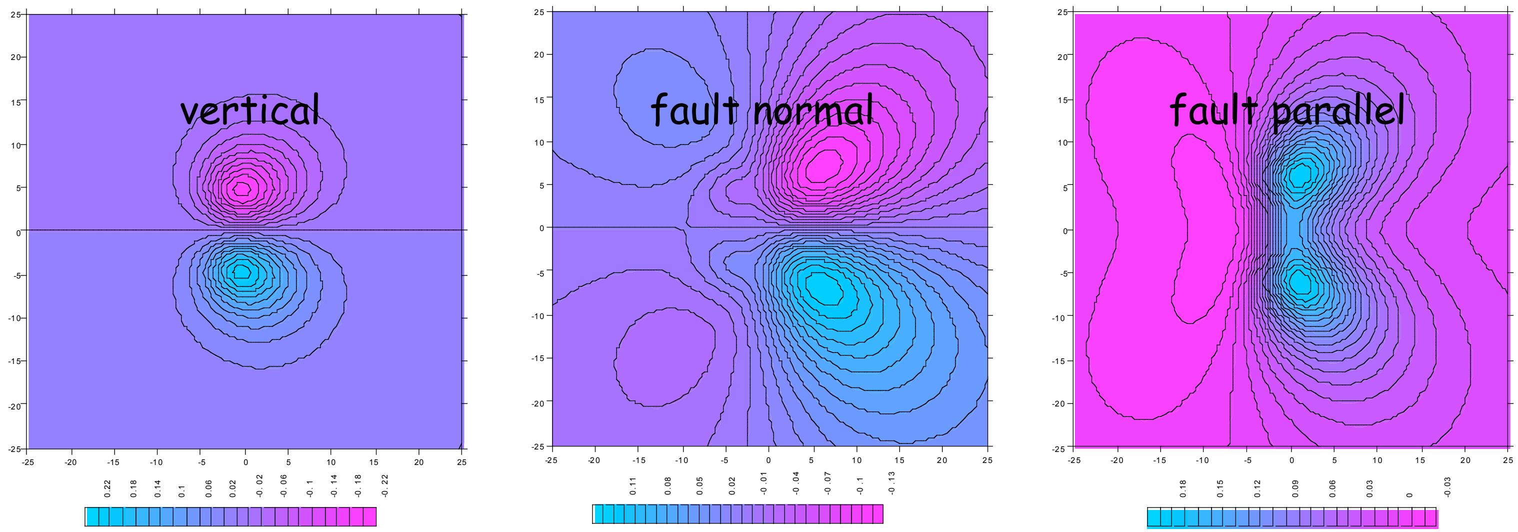


Ground acceleration, velocity and displacement, recorded at a strong-motion seismometer that was located directly above the part of a fault that ruptured during the 1985 Mw = 8.1, Michoacan, Mexico earthquake.

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

Static near-field term from a finite fault

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

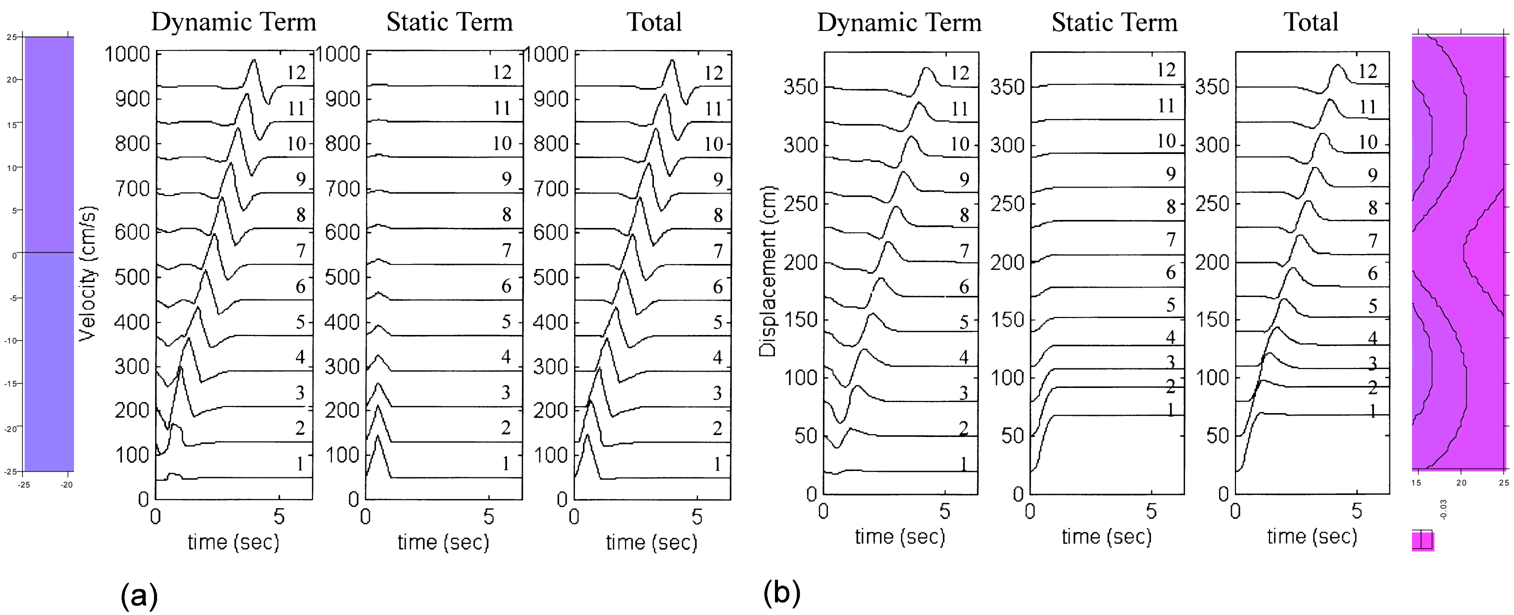
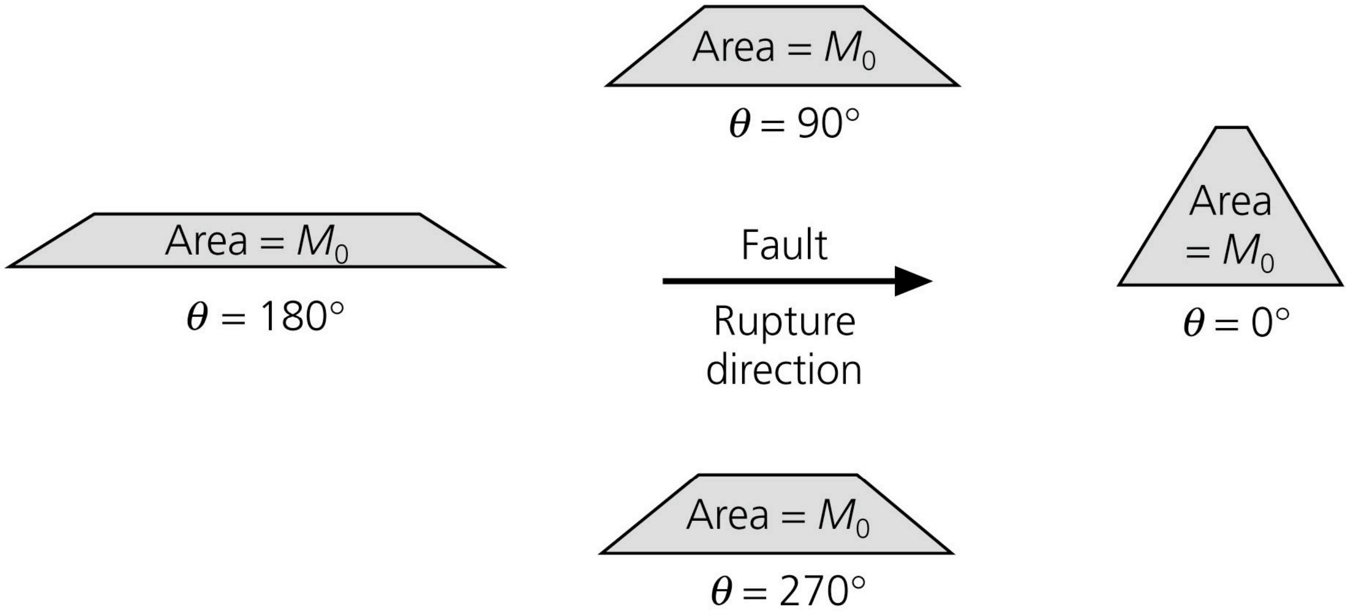


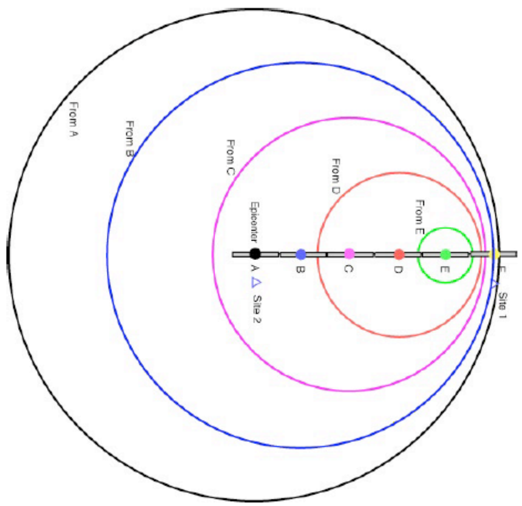
Figure 7. (a) Velocities and (b) displacements of the fault-parallel components at 12 observation points in Figure 6, using the first (dynamic; left), second (static; center), and total (right) integrations of equation (11).

+directivity (Hisada&Bielak, 2003)
& Dr. Ghayamghamian notes

Source effect

Directivity (near fault)





Source effect

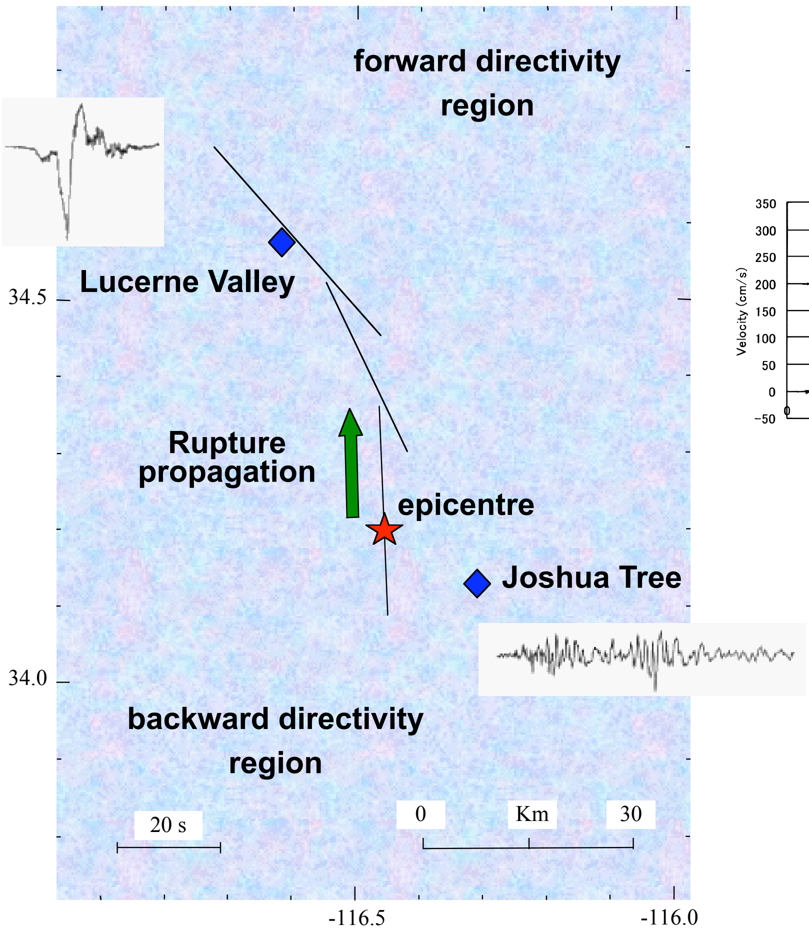
Directivity (near fault)

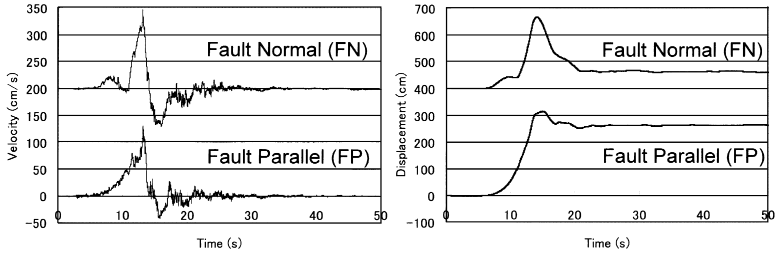
Particularly, in the case of **forward rupture directivity** most of the energy arrives in a single large pulse of motion which may give rise to particularly severe ground motion at sites toward which the fracture propagation progresses.

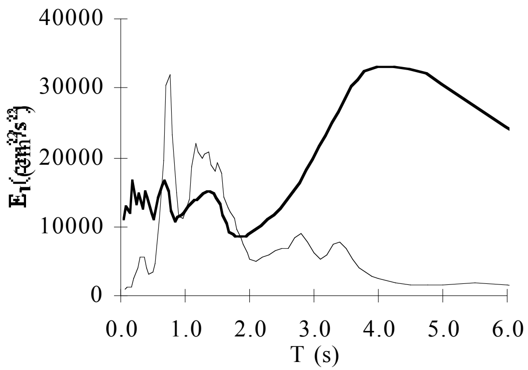
it involves the transmission of large energy amounts to the structures in a very short time.

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

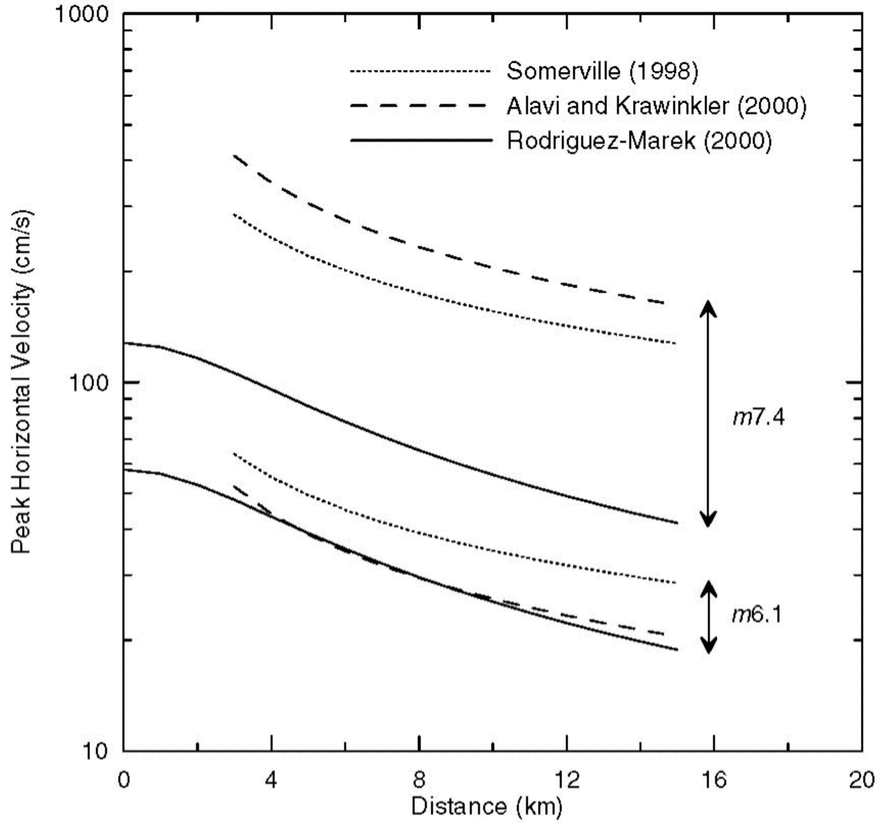






Source effect

regression example...



Rodriguez-Marek (2000):
$$\ln(\text{PHV}) = 2.44 + 0.5\,m - 0.41\,\ln(r^2 + 3.93^2)$$

Somerville (1998):
$$\ln(\text{PHV}) = -2.31 + 1.15\,m - 0.5\,\ln(r)$$

Alavi and Krawinkler (2000):
$$\ln(\text{PHV}) = -5.11 + 1.59\,m - 0.58\,\ln(r)$$

Source effect

Near fault ground motion

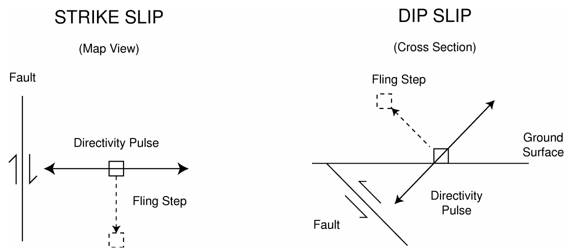


Fig. 4.3. Schematic diagram showing the orientations of fling step and directivity pulse for strike-slip and dip-slip faulting.

Peer report, 2001

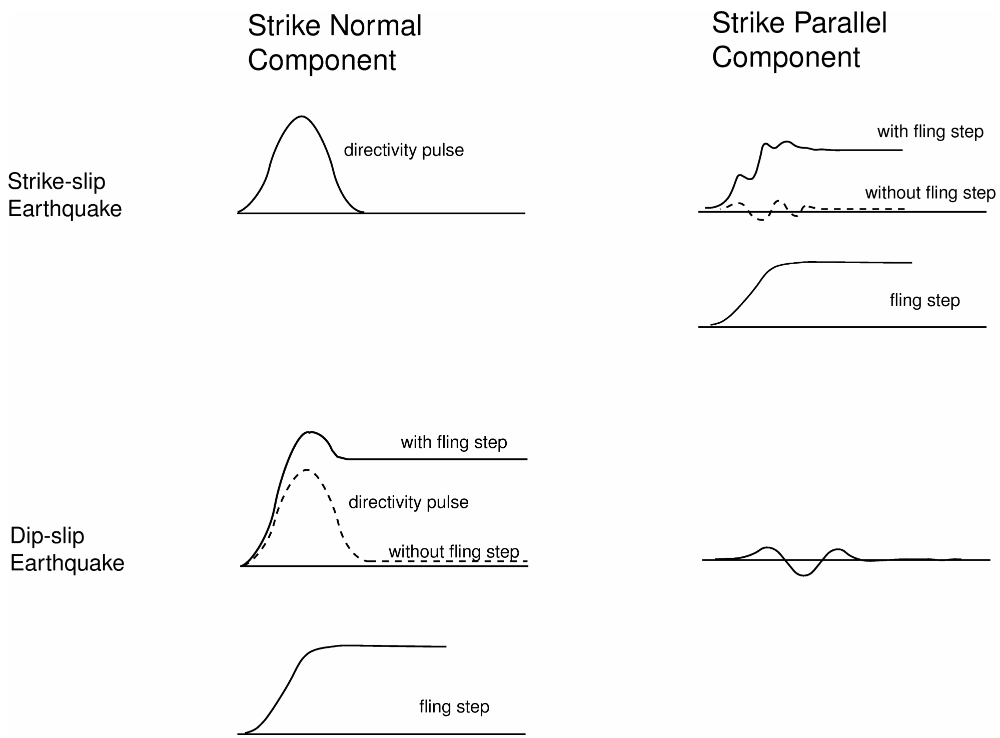


Fig. 4.4. Schematic diagram of time histories for strike-slip and dip-slip faulting in which the fling step and directivity pulse are shown together and separately.

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…

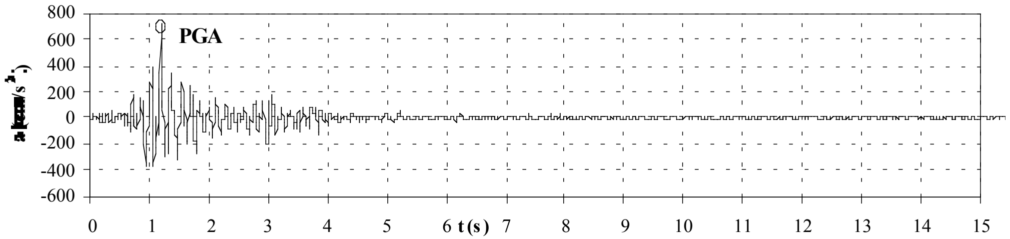


Figure 1 – Acceleration time history. Rocca NS record. 1971 Ancona earthquake (M_L=4.7)

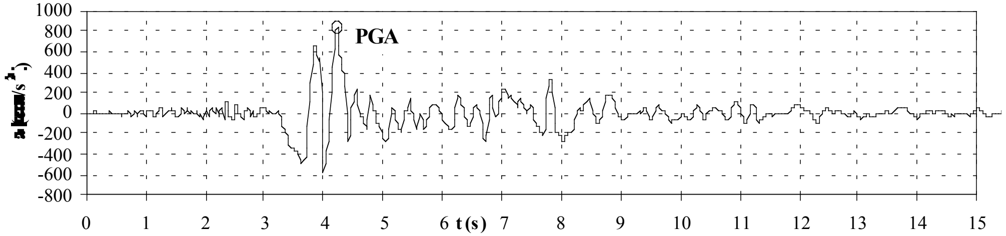


Figure 2 – Acceleration time history. Sylmar N360 record. 1994 Northridge earthquake (M_w=6.7)

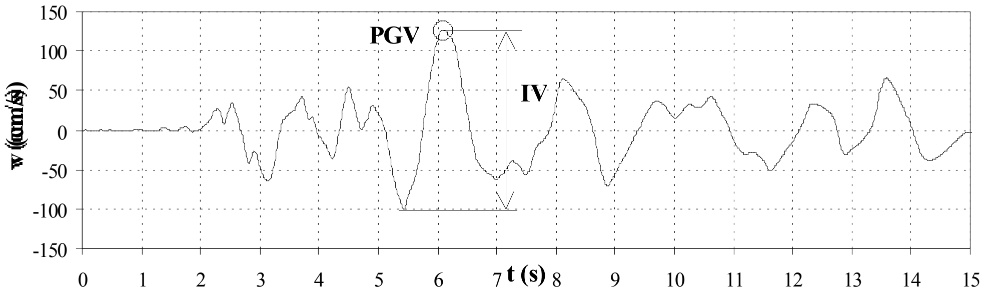


Figure 3 – Velocity time history. Takatori 000 record. 1995 Kobe earthquake (M_w=6.9)

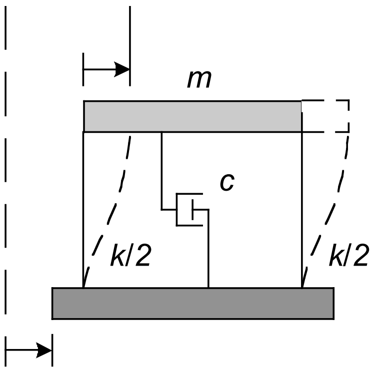
Response spectra

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:

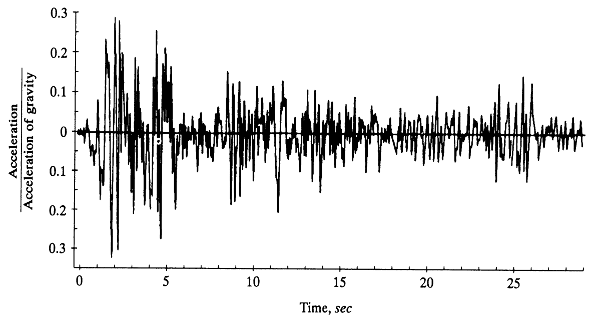
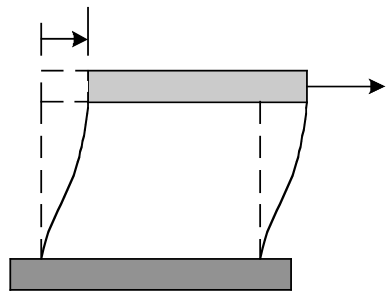


FIGURE 24-15
Accelerogram from El Centro earthquake, May 18, 1940 (*NS* component).

EQUIVALENT STATIC FORCE



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

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

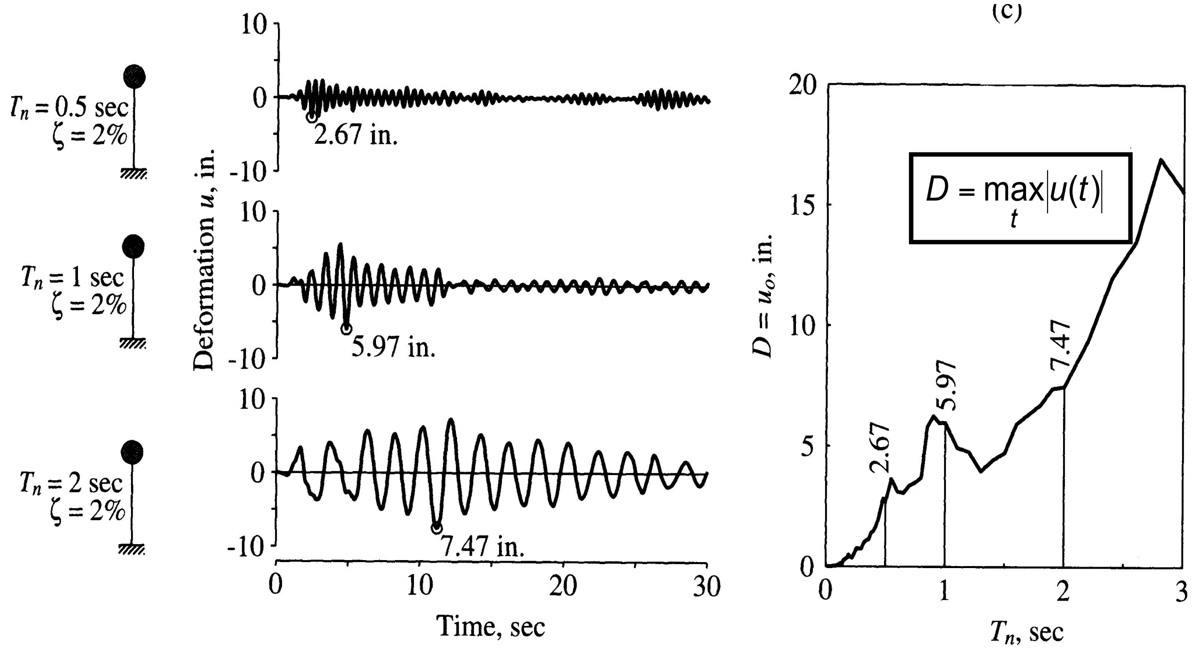
Pseudo acceleration

$f_S(t)$ 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

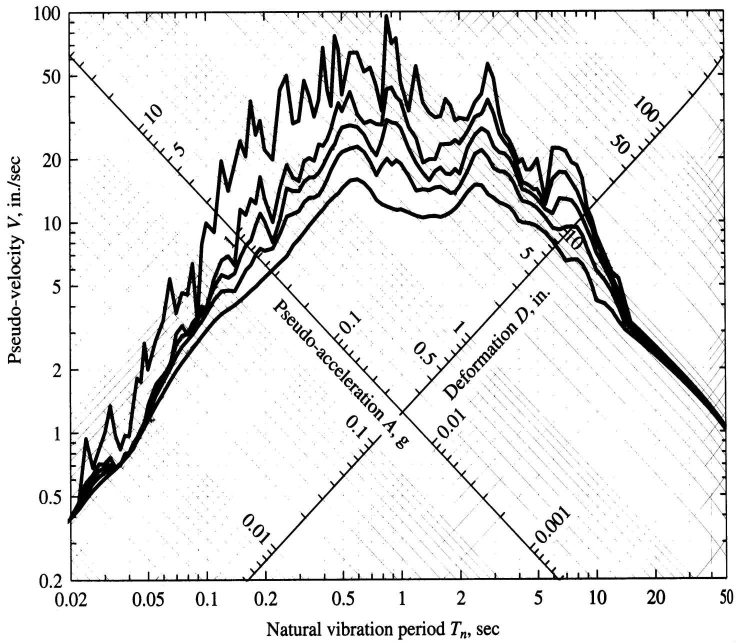
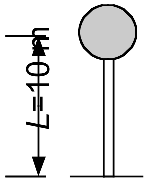


Figure 6.6.4 Combined *D–V–A* response spectrum for El Centro ground motion; ζ = 0, 2, 5, 10, and 20%.

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

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

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

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

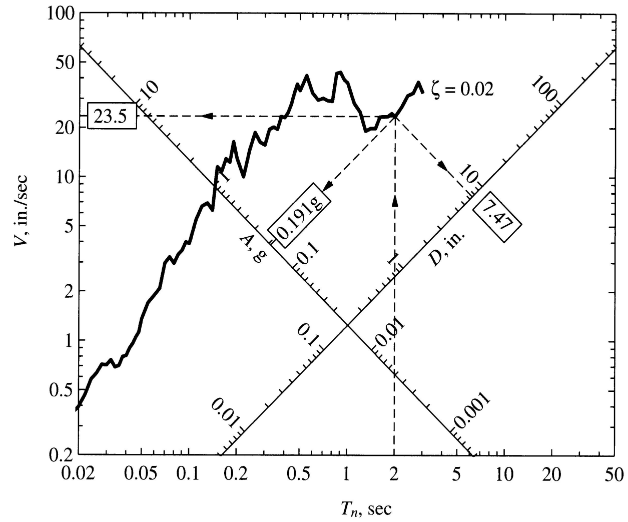
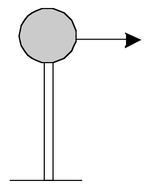
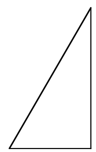


Figure 6.6.3 Combined D–V–A response spectrum for El Centro ground motion; $\zeta = 2\%$.





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.

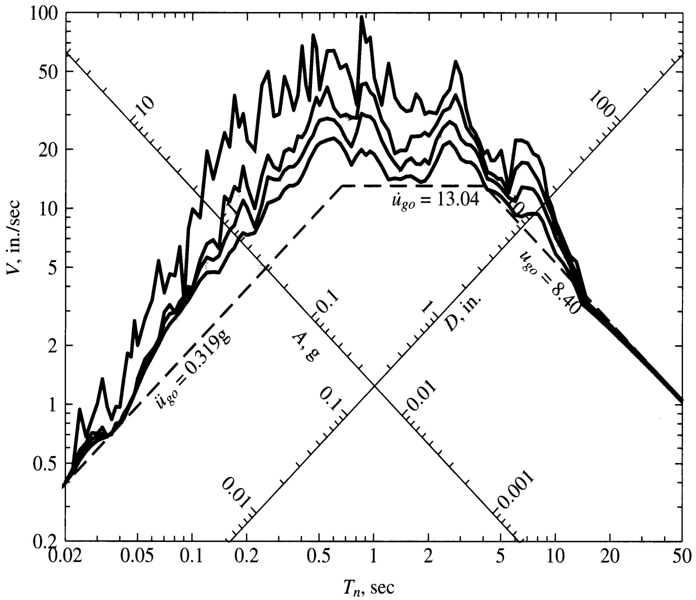


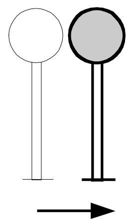
Figure 6.8.1 Response spectrum (ζ = 0, 2, 5, and 10%) and peak values of ground acceleration, ground velocity, and ground displacement for El Centro ground motion.

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

T_n < 0.03 s : rigid system

no deformation

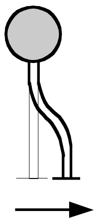
u(t) ≈ 0 → D ≈ 0



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

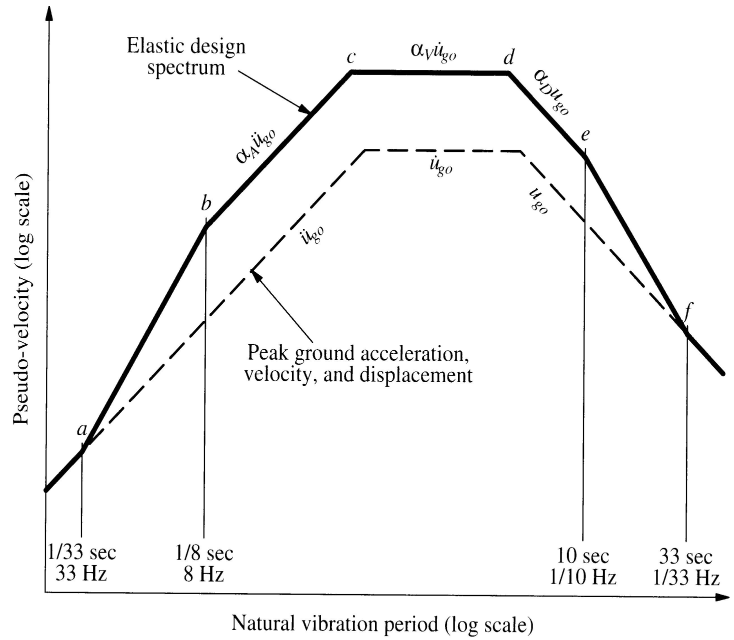


Figure 6.9.3 Construction of elastic design spectrum.

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.

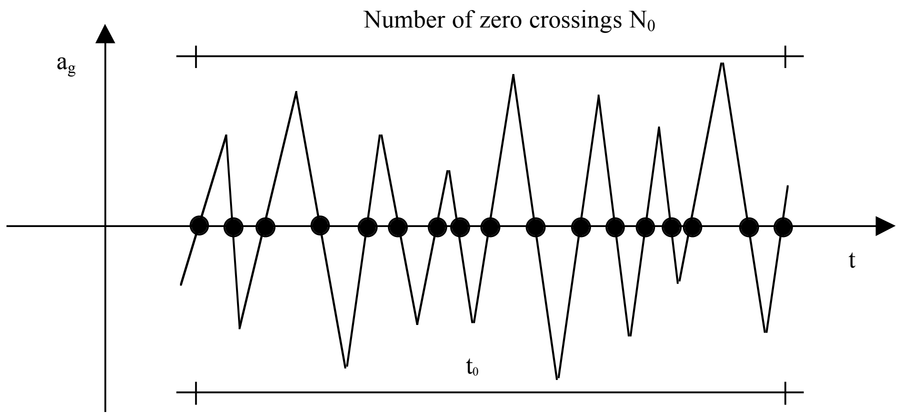
Housner's spectral intensity is the first moment of the area of S_{pa} $(0.1<T<2.5)$ about the S_{pa} axis, implying that the Housner spectral intensity is larger for ground motions with a significant amount of low frequency content.
The I_H parameter captures important aspects of the amplitude and frequency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

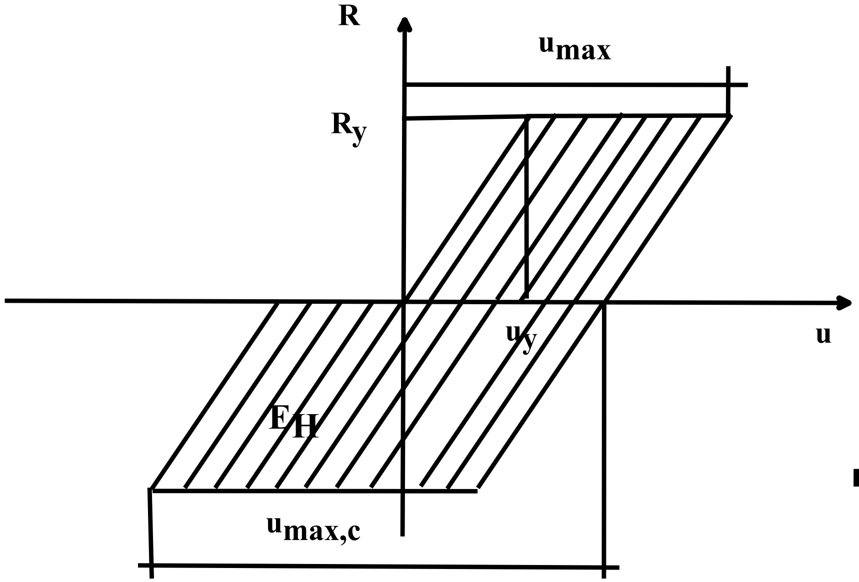
$$C_y = \frac{R_y}{mg} \quad \eta = \frac{R_y}{m\ddot{u}_{g(max)}} = \frac{C_y}{\ddot{u}_{g(max)}/g}$$

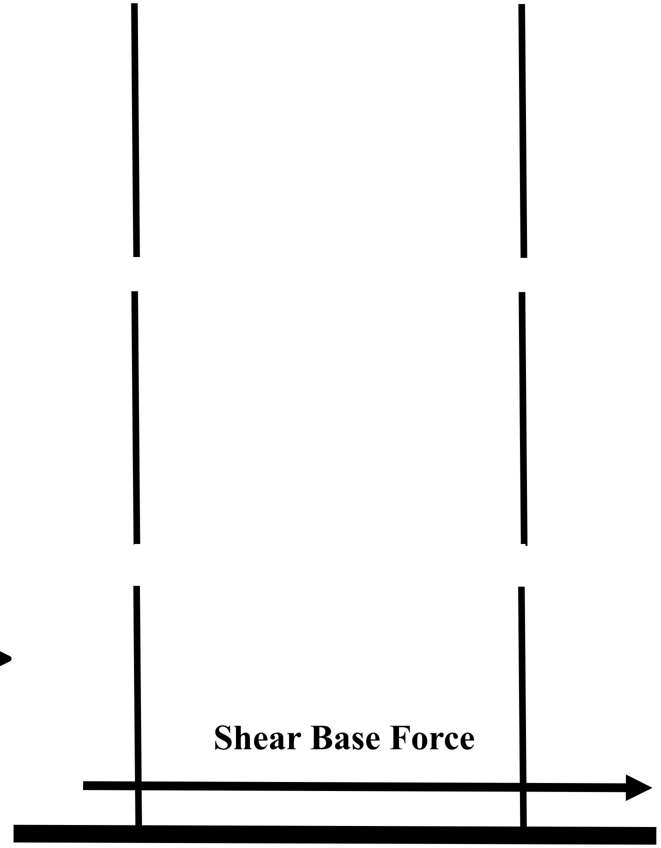
where R_y is the yielding resistance, m is the mass of the system, and $\ddot{u}_{g(max)}$ is the maximum ground acceleration.

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

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

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





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.

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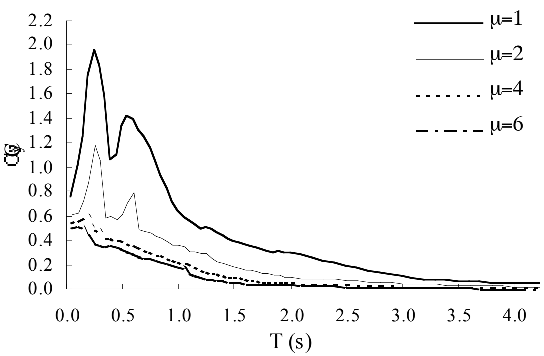
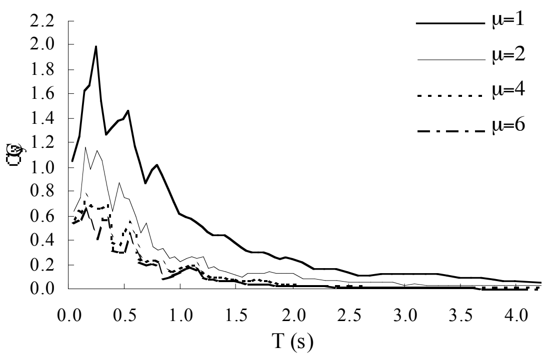
One significant disadvantage of se ismic resistance (C_y) spectra is that the effect of strong motion duration is not considered. An example of constant ductility C_y spectra, corresponding to the 1986 San Salvador earthquake (CIG record) and 1985 Chile earthquake (Llolleo record):it seems tha t the da mage potential of these ground motions is quite similar, even though the CIG and Llolleo are r ecords of t wo 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):

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

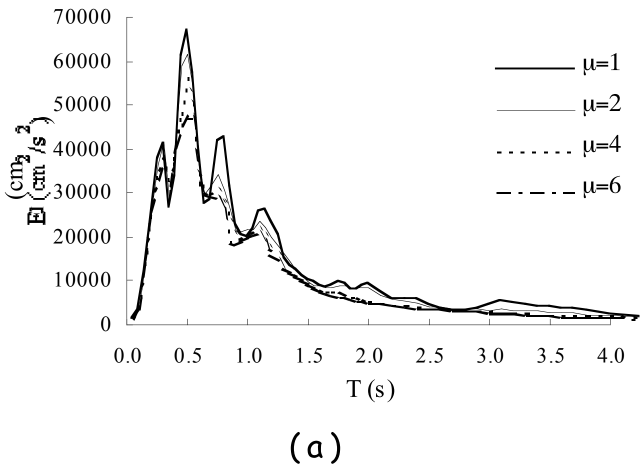
where (E_I) is the input energy, (E_k) is the kinetic energy, (E_ξ) is the damping energy, (E_s) is the elastic strain energy, and (E_H) is the hysteretic energy.

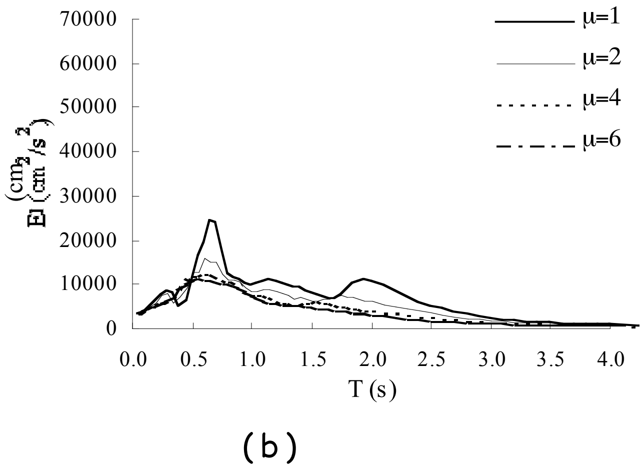
Input energy

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.





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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Outline

Some remarks on SHA

SHA & PBDE

Source & site effects in SHA

Demand parameters

Definition of seismic input

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- Focal mechanism
- Site effects
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VAB Project (EC)

ADVANCED METHODS FOR ASSESSING
THE SEISMIC VULNERABILITY
OF EXISTING MOTORWAY BRIDGES

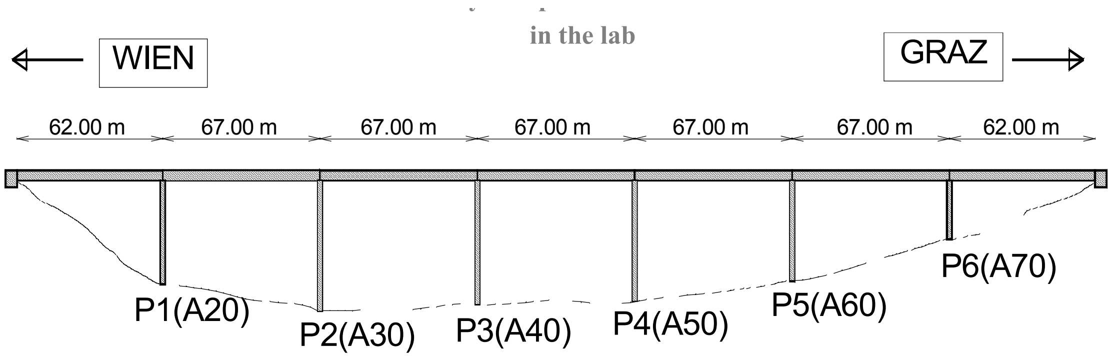
ARSENAL RESEARCH, Vienna, Austria; **ISMES S.P.A**,. Bergamo, Italy;
ICTP, Trieste, Italy; **UPORTO**, Porto, Portugal; **CIMNE**, Barcelona, Spain;
SETRA, Bagneaux, France; **JRC-ISPRA**, EU.

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.



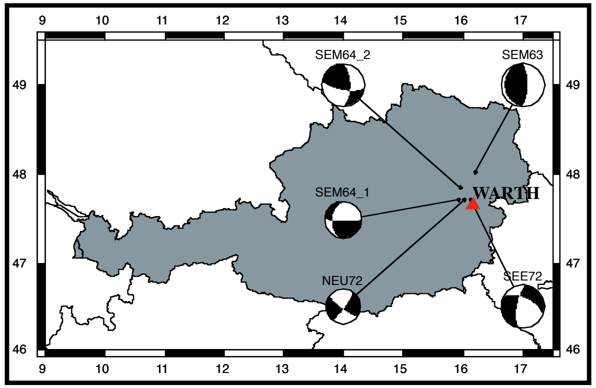
Case study

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

Case study

Databank of geological, geophysical and seismotectonic data

STRUCTURAL MODELS

Bedrock model

1) EUR-I Data set

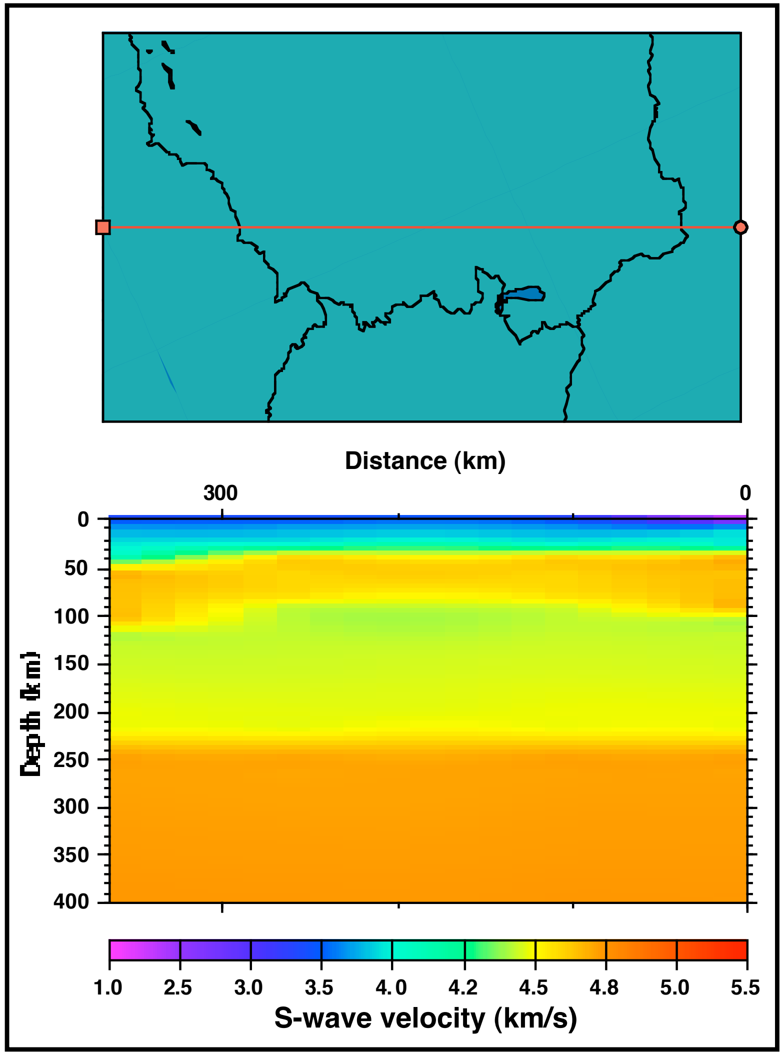
2) updated on the basis of the geological informations collected by CIMG

Local LHET model

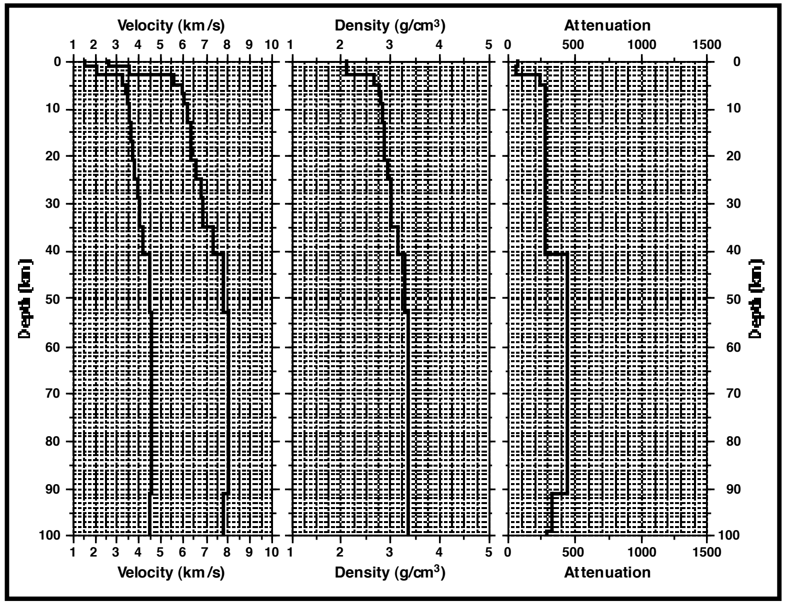
1) available Warth bridge section plan

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

Initial regional model

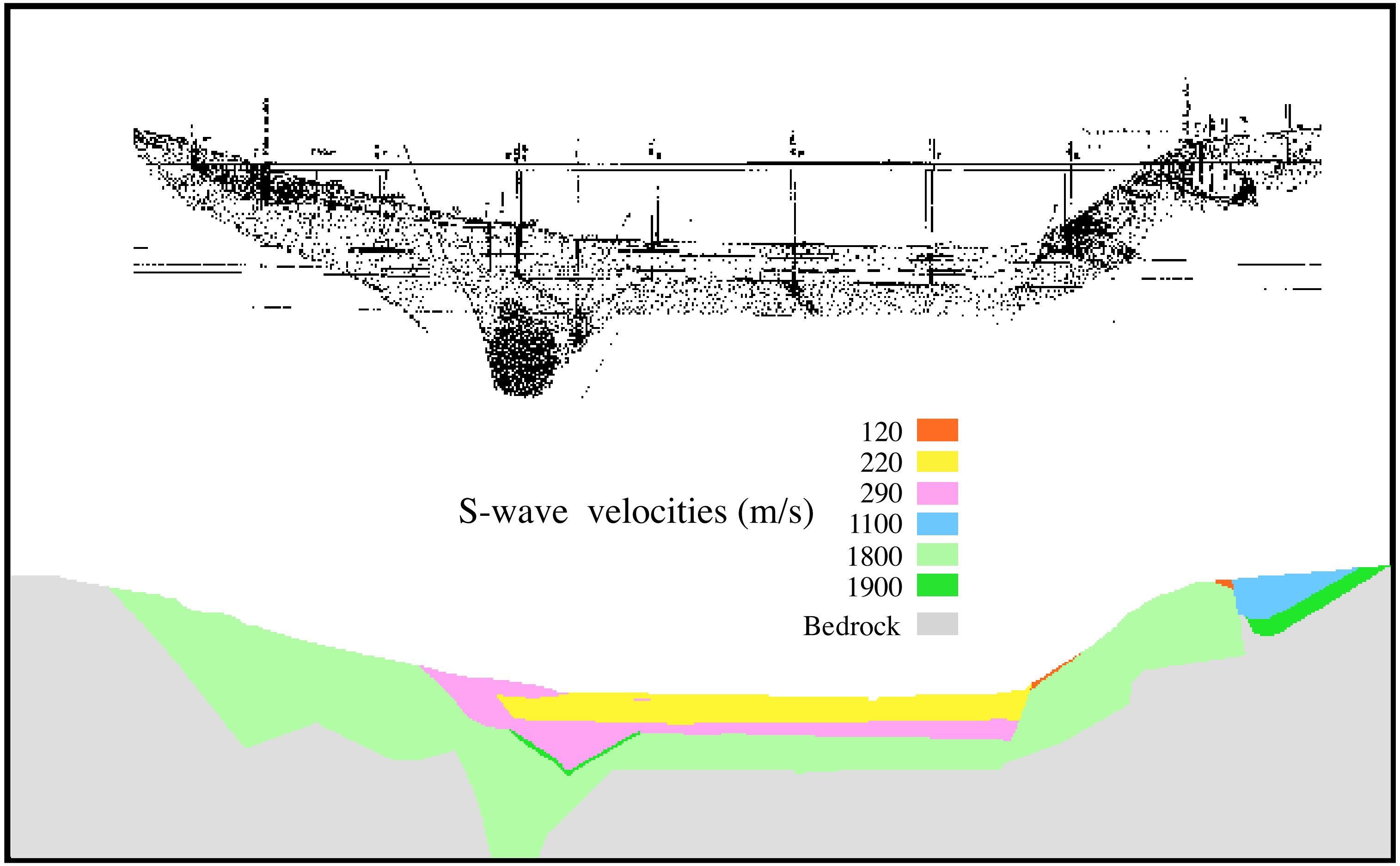


EUR I data set



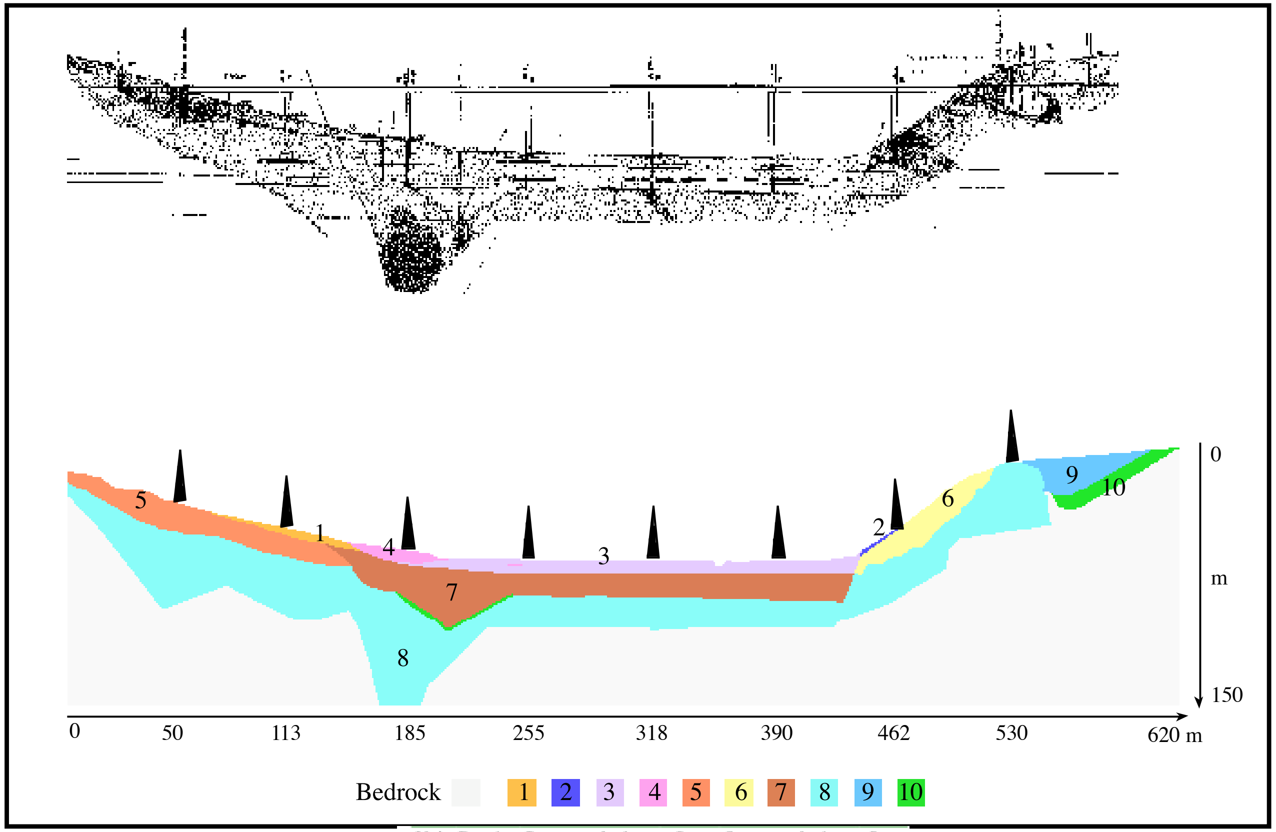
Definition of str. models

Initial LHM - Warth bridge - model



Definition of str. models

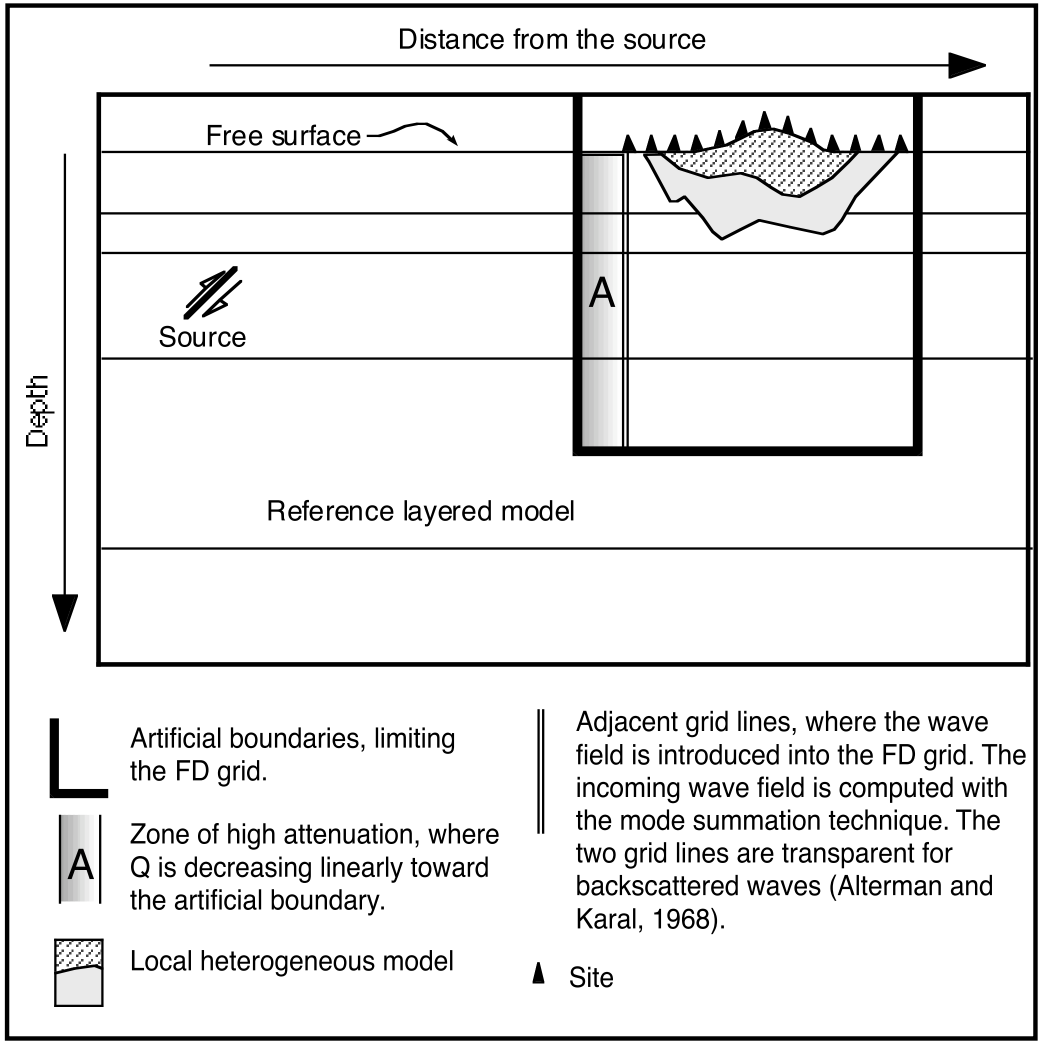
LHM - Warth bridge - model



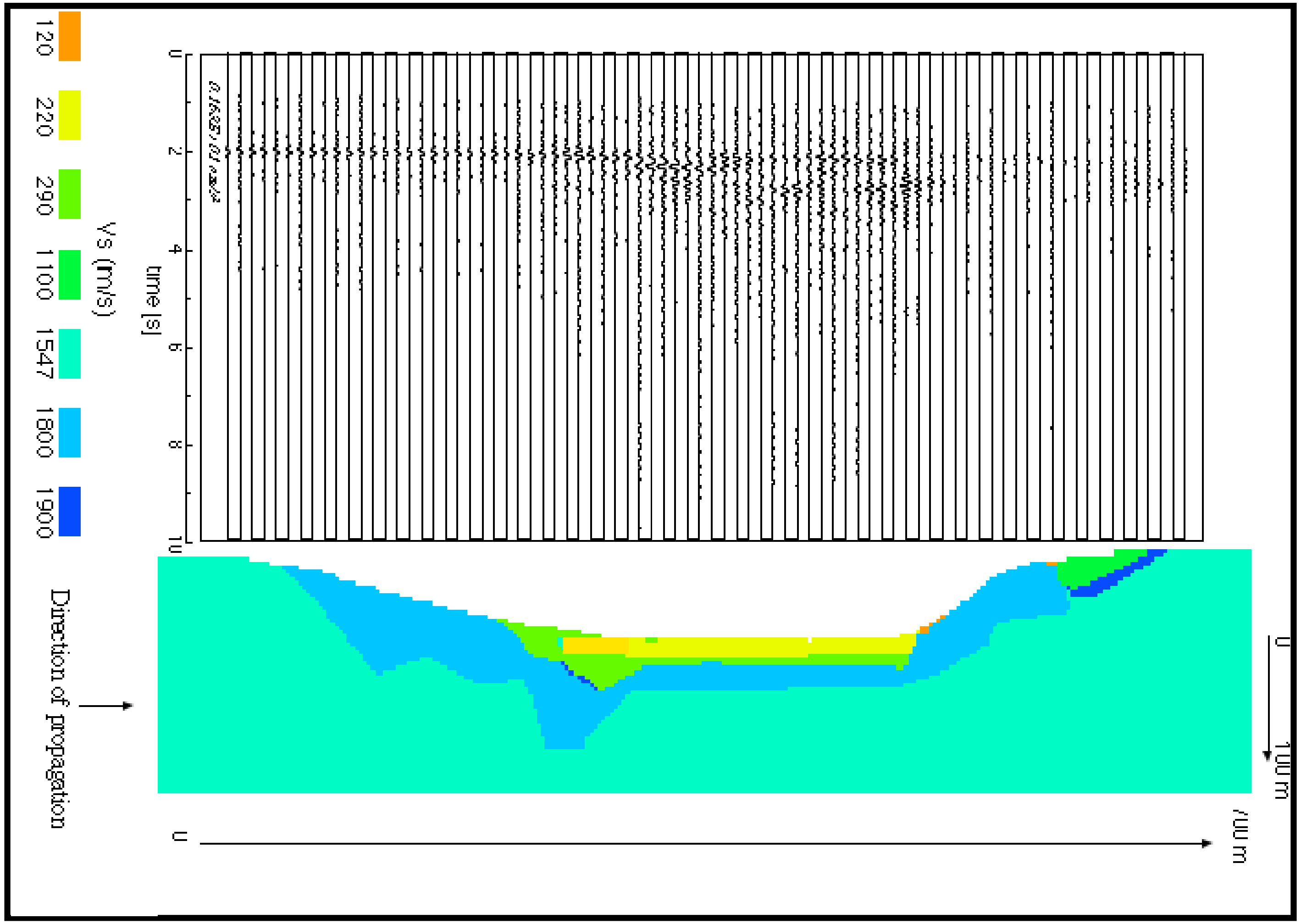
Unit	Density g/cm^3	P-wave velocity km/s	Q_P	S-wave velocity km/s	Q_S
1	1.5	0.30	40.0	0.20	15.0
2	1.7	0.49	40.0	0.25	15.0
3	2.0	0.70	50.0	0.26	20.0
4	1.8	0.70	50.0	0.29	20.0
5	2.3	0.80	50.0	0.30	20.0
6	2.3	0.80	50.0	0.40	20.0
7	1.8	1.70	50.0	0.50	20.0
8	2.3	2.10	150.0	1.00	60.0
9	2.3	3.00	150.0	1.90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

Definition of str. models

Hybrid method: MS-FD

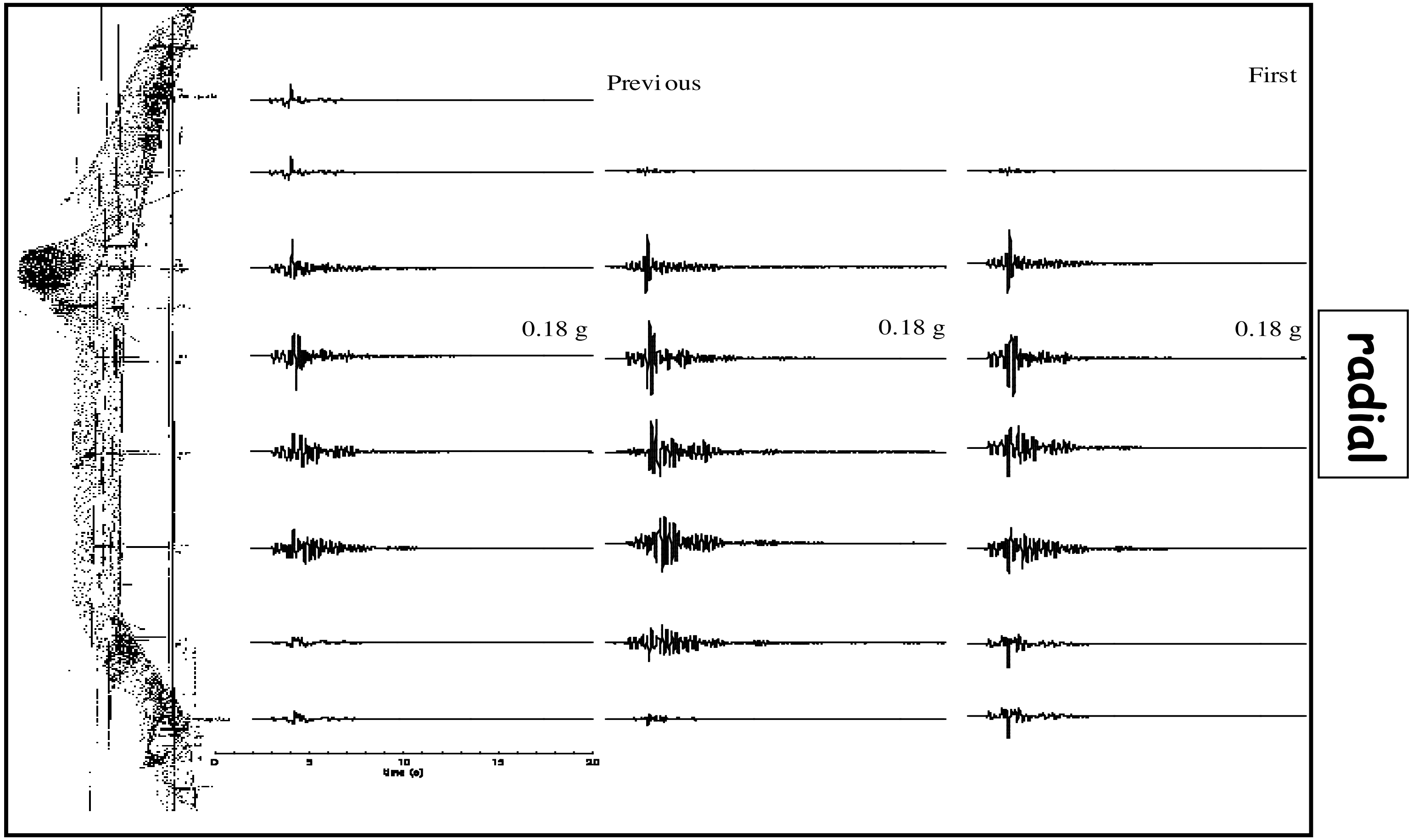


Initial synthesis - radial



Case study: initial scenario

Synthetic accelerations and diffograms



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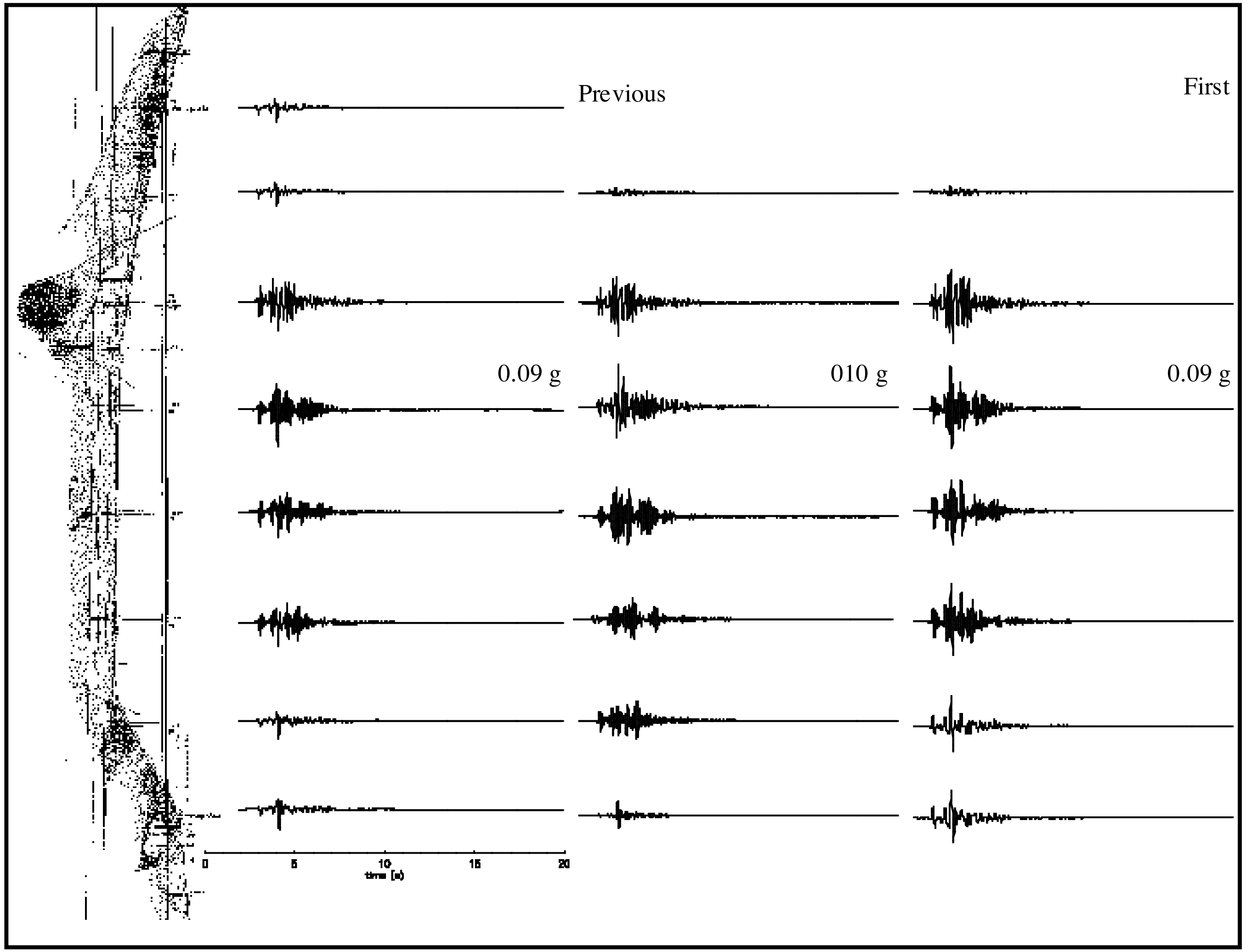
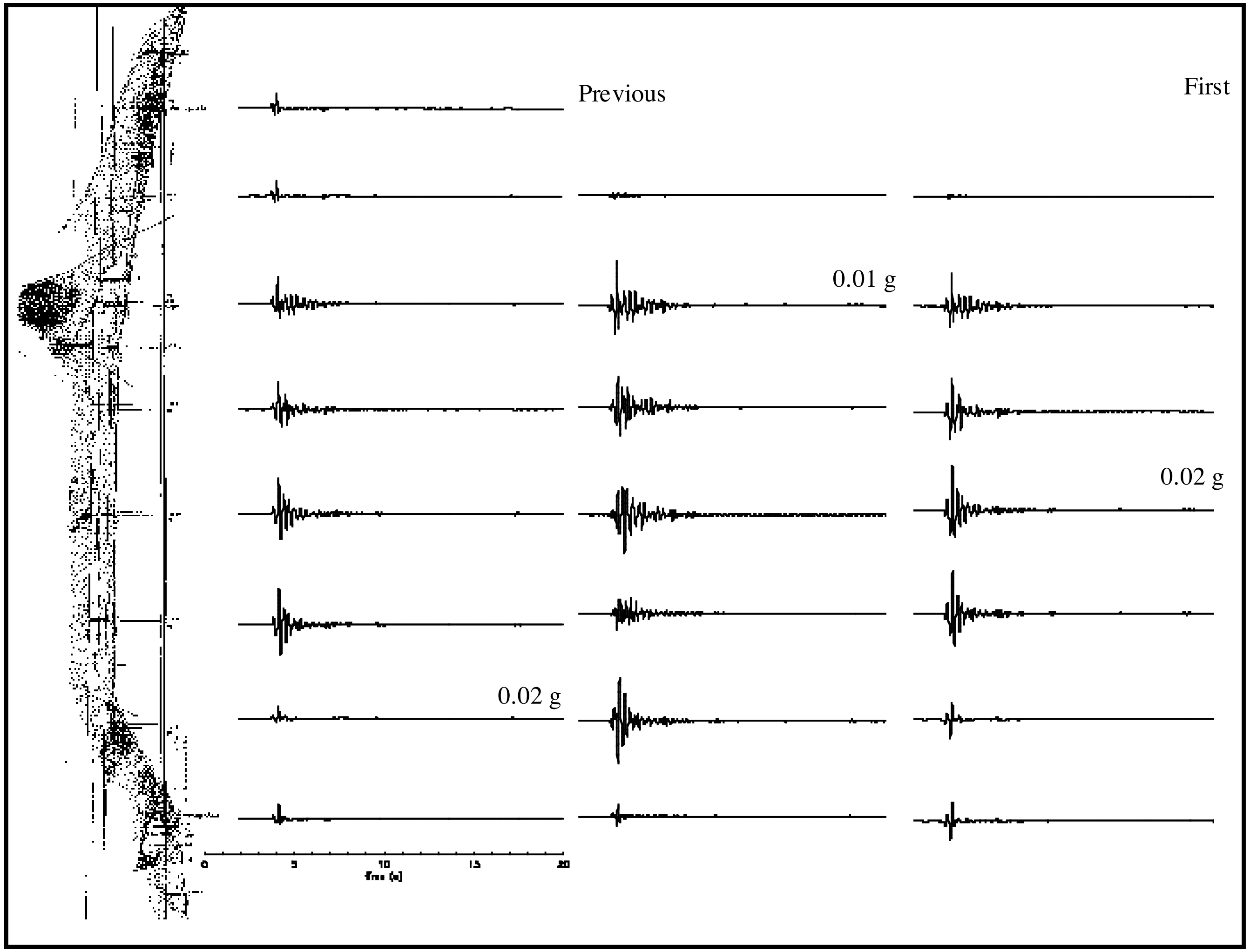


vertical

Case study: initial scenario

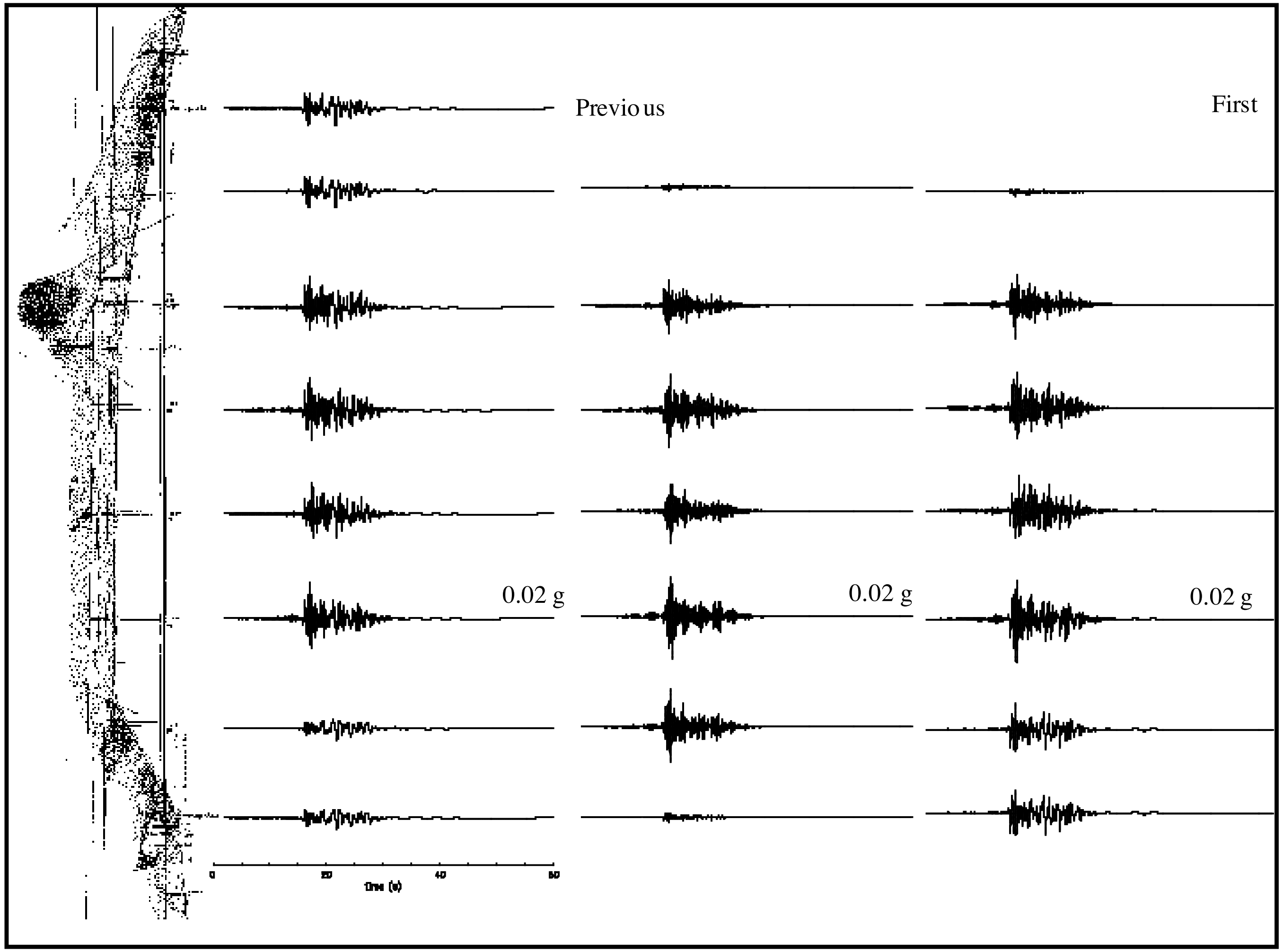
Synthetic accelerations and diffograms



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°)

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2) Rake a

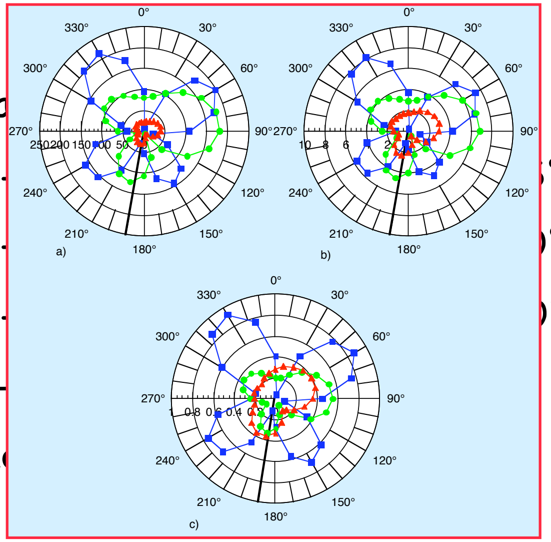
3) Strike- °)

4) Strike- °)

5) Strike- °)

6) Depth-

(Strik



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3) Strik
4) Strik
5) Strik
6) Dept
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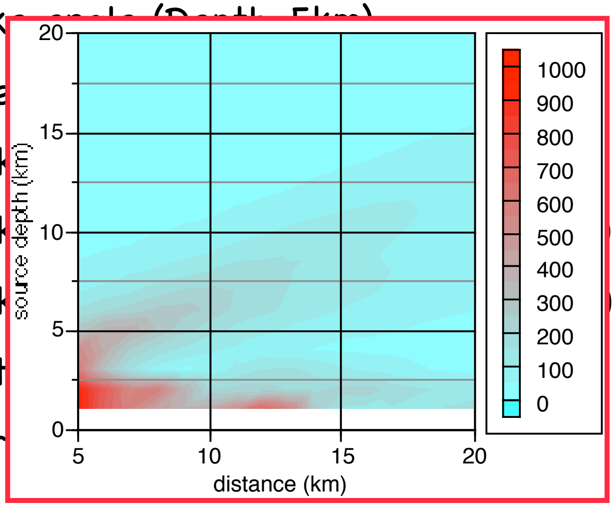
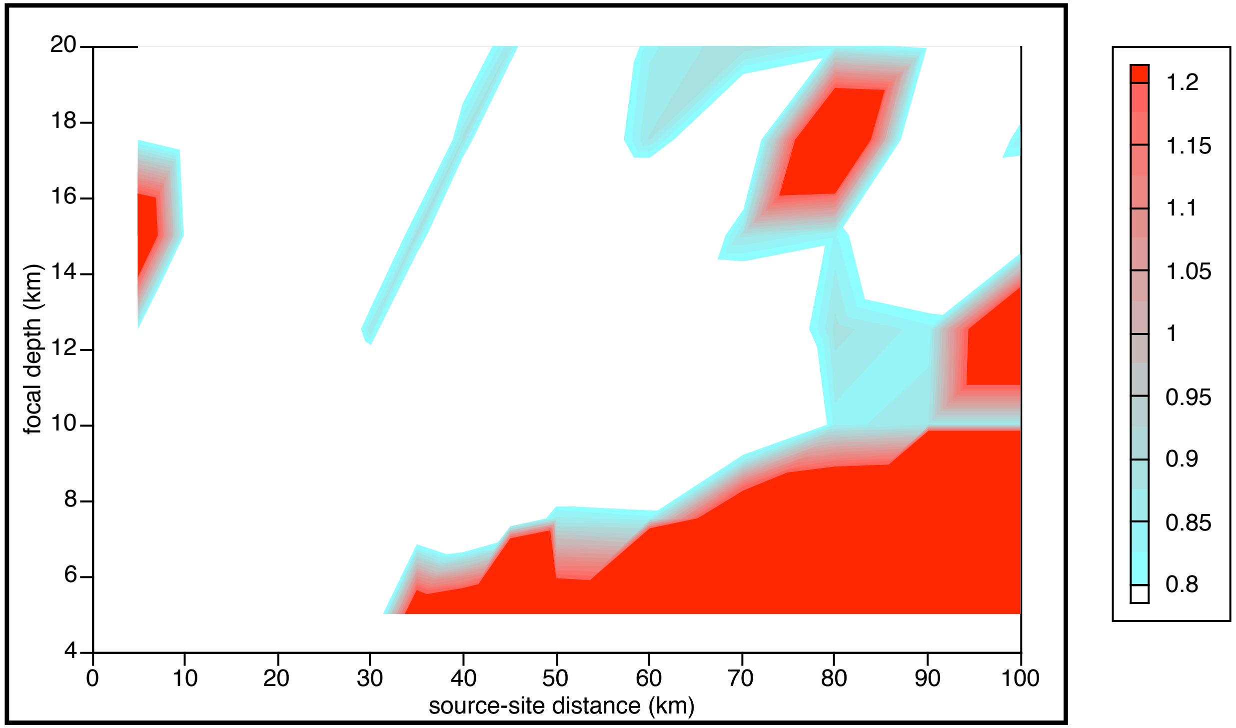


PARAMETRIC STUDY 2 - Fp towards 1Hz

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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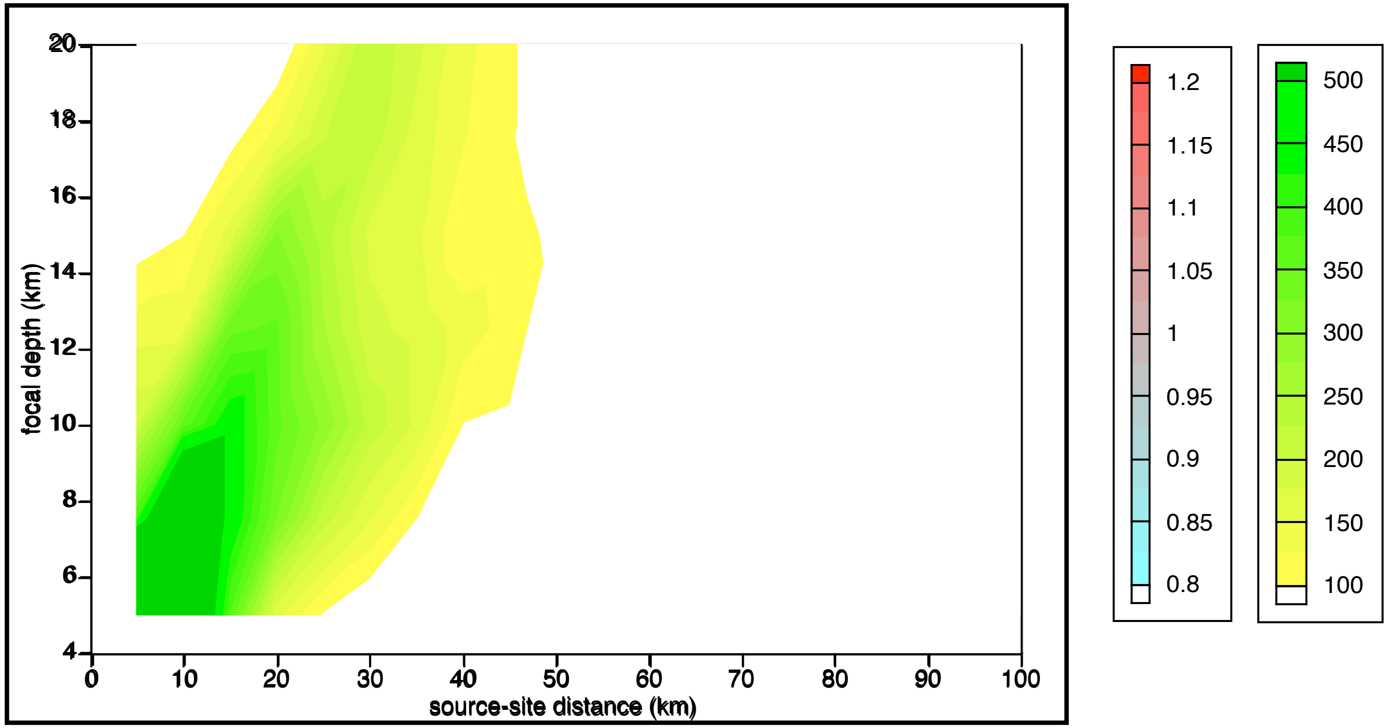

The results show that, in order to reach a relevant value of PGA (e.g. greater than 0.1g) in the desired period range (i.e. 0.8-1.2 s), an alternative and suitable configuration is a source 12 km deep at an epicentral distance of 30 km.

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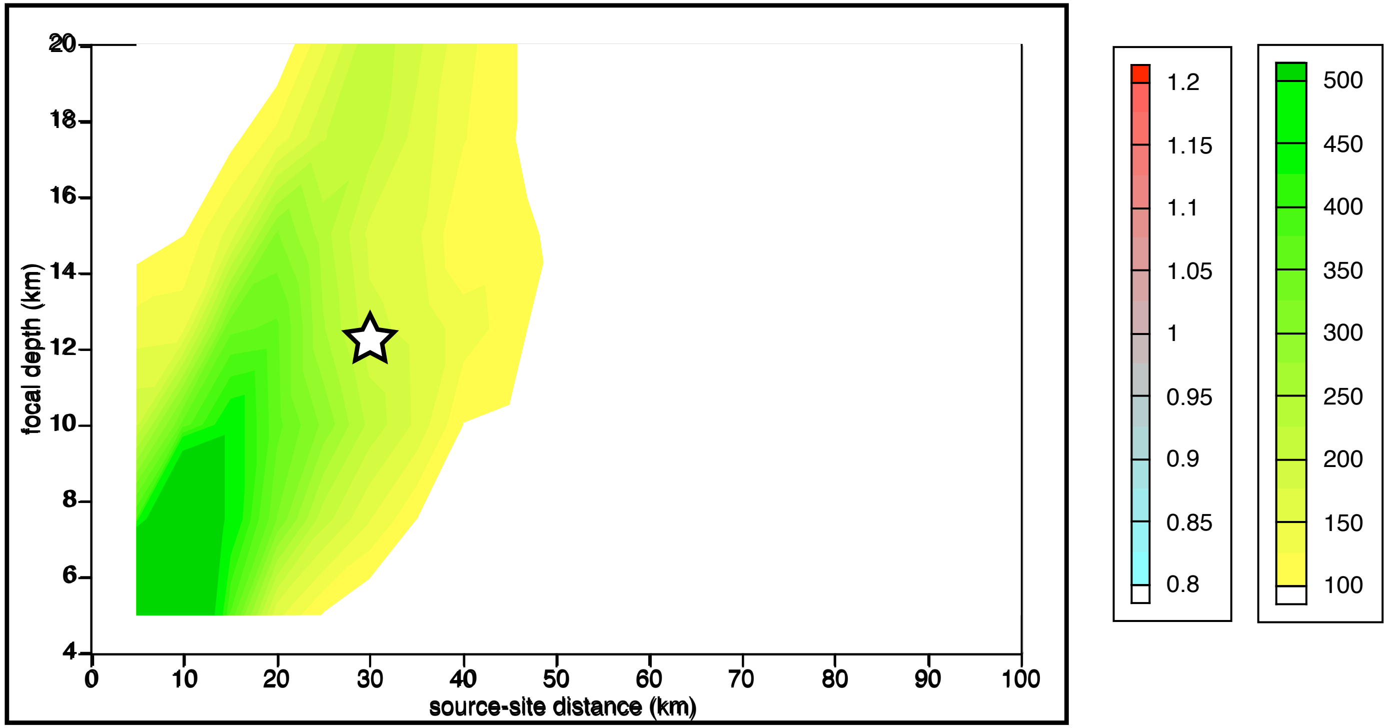

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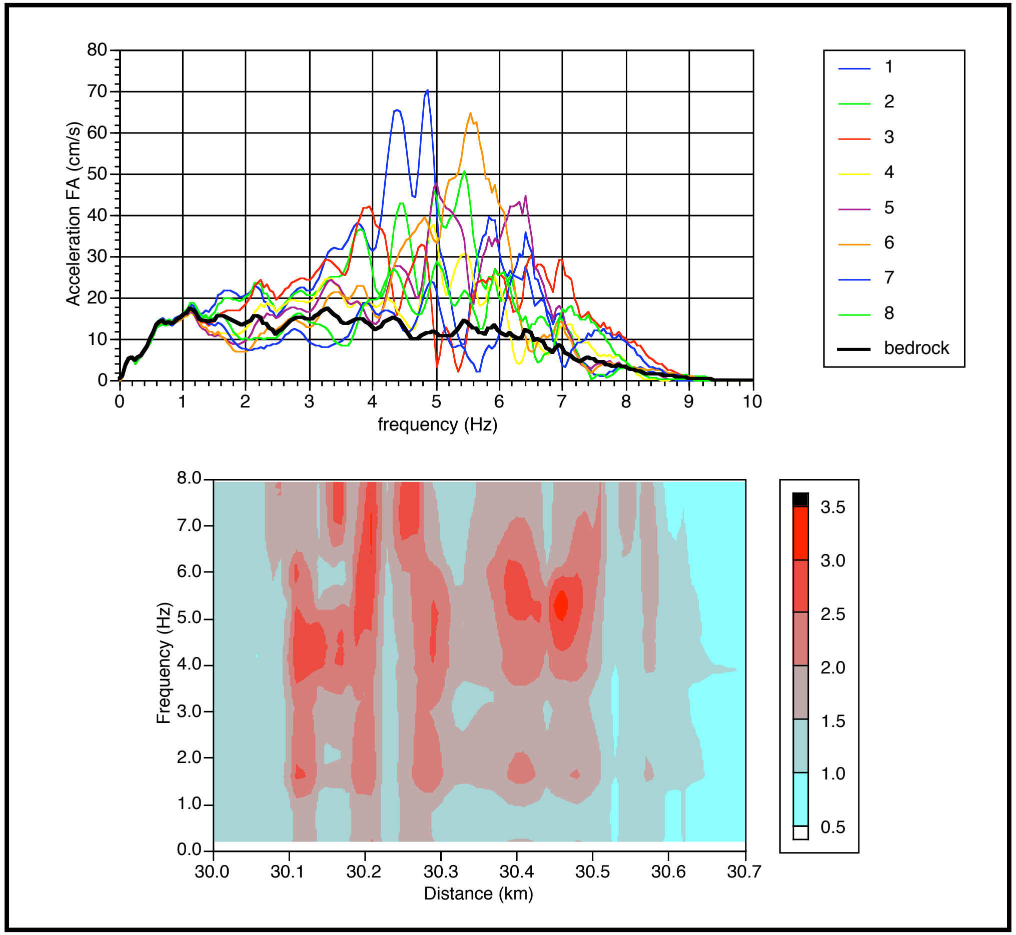
Parametric study 2 - FS & RSR



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

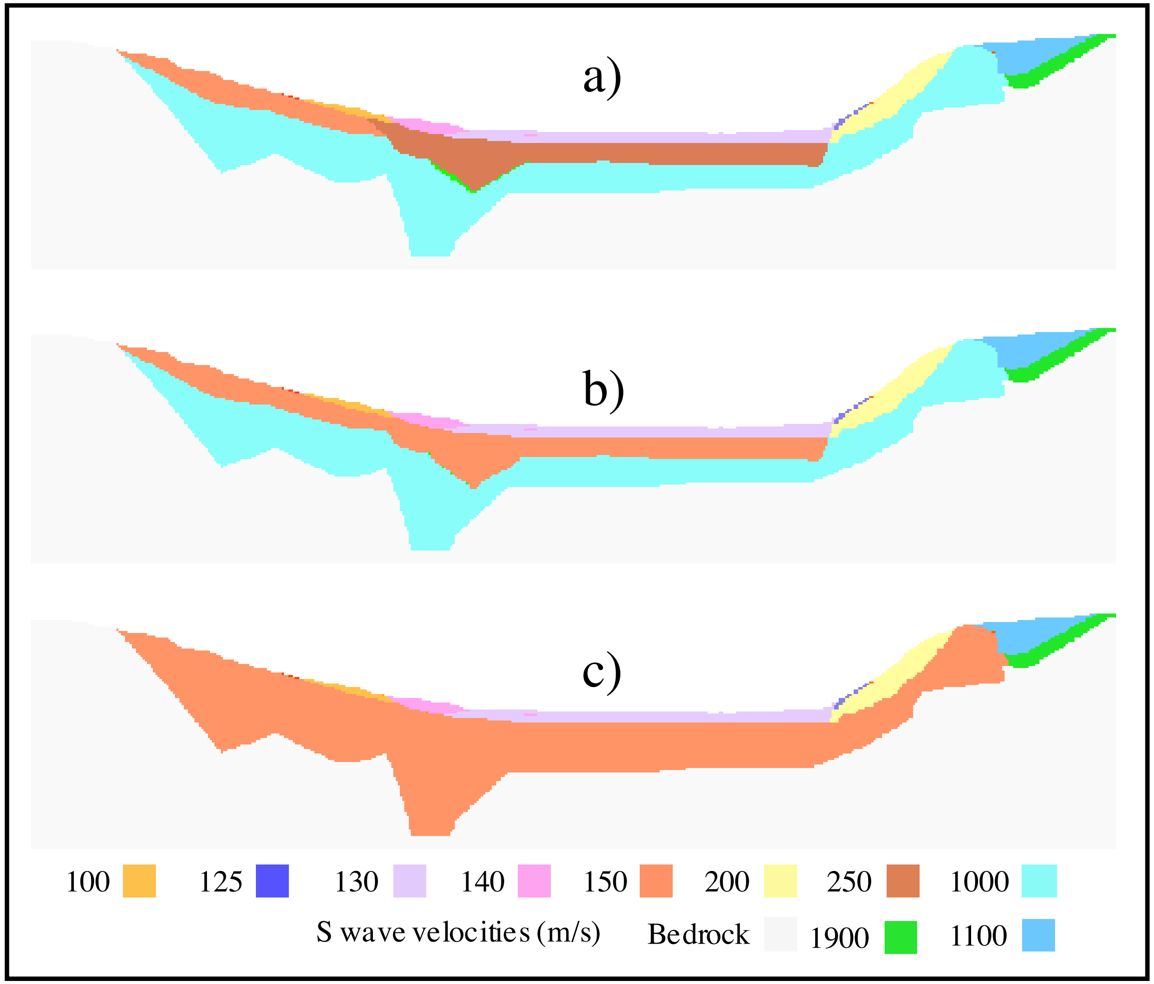
Outline

Seismic input for a critical facility

Parametric studies

- Focal mechanism
- Site effects
- Directivity

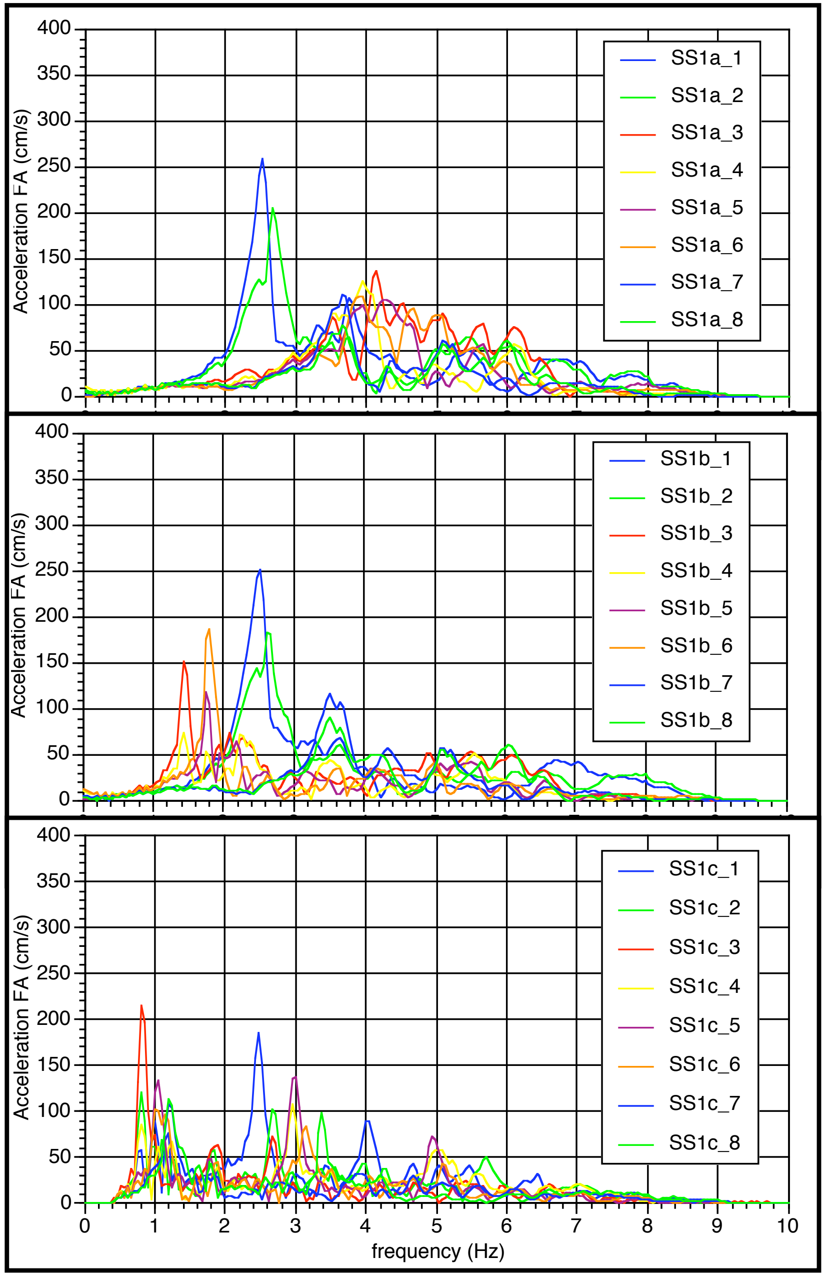
Parametric study 3 - LMp towards 1Hz



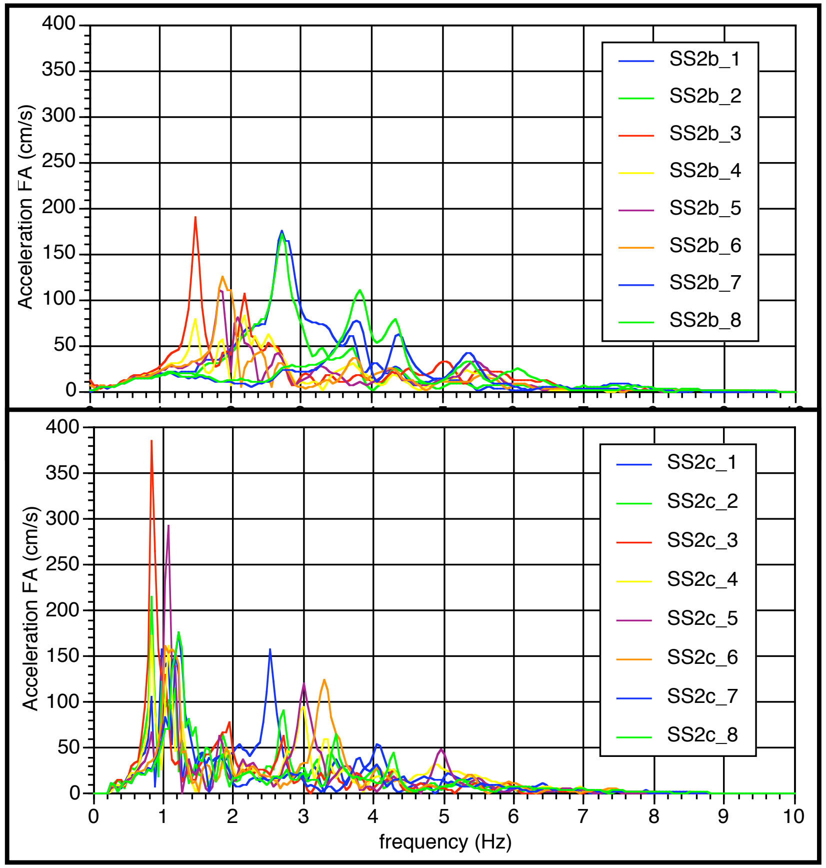
Local geotechnical models of Warth bridge section obtained **lowering successively the S-wave velocities of the uppermost units**

Fourier Amplitude spectra

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



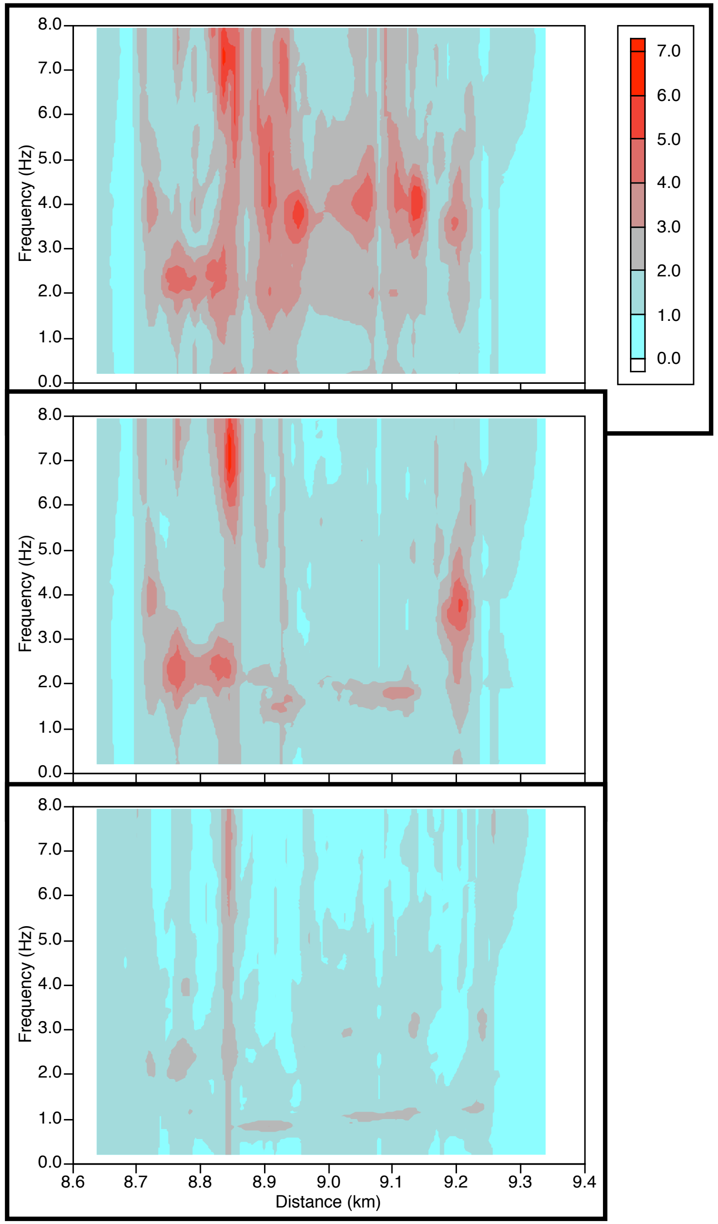
M=6.5; d=30.0km; h=12km



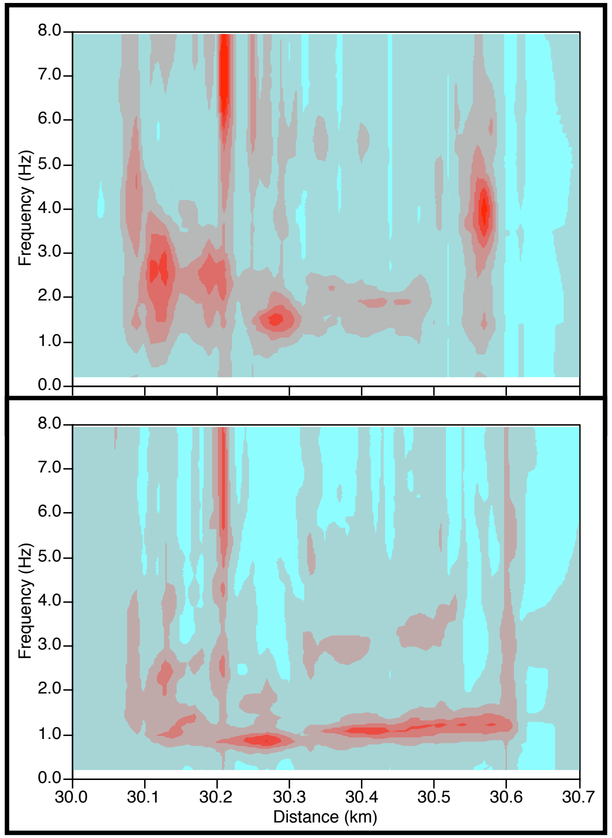
Parametric study 3 - LM

Site response estimation

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

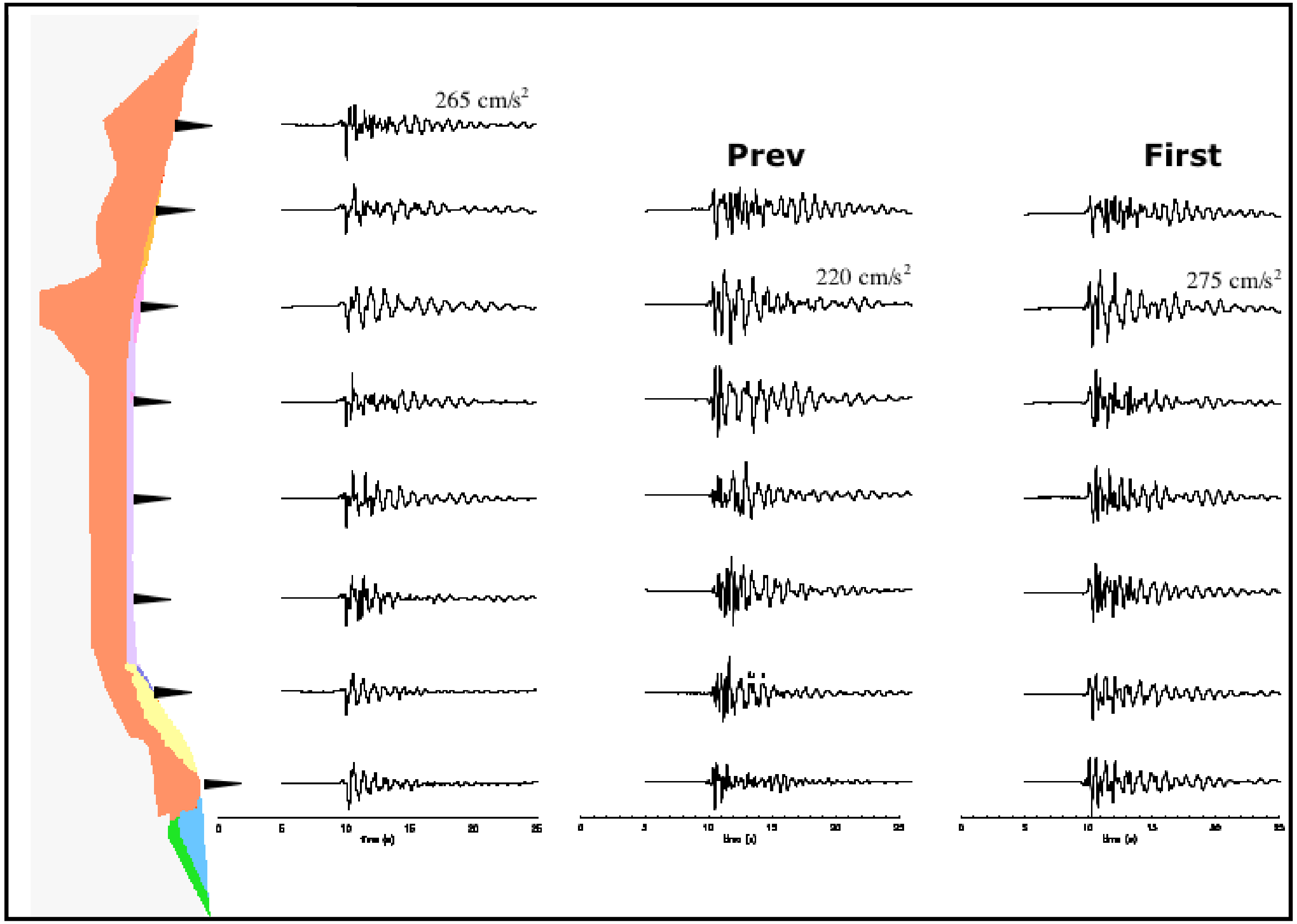


M=6.5; d=30.0km; h=12km



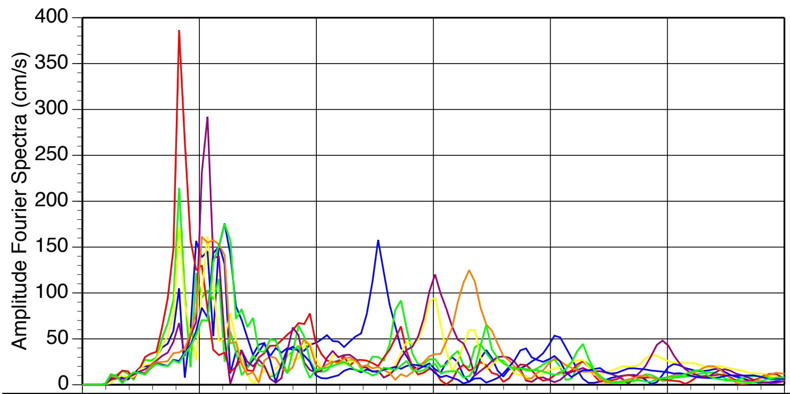
Parametric study 3 - LM

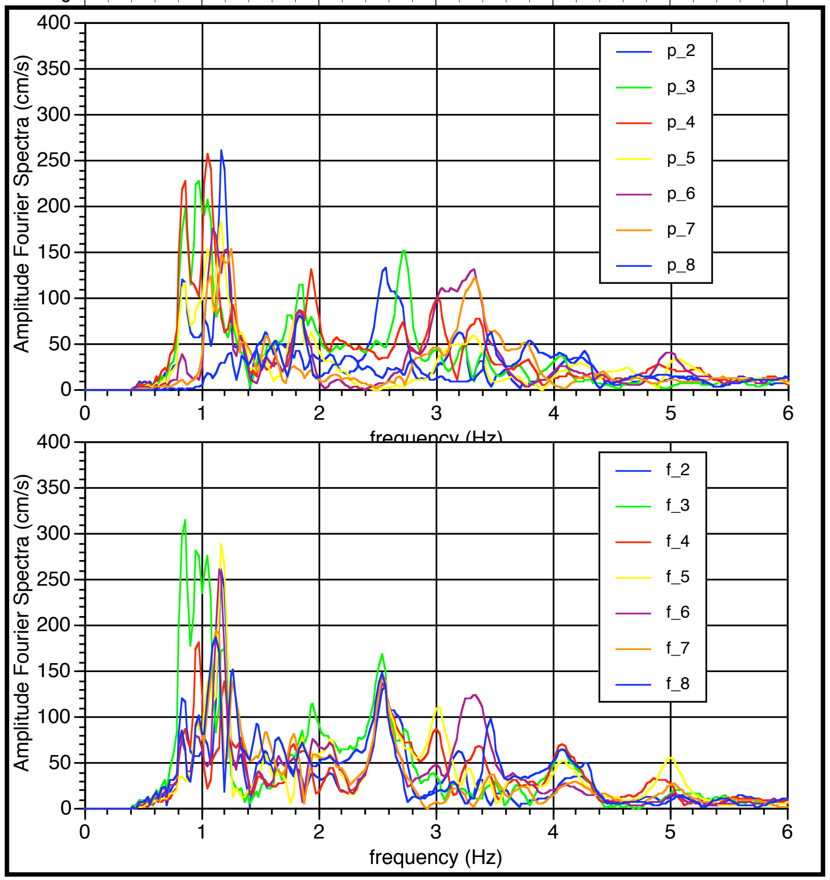
Synthetic accelerations and diffograms



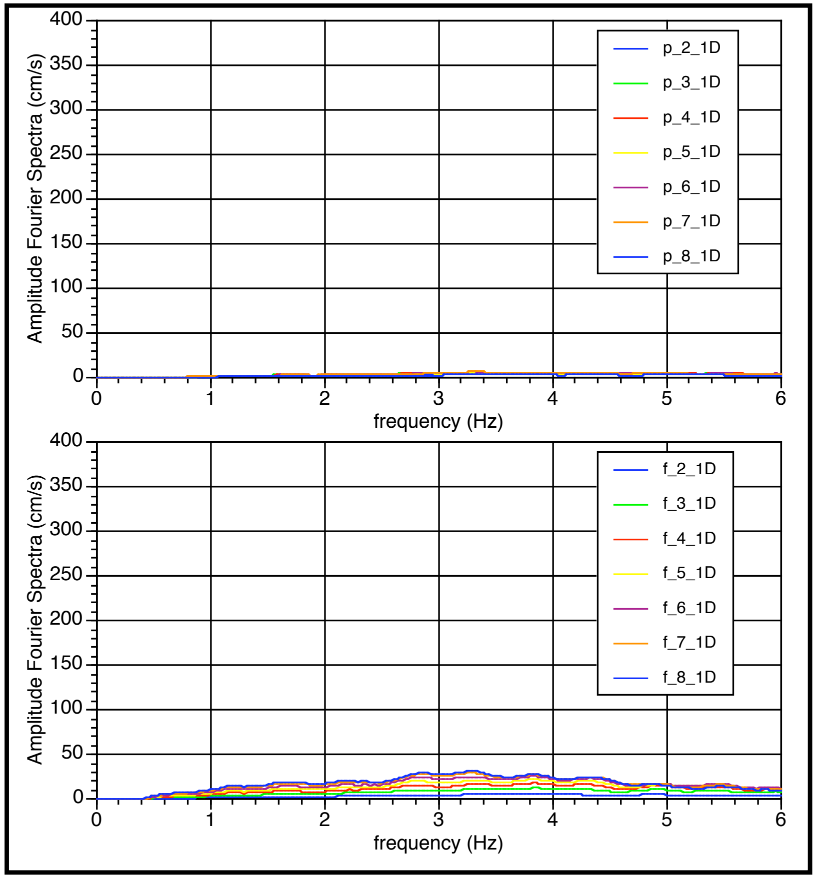
Case study

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

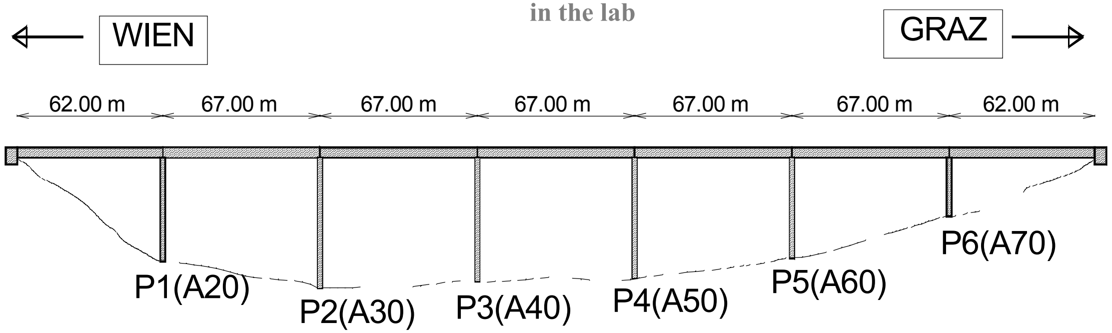
Physical piers A40 & A70 in the lab

Numerical models for the substructured piers A20, A30

Numerical models for the substructured piers A50, A60

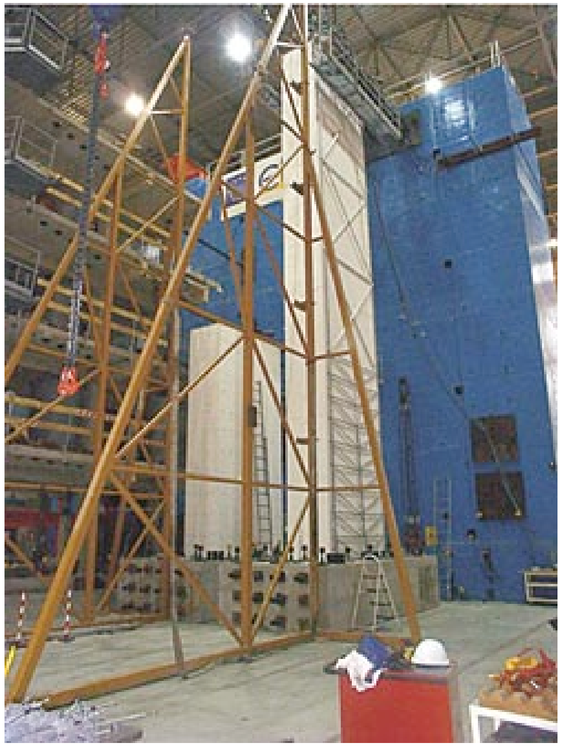
Numerical model for the deck and PSD master

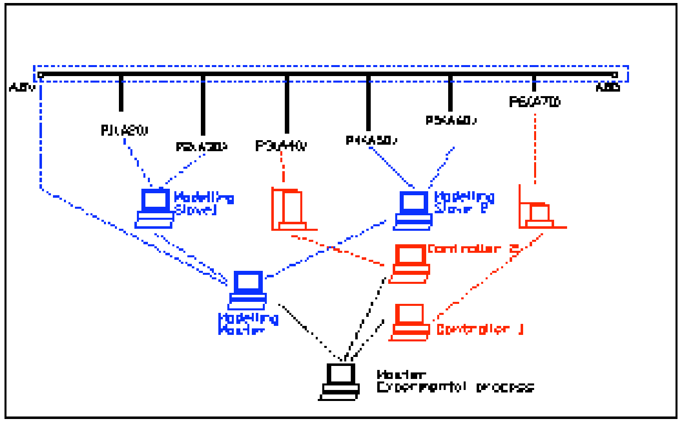
Master experimental process



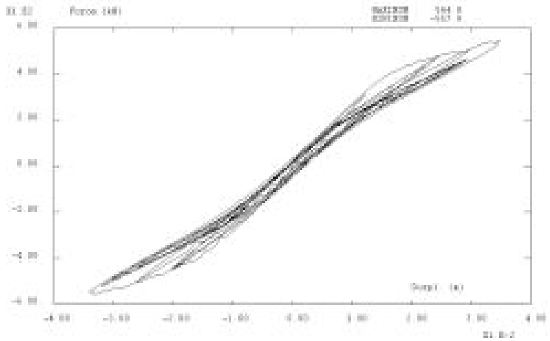
Warth Bridge

Implementation of PSD tests



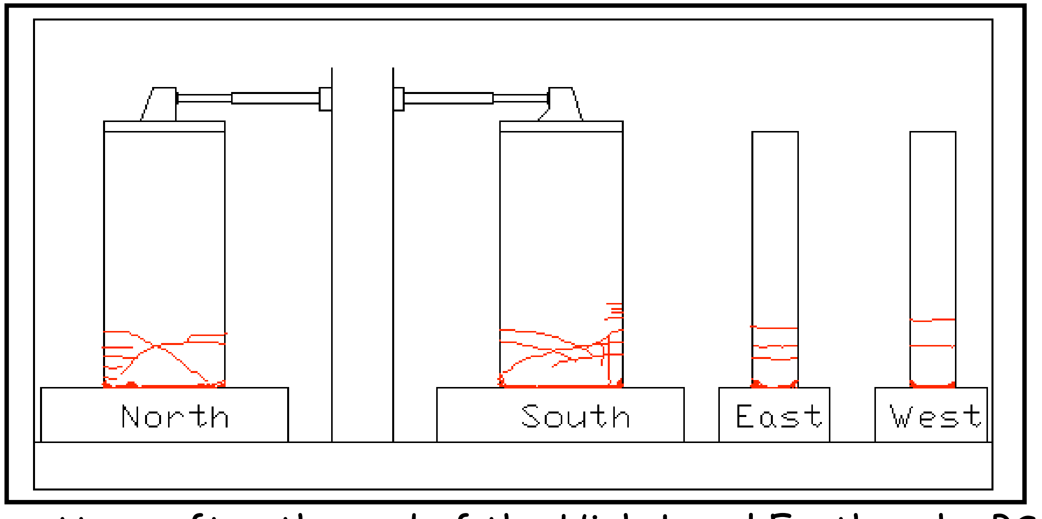


(a) physical piers in the lab, (b), schematic representation
(c) workstations running the PSD algorithm and controlling the test



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



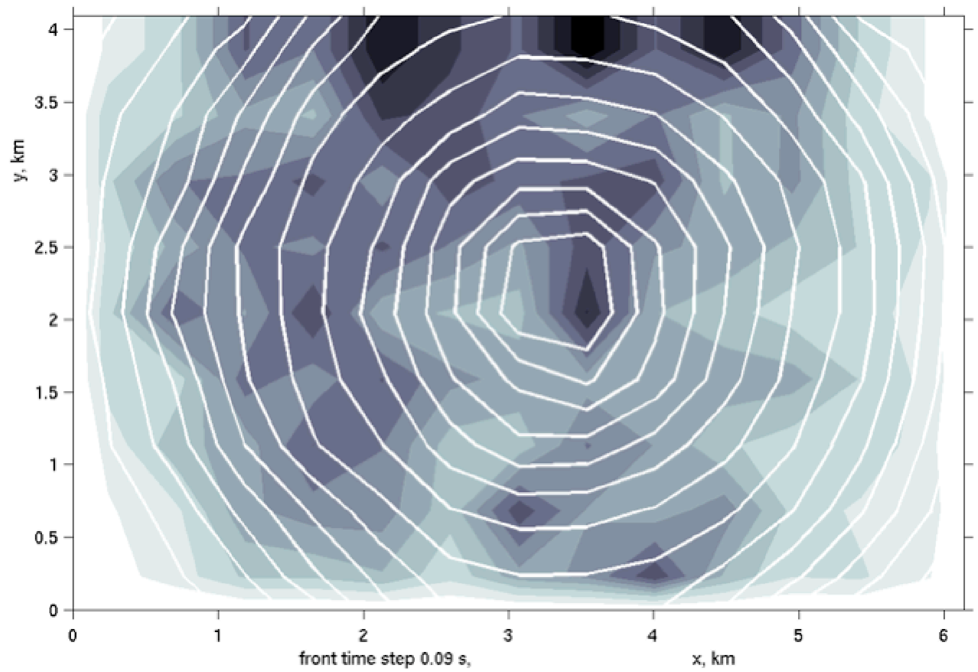
Damage pattern after the end of the High-Level Earthquake PSD test, short pier A70.

Outline

Seismic input for a critical facility

- Parametric studies
  - Focal mechanism
  - Site effects
  - Directivity

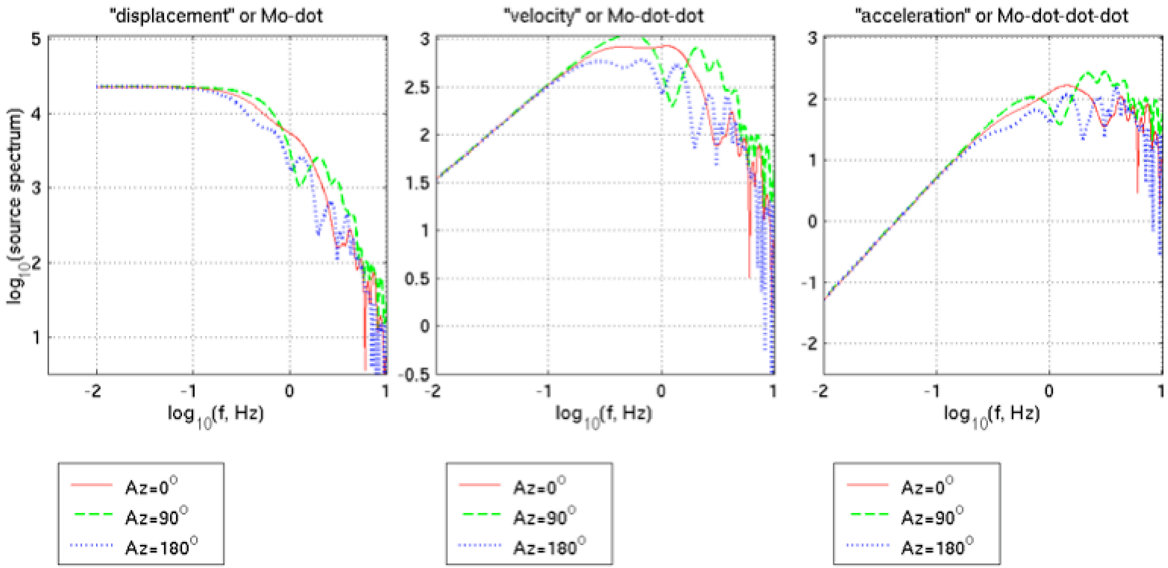
Parametric study 4 - ESp towards directivity



Parametric study 4 - ES

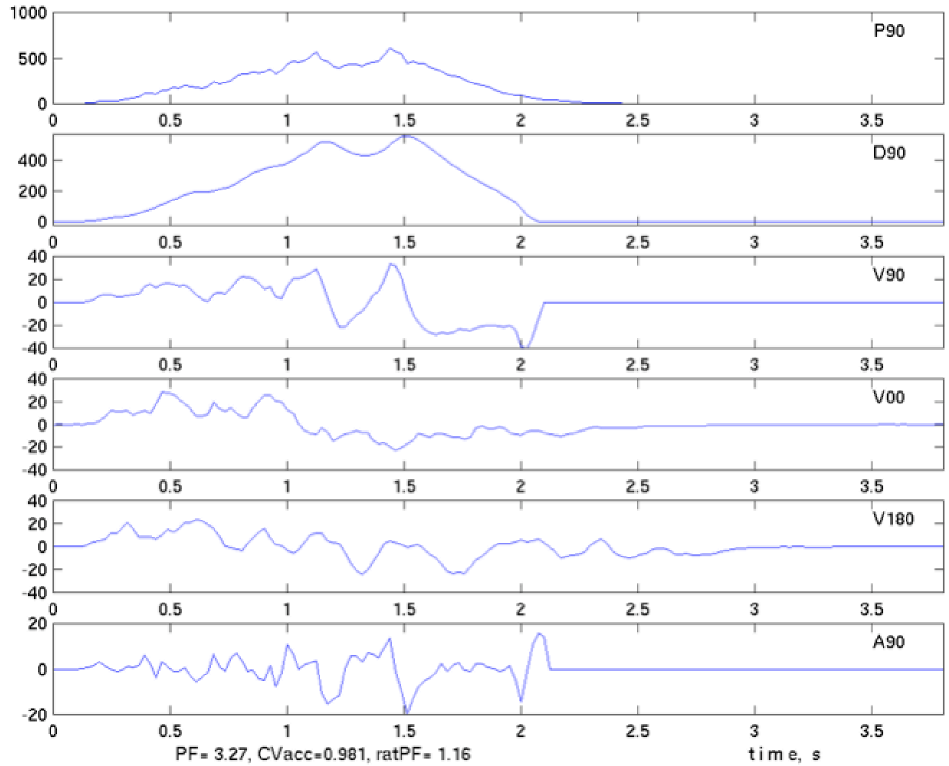
Rupture model: bilateral at 3 positions

Parametric study 4 - ESp towards directivity



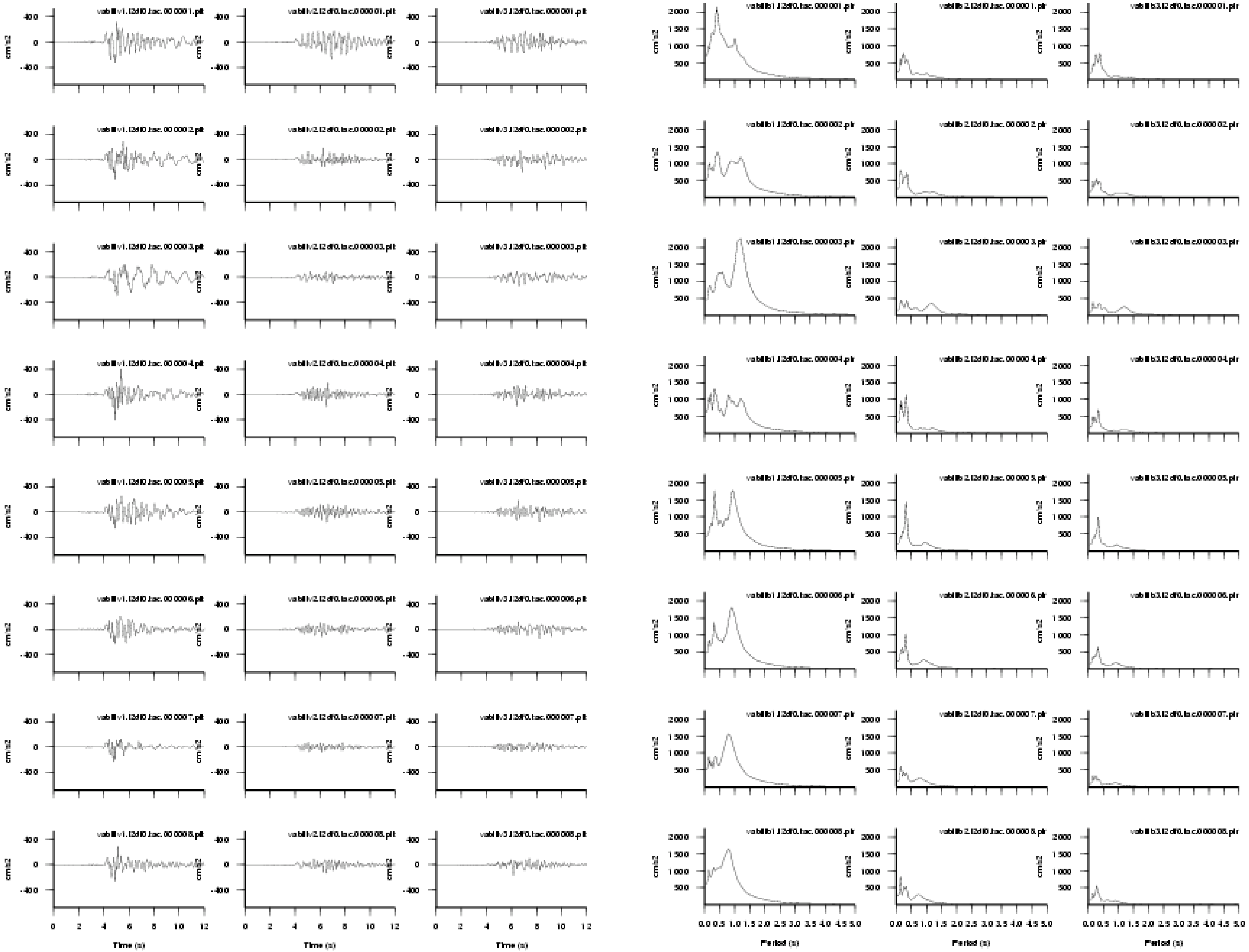
Rupture model: bilateral at 3 positions

Parametric study 4 - ESp towards directivity



Rupture model: bilateral at 3 positions

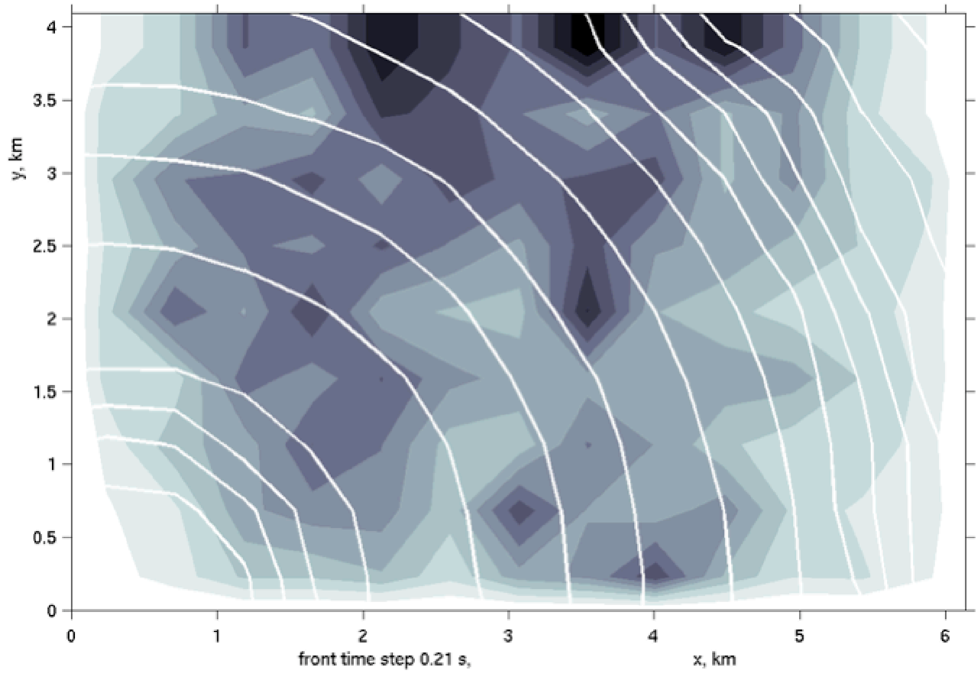
Parametric study 4 - ESp towards directivity



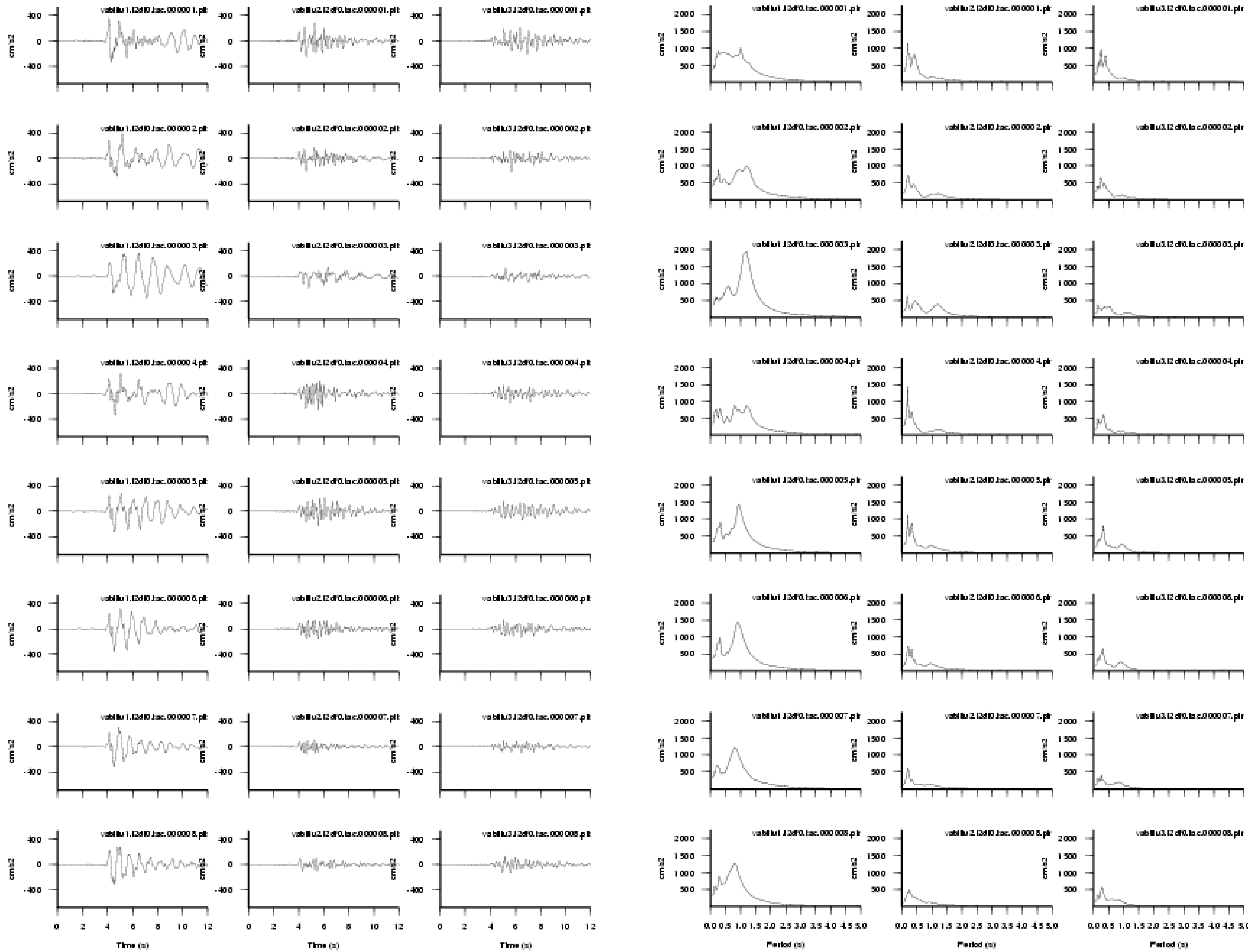
Parametric study 4 - ES

Rupture model: bilateral at 3 positions

Parametric study - ESp towards directivity



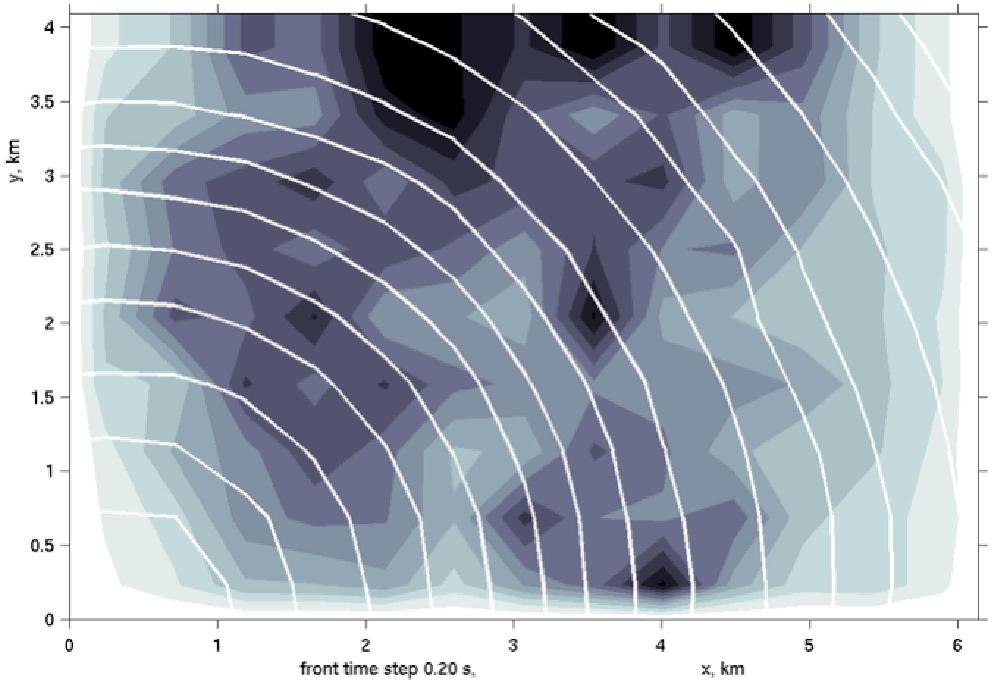
Parametric study - ESp towards directivity



Parametric study 4 - ES

Rupture model: unilateral at 3 positions

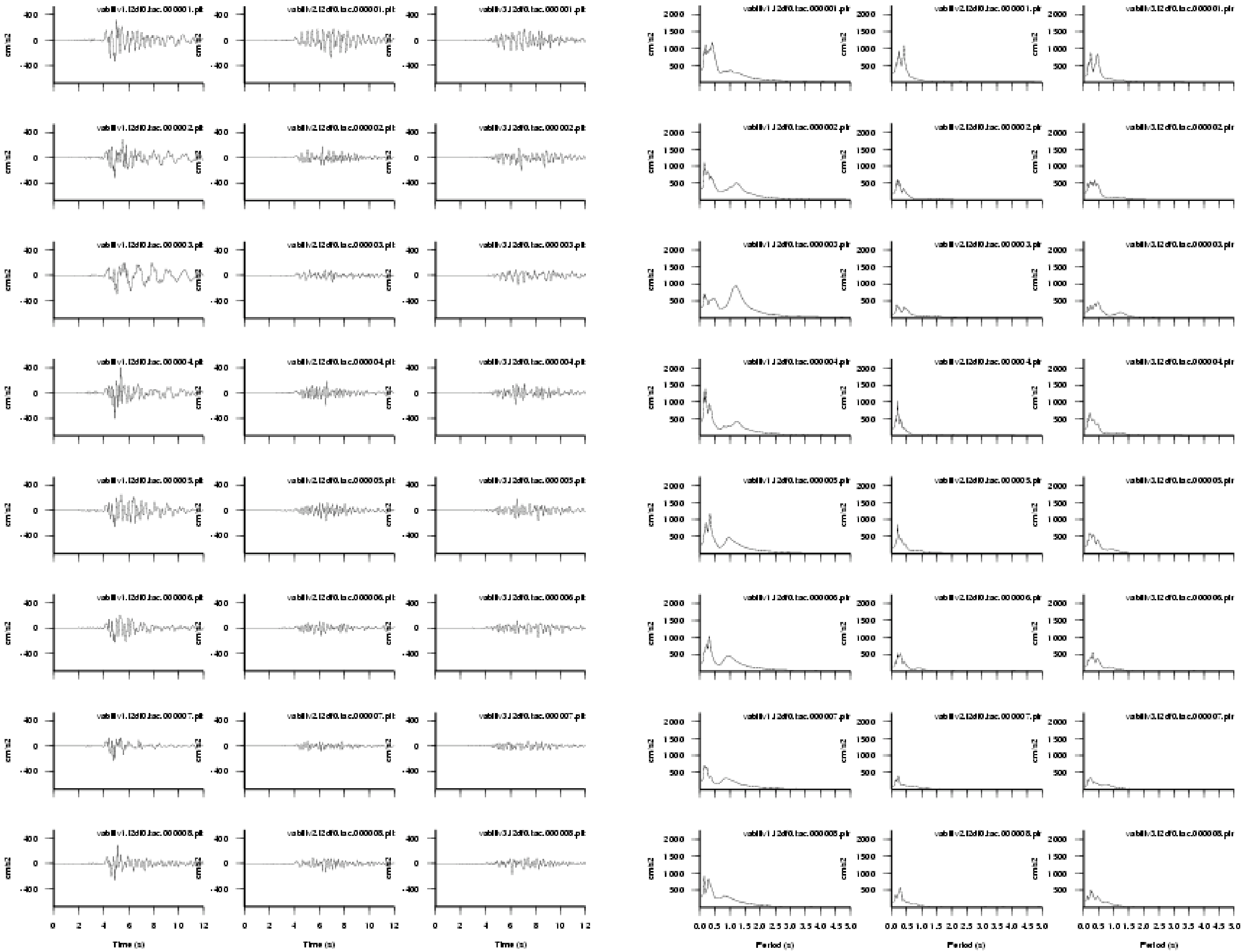
Parametric study - ESp towards directivity



Parametric study 4 - ES

Rupture model: un. different v_r at 3 positions

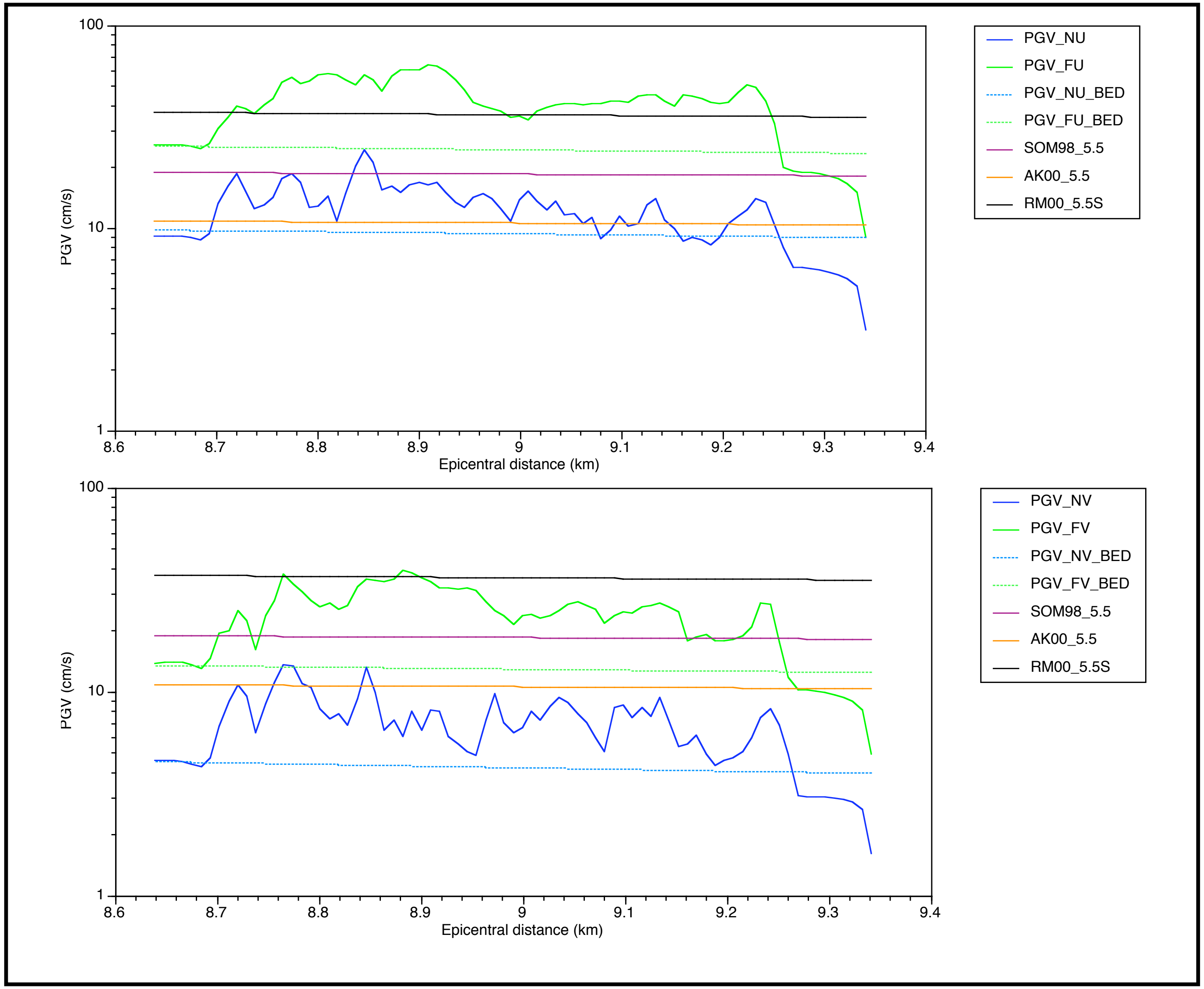
Parametric study - ESp towards directivity



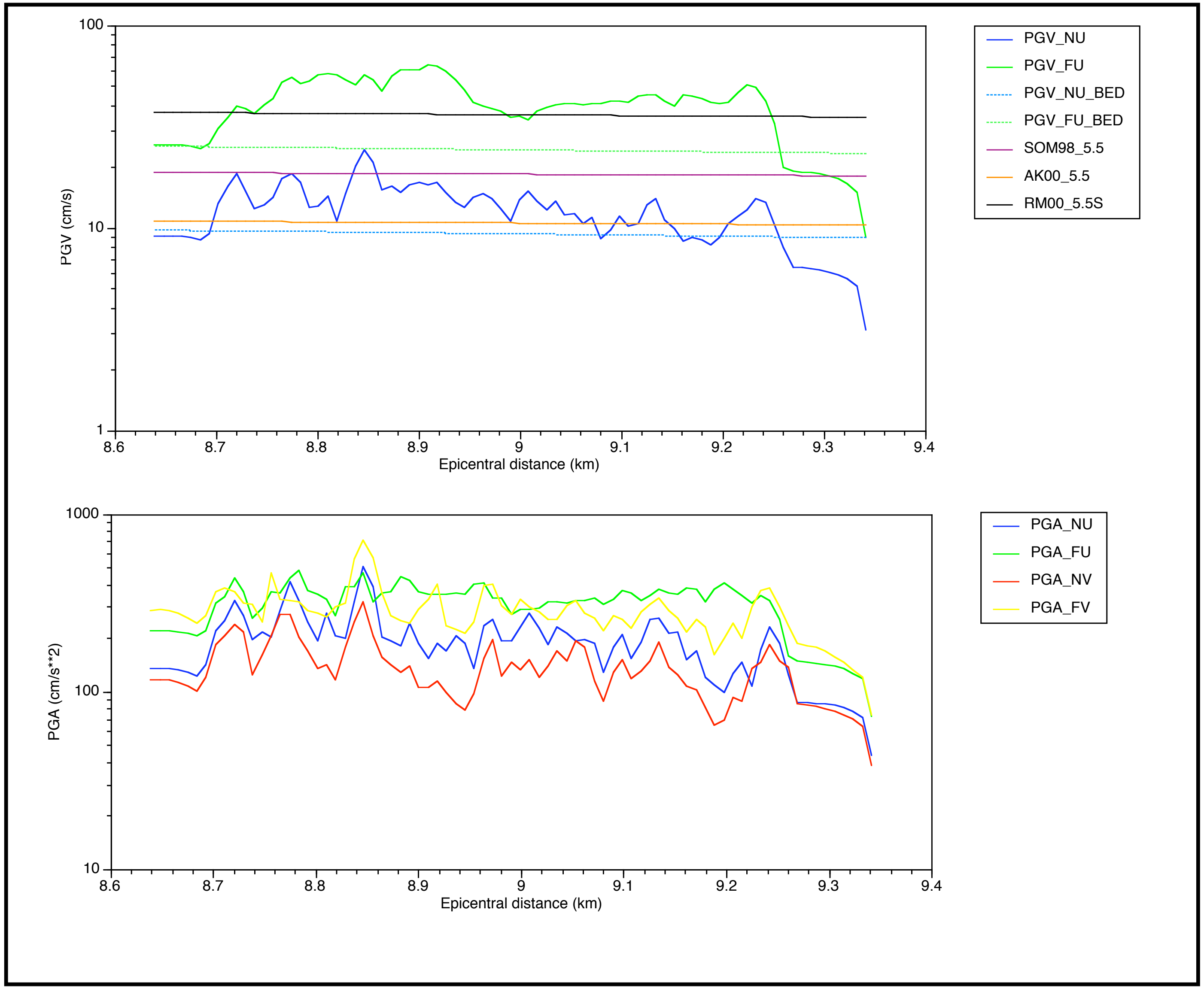
Parametric study 4 - ES

Rupture model: un. different v_r at 3 positions

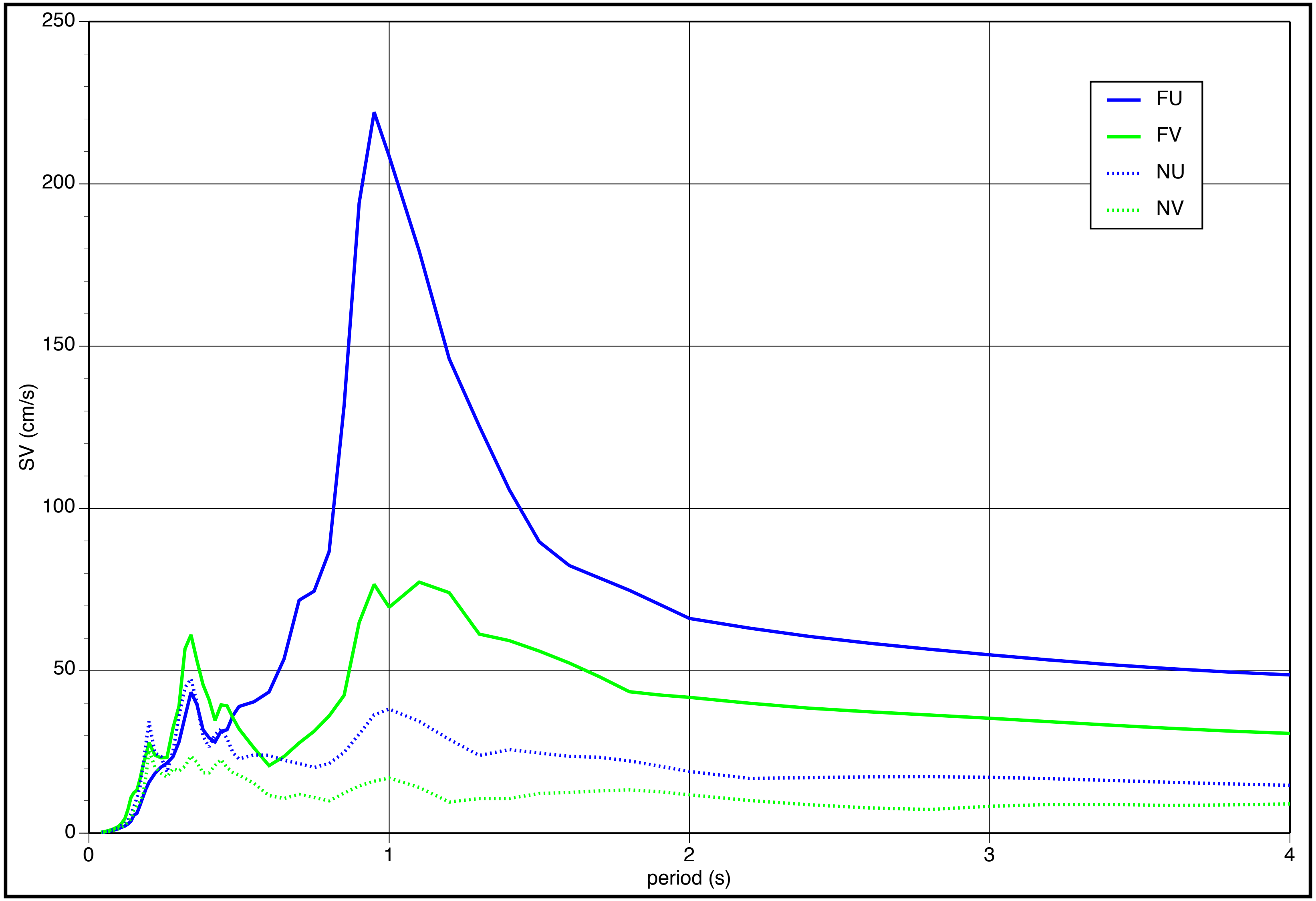
PGV - PGA and directivity



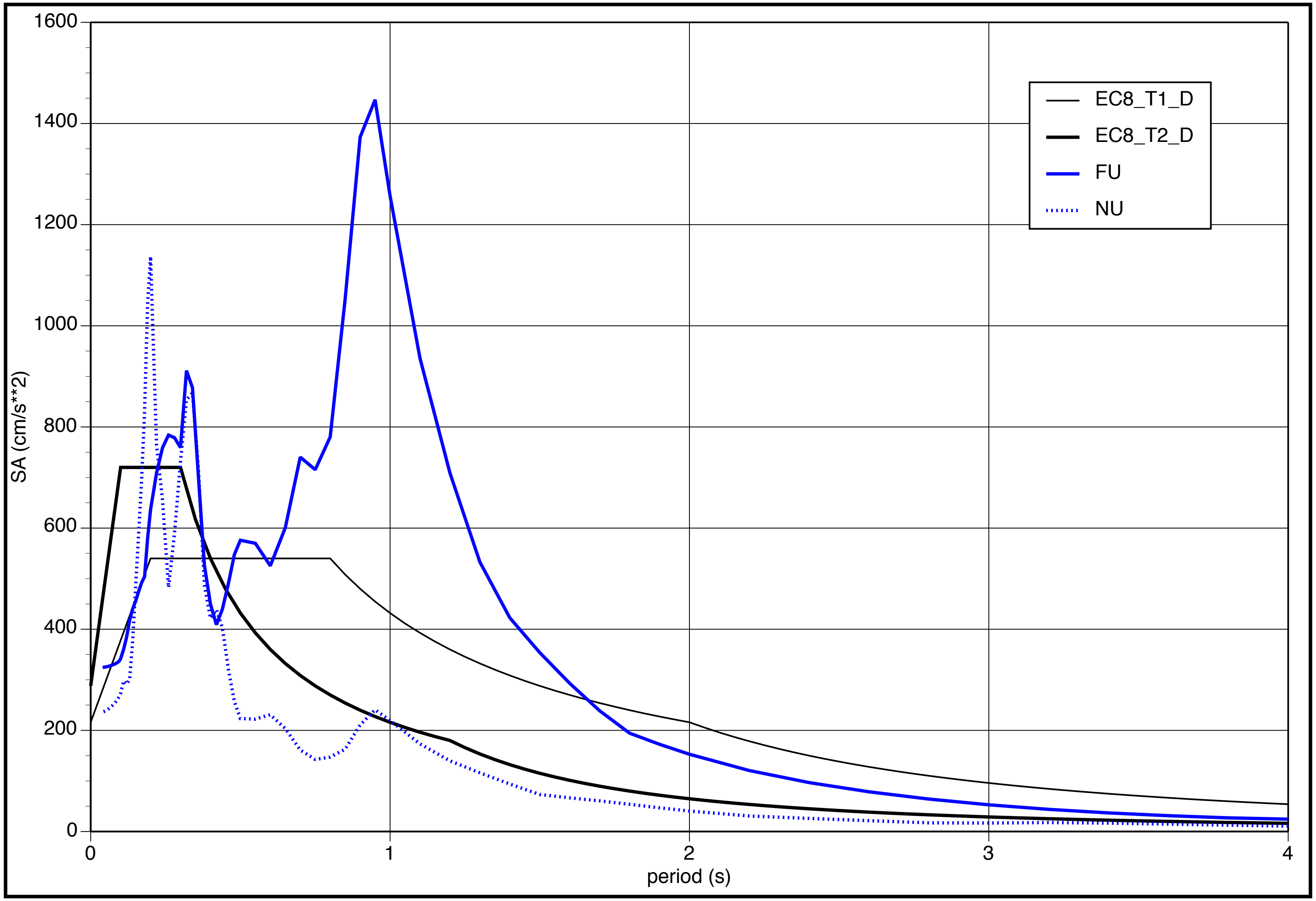
PGV - PGA and directivity



Parametric study 4 - ESp towards directivity



Parametric study 4 - ESp towards directivity



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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.