Anisotropy & ground motions for engineering

ErSE390 Seismic waves

Table of contents

During this course, many phenomena that affect seismic waves haven't been looked at so far. Some problems arise due to the multi-scale nature of these phenomena, where microscopic processes influence wave propagation on macroscopic scales. Furthermore, the interaction of seismic waves with complex structures leads to a plethora of effects to investigate. Finally, we mostly focused on elastic media, although acoustic and poroelastic media are equally important.

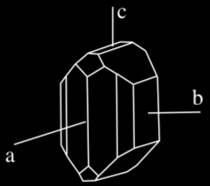
In the following, we will mention a few topics, mostly with the intent to provoke curiosity and motivate you to further dive into these fields and subjects of studies.

Anisotropy

Seismic wave propagation in the Earth is influenced by anisotropic rocks (or media). First, let us distinguish between:

intrinsic anisotropy

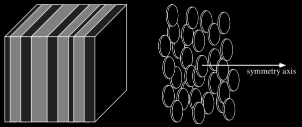
anisotropic rocks with lattice-preferred orientation (LPO) minerals, e.g., olivine



olivine (orthorhombic)

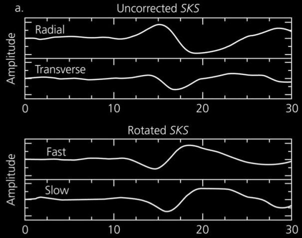
apparent anisotropy

anisotropic rocks with shape-preferred orientation (SPO), fine layering, fractures, etc., which causes seismic anisotropy at longer wavelengths compared to the scalelength of the heterogeneity

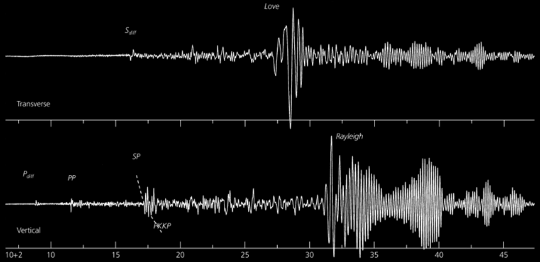


The two major observations of seismic anisotropy are:

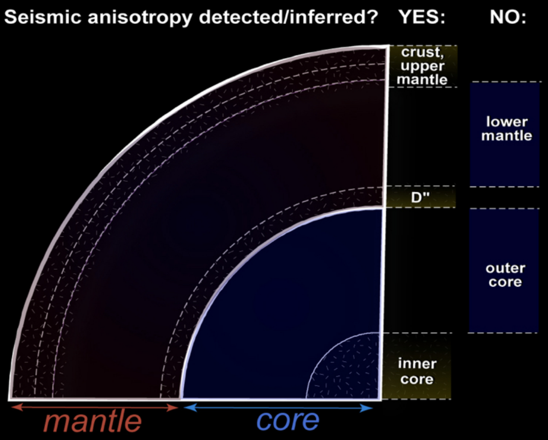
Shear-wave splitting:
for example on SKS, PKS (polarized in radial direction at the CMB) for crust/mantle anisotropy



Love/Rayleigh discrepancy:
fast Love waves, slower Rayleigh waves.



Both observations, although more clearly in SKS splitting, come with a dependency on azimuth (e.g., in the Pacific).



Observed anisotropy is assumed to come from the crust, upper mantle, D″ region and the inner core. Inner core anisotropy is thought to have a symmetry axis in the direction of the Earth's rotation axis.

Stress-strain relationship

For seismic wave propagation, Hooke's law for a fully anisotropic elastic media describing the stress-strain relationship can be written as

$$\tau_{ij} = c_{ijkl}\,\epsilon_{ij}$$

with stress tensor τ, strain tensor ϵ and the elastic tensor $\mathbf{c}$ characterizing the anisotropic media. Due to the symmetries $c_{ijkl} = c_{jikl} = c_{ijlk} = c_{klij}$, the fully anisotropic elastic tensor has 21 free parameters.

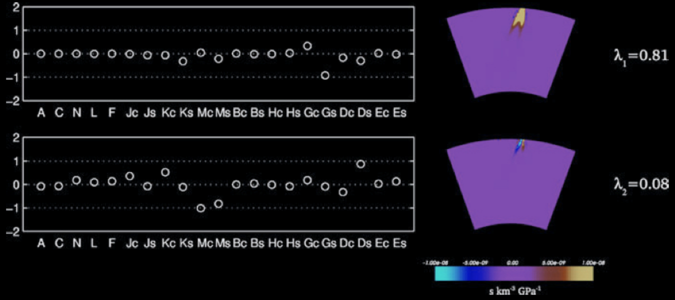
Often, an additional hexagonal symmetry is assumed for seismological problems. This symmetry has a principal axis with any direction normal to this axis having the same properties.

In case the symmetry axis is radial, its called radial anisotropy or **transverse isotropy** in global seismology. In exploration, if the axis is vertical it is called **vertical transverse isotropy** (VTI). Transversely isotropic media can be characterized by 5 independent parameters, e.g., $(\alpha_v, \alpha_h, \beta_v, \beta_h, \eta)$ or by a Love parameterization (A, C, L, N, F). As example, vertically polarized shear-wave speed $\beta_v = \sqrt{\frac{L}{\rho}}$ and horizontally polarized $\beta_h = \sqrt{\frac{N}{\rho}}$.

General hexagonal anisotropy is additionally specified by a direction of its symmetry axis, i.e., by including two angles for the orientation. It has thus a total of 7 independent parameters. Such a tilted principal axis leads to **tilted transverse isotropy** (TTI), mostly used in exploration. This also leads to **azimuthal anisotropy**, often used in global seismology, with a dependency on the azimuthal orientation.

Principal component analysis

Constraining all anisotropic parameters by seismic measurements remains a major challenge:



A principal component analysis for example of SKS-measurements reveals mostly a sensitivity towards only the G_c and G_s parameters [Sieminski et al., 2009], which are simply linked to Thomson's parameter γ.

For finely layered isotropic media, [Backus, 1962] showed that by using a moving average the "effective" media properties seen by a longer wavelength signal become transversely isotropic:

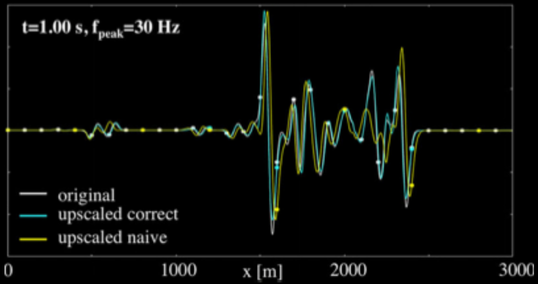
$$
\begin{aligned}
C &= < \frac{1}{\lambda + 2\mu} >^{-1} \\
L &= < \frac{1}{\mu} >^{-1} \\
F &= C < \frac{\lambda}{\lambda + 2\mu} >^{-1} \\
M &= < \mu > \\
A &= F^2/C + 4M - 4 < \frac{\mu^2}{\lambda + 2\mu} >
\end{aligned}
$$

and $B = A - 2M$. Finding the effective medium at longer wavelengths refers to a concept called upscaling.

Homogenization

Assume we want to solve the wave equation for a general medium with small-scale heterogeneities, however, we are interested only in the propagation of longer-wavelength signals.

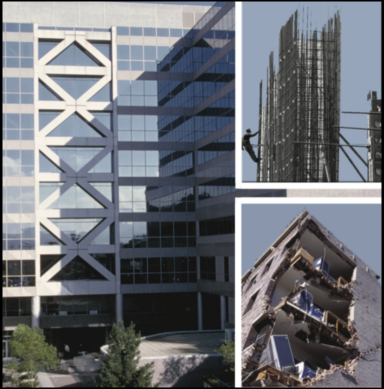
Separating large- and fine-scale heterogeneities, a two-scale homogenization method can be used to compute the "effective" media properties and seismic wave equations equivalent to the initial problem. This involves solving a non-trivial "cell problem" to find the effective medium. However, it can drastically reduce the computational costs of calculating accurate seismograms for a medium with small-scale heterogeneities [Capdeville et al., 2015, Fichtner and Hanasoge, 2017]:



Ground motions for engineering

Engineering seismology

Engineering seismology is interested in the strong ground motion near earthquakes. Since damage on buildings and infrastructures are primarily due to the acceleration, ground motion at a site is either characterized by **accelerations** or shaking **intensities**, where the latter commonly is the Modified Mercalli Intensity (MMI) scale.



Characteristics

For quantitative analysis, ground motion for engineering is mainly characterized into

amplitude-based quantities

peak-ground acceleration (PGA),
root-mean-square acceleration (RMSA), ..

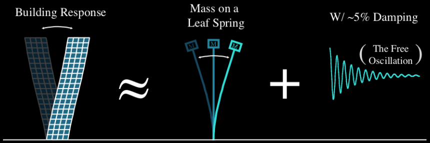
Peak acceleration approximately decays as $P(M, r) = a\,10^{b\,M} r^{-c}$ with a, b, c constants depending on rock, event depth, frequency, ..

duration-based quantities

Arias intensity (AI), Housner intensity, duration of shaking, ..

Motion intensity is defined as $I(t) = \frac{\pi}{2\,g}\int_0^t a^2(\tau)d\tau$ with acceleration $a(t)$ and g the gravity acceleration. Arias intensity is the maximum value of $I(t)$.

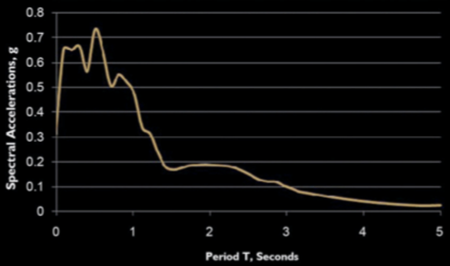
Since the motion of a building is mainly affected by accelerations rather than velocities, the peak-ground acceleration (PGA) has been often used to quantify seismic shaking. An additional quantity more meaningful for building responses is the response spectral acceleration (SA) which gives the maximum acceleration experienced by a damped, single-degree-of-freedom oscillator:



$$\frac{d^2x}{dt^2} + 2\xi\omega_0\frac{dx}{dt} + \omega_0^2\, x = F(t)$$

with $\omega = \sqrt{\frac{k}{m}}$ and $\xi = \frac{c}{2m\omega_0}$, driven by the ground motion $F(t)$.

Building response



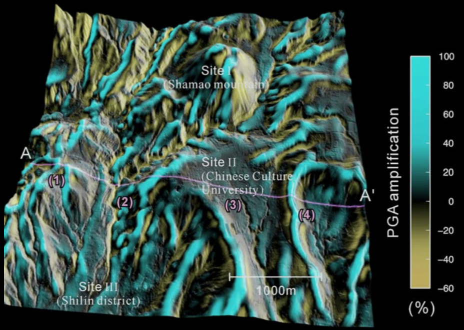
A small building has a resonant frequency of ∼0.2 s, a 10-story building of ∼1 s.

The response spectral acceleration indicates in which frequency range most of the ground motion energy can cause damage.

Site amplifications are often due to sedimentary layers. For example, the Mexico City event, 1985, was 3 minute shaking at a dominant period of 2 s. Buildings of 6-15 stories were most vulnerable.

Ground motion amplifications

Ground motions can not only amplify due to local soil properties, but also due to elastic focussing at the surface. As example, topography can amplify ground motions [Lee et al., 2009]:



More accurate modeling can thus help improving seismic hazard analysis with better physics-based ground motion simulations.

More details can be found in these references:

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