The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2167-34

Advanced School on Direct and Inverse Problems of Seismology

27 September - 8 October, 2010

Seismic waves physics:
a (partially) guided tour

Fabio ROMANELLI
Dept. of Geosciences
University of Trieste/ICTP SAND Group
Trieste

The Abdus Salam International Centre for Theoretical Physics

Advanced School on
Direct and Inverse Problems of Seismology

Seismic waves physics: a (partially) guided tour

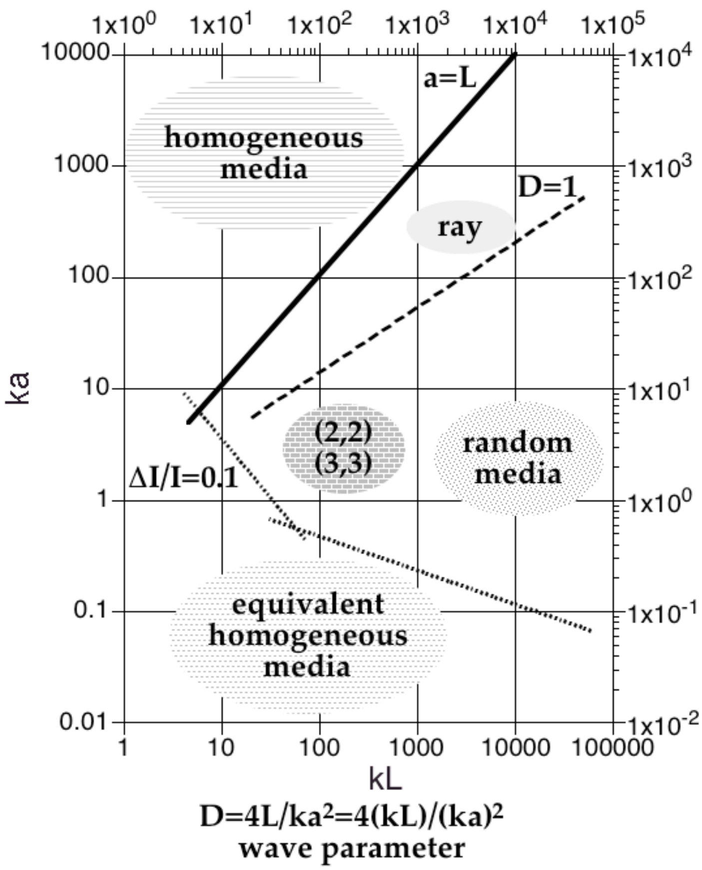
Fabio ROMANELLI

Dept. of Geosciences - Università degli studi di Trieste

SAND Group - ICTP

romanel@units.it

Road map



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 physics

Basic physical concepts

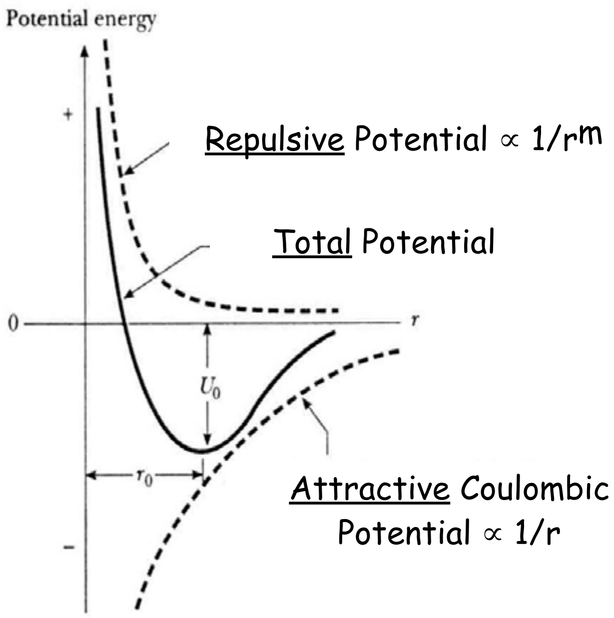
What is a wave?
Discrete and continuous models
Born of wave equation
Dispersion

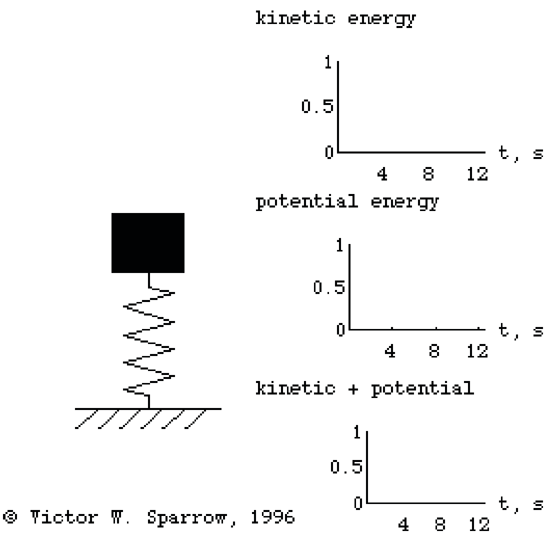
Basic physical concepts 2

PDE: Poisson, diffusion and wave equation
Scattering and diffusion

What is a **wave**?

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

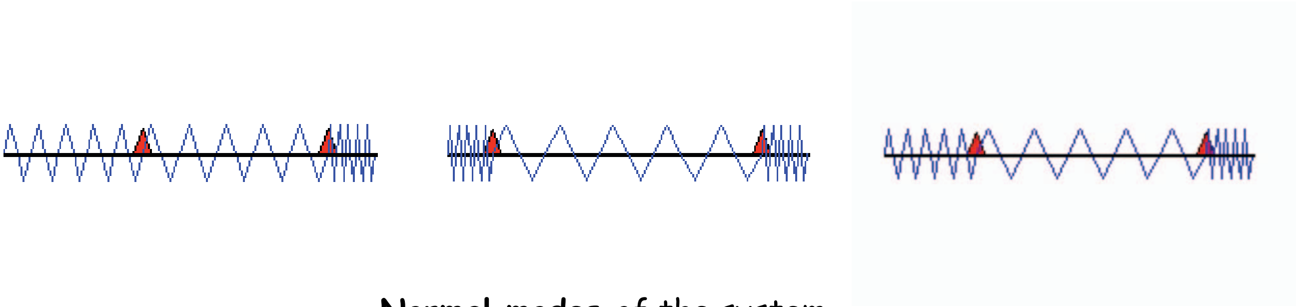




What is a **wave?** - 2

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

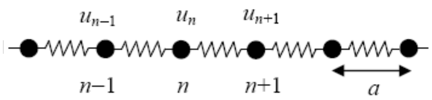
Coupling of harmonic oscillators → the disturbances can **propagate**, **superpose** and **stand**



Normal modes of the system

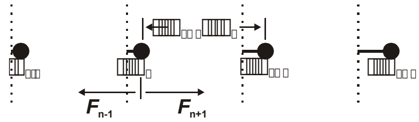
Monoatomic **1D lattice**

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. 3 types of wave motion are possible:
2 transverse, 1 longitudinal (or compressional). For 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

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

A similar equation can 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.

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

Dispersion
- discreteness
- stiffness
- geometry
- boundaries

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

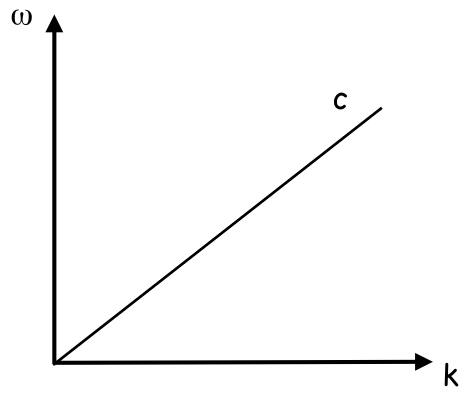
$$\left(\frac{\partial^2}{\partial x^2} - \frac{\mu}{F}\frac{\partial^2}{\partial t^2}\right)\phi = 0 \Rightarrow \quad \omega = \pm kc$$

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 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(λ). 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):

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

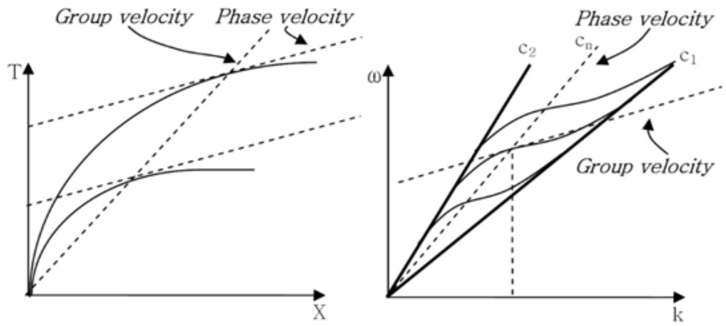
and thus in the normal dispersion case

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 examples

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

Dispersion in lattices

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

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

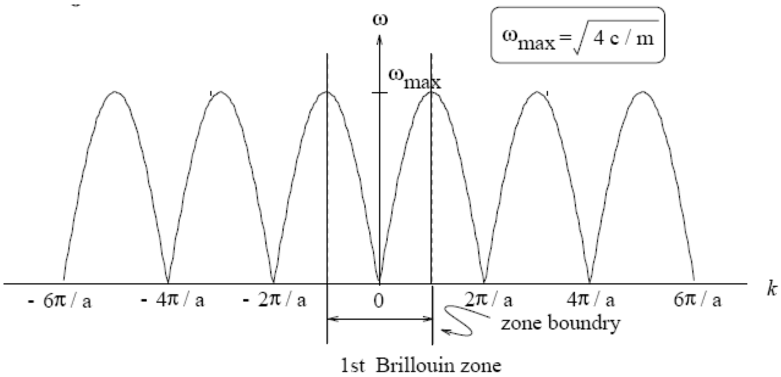
This equation can be further simplified by canceling the common factor e^{ikna} , which leads to

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

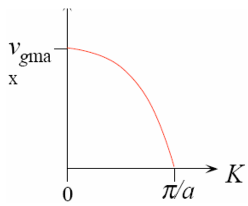
We find thus the dispersion relation for the frequency:

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

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



Monatomic 1D lattice – continued



Phase and group velocity. The phase velocity is defined by

$v_p = \dfrac{\omega}{k}$ and the group velocity by $v_g = \dfrac{d\omega}{dk}$

The physical distinction between the two velocities is that v_p is the velocity of propagation of the plane wave, whereas the v_g is the velocity of the propagation of the wave packet. The latter is the velocity for the propagation of energy in the medium. For the particular dispersion relation $\omega = \sqrt{\frac{4C}{M}}\left|\sin\frac{ka}{2}\right|$ the group velocity is given by $v_g = \sqrt{\frac{Ca^2}{M}}\cos\frac{ka}{2}$.
Apparently, the group velocity is zero at the edge of the zone where $k = \pm \pi/a$. Here the

Long wavelength limit. The long wavelength limit implies that $\lambda >> a$. In this limit $ka << 1$.

We can then expand the sine in 'ω' and obtain for the positive frequencies: $\omega = \sqrt{\frac{C}{M}}ka.$

We see that the frequency of vibration is proportional to the wavevector. This is equivalent to the statement that velocity is independent of frequency. In this case:

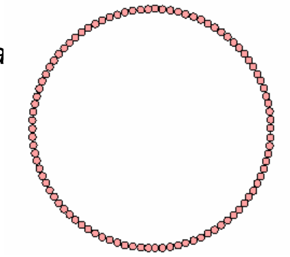
$v_p = \dfrac{\omega}{k} = \sqrt{\dfrac{C}{M}}a.$ which is consistent with the expression we obtained earlier for elastic waves.

Monatomic 1D lattice – continued

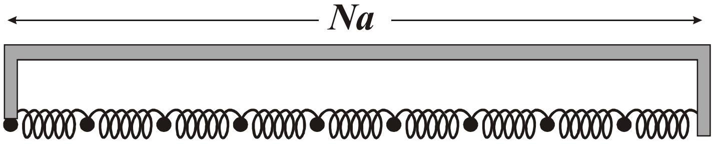
Finite chain – Born – von Karman periodic boundary condition.

Unlike a continuum, there is only a finite number of distinguishable vibrational modes. But how many?

Let us impose on the chain ends the Born – von Karman periodic boundary conditions specified as following: we simply join the two remote ends by one more spring in a ring or device in the figure below forcing atom N to interact with ion 1 via a spring with a spring constant C. If the atoms occupy sites a, $2a$, …, Na



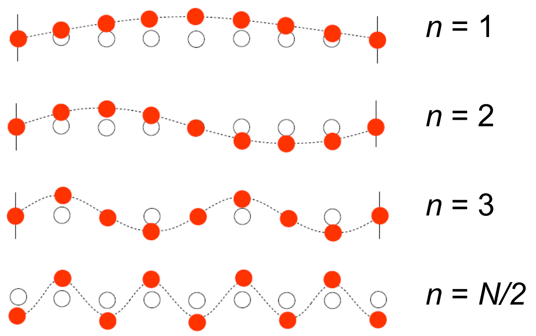
The boundary condition is $u_{N+1} = u_1$ or $u_N = u_0$.

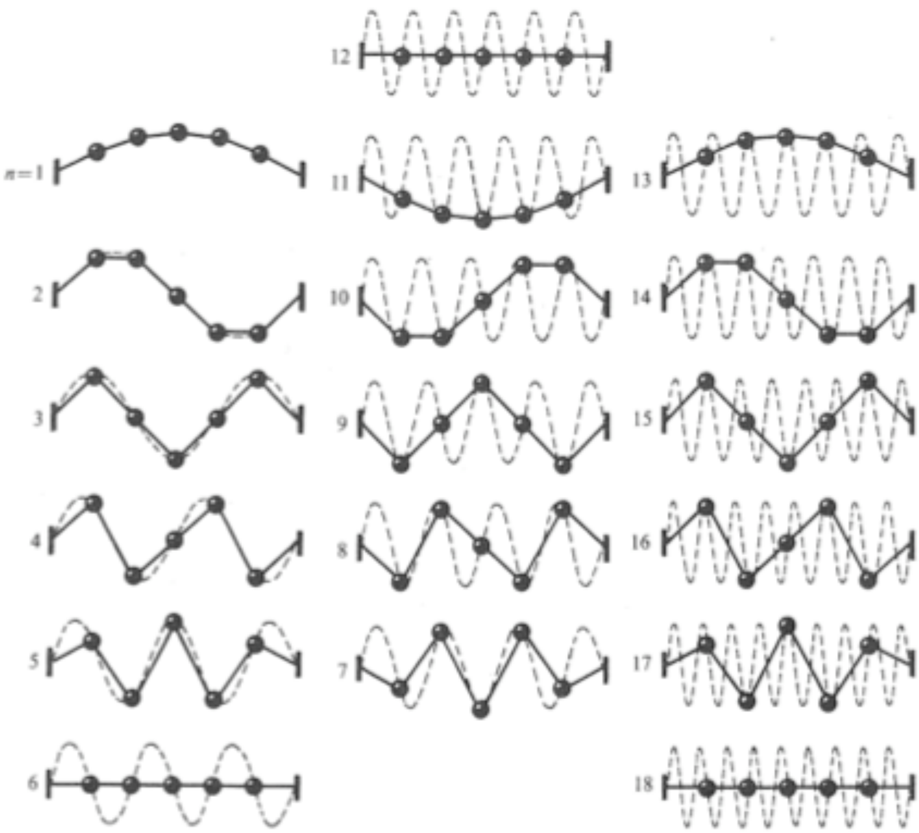


With the displacement solution of the form $u_n = A\exp[i(kna - wt)]$, the periodic boundary condition requires that $\exp(\pm ikNa) = 1$, which in turn requires 'k' to have the form:

$$k = \frac{2\pi}{a}\frac{n}{N} \quad \text{(n – an integer), and} \quad -\frac{N}{2} \le n \le \frac{N}{2}, \text{ or}$$

$$k = \pm\frac{2\pi}{Na}, \pm\frac{4\pi}{Na}, \pm\frac{6\pi}{Na}, \ldots, \pm\frac{\pi}{a} \quad (N \text{ values of } k).$$

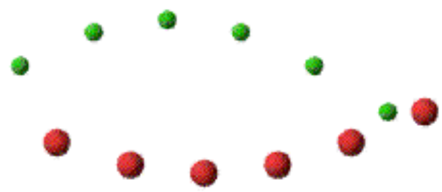




Acoustic and optical modes

Monoatomic chain
acoustic longitudinal mode

Monoatomic chain
acoustic transverse mode



Diatomic chain
acoustic transverse mode

Diatomic chain
optical transverse mode

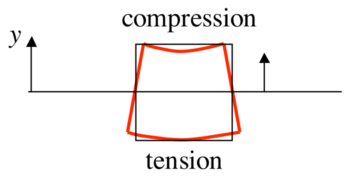
Dispersion examples

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

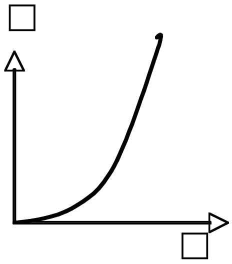
Stiffness...

☑ 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



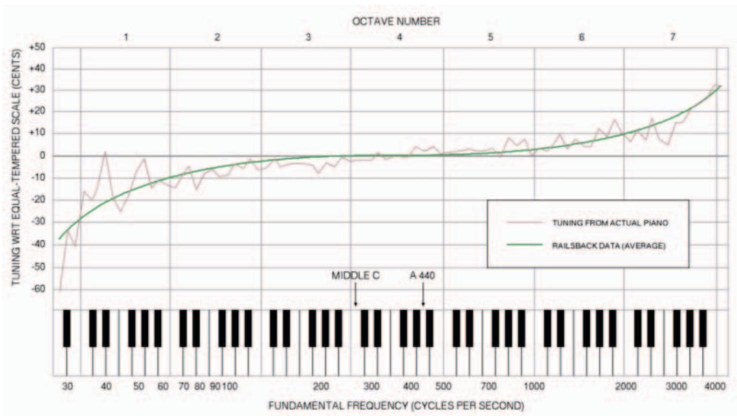
$$\left(\frac{\partial^4}{\partial x^4} - \frac{\rho A}{EI}\frac{\partial^2}{\partial t^2}\right)w = 0 \Rightarrow \omega = \pm k^2\sqrt{\frac{EI}{\rho A}}$$



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.

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



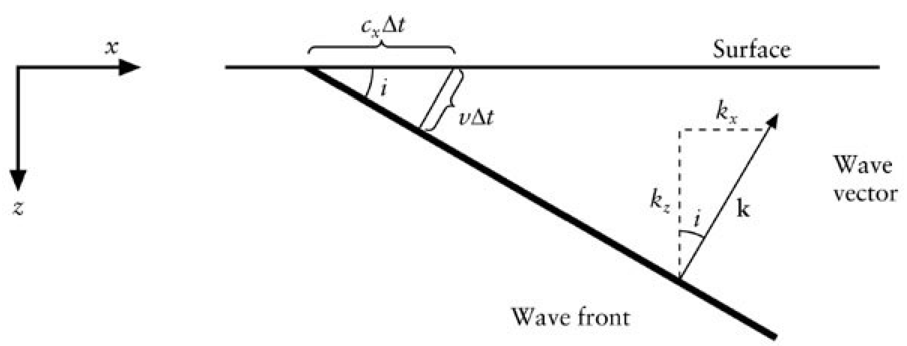
$$\Rightarrow \omega \approx \pm k\sqrt{\frac{E}{\rho}}\left(1 + \frac{1}{2}k^2\sqrt{\frac{I}{A}}\right)$$

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)!

Apparent horizontal velocity



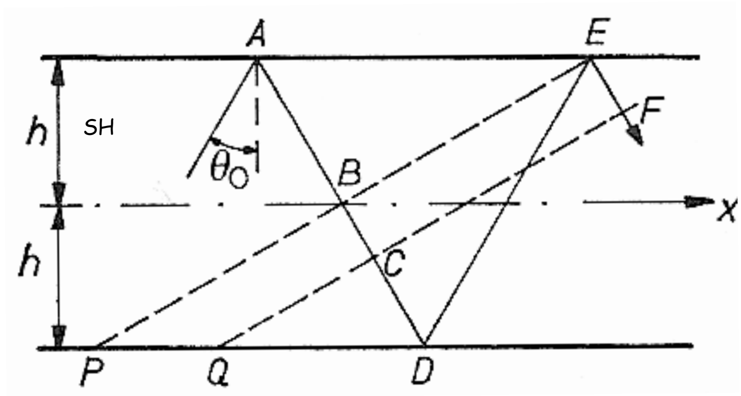
$$k_x = k\sin(i) = \omega\frac{\sin(i)}{\alpha} = \frac{\omega}{c}$$

$$k_z = k\cos(i) = \sqrt{k^2 - k_x^2} = \omega\sqrt{\left(\frac{1}{\alpha}\right)^2 - \left(\frac{1}{c}\right)^2} = \frac{\omega}{c}\sqrt{\left(\frac{c}{\alpha}\right)^2 - 1} = k_x r_\alpha$$

In current terminology, k_x is k!

SH Waves in plates: Geometry

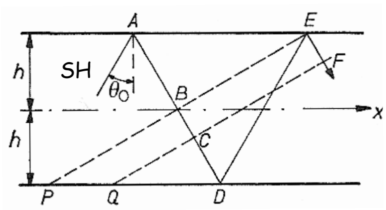
In an elastic half-space no SH type surface waves exist. Why?
Because there is total reflection and no interaction between an evanescent P wave and a phase shifted SV wave as in the case of Rayleigh waves. What happens if we have a layer delimited by two free boundaries, i.e. a homogeneous plate?



Repeated reflection in the layer allow interference between incident and reflected SH waves: SH reverberations can be totally trapped.

SH waves: trapping

$$u_y = A\exp[i(\omega t + \omega\eta_\beta z - kx)] + B\exp[i(\omega t - \omega\eta_\beta z - kx)]$$



$$k = k_x = \frac{\omega}{c}; \quad \omega\eta_\beta = k_z = \frac{\omega}{c}\sqrt{\frac{c^2}{\beta^2} - 1} = kr_\beta$$

$$u_y = A\exp[i(\omega t + kr_\beta z - kx)] + B\exp[i(\omega t - kr_\beta z - kx)]$$

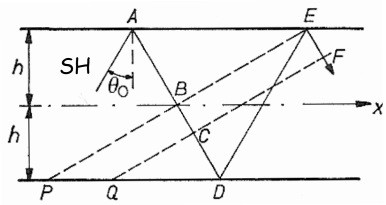
The formal derivation is very similar to the derivation of the Rayleigh waves. The conditions to be fulfilled are: free surface conditions

$$\sigma_{zy}(0) = \mu \left.\frac{\partial u_y}{\partial z}\right|_0 = ikr_\beta\mu\left\{A\exp[i(\omega t - kx)] - B\exp[i(\omega t - kx)]\right\} = 0$$

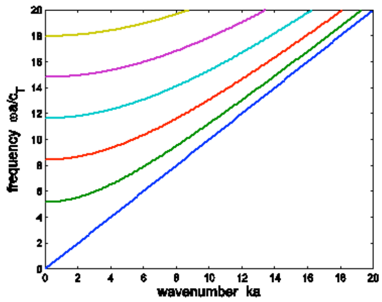
$$\sigma_{zy}(2h) = \mu \left.\frac{\partial u_y}{\partial z}\right|_{2h} = ikr_\beta\mu\left\{A\exp[i(\omega t + kr_\beta 2h - kx)] - B\exp[i(\omega t - kr_\beta 2h - kx)]\right\} = 0$$

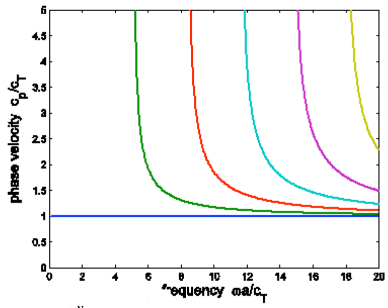
SH waves: eigenvalues...

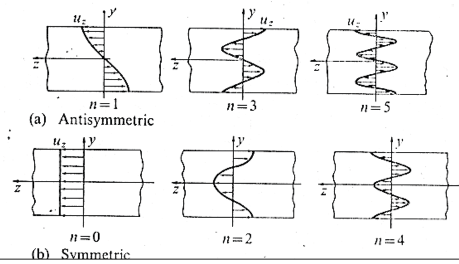
that leads to: $kr_\beta 2h = n\pi$ with n=0,1,2,...



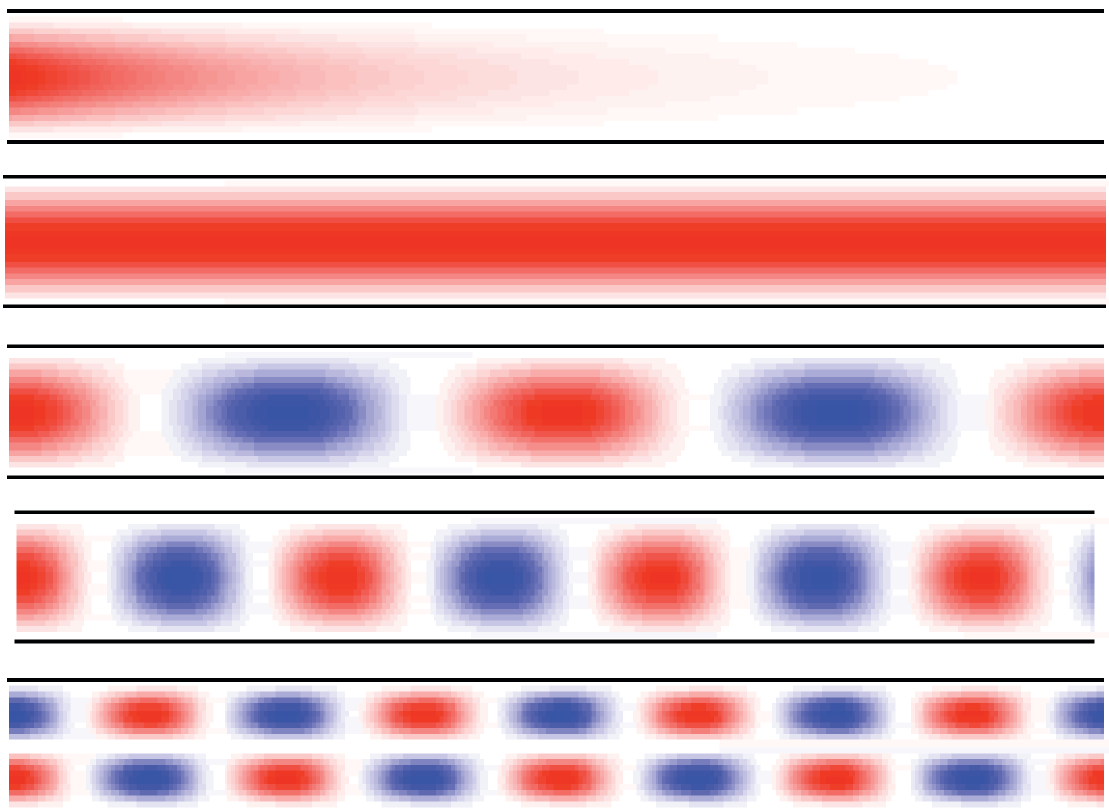
$$\omega^2 = k^2\beta^2 + \left(\frac{n\pi\beta}{2h}\right)^2 \qquad c = \beta\left[1 - \left(\frac{n\pi\beta}{2h\omega}\right)^2\right]^{-\frac{1}{2}}$$







EM waveguide animations

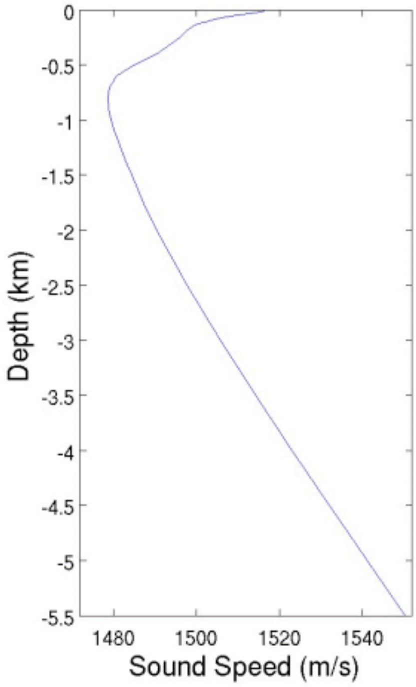


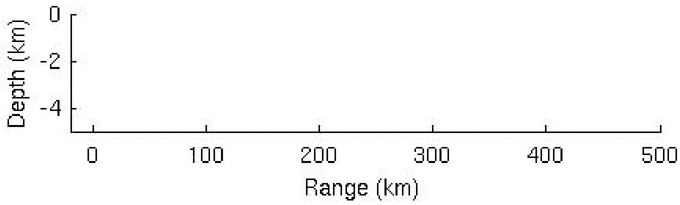
Created by Hsiu C. Han, 1996

http://www.ee.iastate.edu/~hsiu/descriptions/paral.html

Acoustic waveguides...

SOFAR channel (Sound Fixing And Ranging channel)

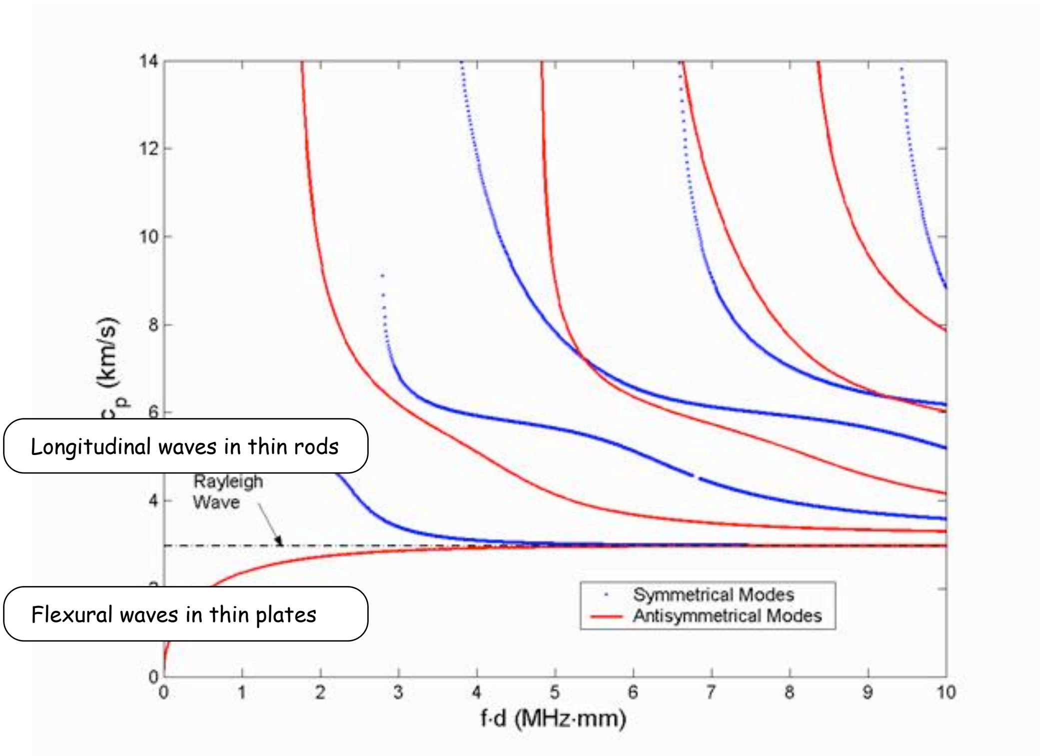




Sound speed as a function of depth at a position north of Hawaii in the Pacific Ocean derived from the 2005 World Ocean Atlas. The SOFAR channel axis is at ca. 750-m depth.

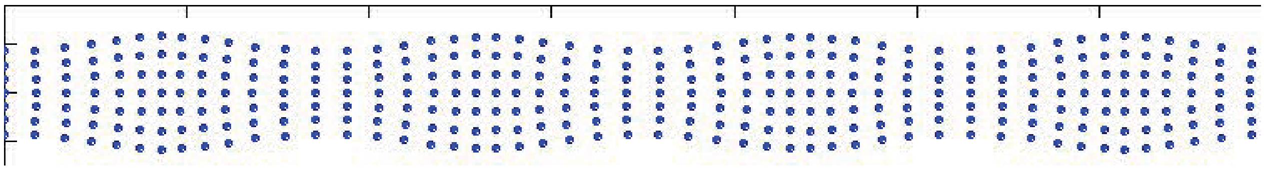
Waves in plates

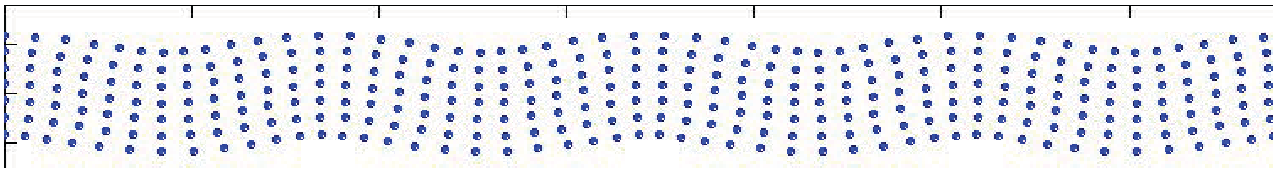
In low frequency plate waves, there are two distinct type of harmonic motion. These are called symmetric or **extensional** waves and antisymmetric or **flexural** waves.



Lamb waves

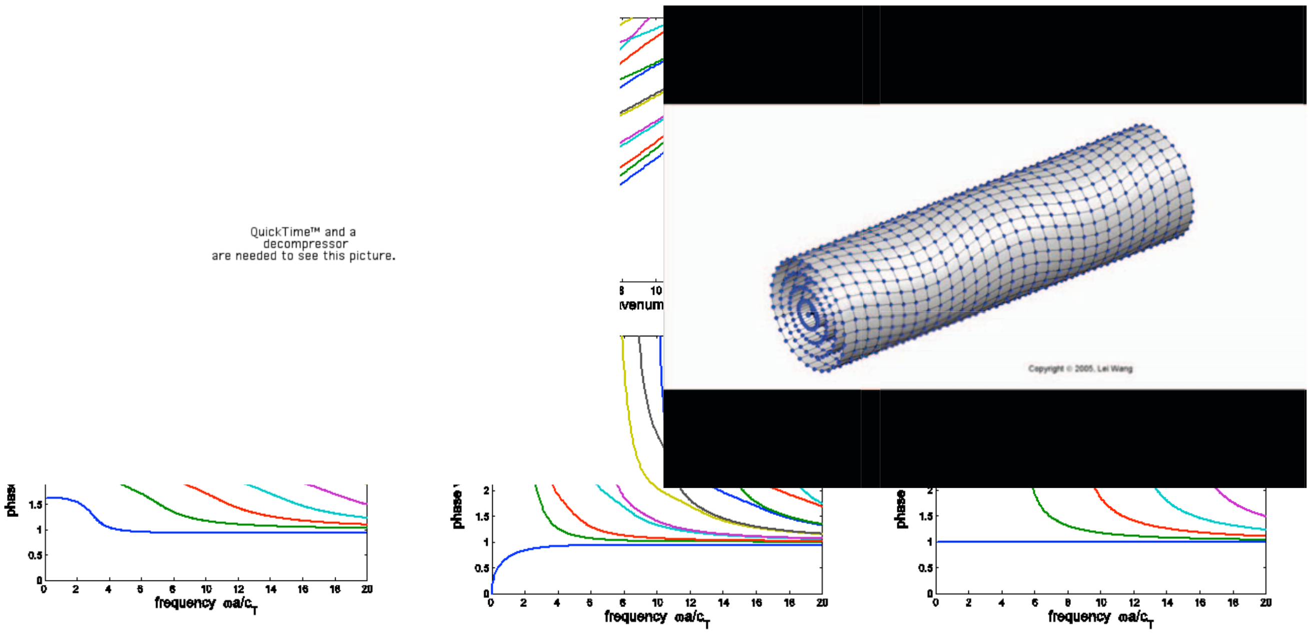
Lamb waves are waves of plane strain that occur in a free plate, and the traction force must vanish on the upper and lower surface of the plate. In a free plate, a line source along y axis and all wave vectors must lie in the x-z plane. This requirement implies that response of the plate will be independent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



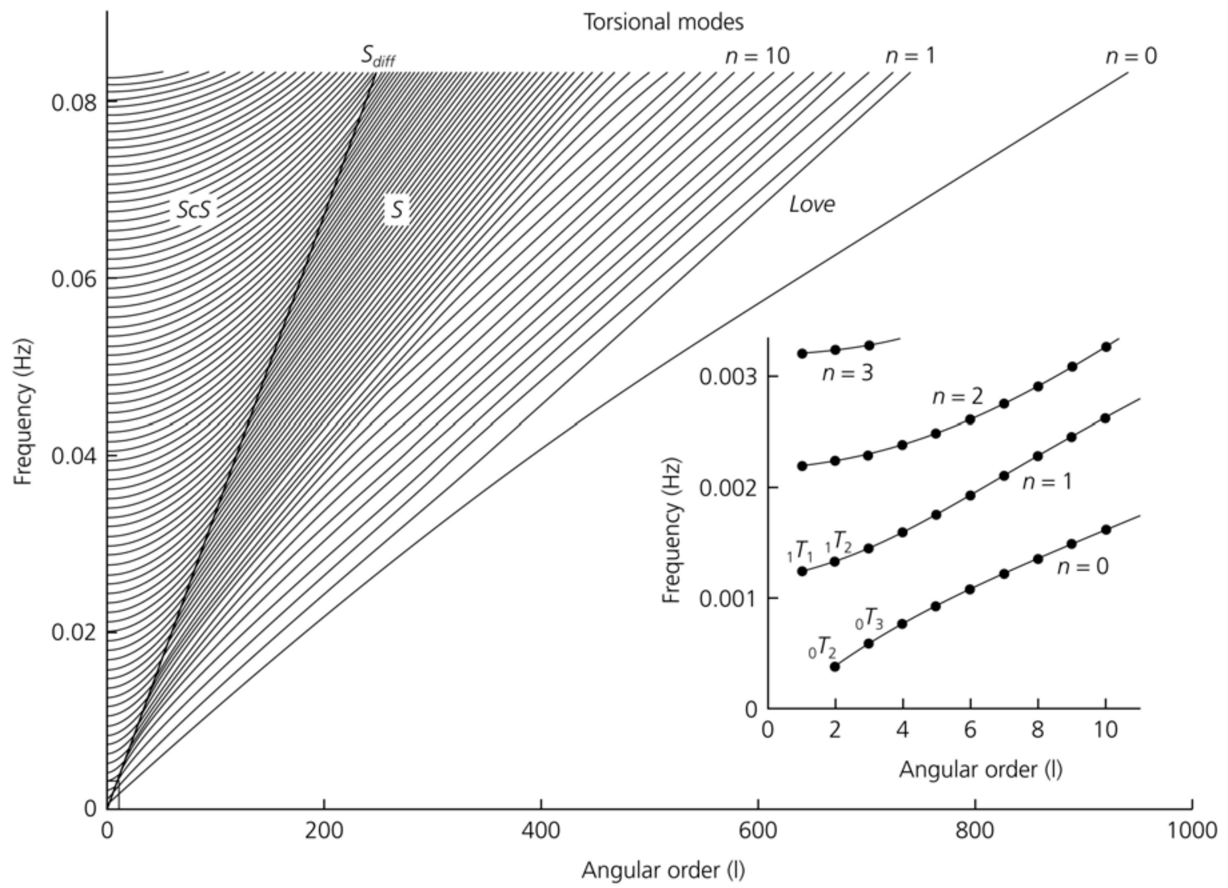


Elastic waves in rods

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**? - 4

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**

(Seismic) wave propagation

Basic physical concepts

What is a wave?
Discrete and continuous models
Born of wave equation
Dispersion

Basic physical concepts 2

PDE: Poisson, diffusion and wave equation
Scattering and diffusion

Mathematic reference: Linear **PDE**

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

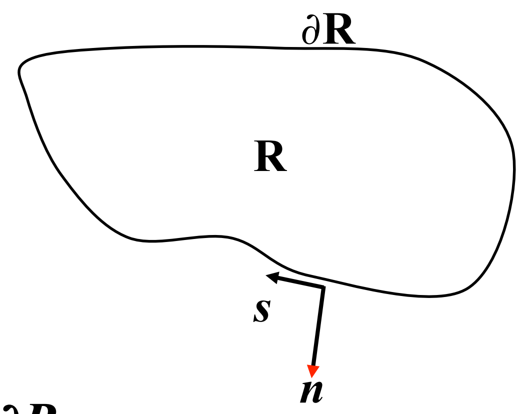
Parabolic equations a **smooth-spreading flow** of an initial disturbance

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

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

Wave Equation

Hyperbolic Equation

$b^2 - 4ac = 0 - 4(1)(-c^2) > 0$: Hyperbolic

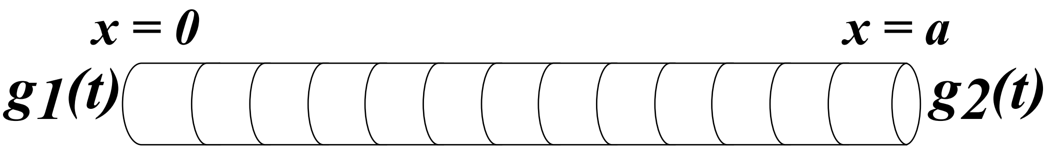
$$\boxed{\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2}}, \quad 0 \le x \le a, \quad 0 \le t$$

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

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

Heat Equation: Parabolic PDE

Heat transfer in a one-dimensional rod



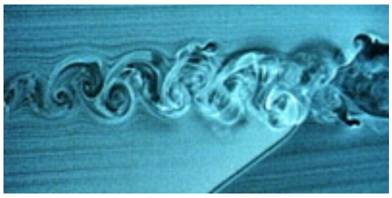
$$\boxed{\frac{\partial u}{\partial t} = d \frac{\partial^2 u}{\partial x^2},} \quad 0 \le x \le a, \quad 0 \le t \le T$$

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

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

Coupled PDE

Navier-Stokes Equations



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

(Seismic) wave propagation

Basic physical concepts

What is a wave?
Discrete and continuous models
Born of wave equation
Dispersion

Basic physical concepts 2

PDE: Poisson, diffusion and wave equation
Scattering and diffusion

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.

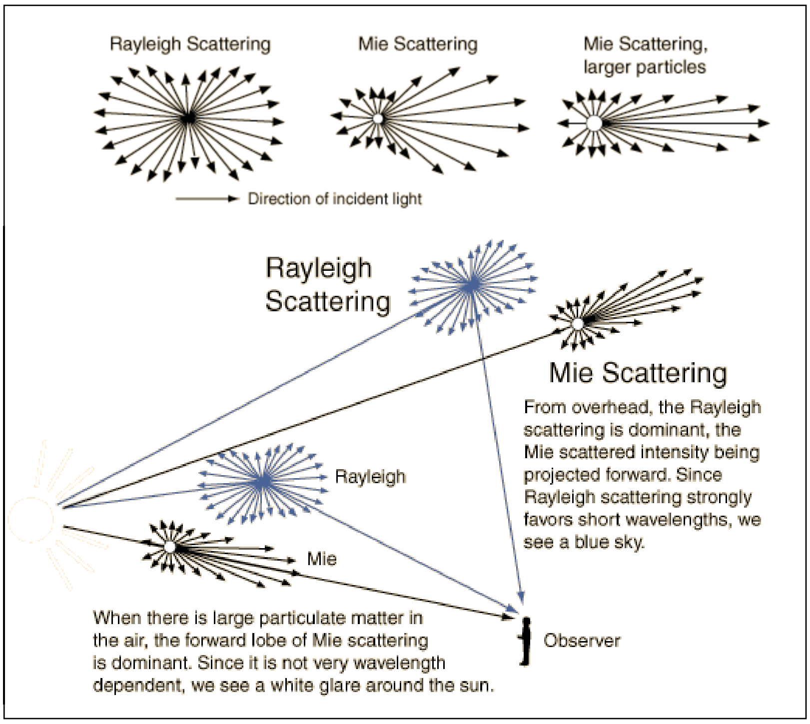
Scattering **occurs at all wavelengths** (spectrally not selective) in the electromagnetic spectrum, for any material whose refractive index is different from that of the surrounding medium (**optically inhomogeneous**).

Scattering of EM wavefield (1)

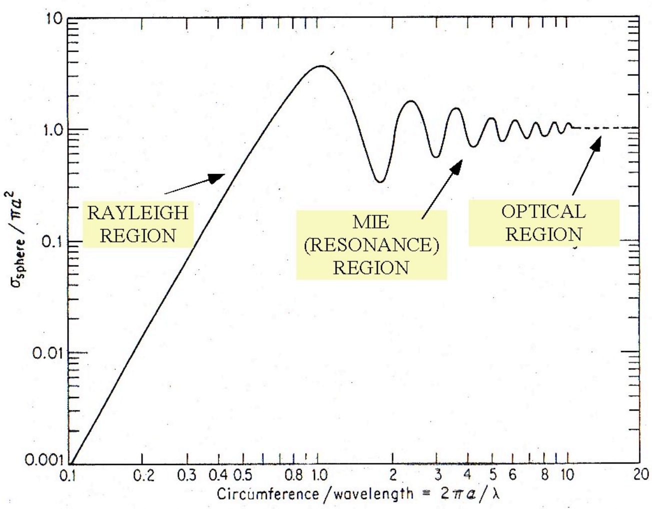
The amount of scattered energy depends strongly on the ratio of: particle size (a) to wavelength (λ) of the incident wave

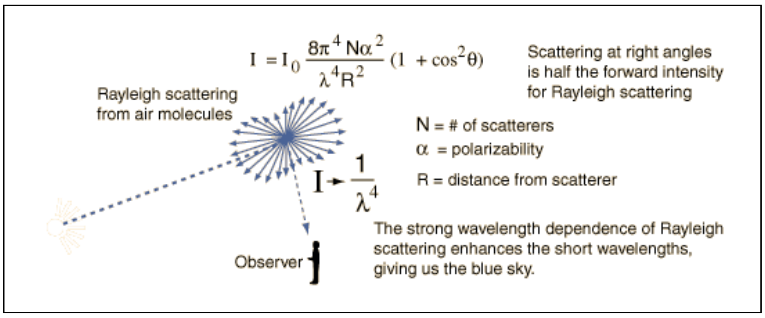
When **(a < λ/10)**, the scattered intensity on both forward and backward directions are equal. This type of scattering is called **Rayleigh scattering**.

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

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

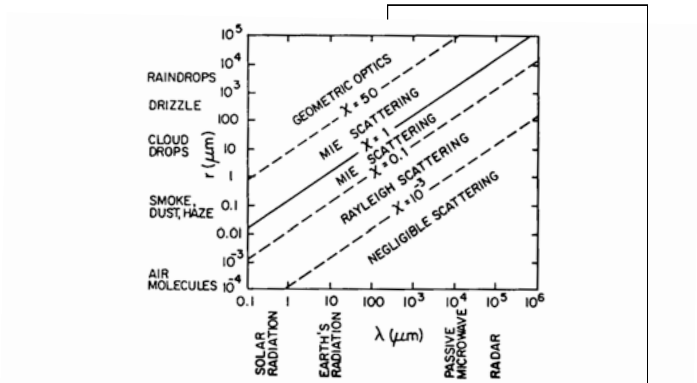
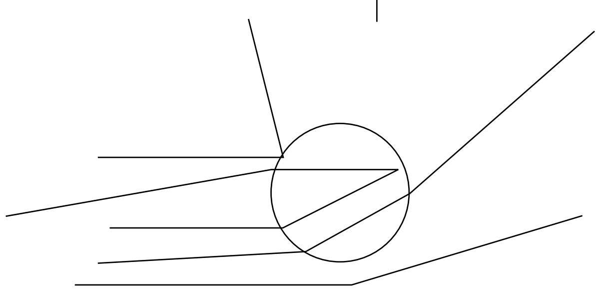


FIGURE 3.18. Scattering regimes. [Adapted from Wallace and Hobbs (1977). Reprinted by permission of Academic Press.]



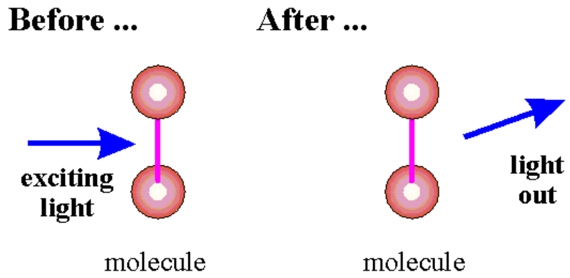
For (a >> λ), the Scattering characteristics are determined from explicit Reflection, Refraction and Diffraction: **Geometric "Ray" Optics**

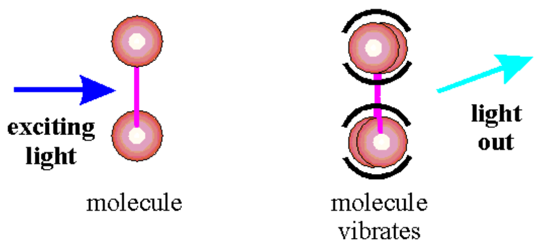
Scattering of EM wavefield (3)

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.

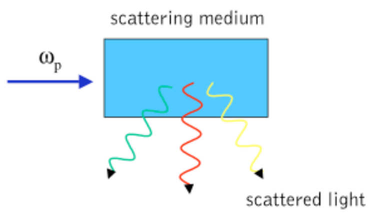
Rayleigh scattering - Light out has same frequency as light in, with scattering at many different angles.





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)

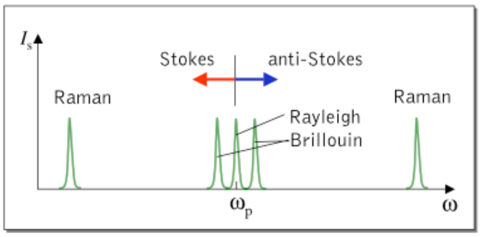


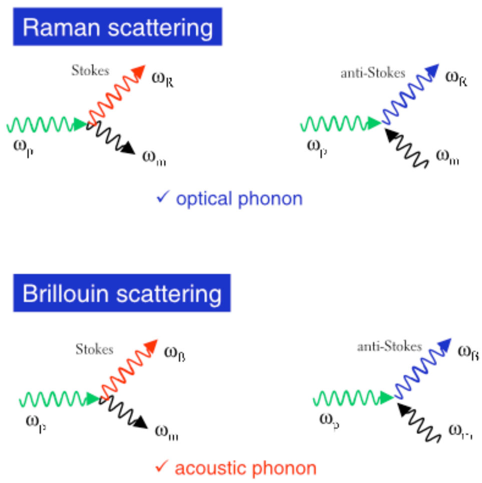
Rayleigh scattering
- scattering from *nonpropagating* density fluctuations (elastic)

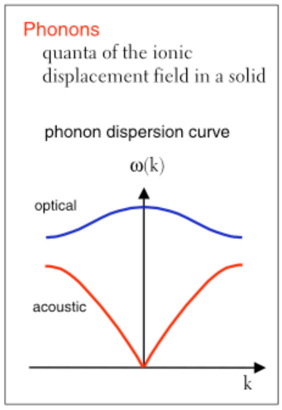
Brillouin scattering
- scattering from *propagating* pressure waves (sound waves, acoustic phonons)

Raman scattering
- interaction of light with vibrational modes of molecules or lattice vibrations of crystals (scattering from optical phonons)

spectrally resolved detection



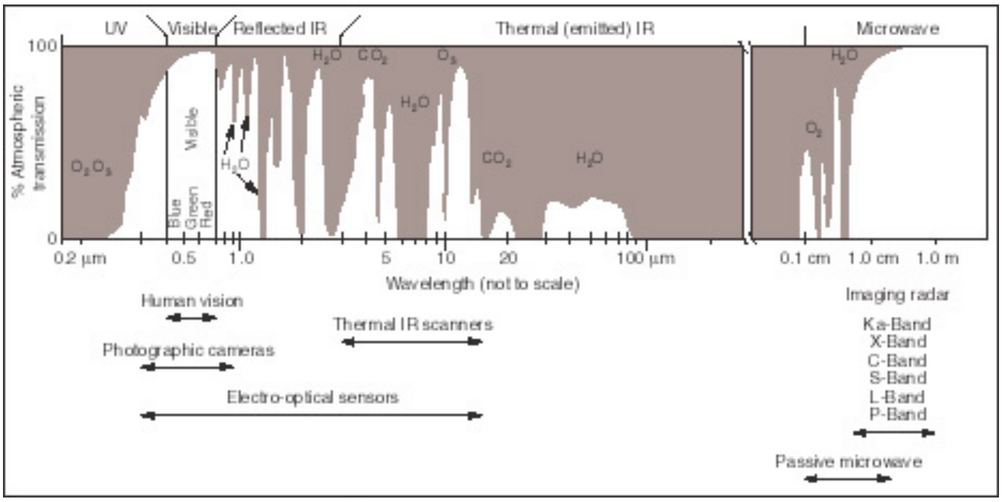




Scattering and **Absorption**

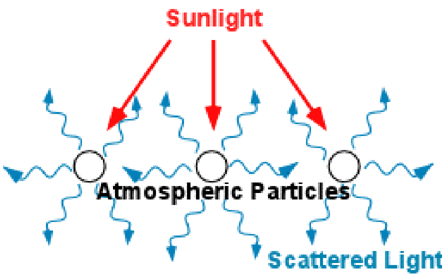
When the photon is absorbed and re-emitted at a different wavelength, this is absorption.

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

Basic physical concepts

What is a wave?
Discrete and continuous models
Born of wave equation
Dispersion

Basic physical concepts 2

PDE: Poisson, diffusion and wave equation
Navier-Stokes equation
Scattering and diffusion
Application to the seismic wavefield

Basic parameters for **seismic wavefield**

The governing parameters for the seismic scattering are:

wavelength of the wavefield (or wavenumber k)
λ (10^0-10^6 m)

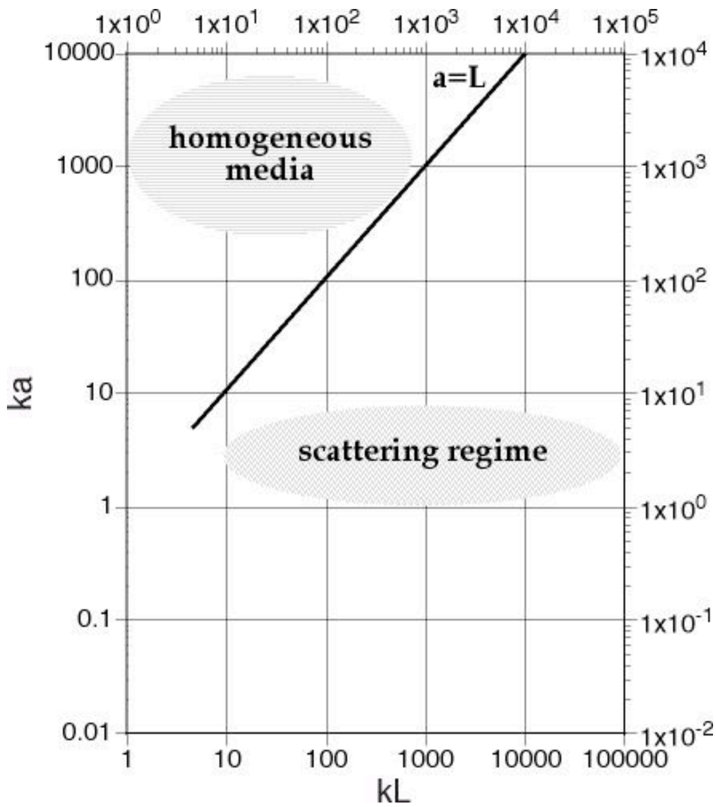
correlation length, or dimension, of the heterogeneity
a ($10^?$-10^5 m)

distance travelled in the heterogeneity
L (10^0-10^6 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:

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

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

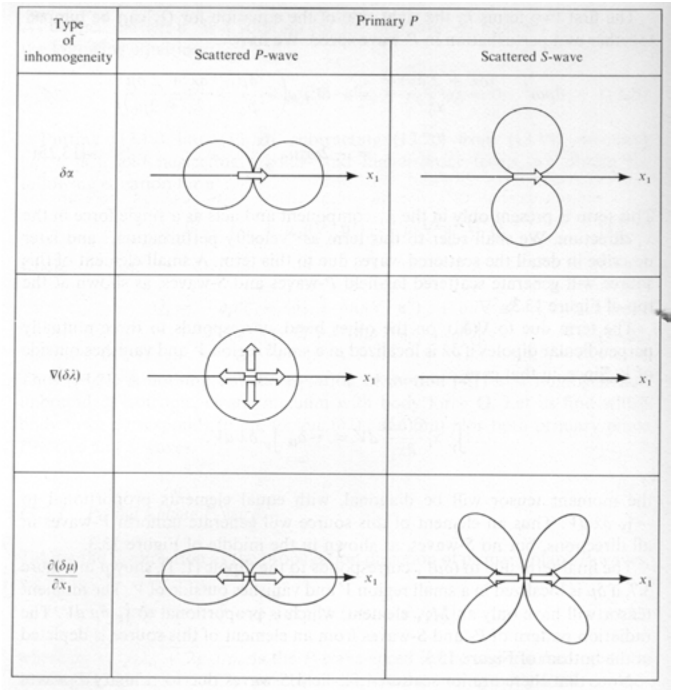
$$\rho_0 \ddot{u}_i^1 - (\lambda_0 + \mu_0)(\nabla \cdot \mathbf{u}^1)_{,i} - \mu_0 \nabla^2 \mathbf{u}_i^1 = Q_i$$

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**):

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

Power Spectra of scattered waves

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

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

Wave parameter

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

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

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

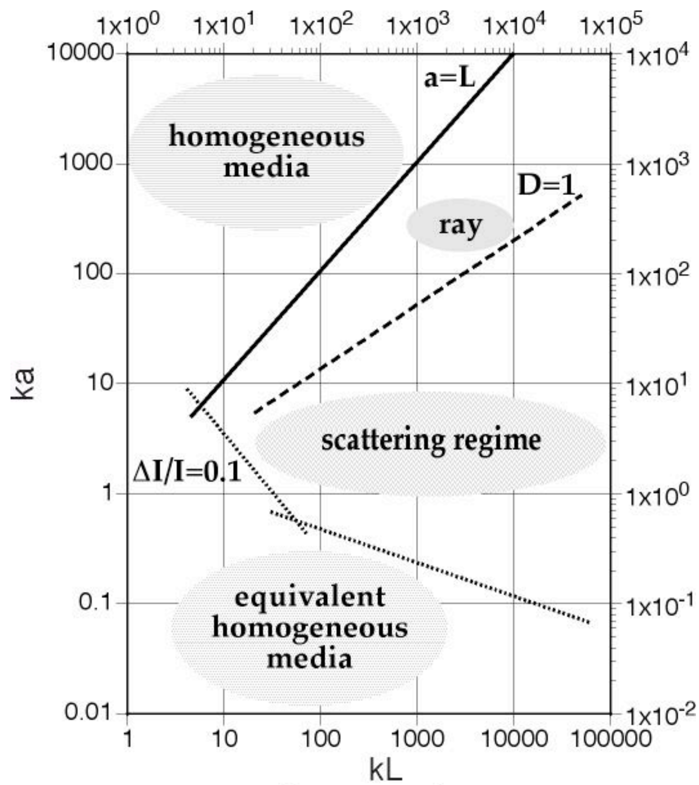
the **perturbations** (P &A) are function of the **wave parameter**:

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

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

when D<1, geometric ray theory is valid

Seismic Scattering (2)



D=4L/ka²=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)

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

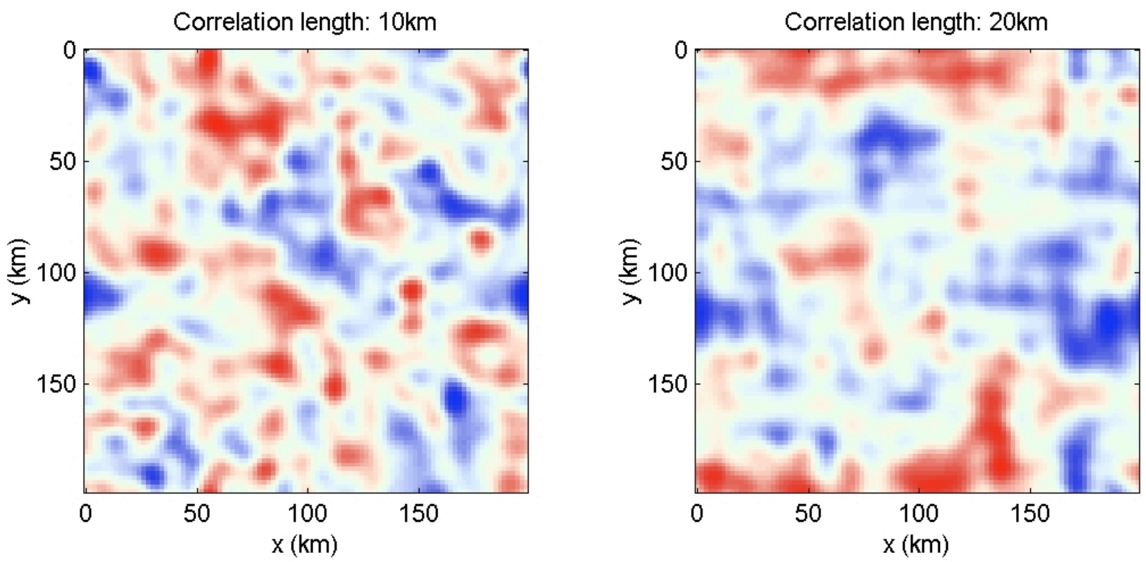
$$d = \frac{cl^*}{3} \quad l^* = \frac{l}{\Sigma - \Sigma'} \quad \text{(acoustic)}$$

$$d = \frac{1}{1 + 2K^3}\left(\frac{c_p l_p^*}{3} + 2K^2 \frac{c_s l_s^*}{3}\right) \quad \text{(elastic)}$$

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…

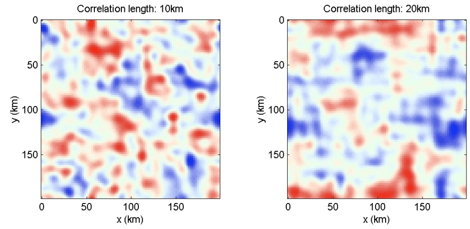
Scattering in random media

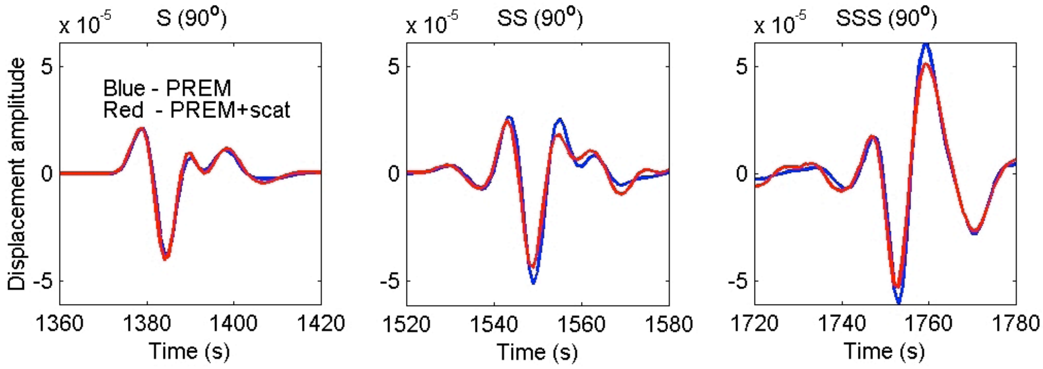


How is a propagating wavefield affected by random heterogeneities?

Synthetic seismograms

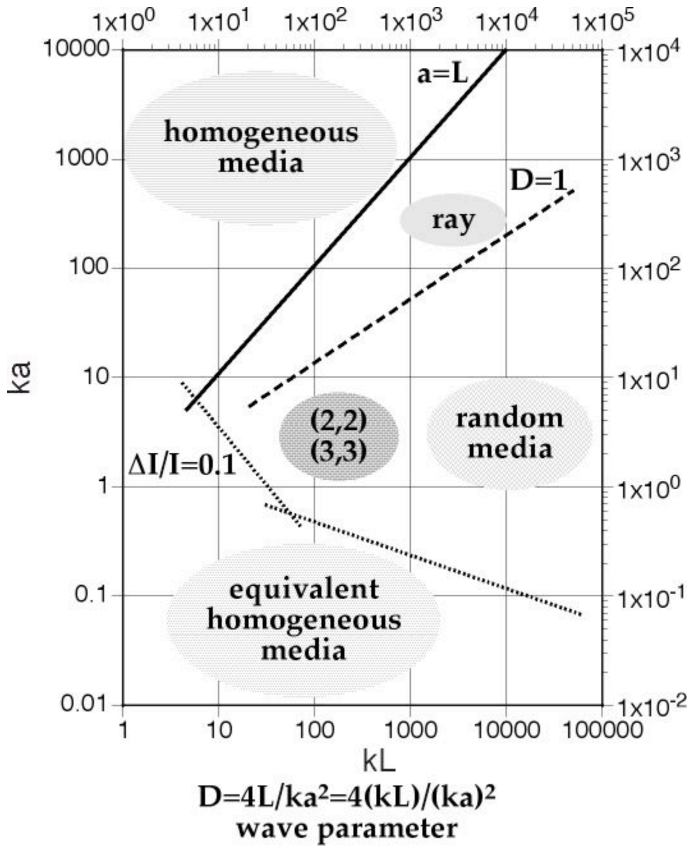
Synthetic seismograms for a global model with random velocity perturbations.





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)

What is a **wave?** - 5

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

Long Gravity waves

Having considered gravity waves whose length is small compared with the depth of the liquid, let us now discuss the opposite limiting case of waves whose length is large compared with the depth. These are called **long waves**.

Let us examine the propagation of long waves in a channel that is supposed to be along the x-axis, and of infinite length. The cross-section of the channel may have any shape, and may vary along its length. We denote the cross-sectional area of the liquid in the channel by $S = S(x,t)$. The depth and width of the channel are supposed small in comparison with the wavelength.

We shall here consider longitudinal waves, in which the liquid moves along the channel. In such waves the velocity component v_x along the channel is large compared with the components v_y, v_z. We denote v_x by v simply, and omit small terms.

Selected References

Aki, K. and Richards, P. G., 1980. Quantitative Seismology, Freeman & Co., San Francisco.

Ewing W.M., Jardetzky W.S., Press F., 1957, Elastic Waves in Layered Media, McGraw-Hill.

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

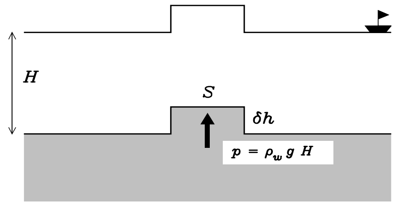
Snieder, R., 2002. General theory of elastic wave scattering , in Scattering and Inverse Scattering in Pure and Applied Science, Eds. Pike, R. and P. Sabatier, Academic Press, San Diego, 528-542.

Turner, J. A., 1998. Scattering and Diffusion of Seismic Waves, Bull. Seism. Soc. Am., 88, 1, 276-283.

A bird's eye view on Tsunami Physics

- Introduction
  - VERY basic tsunami physical concepts
  - Modal approach (off-shore sources)
- Examples of Tsunami modeling
  - New insights into tsunami measurement

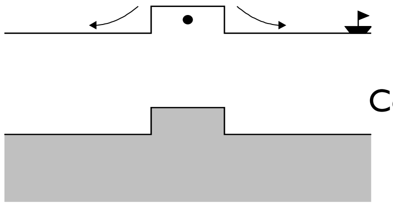
Very basic tsunami physics...



Bottom uplift
&
Waterberg formation

Energy

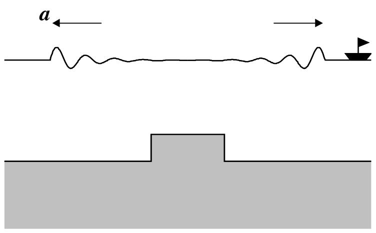
$$E_R \approx 4.8 + 1.5M$$
$$E_T = \frac{1}{2}\rho g L \lambda (\delta h)^2$$
$$L \sim 10^6 m;\ \lambda \sim 10^4 m;\ \delta h \sim 5m$$
$$E_R \approx 10^{18} J \geq 10^2 E_T$$



Center of mass falls...

Wavelength

$$\frac{\lambda}{H} \sim 40;\ \frac{H}{a} \sim 3 \cdot 10^3$$
$$\lambda >> H >> a$$



Potential energy goes to tsunami energy

Tsunami is a shallow-water gravity wave with great wavelength and tiny amplitude

Dispersion & Non linearity

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

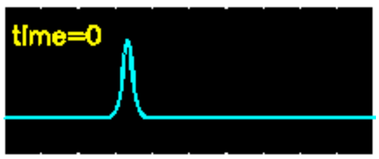
u=u(x,t) measures the elevation at time t and position x, i.e. the height of the water above the equilibrium level

Dispersive term

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

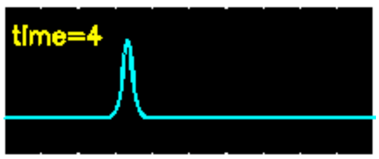
Nonlinearity

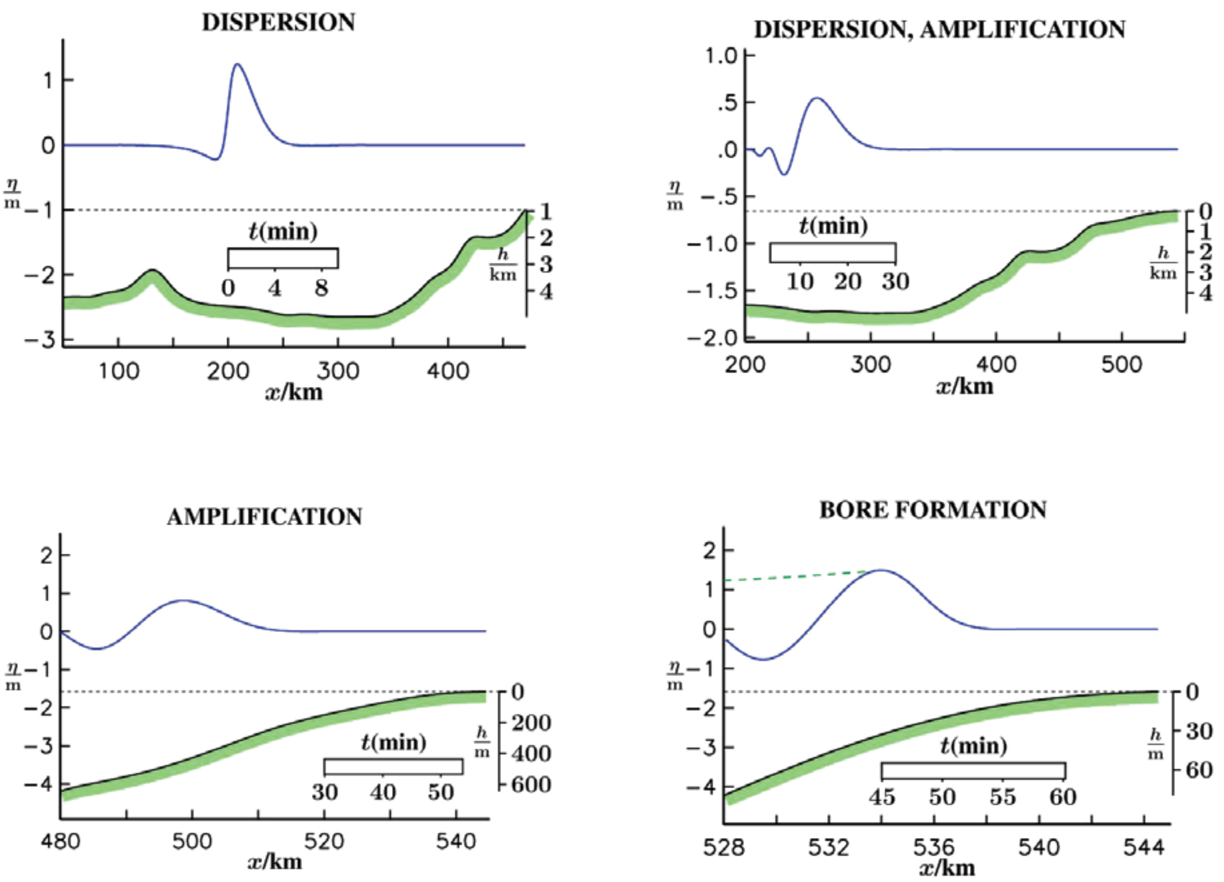
$$u_t + u\,u_x = 0$$



KdV

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





Courtesy of: Geir Pedersen <geirkp@math.uio.no>

Navier-Stokes equations

Newton's law + Conservation of matter + Viscosity

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot grad)\mathbf{v} = -grad(P) - \rho grad(\phi) + $$
$$+\eta \Delta \mathbf{v} + (\eta + \eta')grad\big(div(\mathbf{v})\big)$$

and in the incompressible case...

$$\frac{\partial \Omega}{\partial t} + rot(\Omega \times \mathbf{v}) = \frac{\eta}{\rho}\Delta \Omega$$

Gravity waves: dispersion

$$F(z) = 2Ae^{-kh}\cosh\left[k(z+h)\right]$$

and the boundary at the top gives the dispersion relation for incompressible, irrotational, small amplitude "gravity" waves:

$$\omega^2 = kg\left[\tanh(kh)\right]$$

deep water (kh goes to infinity)

$$\omega^2 = kg$$

$$c = \sqrt{\frac{g}{k}} = \sqrt{\frac{g\lambda}{2\pi}}$$

$$u = \frac{\partial\omega}{\partial k} = \frac{1}{2}c = \frac{1}{2}\sqrt{\frac{g}{k}} = \frac{1}{2}\sqrt{\frac{g\lambda}{2\pi}}$$

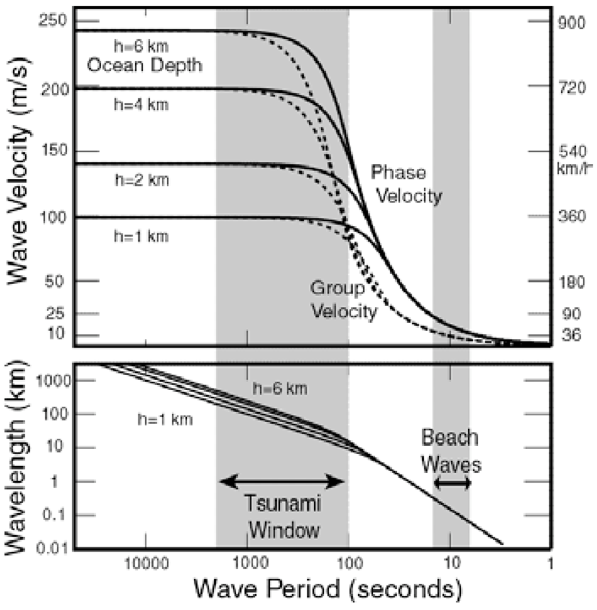
shallow water (kh goes to zero)

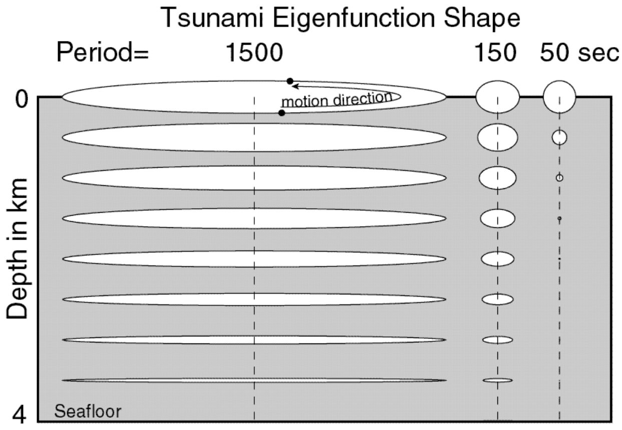
$$\omega^2 = k^2gh$$

$$c = \sqrt{gh}$$

$$u = \frac{\partial\omega}{\partial k} = c = \sqrt{gh}$$

Tsunami eigenvalues & eigenfunctions





Ward, S. N., 2000. Tsunamis. Encyclopedia of Physical Science and Technology, Academic Press, California, 2000.

Panza G.F., Romanelli F. and Yanovskaya, T., 2000.
Synthetic Tsunami mareograms for realistic oceanic models, Geophysical Journal International, 141, 498-508.

Modal approach - sketch

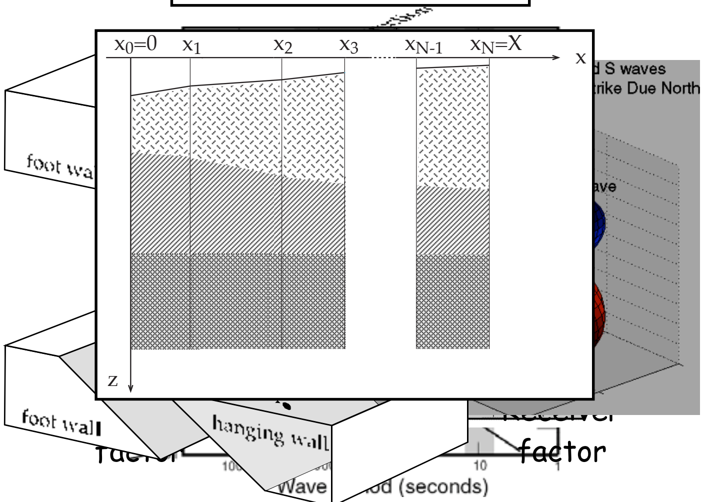
Equations of elastic motion with gravity + boundary conditions

FULL coupling between the fluid and solid layers

Eigenvalues & Eigenfunctions

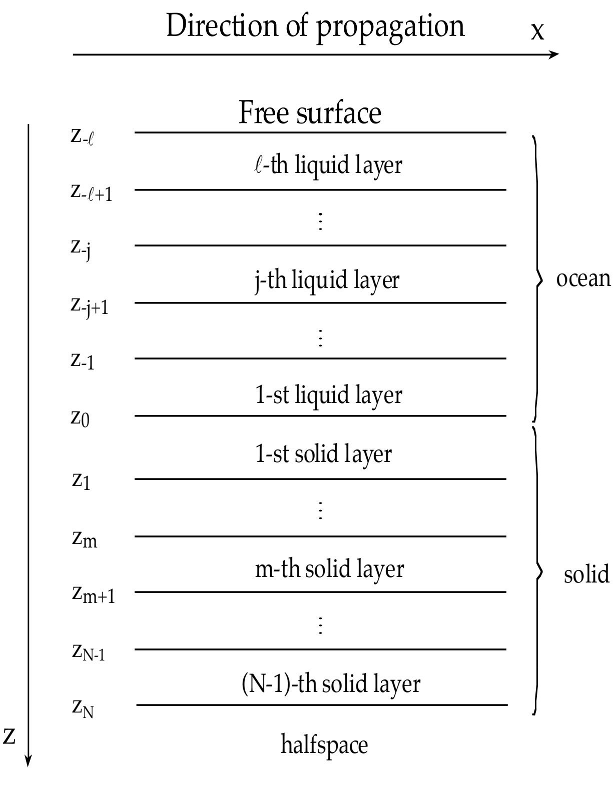
Seismic source excitation

Tsunami mode propagation in LHM



$$U(X,\varphi,z,\omega,t) = \frac{\exp(-i\pi/4)}{\sqrt{8\pi}}\,\frac{\exp[i\omega(t-\tau)]}{\sqrt{J}}\,\left.\frac{\chi(h_s,\varphi)R(\omega)}{\sqrt{\omega c}\sqrt{v_g I_1}}\right|_s\,\left.\frac{u(z,\omega)}{\sqrt{v_g I_1}}\right|_X$$

Modal approach: formulation



Reference 1-D model

- **EQUATIONS OF MOTION**

$$\alpha^2\nabla(\nabla\cdot\mathbf{u}) - g\mathbf{e}_z\nabla\cdot\mathbf{u} = \frac{\partial^2\mathbf{u}}{\partial t^2}$$

$$\alpha^2\nabla(\nabla\cdot\mathbf{u}) - \beta^2\nabla\times(\nabla\times\mathbf{u}) = \frac{\partial^2\mathbf{u}}{\partial t^2}$$

- **BOUNDARY CONDITIONS**

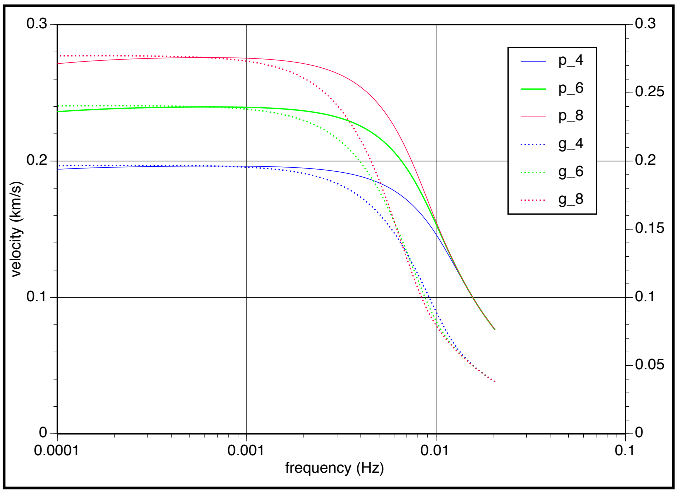
$$\alpha^2\nabla\cdot\mathbf{u} - gw = 0$$

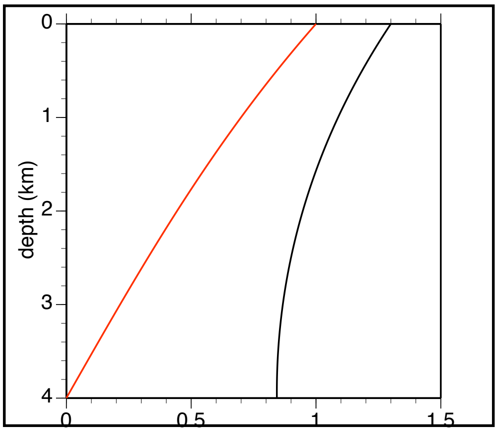
$$w_{-j}(z_{-j}) = w_{-j-1}(z_{-j}) \qquad u_{-j}(z_{-j}) = u_{-j-1}(z_{-j})$$
$$p_{-j}(z_{-j}+w_{-j}) = p_{-j-1}(z_{-j}+w_{-j-1})$$

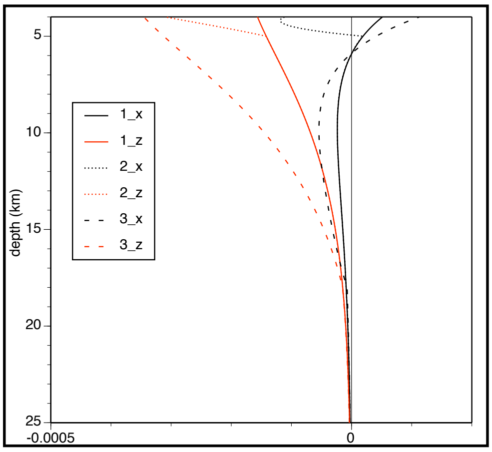
$$w_{-1}(z_0) = w_1(z_0)$$
$$p_{-1}(z_0) = \sigma_1(z_0) \qquad 0 = \tau_1(z_0)$$

$$w_m(z_m) = w_{m+1}(z_m) \qquad u_m(z_m) = u_{m+1}(z_m)$$
$$\sigma_m(z_m) = \sigma_{m+1}(z_m) \qquad \tau_m(z_m) = \tau_{m+1}(z_m)$$

Modal approach: Eigenvalues

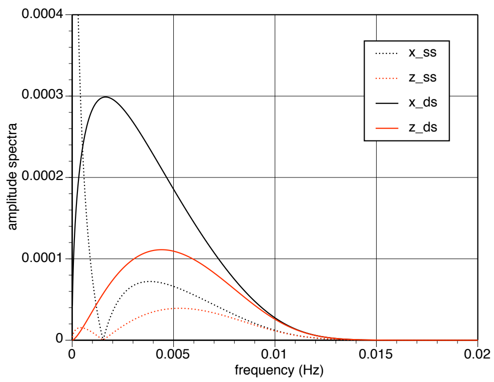






Eigenfunctions of the radial and vertical (normalized to 1 at the free-surface) component of motion at frequency equal to 0.007 Hz, in the fluid. The curves for three crustal models 1, 2 and 3, are totally overlapped; on the bottom, the eigenfunctions in the solid layers are shown

Modal approach: excitation spectra

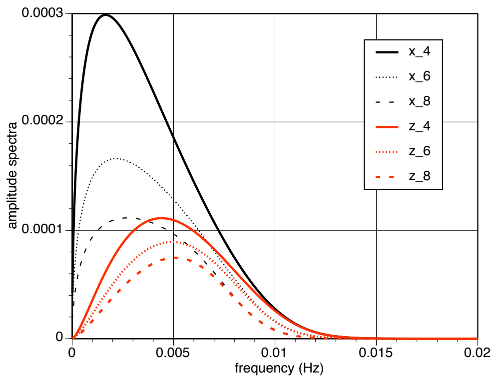


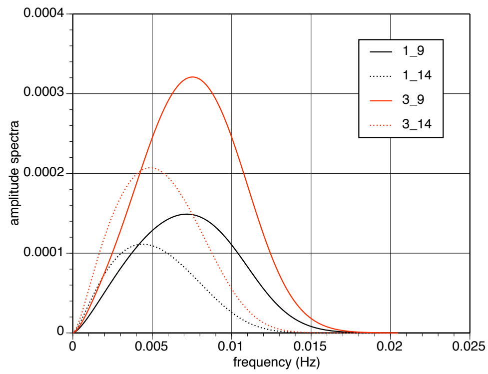
Amplitude spectra calculated for a double–couple source (10^{13} Nm seismic moment) at 500 km from the receiver:

a) for pure strike-slip and pure dip-slip;

b) for a liquid layer 4, 6 and 8 km thick;

c) for different crustal model and source depths.



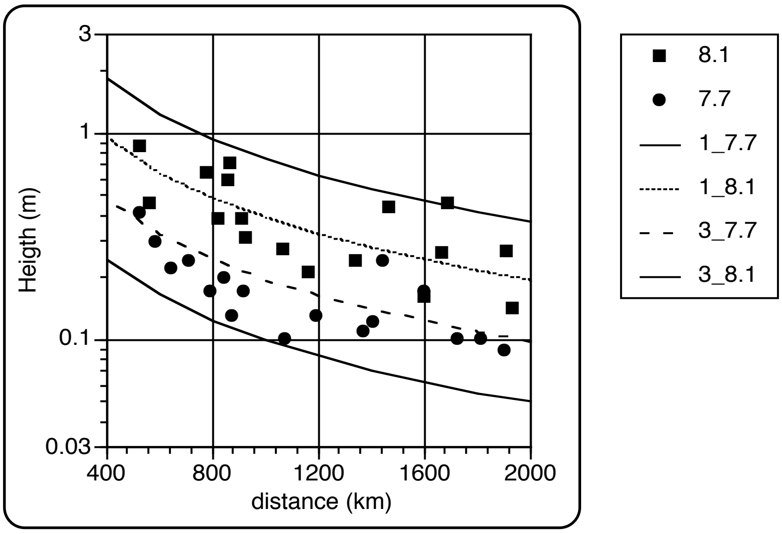


Modal approach: 1D tsunami motion

$$\mathbf{U}(X,\varphi,z,\omega,t)=\frac{\exp(-i\pi/4)}{\sqrt{8\pi}}\ \frac{\exp[i\omega(t-X/c)]}{\sqrt{X}}\ \frac{\chi(h_s,\varphi)R(\omega)}{\sqrt{\omega c}\sqrt{v_g I_1}}\ \frac{\mathbf{u}(z,\omega)}{\sqrt{v_g I_1}}$$

Curves of the maximum height of the calculated tsunami signal (vertical component) versus the epicentral distance.

Each acronym shows the 1-D model (1 or 3) and the magnitude (M_w) adopted in the calculations. The symbols denote the data, for two different magnitudes (squares for M_s=8.1, circles for M_s=7.7), shown by Abe (1995).



Modal approach: 2D tsunami motion

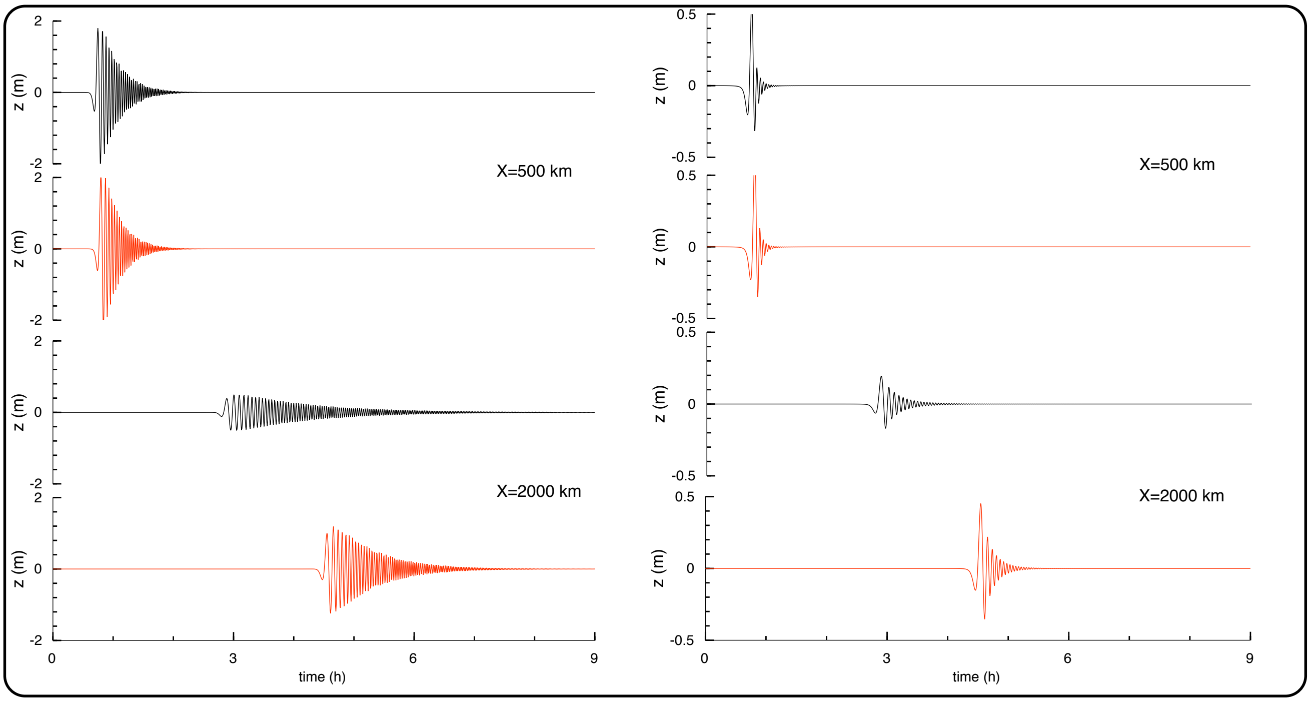
$$\mathbf{U}(X,\varphi,z,\omega,t)=\frac{\exp(-i\pi/4)}{\sqrt{8\pi}}\ \frac{\exp[i\omega(t-X/c)]}{\sqrt{X}}\ \frac{\chi(h_s,\varphi)R(\omega)}{\sqrt{\omega c}\sqrt{v_g I_1}}\ \frac{\mathbf{u}(z,\omega)}{\sqrt{v_g I_1}}$$

$$\mathbf{U}(X,\varphi,z,\omega,t)=\frac{\exp(-i\pi/4)}{\sqrt{8\pi}}\ \frac{\exp[i\omega(t-\tau)]}{\sqrt{J}}\ \left.\frac{\chi(h_s,\varphi)R(\omega)}{\sqrt{\omega c}\sqrt{v_g I_1}}\right|_s\ \left.\frac{\mathbf{u}(z,\omega)}{\sqrt{v_g I_1}}\right|_X$$

- **SHOALING FACTOR**

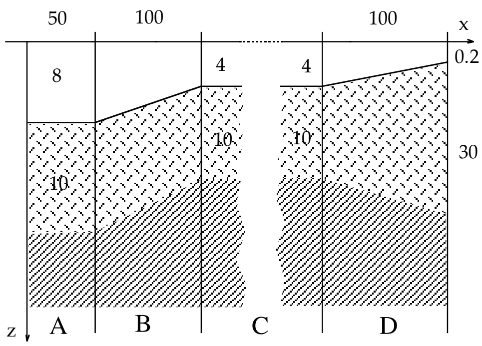
$$\left|\frac{W(X_2,0,\omega)}{W(X_1,0,\omega)}\right|=\left[\frac{w(0,\omega)|_2\sqrt{v_g I_1}\big|_1}{w(0,\omega)|_1\sqrt{v_g I_1}\big|_2}\right]\frac{\sqrt{J_1}}{\sqrt{J_2}}\cong\sqrt[4]{\frac{H_1}{H_2}}$$

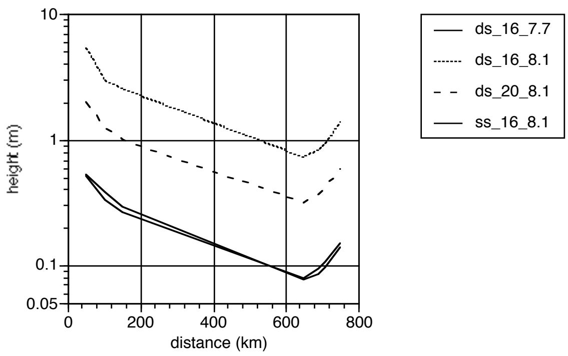
Example: synthetic signals for the tsunami mode (vertical component) excited by a dip-slip mechanism with M_0=2.2 10^{21} Nm. h_s = 14 km; h_s = 34 km.

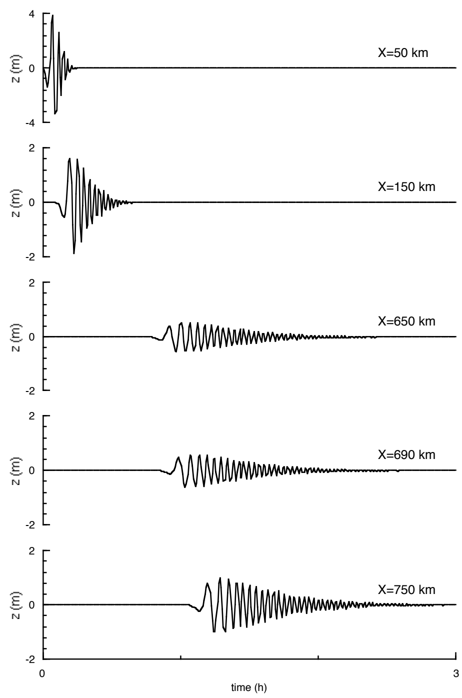


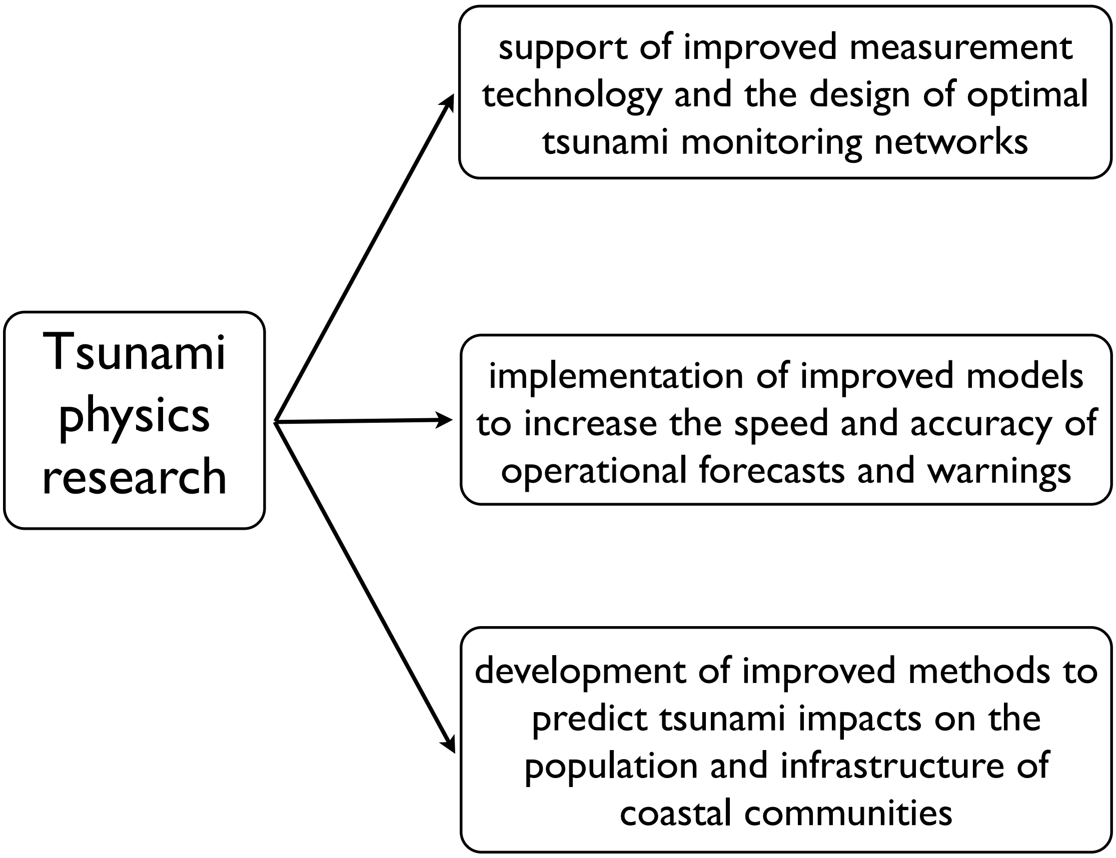
For each of the two source-receiver distances considered, the upper trace refers to the 1-D model and the lower trace to a laterally varying model. In the laterally varying model the liquid layer is getting thinner with increasing distance from the source, with a gradient of 0.00175 and the uppermost solid layer is compensating this thinning.

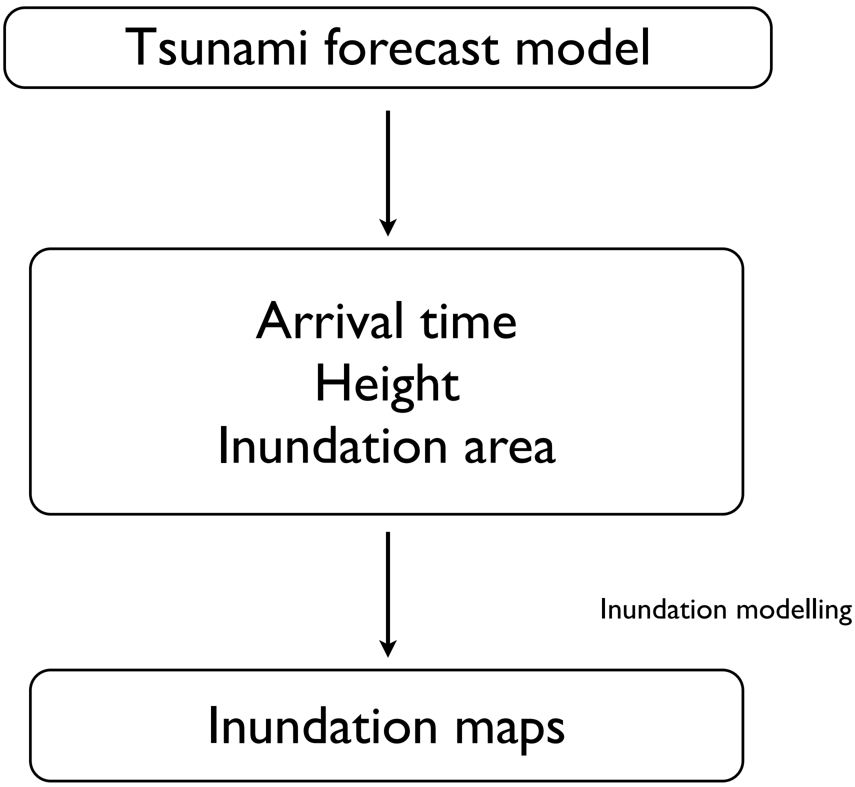
Example: sketch of a laterally heterogeneous model for a realistic scenario. Synthetic mareograms (vertical) calculated at various distances along the section. The extension of zone C is 500 km.





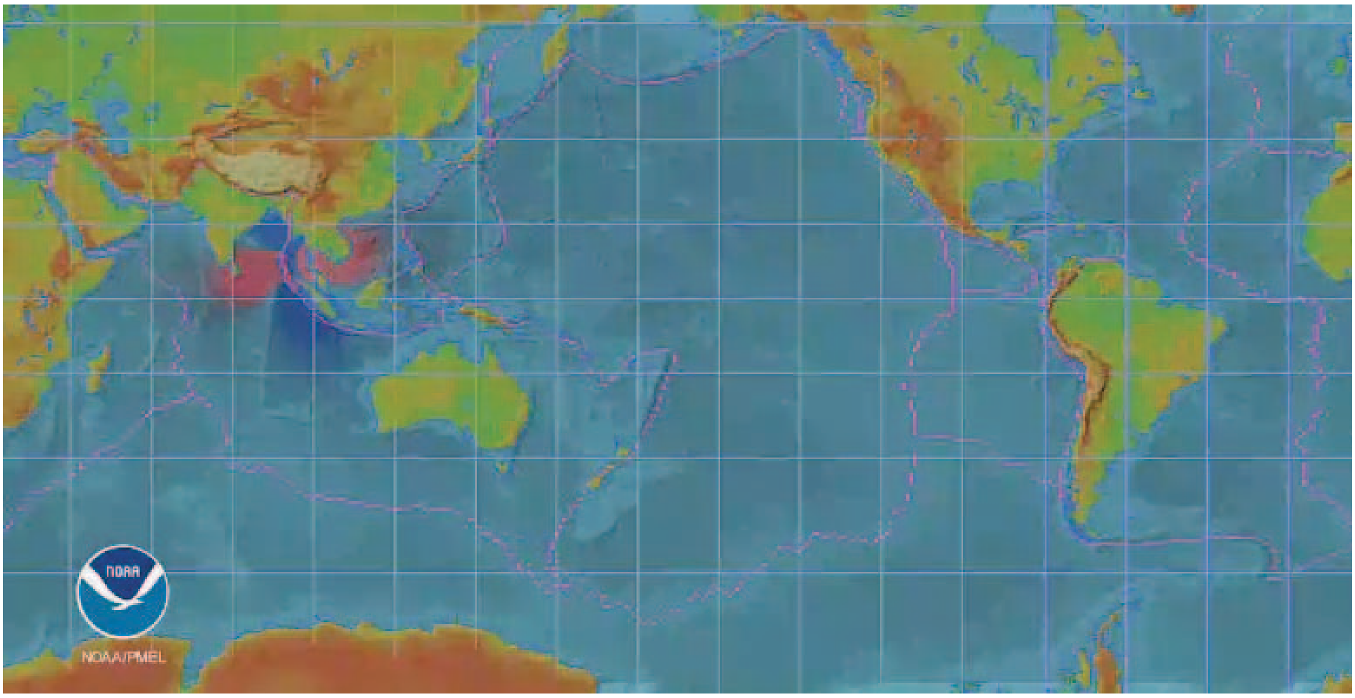






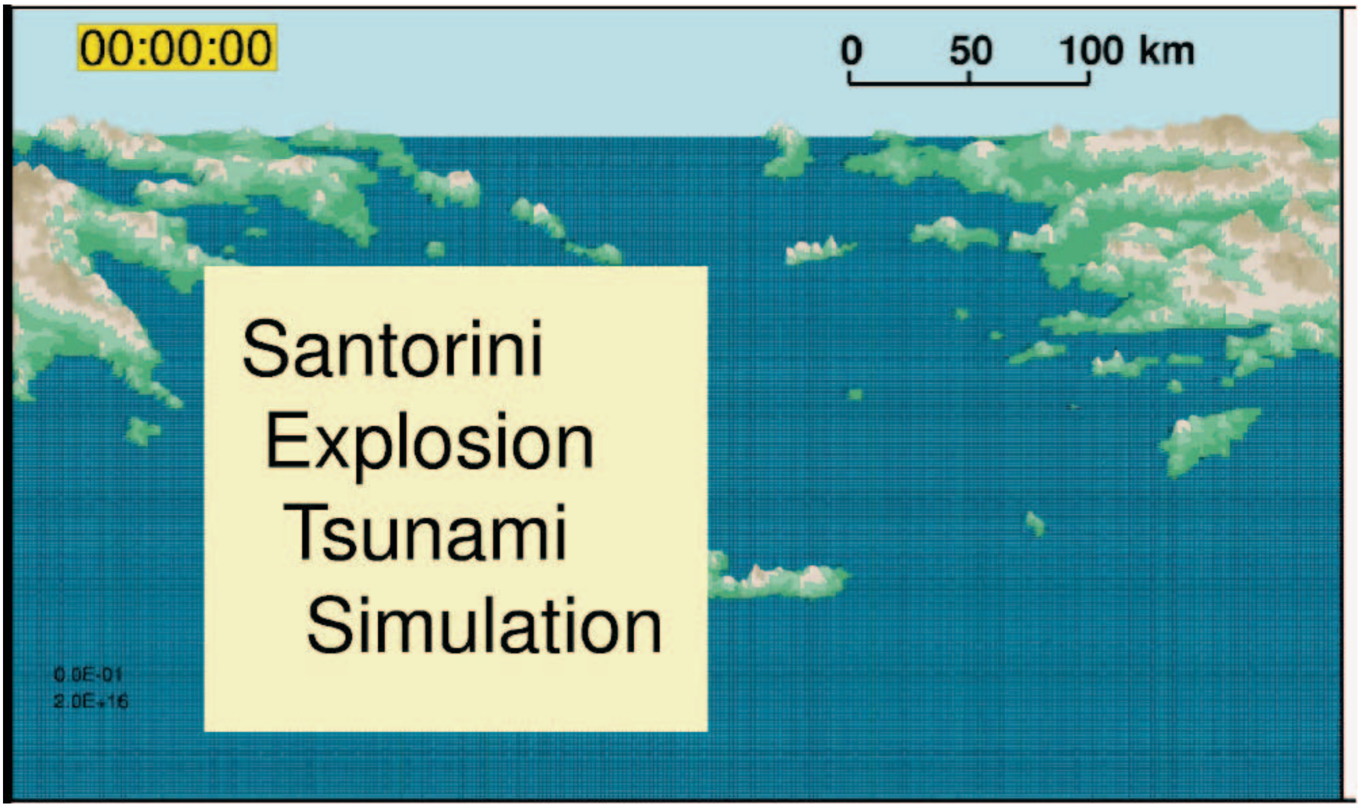
maximum wave height and maximum current speed as a function of location, maximum inundation line, as well as time series of wave height at different locations indicating wave arrival time

December 26, 2004 Indonesia (Sumatra)
Global tsunami propagation



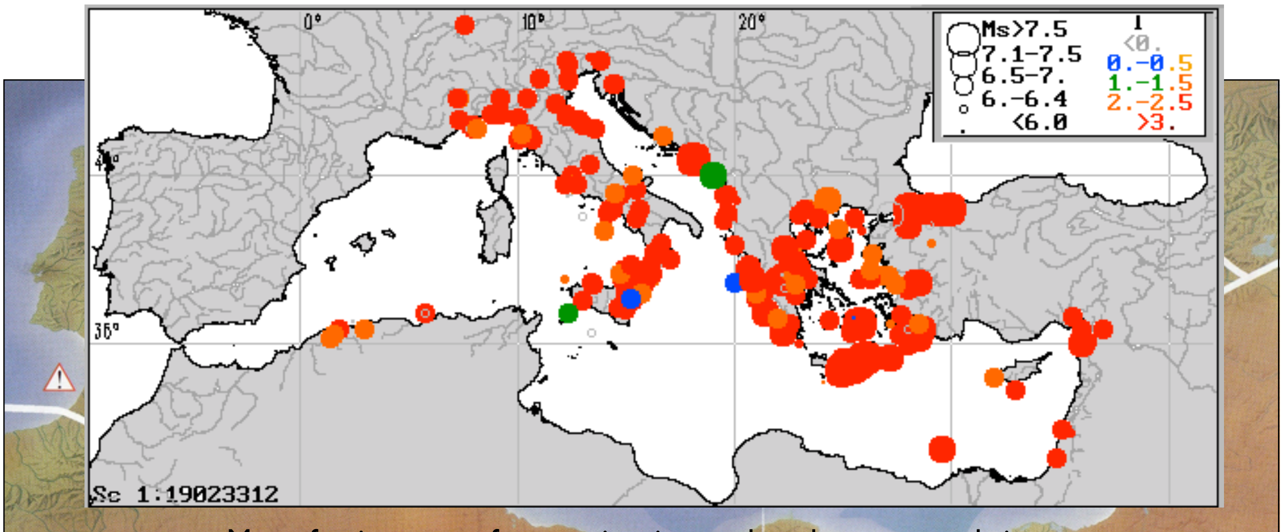
http://nctr.pmel.noaa.gov/model.html

Santorini Tsunami Simulation 3D



Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/

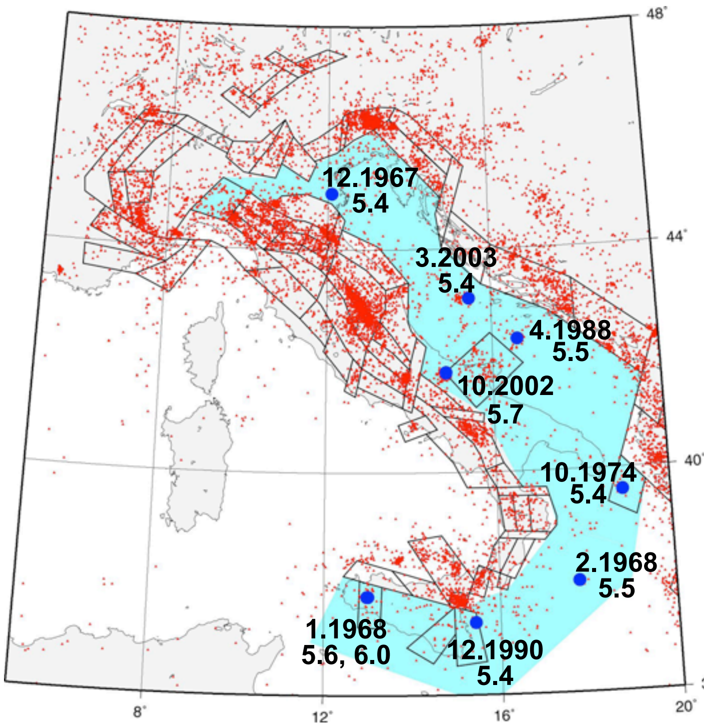
The Mediterranean Sea and Tsunamis



Map of epicenters of tsunamigenic earthquakes occurred since 1380 B.C. to 1996 within the Mediterranean region. The size of circles is proportional to the event magnitude, the color to the tsunami intensity

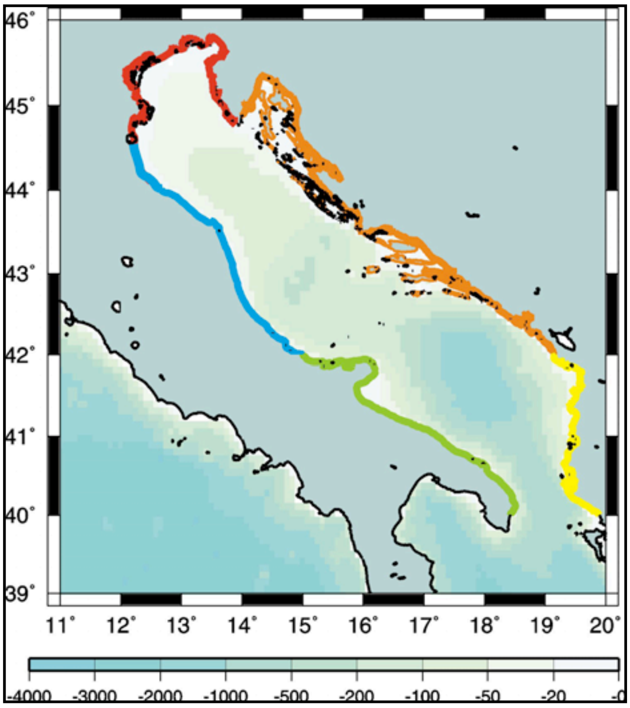
data from: 'Mediterranean Tsunami Catalog, from 1628B.C. to present of the Institute of Computational Mathematics and Mathematical Geophysics (Computing Center) Siberian Division, Russian Academy of Sciences. Tsunami Laboratory

Seismicity in the Adriatic basin



Earthquakes with M≥5.4 (1964-2004)

Distribution of historical tsunami in the Adriatic basin

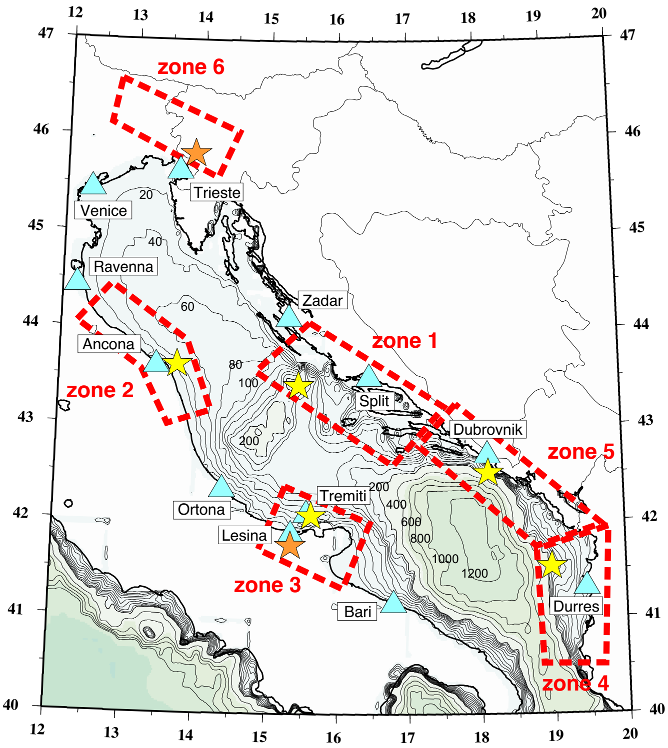


Tsunami reported in
ICTP Technical Report 2005:

CATALOGUE OF REPORTED
TSUNAMI EVENTS IN THE
ADRIATIC SEA
(from 58 B.C. to 1979 A.D.)

10	North-Adriatic coasts
14	Central-Adriatic Italian coasts
11	South-Adriatic Italian coasts
10	Croatian, Serbian and Montenegro coasts
13	Albanian coasts

Hazard scenarios for the Adriatic basin

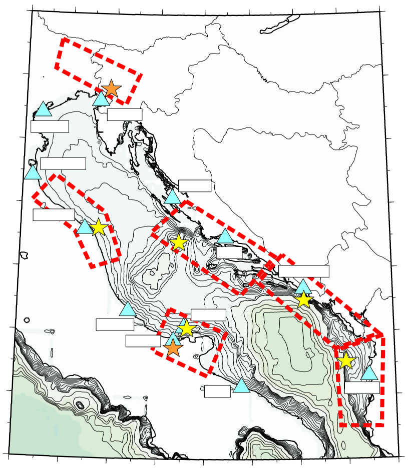


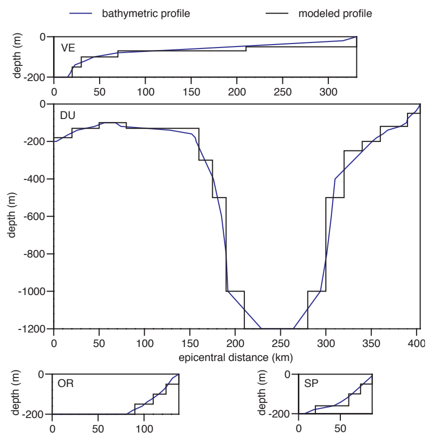
Bathymetric map of the Adriatic Sea. The bathymetric contours are drawn with a step of 20 m in the range from 0 to –200 m and with a step of 200 m in the range from –200 m to –1200 m.

The contours of the six tsunamigenic zones are shown in red, the blue triangles correspond to the 12 receiver sites, the stars correspond to the epicenters of the considered events (yellow: offshore, orange: inland).

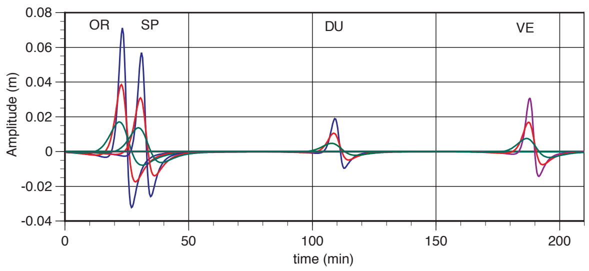
Paulatto M., Pinat T., Romanelli F. , 2007. Tsunami hazard scenarios in the Adriatic Sea domain". Natural Hazards And Earth System Sciences (on line), vol. 7, pp. 309-325.

Tsunami scenarios in Adriatic Sea - Zone 1





Bathymetric profiles to (from top) Venice (VE), Durres (DU), Ortona (OR) and Split (SP)



Synthetic mareograms for H =10 km (blue), 15 km (red), 25 km (green). Magnitude: M =6.5.

M		6.5			7.0			7.5		*Travel*
H (km)	10	15	25	10	15	25	10	15	25	*time (min)*
Durres	0.02	0.01	<0.01	0.11	0.06	0.03	0.60	0.33	0.15	*109*
Ortona	0.07	0.04	0.02	0.40	0.22	0.10	**2.25**	**1.22**	0.54	*23*
Split	0.06	0.03	0.01	0.32	0.17	0.08	**1.80**	0.98	0.43	*31*
Venice	0.03	0.02	0.01	0.17	0.09	0.04	0.97	0.53	0.24	*188*

Maximum amplitudes and related arrival times for different depths and magnitude

Tsunami scenarios in Adriatic Sea - Zone 6

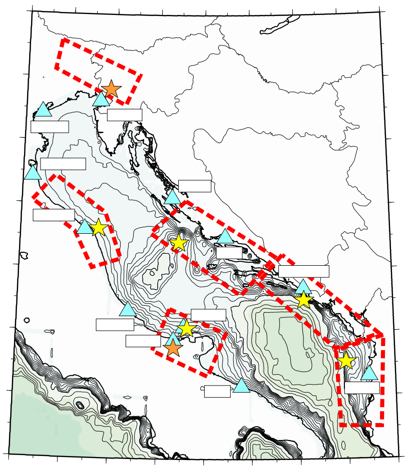
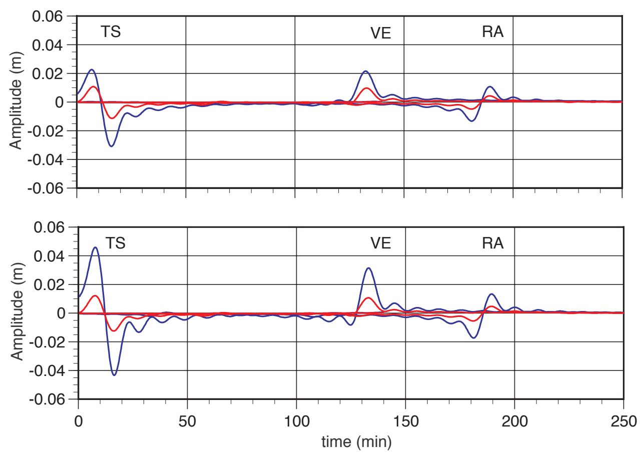


Table 7. Main parameters identifying the three sites of Zone 6.

Site	Latitude	Longitude	Epicentral dist. *R*
Trieste (TS)	45.67° N	13.77° E	30 km, 50 km
Venice (VE)	45.45° N	12.35° E	130 km, 150 km
Ravenna (RA)	44.42° N	12.20° E	210 km, 230 km

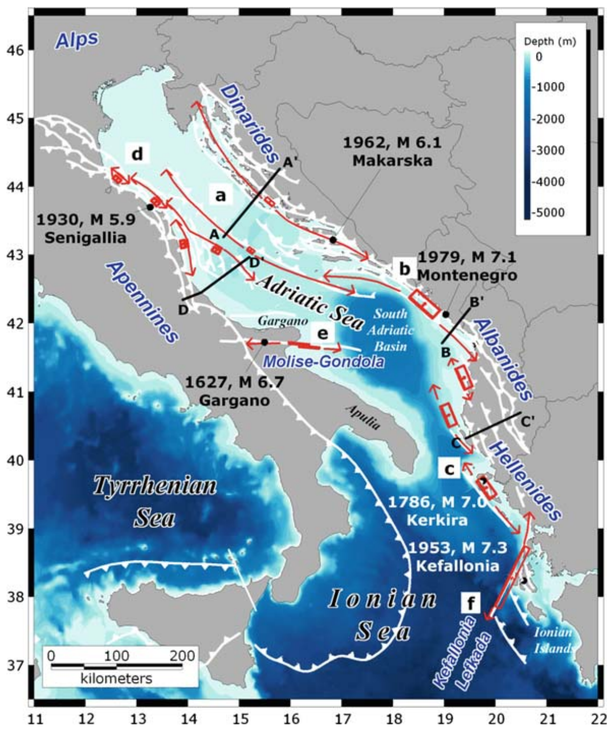


Synthetic mareograms for Zone 6, magnitude, M=7.0. Above: dip angle=45°; below: dip angle=30°. Blue line, d=20 km; red line, d=40 km.

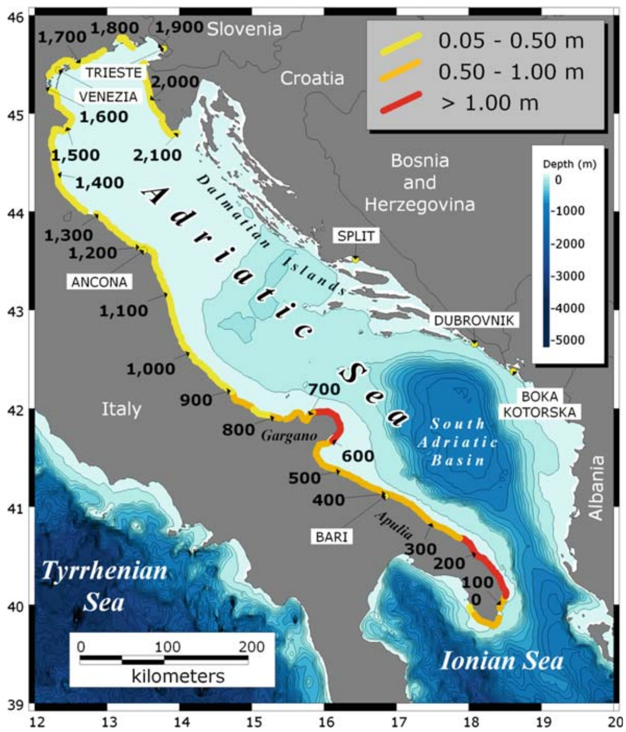
M	6.5		7.0		*Travel*
d (km)	20	40	20	40	*time (min)*
Trieste, dip = 45°	<0.01	<0.01	0.02	0.01	*7*
Trieste, dip = 30°	<0.01	<0.01	0.05	0.01	*8*
Venice, dip = 45°	<0.01	<0.01	0.02	0.01	*132*
Venice, dip = 30°	<0.01	<0.01	0.03	0.01	*133*
Ravenna, dip = 45°	<0.01	<0.01	0.01	<0.01	*189*
Ravenna, dip = 30°	<0.01	<0.01	0.01	<0.01	*189*

Maximum amplitudes and related arrival times for different depths and magnitude

Updating...



Tectonic sketch map of the Adriatic basin.
From Tiberti et al., 2009



Combined threat levels posed by all SZs considered by Tiberti et al., 2009

Pageoph, Volume 164, Numbers 2-3 / March, 2007

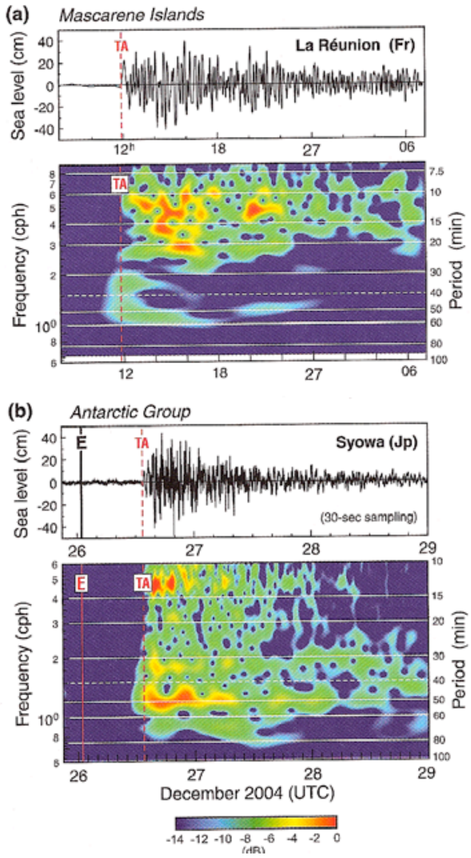
Tsunami and its Hazard in the Indian and Pacific Oceans

K. Satake, E. A. Okal and J. C. Borrero

Measurement of tsunami waves

Tide gauges can measure TW along the coast...

Tsunami records and their f-t diagram: solid line (E) is the time of main shock, dashed line (TA) is Tsunami arrival



The 26 December 2004 Sumatra Tsunami: Analysis of Tide Gauge Data from the World Ocean Part 1. Indian Ocean and South Africa

Alexander B. Rabinovich and Richard E. Thomson

Measurement of tsunami waves

Tide gauges can measure TW along the coast, but their detection in open ocean is challenging, due to their wavelengths and amplitudes.

ocean bottom sensors

(pressure gauges & seismometers)

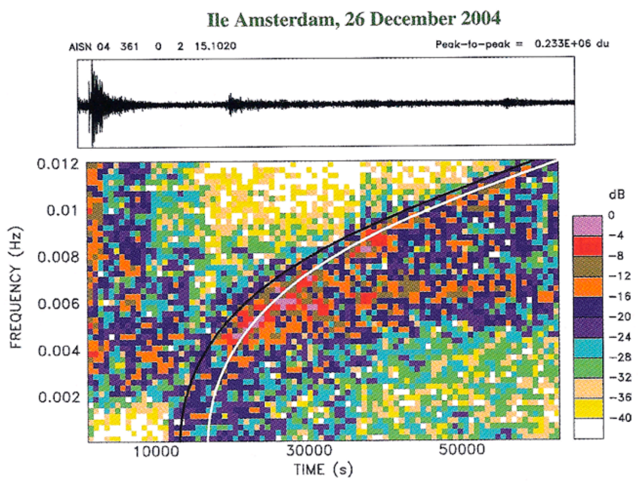


Figure 4

Spectrogram of the tsunami recording at AIS (Ile Amsterdam). The individual pixels identify the spectral amplitude present in the wave train as a function of time (abscissa) and frequency (ordinate), according to the logarithmic scale at right. In order to emphasize the high frequencies in the record, we processed the raw seismogram, without deconvolution of the instrument response. The black curve is the dispersion expected from equation (1) for a 4-km deep ocean basin and a source at the epicenter of rupture. The white curve uses a 3.5-km basin and places the source at the centroid of rupture (TSAI *et al.*, 2005).

Seismic Records of the 2004 Sumatra and Other Tsunamis: A Quantitative Study

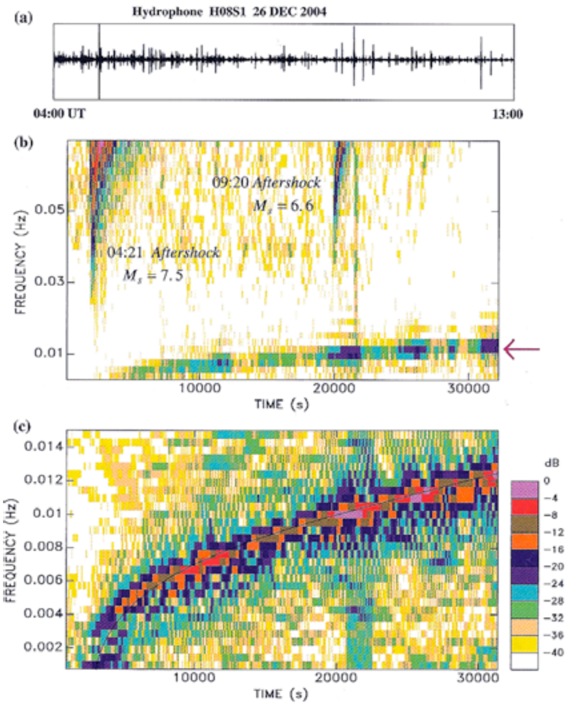
Emile A. Okal

Measurement of tsunami waves

Tide gauges can measure TW along the coast, but their detection in open ocean is challenging, due to their wavelengths and amplitudes.

ocean bottom sensors

hydrophones
(towards "high" frequency bands...)



a) Raw time series
b) spectrogram
c) close-up of the tsunami branch and comparison with
$w^2 = gk\tanh(kH)$

Quantification of Hydrophone Records of the 2004 Sumatra Tsunami
Emile A. Okal, Jacques Talandier and Dominique Reymond

Measurement of tsunami waves

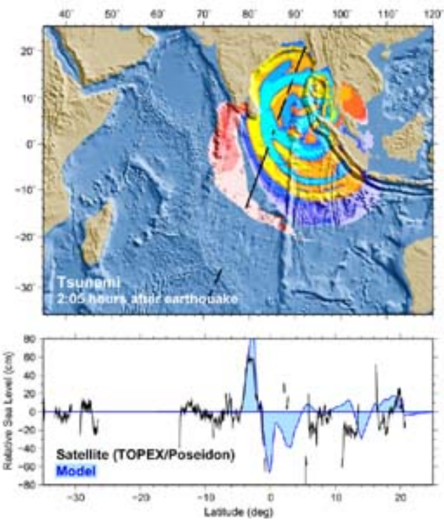
Tide gauges can measure TW along the coast, but their detection in open ocean is challenging, due to their wavelengths and amplitudes.

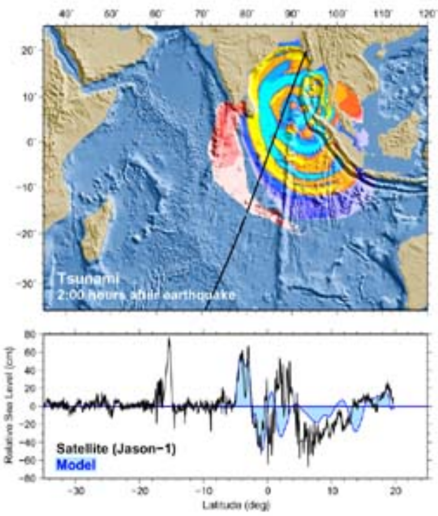
ocean bottom sensors (pressure gauges or seismometers)

sea level measurement (GPS receivers on buoys)

satellite altimetry

NOAA

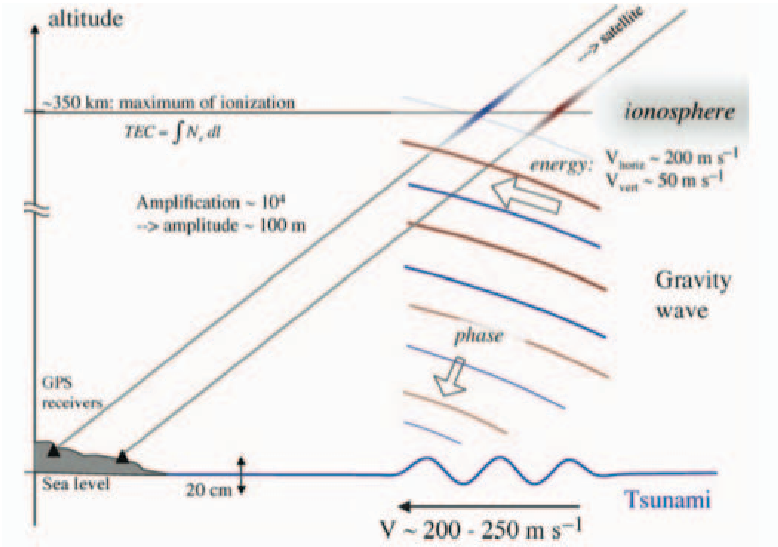




Tsunami signature in the ionosphere

By dynamic coupling with the atmosphere, acoustic-gravity waves are generated

Traveling Ionospheric Disturbances (TID) can be detected and monitored by high-density GPS networks



Tsunami signature in the ionosphere

Hines (1960): atmospheric Internal Gravity Waves

Peltier & Hines (1972): can generate ionospheric signatures in the plasma

Lognonné et al. (1998): Analytical Coupled model

Artru et al. (2005): ionospheric imaging can detect tusnami signatures. GPS JAPAN net was used to map Chilean Tsunami of 2001

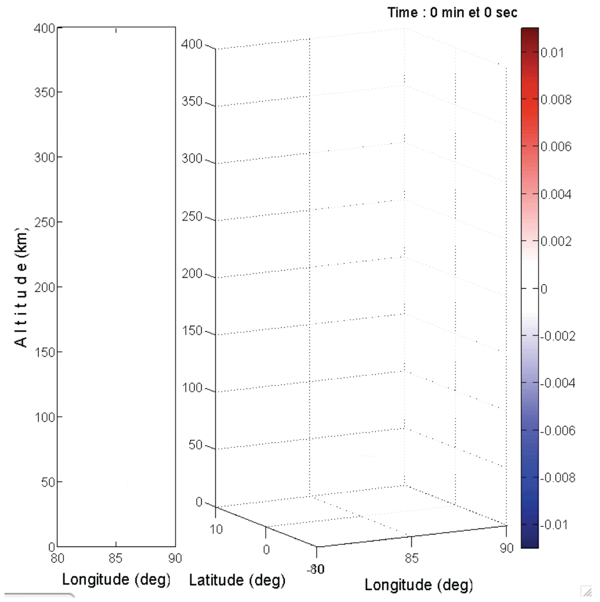
Occhipinti et al. (2006): Sumatra tsunami mapped

Three-dimensional waveform modeling of ionospheric signature induced by the 2004 Sumatra tsunami

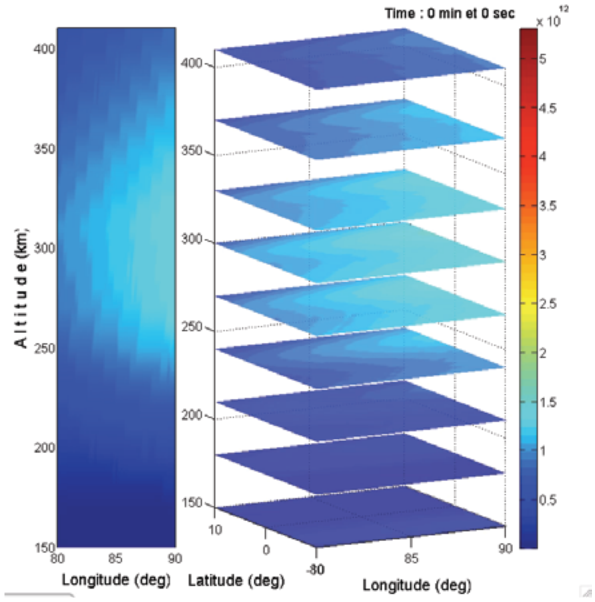
Giovanni Occhipinti, Philippe Lognonné, E. Alam Kherani and Helene Hebert
GRL, 2006, 33

Tsunami signature in the ionosphere

Tsunami-generated IGWs and the response of the ionosphere to neutral motion at 2:40 UT.

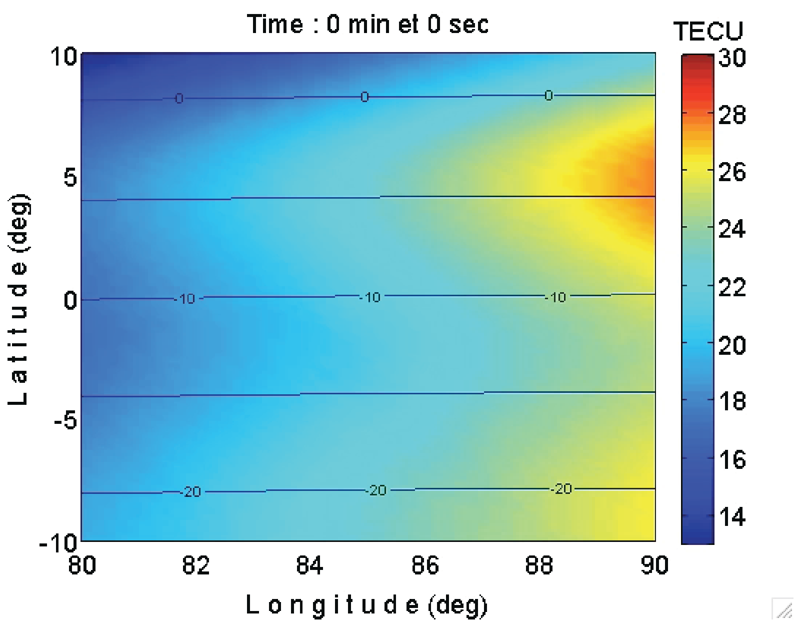


Normalized vertical velocity



Perturbation in the ionospheric plasma

Tsunami signature in the ionosphere



SHA: Road map

- Some remarks on SHA
  - Source & site effects
  - Integrated methodology
- Groundshaking scenarios modelling
  - Methodology & Case studies

SHA dualism

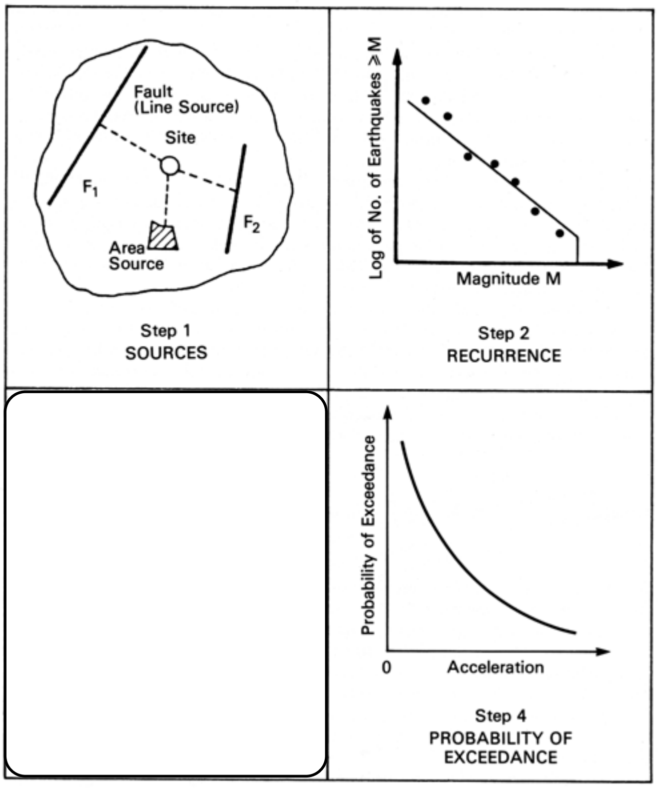


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

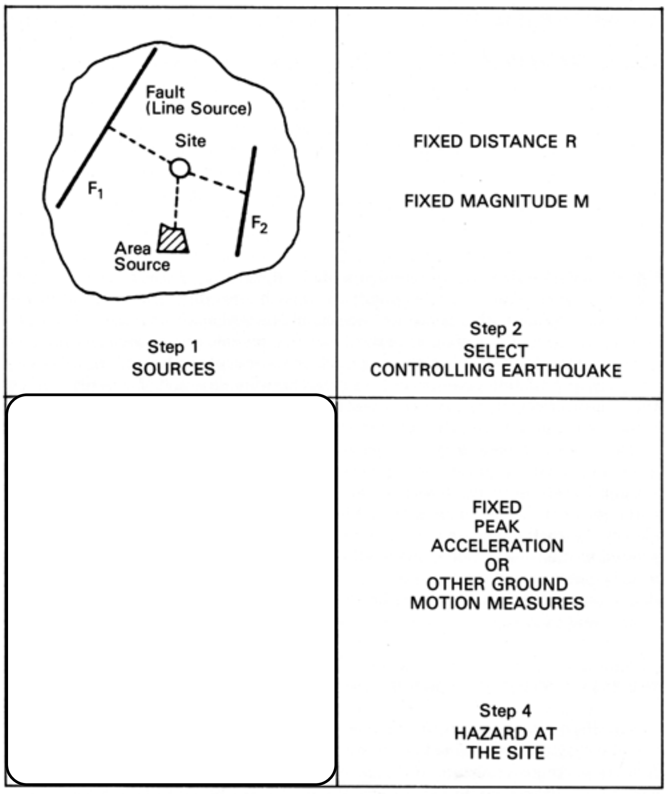
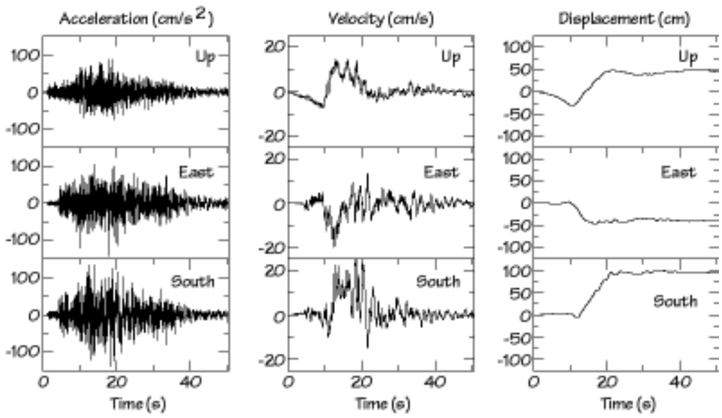


FIGURE 4.1 Basic steps of deterministic seismic hazard analysis (after TERA Corporation 1978).

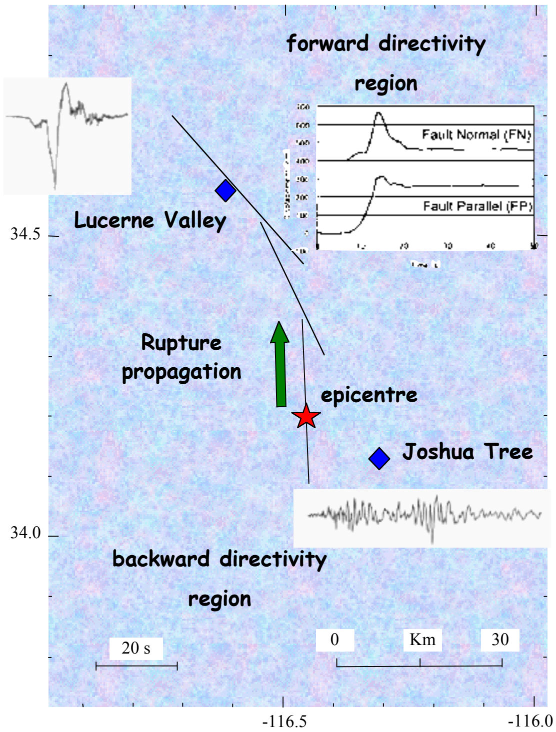
Probabilistic and Deterministic procedures (after Reiter, 1990)

Source effects...



Michoacan, 1985

Fling & Directivity
aka
Near-field (& source)



Landers, 1992

Near fault ground motion

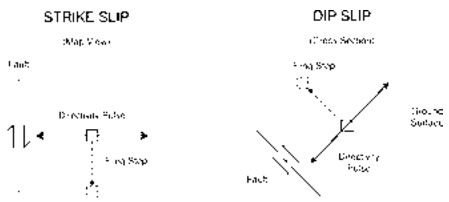


Fig. 4.3. Schematic diagram showing the orientations of fling step and directivity pulse for strike-slip and dip-slip faulting.

Peer report, 2001

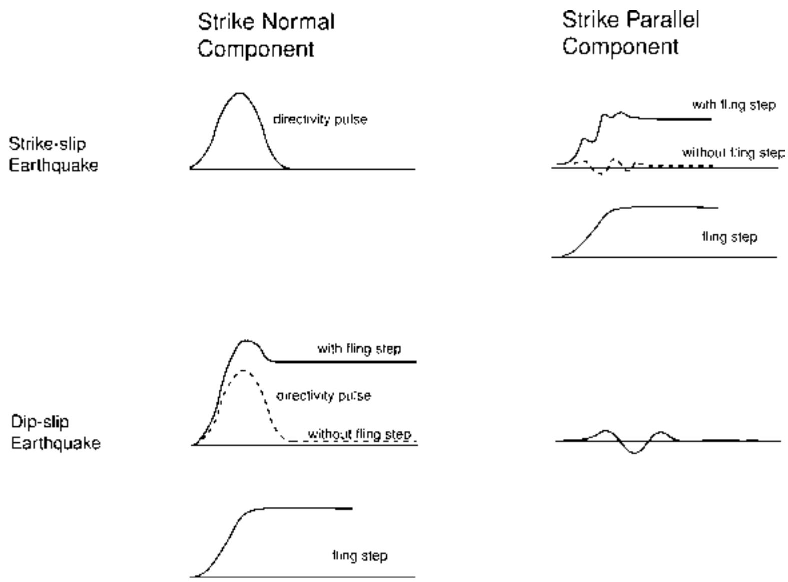
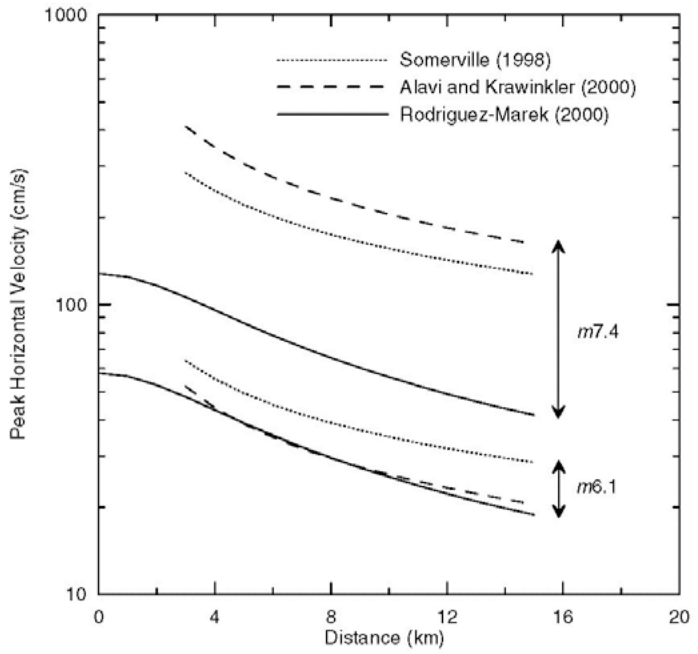


Fig. 4.4. Schematic diagram of time histories for strike-slip and dip-slip faulting in which the fling step and directivity pulse are shown together and separately.

Regression example...



Peer report, 2001

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

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

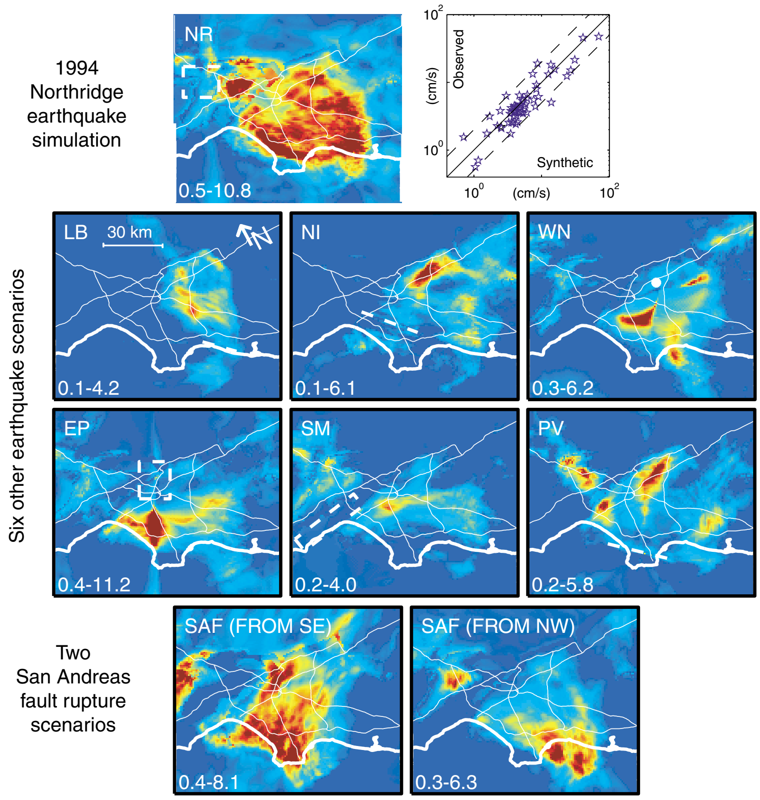
Alavi and Krawinkler (2000):
$\ln(\mathrm{PHV}) = -5.11 + 1.59\,m - 0.58\,\ln(r)$

Amplification patterns...

....may vary greatly among the earthquake scenarios, considering different source locations (and rupture ...)

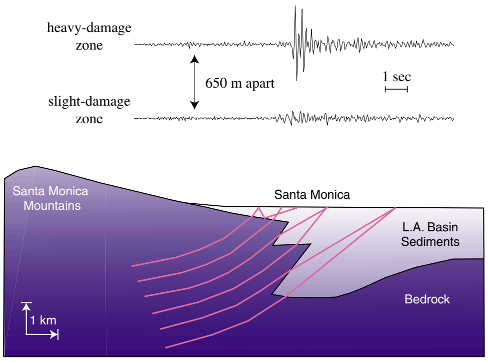
Peak Velocity Amplification from the 3D Simulations of Olsen (2000)

SCEC Phase 3 Report



Important issues in SRE

- Near surface effects: impedance contrast, velocity
    - geological maps, v_{30}
- Basin effects
    - Basin-edge induced waves
    - Subsurface focusing



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 effects 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?

PGA as a demand parameter…

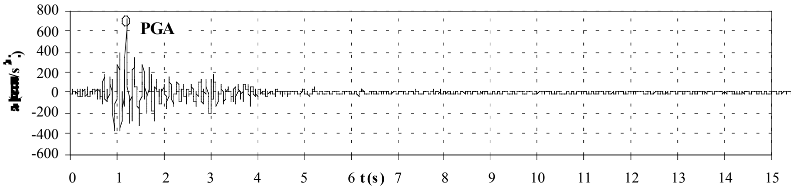


Figure 1 – Acceleration time history. Rocca NS record. 1971 Ancona earthquake (M_L=4.7)

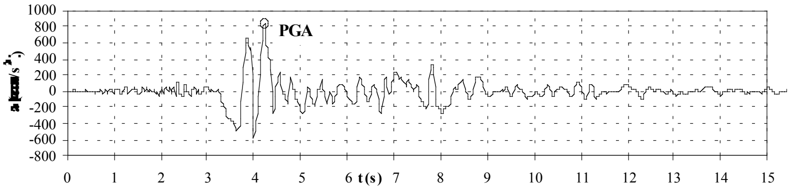
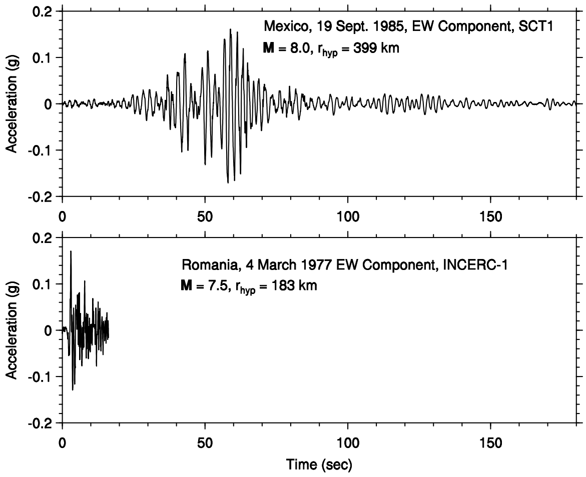


Figure 2 – Acceleration time history. Sylmar N360 record. 1994 Northridge earthquake (M_w=6.7)



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

Integrated SHA

Intermediate-term medium-range predictions

Restrained area for expected sources + time

Pattern recognition of earthquake prone areas (nodes)

Ground motion scenarios

Space& time info for seismic Risk

Seismic Input for engineering analysis

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.

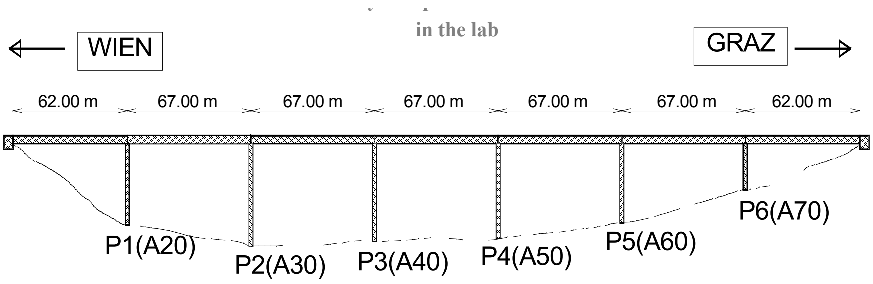
Effects on bridge seismic response of asynchronous motion at the base of bridge piers

Romanelli F., Panza G.F. , Vaccari, F., 2004.
Realistic Modelling of the Effects of Asynchronous motion at the Base of Bridge Piers, Journal of Seismology and Earthquake Engineering, Vol. 6, No. 2, pp. 19-28

Warth bridge

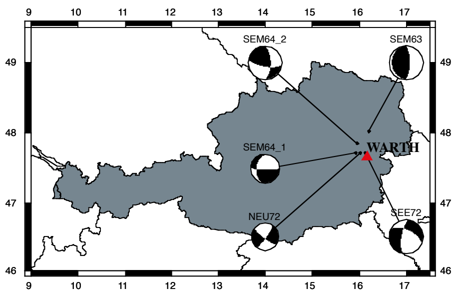
The bridge was designed for a horizontal acceleration of 0,04 g using the quasi static method.

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.



Warth bridge - Seismic sources

1) **Database of focal mechanism**



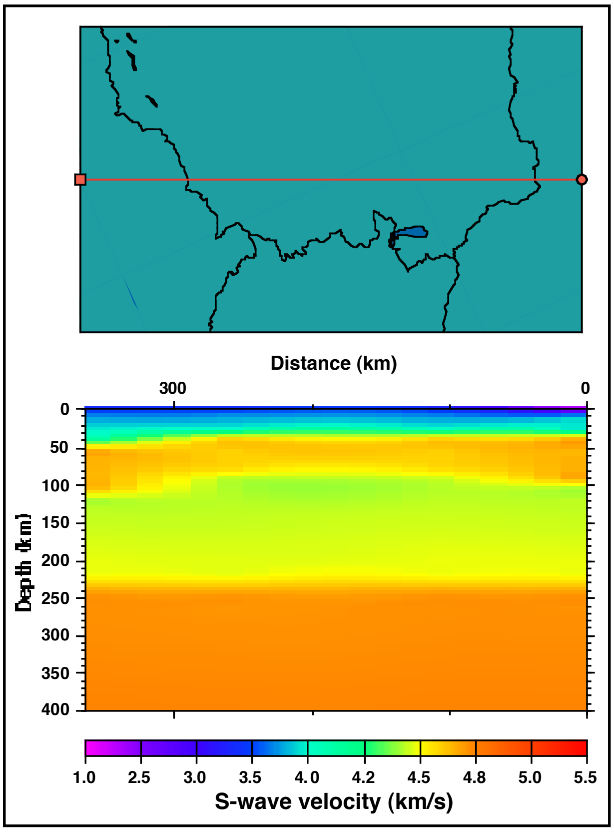
2) **Parametric study on focal mechanism:**
strike
dip
rake
depth

Maximum Historical Earthquake

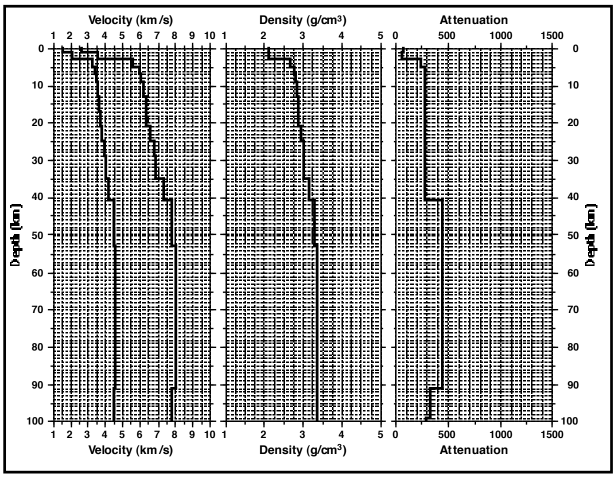
Maximum Credible Earthquake

Maximum Design Earthquake

Warth bridge - Regional model

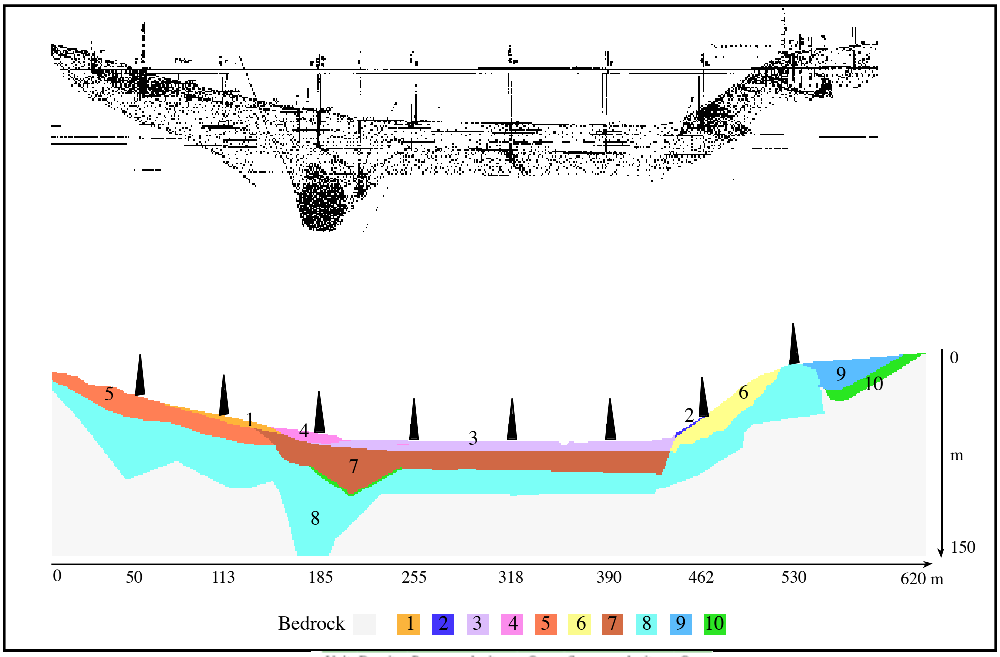


EUR I data set



SHA

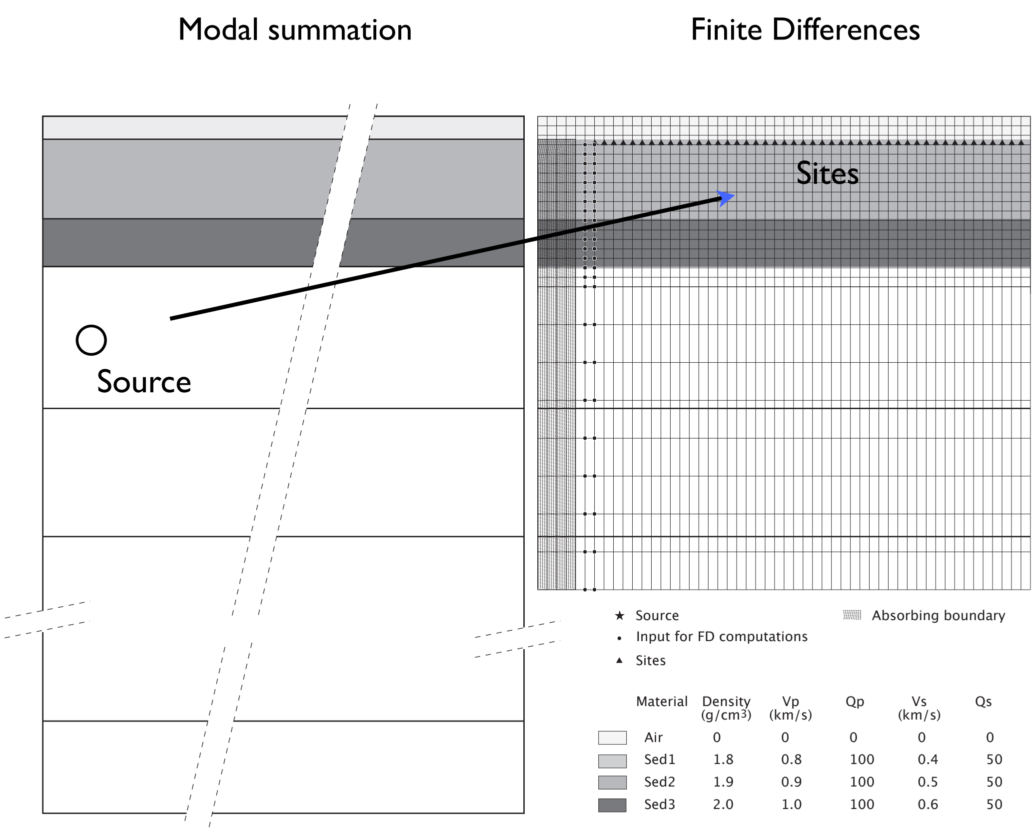
Warth bridge - Local model



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

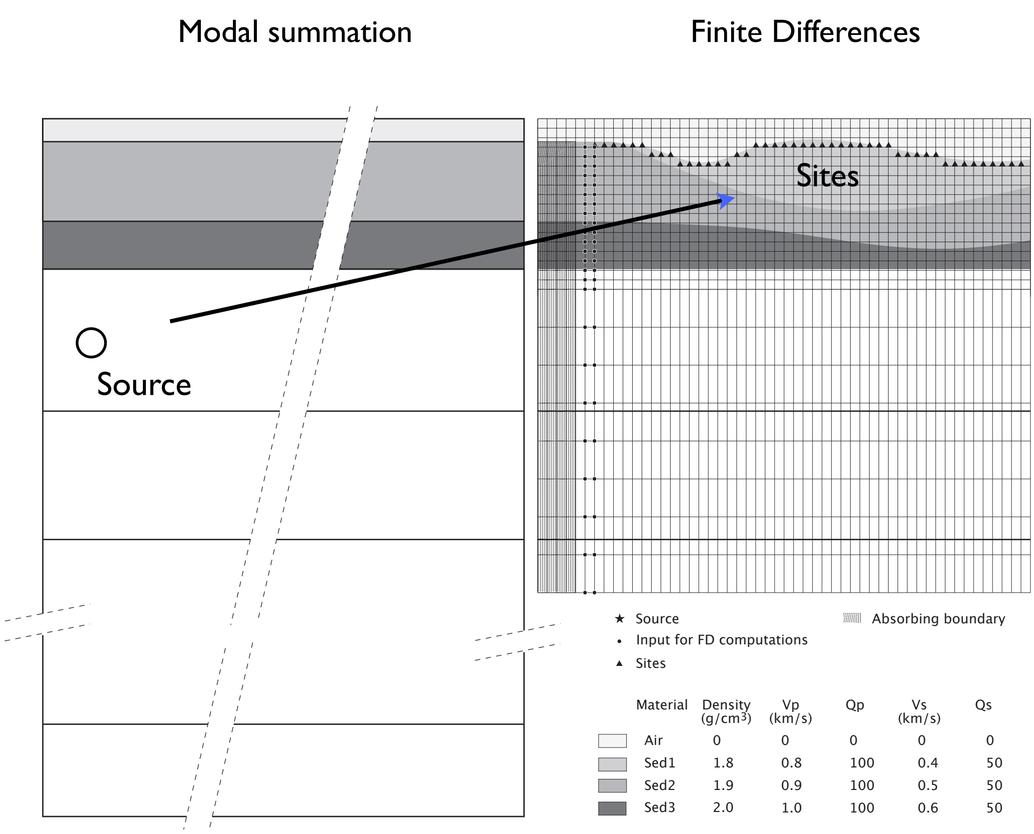
SHA

Methodology - Hybrid technique (local scale)



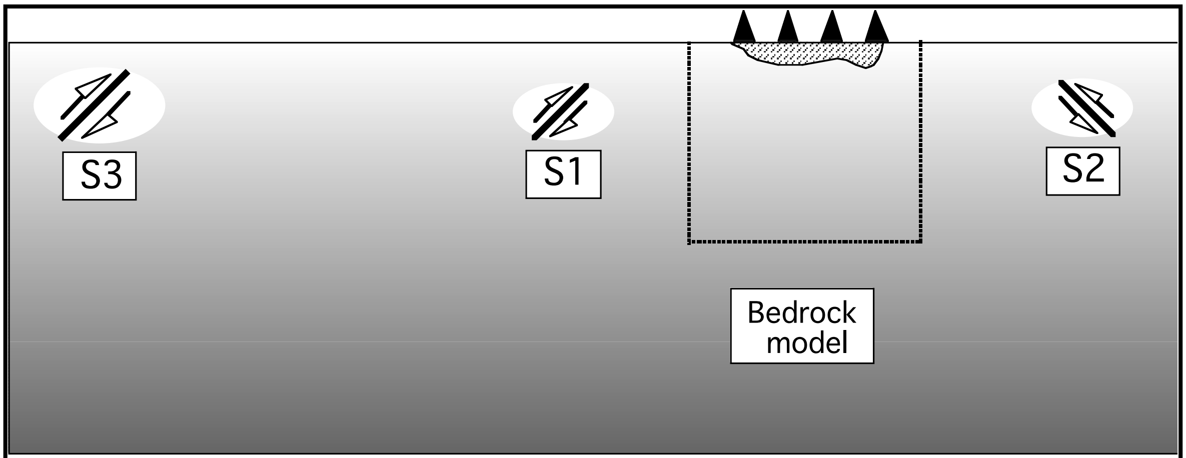
Material	Density (g/cm3)	Vp (km/s)	Qp	Vs (km/s)	Qs
Air	0	0	0	0	0
Sed1	1.8	0.8	100	0.4	50
Sed2	1.9	0.9	100	0.5	50
Sed3	2.0	1.0	100	0.6	50

Methodology - Hybrid technique



Material	Density (g/cm3)	Vp (km/s)	Qp	Vs (km/s)	Qs
Air	0	0	0	0	0
Sed1	1.8	0.8	100	0.4	50
Sed2	1.9	0.9	100	0.5	50
Sed3	2.0	1.0	100	0.6	50

Different source-sites configurations



S3
Mw = 6.0
Distance = 50 km

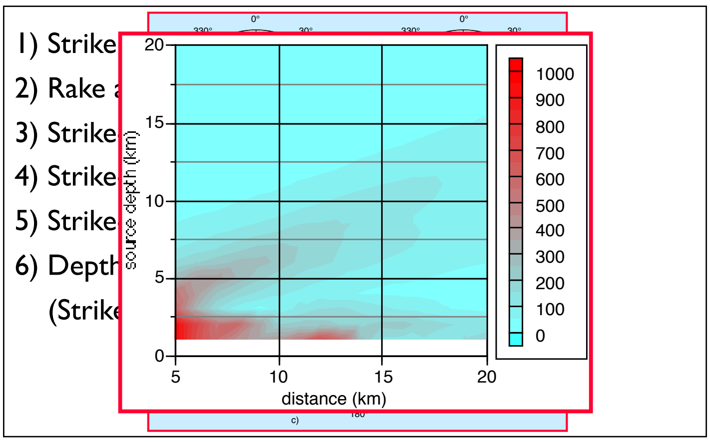
S1
Strike = 190°
Dip = 70°
Rake = 324°
Depth = 5 km
Mw = 5.5
Distance = 8.7 km

S2
Mw = 5.5
Distance = reverse

PARAMETRIC STUDY 1
Focal Parameters towards MCE

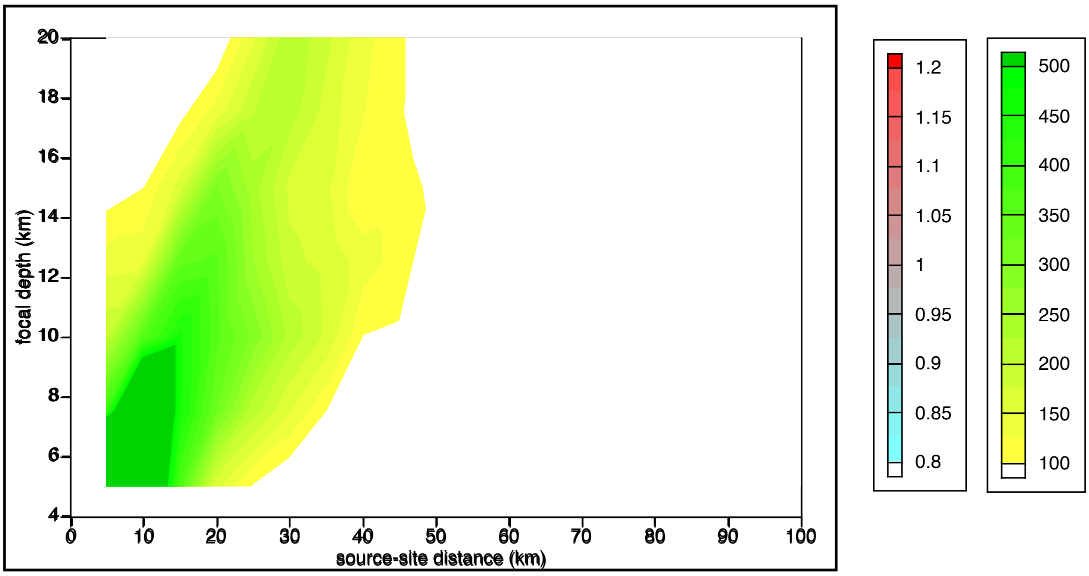
All the focal mechanism parameters of the original source model have been varied in order to find the combination producing the maximum amplitude of the various ground motion components.

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



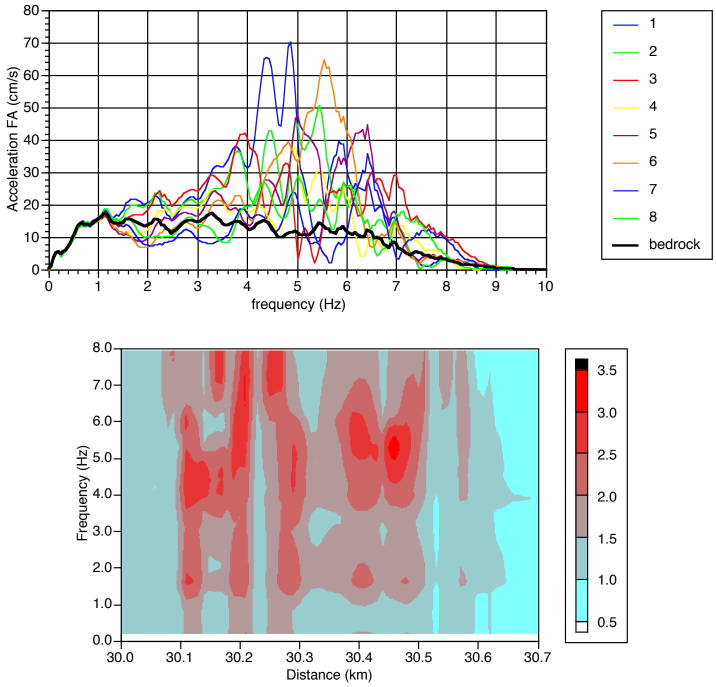
PARAMETRIC STUDY 2 - Fp towards 1Hz

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.



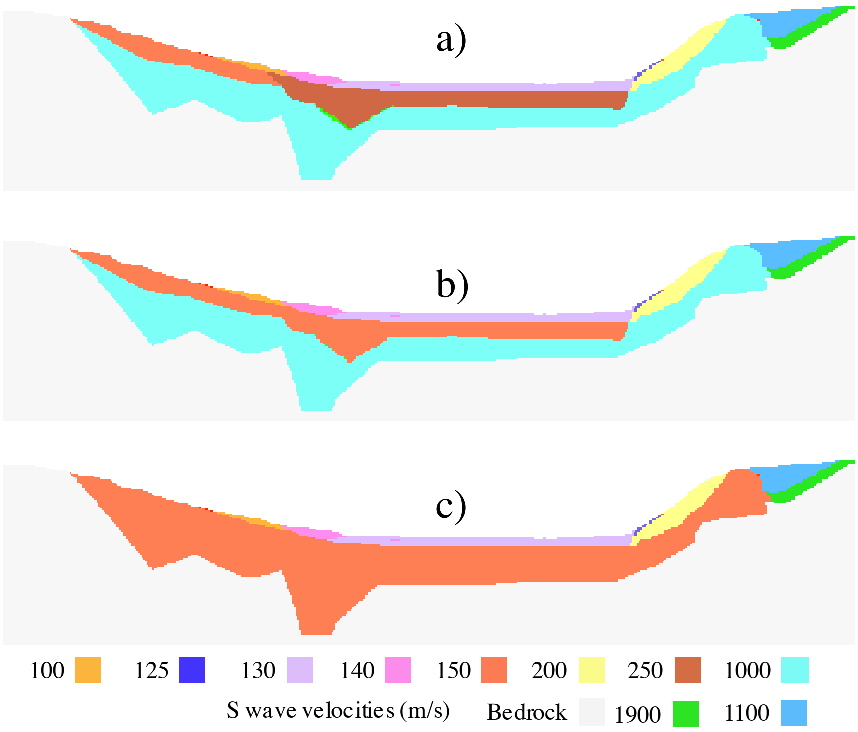
The results show that, in order to reach a relevant value of PGA (e.g. greater than 0.1g) in the desired period range (i.e. 0.8-1.2 s), an alternative and suitable configuration is a source 12 km deep at an epicentral distance of 30 km.

Parametric study 2 - FS & RSR



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

Parametric study 3 - LMp towards 1Hz

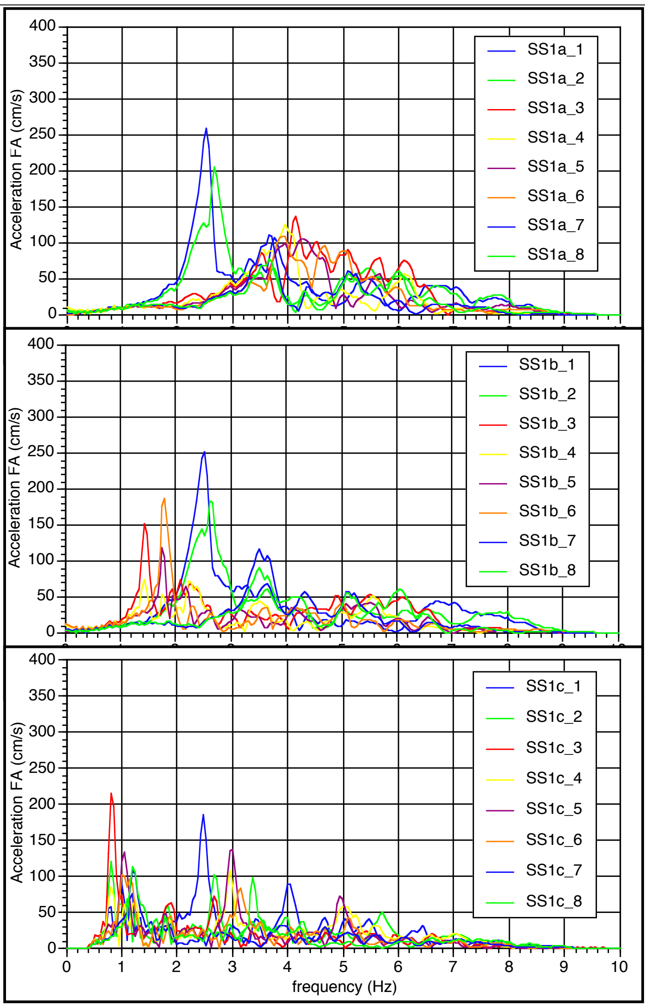


Local geotechnical models of Warth bridge section obtained lowering successively the S-wave velocities of the uppermost units

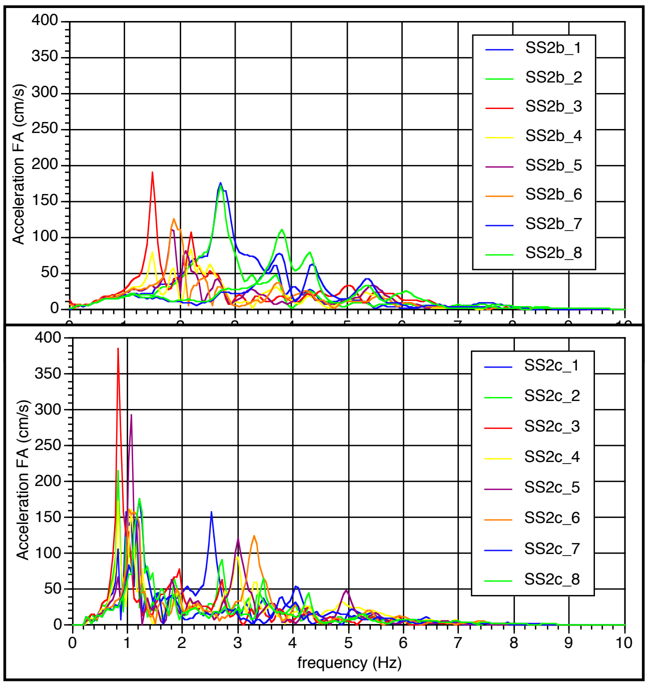
SHA

Fourier Amplitude spectra

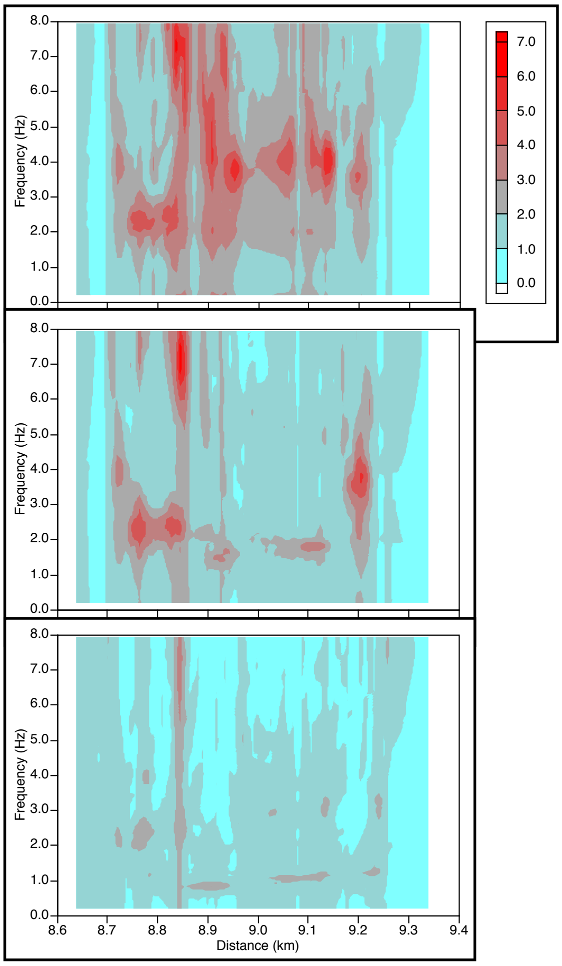
M=5.5; d=8.6km; h=5km



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

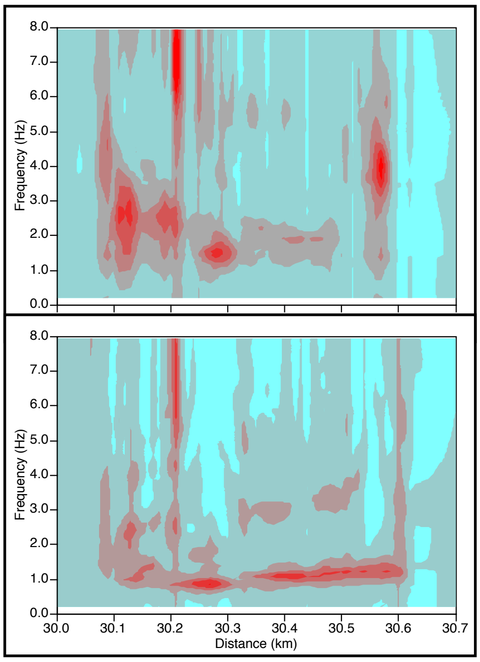


SHA

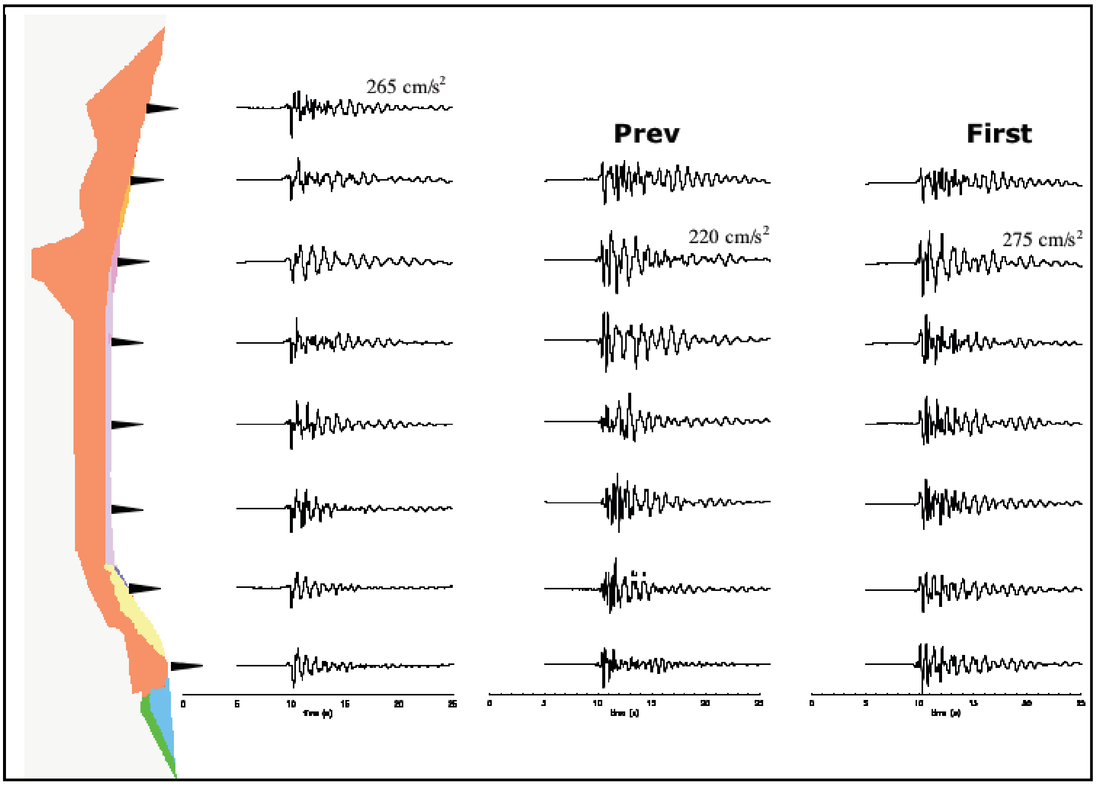


Site response estimation M=5.5; d=8.6km; h=5km

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

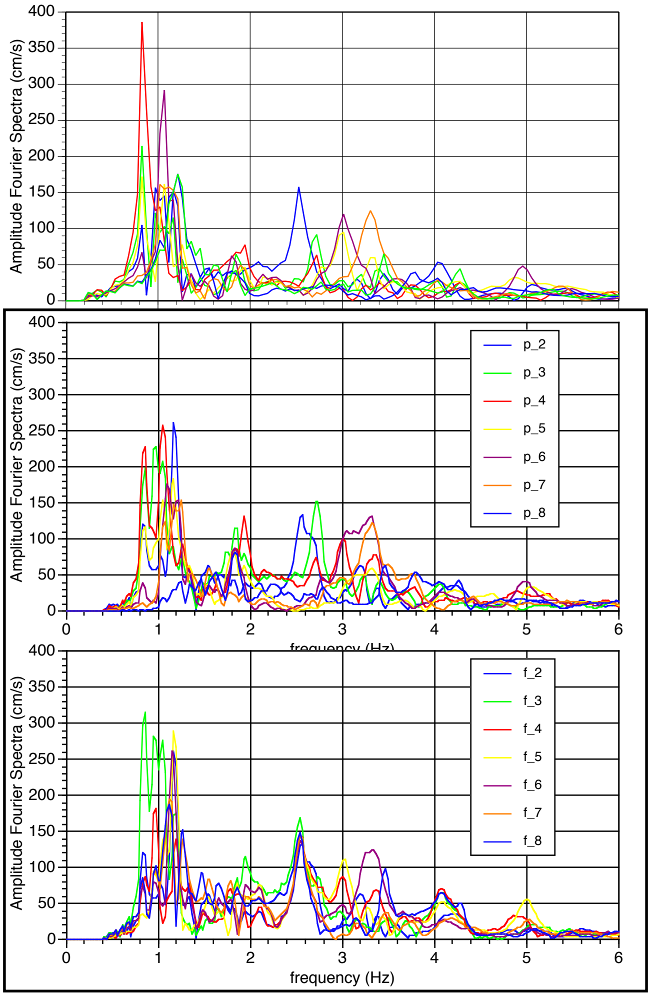


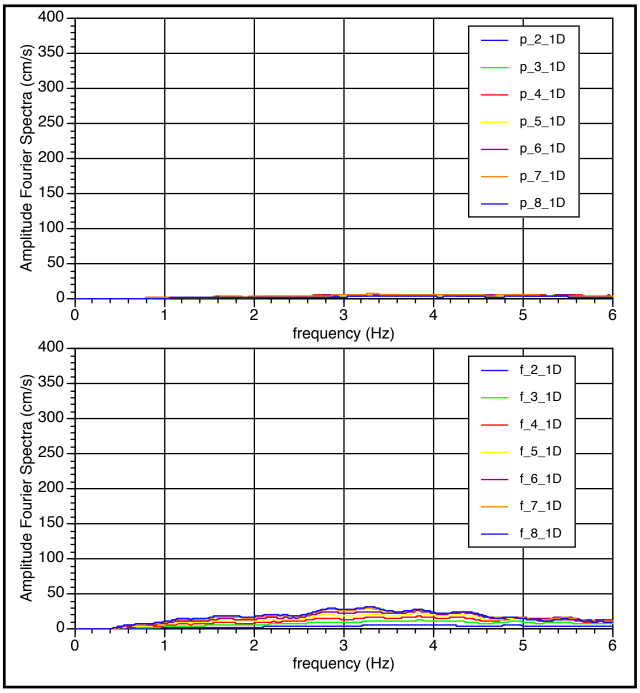
Synthetic accelerations and diffograms



Fourier AS of diffograms

Bedrock





SHA

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

Master experimental process

Numerical models for the substructured piers A20, A30

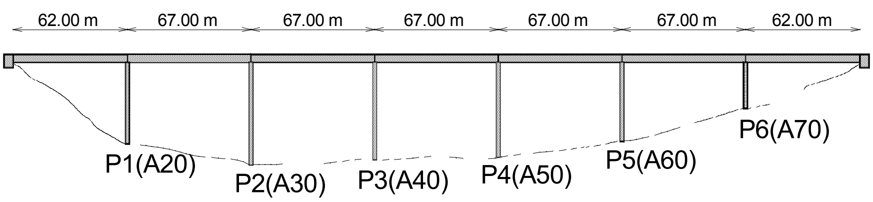
Numerical models for the substructured piers A50, A60

Numerical model for the deck and PSD master

Warth Bridge

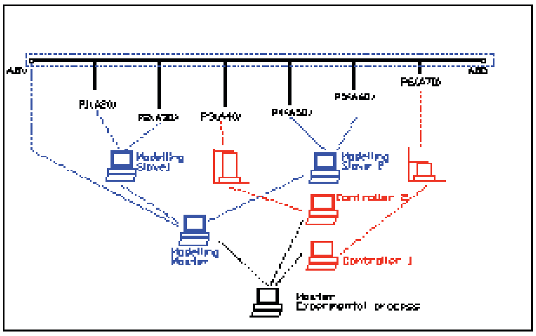
WIEN

GRAZ

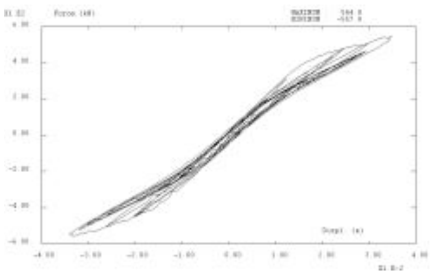


SHA

Implementation of PSD tests

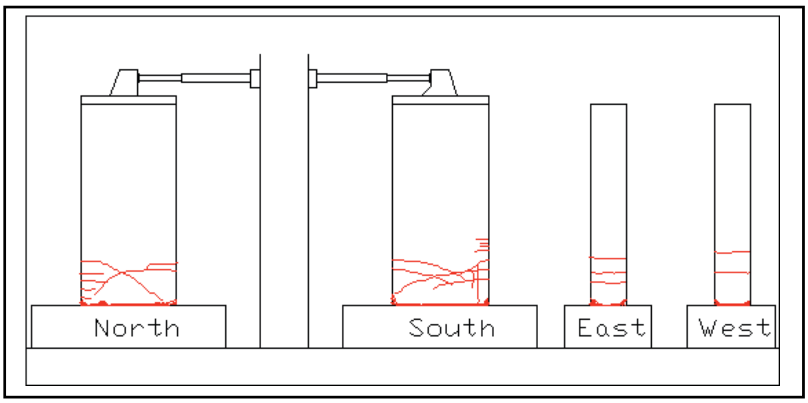


(a) physical piers in the lab, (b), schematic representation
(c) workstations running the PSD algorithm and controlling the test



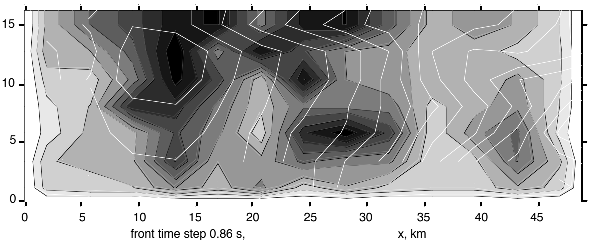
Force-displacement for Low-level earthquake - experimental results Pier A40

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



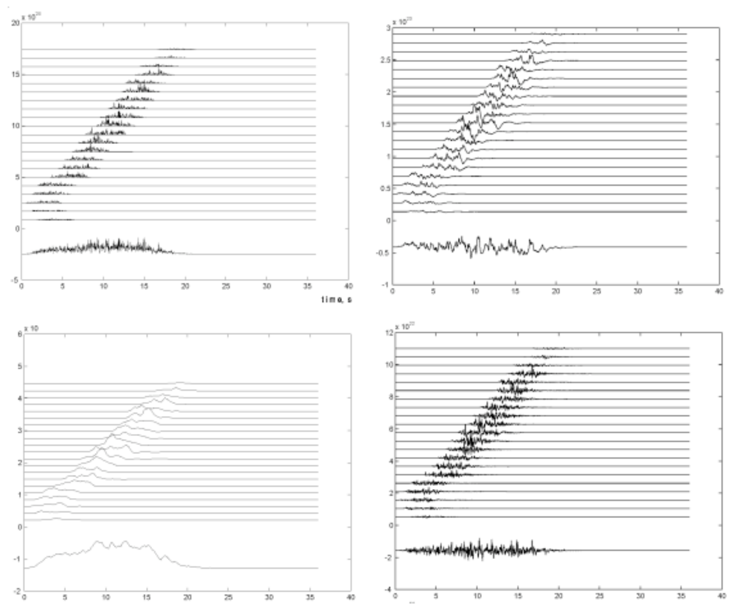
Damage pattern after the end of the High-Level Earthquake PSD test, short pier A70.

Extended source model

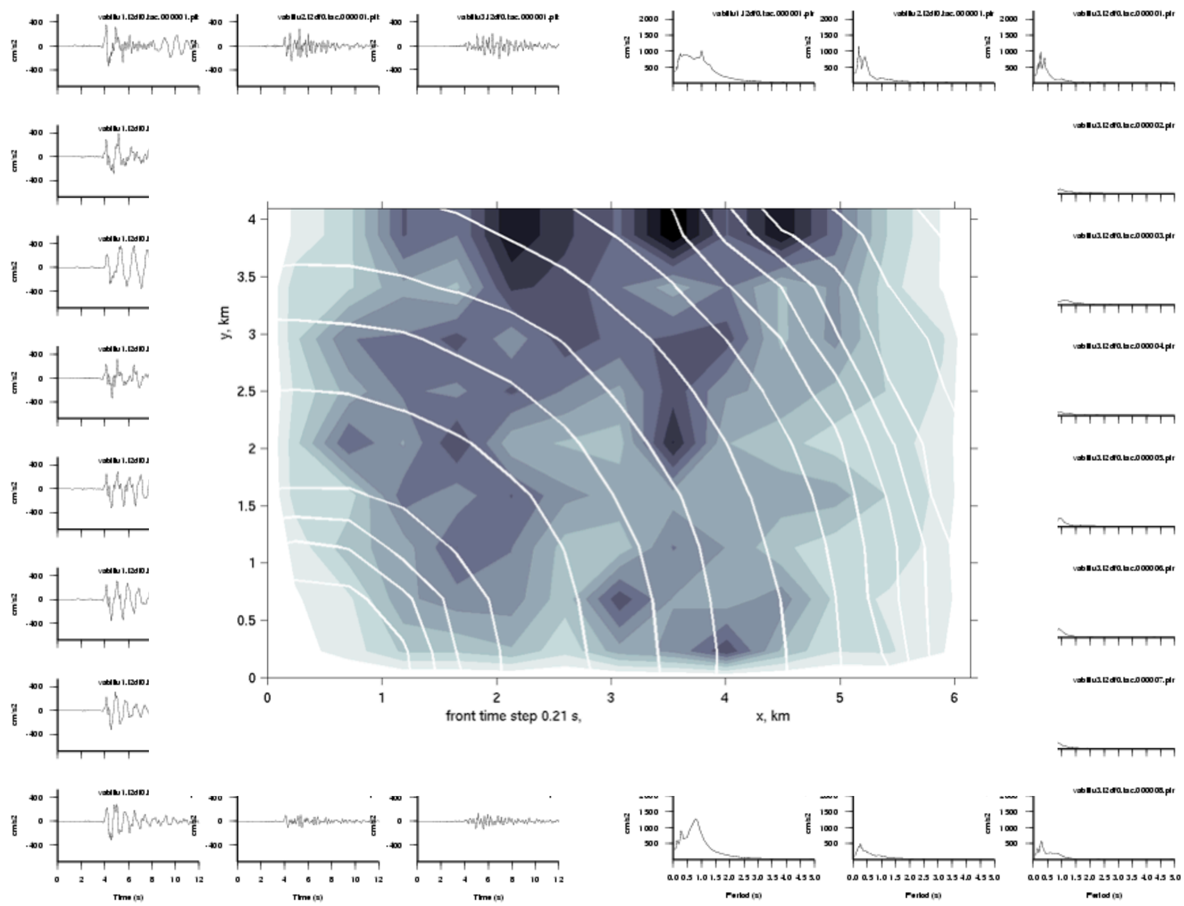


2-dimensional final slip distribution over a source rectangle, shown as a density plot. Preset magnitude value Mw=7.0. Rupture front evolution was simulated kinematically from random rupture velocity field.

Space-time histories for each of 21 subevents of the simplified “line” source model of a simulated Mw=7 earthquake, and sum over subevents, giving the entire-source far-field time function

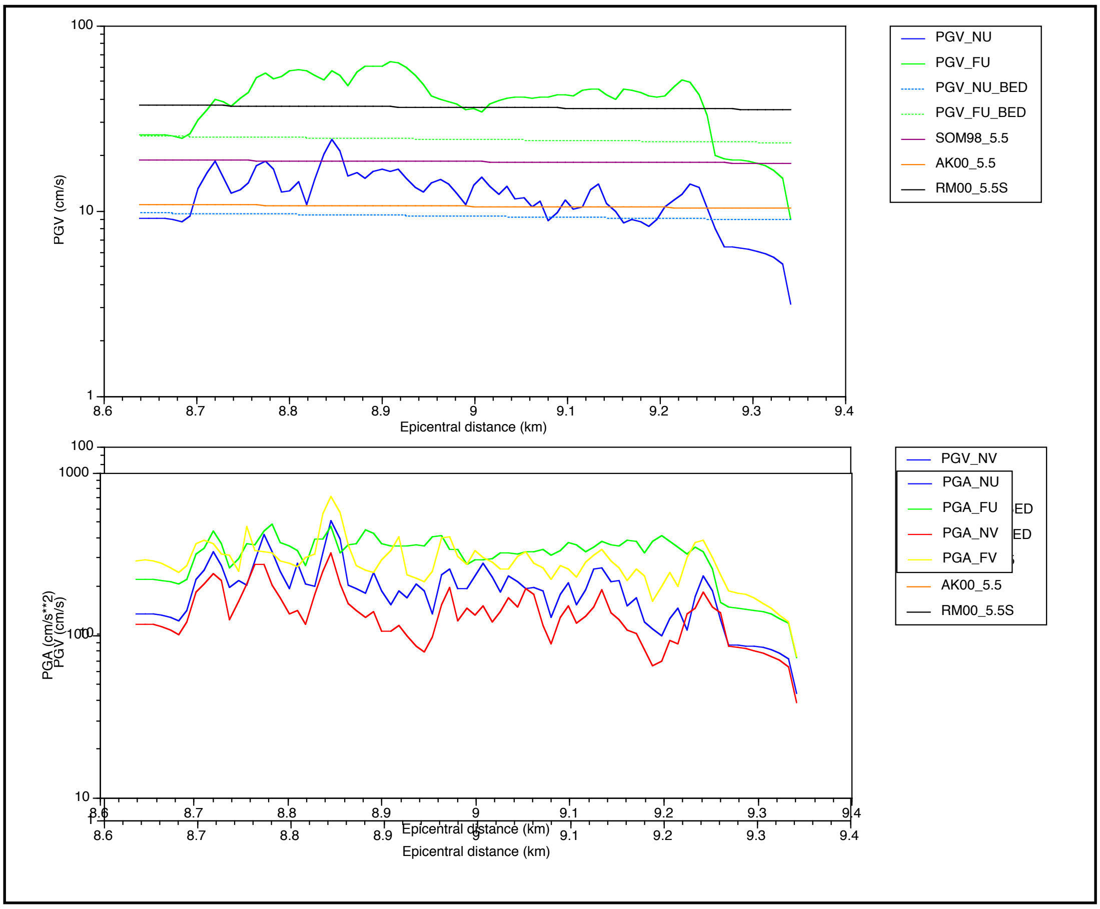


Directivity parametric study



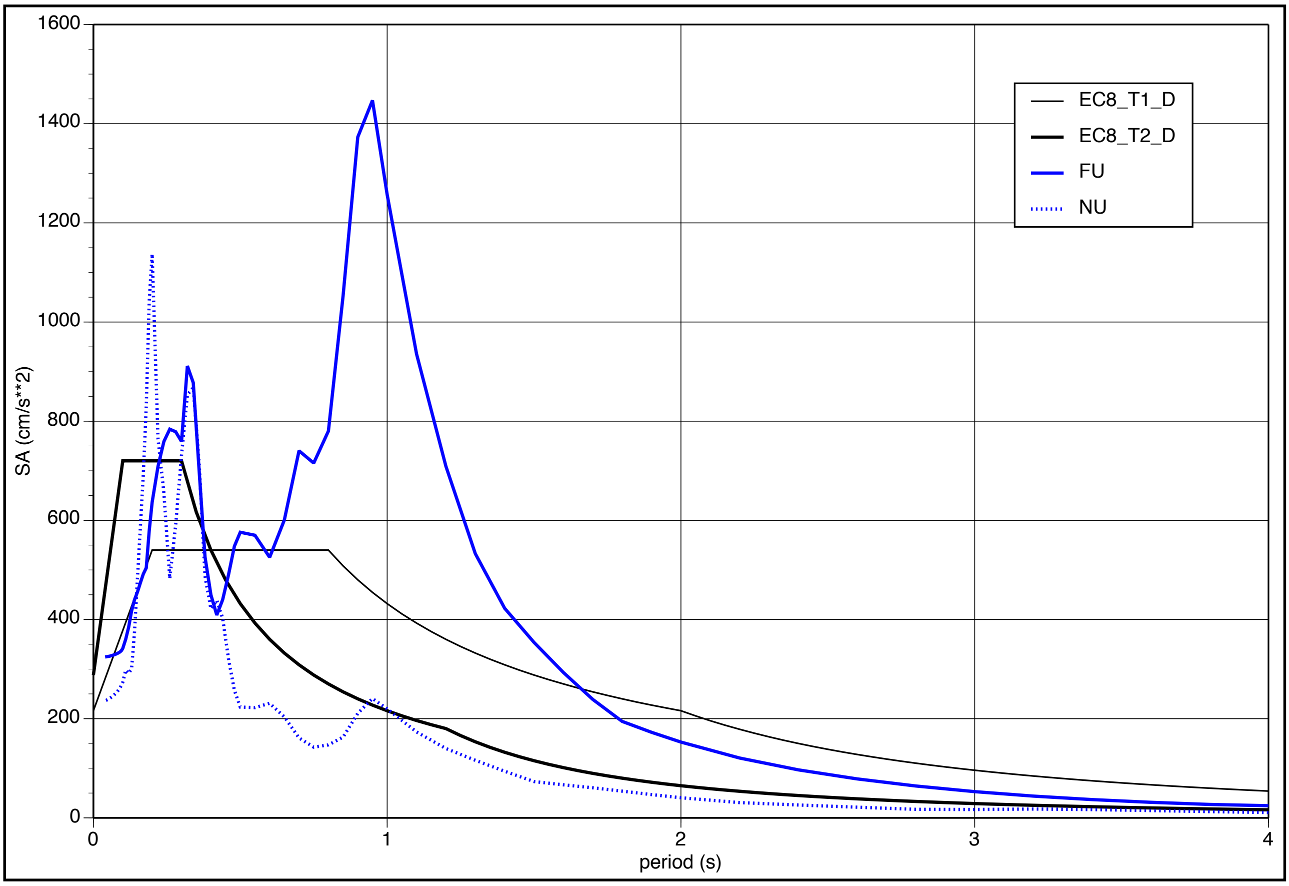
SHA

Directivity & PGV - PGA



SHA

Directivity & SA



SHA