Introduction to Seismology - Body Waves

Seismology Lecture #1

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Types of seismology

- **Theoretical Seismology** - Study of the physics of wave propagation

- **Observational Seismology** -
  - **Source seismology** - study of earthquakes and other seismic sources
  - **Structural seismology** - study of the structures waves propagate through
    - Active source seismology - exploration
    - Local and regional imaging
    - Global seismology
Waves

**single frequency wave**

- **Amplitude**
- **Space**

**Period** = Frequency $^{-1}$
$T = \frac{1}{f}$

**Wavelength** = Wavenumber $^{-1}$
$\lambda = \frac{1}{k}$

**Speed (c):**
$c = \lambda f = \frac{f}{k} = \frac{\lambda}{T}$
The Wave Equation...
The Wave Equation

- Newton’s 2nd law: \[ ma = F \]

\[
\rho \frac{\partial^2 u_i}{\partial t^2} = \partial_j \sigma_{ij} + f_i
\]

- density
- acceleration
- stress tensor
- body forces: e.g. earthquakes, gravity

Volume integration is dropped out of each term of this equation
The Wave Equation

- Newton’s 2nd law: \( ma = F \)

\[ \rho \frac{\partial^2 u_i}{\partial t^2} = \partial_j \sigma_{ij} + f_i \]

- \( i \) is 1, 2, or 3, representing three equations in 3D
- \( j \) represents a summation

\[ \partial_j \sigma_{ij} = \partial_1 \sigma_{i1} + \partial_2 \sigma_{i2} + \partial_3 \sigma_{i3} \]
The Wave Equation

- Newton’s 2nd law: \( ma = F \)

\[
\rho(x, t) \frac{\partial^2 u_i(x, t)}{\partial t^2} = \partial_j \sigma_{ij}(x, t) + f_i(x, t)
\]

- Everything is a function of **space and time**
The Wave Equation

• Newton’s 2nd law: \( ma = F \)

\[ \rho \frac{\partial^2 u_i}{\partial t^2} = \partial_j \sigma_{ij} + f_i \]

\[ \rho(x, t) \frac{\partial^2 u_1(x, t)}{\partial t^2} = \partial_1 \sigma_{11}(x, t) + \partial_2 \sigma_{12}(x, t) + \partial_3 \sigma_{13}(x, t) + f_1(x, t) \]

\[ \rho(x, t) \frac{\partial^2 u_2(x, t)}{\partial t^2} = \partial_1 \sigma_{21}(x, t) + \partial_2 \sigma_{22}(x, t) + \partial_3 \sigma_{23}(x, t) + f_2(x, t) \]

\[ \rho(x, t) \frac{\partial^2 u_3(x, t)}{\partial t^2} = \partial_1 \sigma_{31}(x, t) + \partial_2 \sigma_{32}(x, t) + \partial_3 \sigma_{33}(x, t) + f_3(x, t) \]
The Wave Equation

- Newton’s 2nd law: \( ma = F \)

\[
\rho(x, t) \frac{\partial^2 u_i(x, t)}{\partial t^2} = \partial_j \sigma_{ij}(x, t) + f_i(x, t)
\]

- What forces are created when a medium is deformed?

- This is described by so-called **constitutive relationships**
Hooke’s Law

- For a spring, this is described by linear 1D Hooke’s law

\[ F = kx \]

- force
- deformation
- spring constant
Stress tensor - 3D

- 3 Normal stresses
- 6 Shear stresses

\[ \sigma = \begin{bmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} \\
\sigma_{21} & \sigma_{22} & \sigma_{23} \\
\sigma_{31} & \sigma_{32} & \sigma_{33}
\end{bmatrix} \]
Strain tensor - 3D deformation tensor

\[ u_i(x + \delta x) = u_i(x) + \frac{\partial u_i(x)}{\partial x_j} \delta x_j \]

• To first order:

\[ \delta u_i(x) = \frac{\partial u_i(x)}{\partial x_j} \delta x_j \]

Component of deformation tensor [dimensionless]
Strain tensor - 3D

\[ \varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) = \]

\[
\begin{bmatrix}
\frac{\partial u_1}{\partial x_1} & \frac{1}{2} \left( \frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \right) & \frac{1}{2} \left( \frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1} \right) \\
\frac{1}{2} \left( \frac{\partial u_2}{\partial x_1} + \frac{\partial u_1}{\partial x_2} \right) & \frac{\partial u_2}{\partial x_2} & \frac{1}{2} \left( \frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2} \right) \\
\frac{1}{2} \left( \frac{\partial u_3}{\partial x_1} + \frac{\partial u_1}{\partial x_3} \right) & \frac{1}{2} \left( \frac{\partial u_3}{\partial x_2} + \frac{\partial u_2}{\partial x_3} \right) & \frac{\partial u_3}{\partial x_3}
\end{bmatrix}
\]

Strain tensor - symmetric part
(anti-symmetric component represents rotation, which has no internal deformation)
Strain tensor - 3D

\[ \varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) = \]

\[
\begin{bmatrix}
\frac{\partial u_1}{\partial x_1} & \frac{1}{2} \left( \frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \right) & \frac{1}{2} \left( \frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1} \right) \\
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\end{bmatrix}
\]

Volume change
or dilatation

\[ \theta = \varepsilon_{ii} = \frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = \nabla \cdot \mathbf{u} \]
Hooke’s Law for a continuous medium

- Material is assumed *linearly elastic*, which is valid over small strains and short times scales:

\[
\sigma_{ij} = C_{ijkl} \varepsilon_{kl}
\]

- Applying symmetries \( C_{ijkl} = C_{klij} = C_{jikl} = C_{ijlk} \) ‘only’ 21 components are retained.

\( C_{ijkl} \) : 81 (=\( 3^4 \)) elastic constants relating the 9 stress component to the 9 strain components
Assuming isotropy - only 2 elastic constants

• Simplifying Hooke’s Law to an isotropic continuum:

\[ \sigma_{ij} = \lambda \theta \delta_{ij} + 2\mu \varepsilon_{ij} \]

Kronecker Delta
=1 if \( i = j \)

Lamé constants
Assuming isotropy - only 2 elastic constants

- Simplifying Hooke’s Law to an isotropic continuum:

\[
\sigma_{ij} = \lambda \theta \delta_{ij} + 2\mu \varepsilon_{ij}
\]

\[
\sigma = \begin{bmatrix}
\lambda \theta + 2\mu \varepsilon_{11} & 2\mu \varepsilon_{12} & 2\mu \varepsilon_{13} \\
2\mu \varepsilon_{12} & \lambda \theta + 2\mu \varepsilon_{22} & 2\mu \varepsilon_{23} \\
2\mu \varepsilon_{13} & 2\mu \varepsilon_{23} & \lambda \theta + 2\mu \varepsilon_{33}
\end{bmatrix}
\]

Kronecker Delta
Lamé constants
Assuming isotropy - only 2 elastic constants

- Simplifying Hooke’s Law to an isotropic continuum:
  
  \[ \sigma_{ij} = \lambda \theta \delta_{ij} + 2\mu \varepsilon_{ij} \]

- \( \mu \): shear modulus (also G)

- \( \lambda \) relates to the bulk modulus (\( \kappa \) or K)

\[ \kappa = \lambda + \frac{2}{3} \mu = -V \frac{dP}{dV} \]
Spoiler alert!

- The Earth is not purely elastic, there is an anelastic component.

- The Earth is not purely isotropic, there is also has an anisotropic component and we need more than two elastic moduli to describe this.
The Wave Equation

- Using Hooke’s law for an isotropic medium: \( \sigma_{ij} = \lambda \delta_{ij} + 2 \mu \varepsilon_{ij} \)
- And the definition of the strain tensor
- And ignoring body force (assuming far-field from an earthquake)
- And using: \( \nabla^2 x = \nabla (\nabla \cdot x) - \nabla \times (\nabla \times x) \)

We get the **Seismic Wave Equation** for an isotropic medium:

\[
\rho \frac{\partial^2 u}{\partial t^2} = \nabla \lambda (\nabla \cdot u) + \nabla \mu \cdot [\nabla u + (\nabla u)^T] + (\lambda + 2\mu) \nabla \nabla \cdot u - \mu \nabla \times \nabla \times u
\]
The Wave Equation

\[ \rho \frac{\partial^2 u}{\partial t^2} = \nabla \lambda (\nabla \cdot u) + \nabla \mu \cdot [\nabla u + (\nabla u)^T] + (\lambda + 2\mu) \nabla \cdot u - \mu \nabla \times \nabla \times u \]

**Gradient**: Vector describing the direction and magnitude of change in a quantity

**Divergence**: Scalar describing volume change

**Curl**: Vector describing infinitesimal rotation (think paddle wheel)
Spoiler Alert!

We can solve the wave equation

Ebru Bozdağ’s lecture on solving the wave equation
Seismology #4

http://global.shakemovie.princeton.edu/
Wave types: Body waves

**P wave**
Compressional or longitudinal waves

**S wave**
Shear or transverse waves
Wave types: Body waves

- Assuming a homogeneous medium
  \[\n  \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \lambda (\nabla \cdot \mathbf{u}) + \nabla \mu \cdot \left[ \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right] + (\lambda + 2\mu) \nabla \nabla \cdot \mathbf{u} - \mu \nabla \times \nabla \times \mathbf{u}\n  \]

\[\n\nabla \lambda = \nabla \mu = 0
\]
Wave types: Body waves

- Assuming a homogeneous medium

\[ \rho \frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu) \nabla \nabla \cdot u - \mu \nabla \times \nabla \times u \]

- Represent by two Helmholtz potentials

\[ u = \nabla \varphi + \nabla \times \psi \]

Scalar potential has no curl
\n\[ \nabla \times \nabla \varphi = 0 \]
\n-> Compressional waves

Vector potential has no divergence
\n\[ \nabla \cdot (\nabla \times \psi) = 0 \]
\n-> Shear waves
Wave types: Body waves

- $u = \nabla \phi + \nabla \times \psi$ and again using $\nabla^2 x = \nabla(\nabla \cdot x) - \nabla \times (\nabla \times x)$

- gives: $\nabla^2 \phi = \nabla \cdot u$

- and: $\nabla^2 \psi = -\nabla \times (\nabla \times \psi) = -\nabla \times u$
Wave types: Body waves

- fill in $\mathbf{u} = \nabla \varphi + \nabla \times \psi$ and using $\nabla^2 \mathbf{x} = \nabla (\nabla \cdot \mathbf{x}) - \nabla \times (\nabla \times \mathbf{x})$

\[
\nabla \left[ (\lambda + 2\mu)\nabla^2 \varphi - \rho \frac{\partial^2 \varphi}{\partial t^2} \right] = -\nabla \times \left[ \mu \nabla^2 \psi - \rho \frac{\partial^2 \psi}{\partial t^2} \right]
\]

- One solution: both sides of the equation equal zero.
Wave types: Body waves

\[
\nabla \left[ (\lambda + 2\mu)\nabla^2 \varphi - \rho \frac{\partial^2 \varphi}{\partial t^2} \right] = -\nabla \times \left[ \mu \nabla^2 \psi - \rho \frac{\partial^2 \psi}{\partial t^2} \right]
\]

\[

\nabla^2 \varphi(x, t) = \frac{1}{\alpha^2} \frac{\partial^2 \varphi(x, t)}{\partial t^2}
\]

scalar wave equation

\[
\alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}}
\]

\[

\nabla^2 \psi(x, t) = \frac{1}{\beta^2} \frac{\partial^2 \psi(x, t)}{\partial t^2}
\]

vector wave equation

\[
\beta = \sqrt{\frac{\mu}{\rho}}
\]
Plane waves

\[ \nabla^2 \varphi (x, t) = \frac{1}{\alpha^2} \frac{\partial^2 \varphi (x, t)}{\partial t^2} \]

- A solution to this equation takes the form:

\[ \varphi (x, t) = f (x \pm vt) = Ae^{i(\omega t \pm kx)} \]

- With the velocity:

\[ v = \alpha = \frac{\omega}{|k|} \]
Wave types: Body waves

PSVaxi
Source Depth: 0 km
T = 15 s
Spoiler alert!

- There are also **surface waves**

**Rayleigh wave**

**Love wave**

and **normal modes**

**Spheroidal modes**

**Toroidal modes**

Jessica Irving’s lecture on normal modes and surface waves Seismology #5
Wave types across frequencies

"Shallow"
Active source
Reflection seismology

Today
Surface waves

Jessica Irving's Lecture
Body waves
Normal modes

<— Period (s) —->

<— Frequency (Hz) —->
Body waves interacting with the Earth

Some definitions and characteristics
Wavefront vs ray

wavefront

seismic ray

Phases: P, S
Depth: 0 km

http://web.utah.edu/thorne
Wave components

- **P component** is in the direction of the ray path
- **SV component** lies in the earthquake-receiver plane.
- **SH component** is orthogonal to this.

![Wave components diagram](image)
Interaction with interfaces

Refraction

\[ \frac{\sin i}{\alpha_1} = \frac{\sin r}{\alpha_2} \]

Reflection

\[ i' = i \]
Snell’s Law

Wavefronts align at the interface, here both wavefronts have the same horizontal velocity.

\[ \frac{\sin i}{\alpha_1} = \frac{\sin r}{\alpha_2} = p \]

\(p\) is also known as the *ray parameter* and remains constant along a ray path.
Slowness vector decomposed

**Slowness** = \( 1/\text{velocity} = [\text{s/km}] \)

- **Half-space**
  - \( p = \text{horizontal slowness} \)
  - \( \eta = \text{vertical slowness} \)

**Constants along ray path**

\[ p = \frac{\sin i}{\alpha} \]

\[ \eta_\alpha = \frac{\cos i}{\alpha} \]

\[ s = \frac{\hat{k}_\alpha}{\alpha} \]
Ray parameter is the apparent horizontal slowness at the surface, i.e. the gradient to the travel time curve:

\[ p = \frac{dT}{dX} = \left[ \frac{s}{km} \right] \]

Ray parameter decreases with distance for different ray paths if the velocity increases with depth.
Angular slowness in s/rad remains constant.

\[ p = \frac{r \sin i}{v} \]

- \( v = [\text{km/s}] \)
- \( r = [\text{km/rad}] \)
- \( p = [\text{s/rad}] \)

\( r \) is equal to the radius
\[ = 6371 - \text{depth} \]

\( V_3 > V_2 > V_1 \)
What can you do with the ray parameter?

- Compute the velocity and depth at the turning point

\[ i = \frac{\pi}{2} \]

\[ p = \frac{r_{tp} \sin(\frac{\pi}{2})}{v_{tp}} = \frac{r_{tp}}{v_{tp}} \]
1D Earth model

Entire Earth

Mantle Only
Besides reflection and refraction, energy at an interface also converts.

Conversions in layered media occur between P and SV energy, while SH is an independent system.

Amplitude depend on $impedance = velocity \times density$
## Nomenclature of body waves

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>P wave in the mantle</td>
</tr>
<tr>
<td>S</td>
<td>S wave in the mantle</td>
</tr>
<tr>
<td>K</td>
<td>P wave in the outer core</td>
</tr>
<tr>
<td>I</td>
<td>P wave in the inner core</td>
</tr>
<tr>
<td>J</td>
<td>S wave in the inner core</td>
</tr>
<tr>
<td>c</td>
<td>a reflection from the mantle-outer core boundary</td>
</tr>
<tr>
<td>i</td>
<td>a reflection from the outer- inner core boundary</td>
</tr>
<tr>
<td>m</td>
<td>a reflection from the Moho</td>
</tr>
<tr>
<td>p</td>
<td>a reflection of the surface from an upgoing P-wave near the source</td>
</tr>
<tr>
<td>s</td>
<td>a reflection off the surface from an upgoing S wave near the source</td>
</tr>
</tbody>
</table>
Station components

Vertical components:
- **N**
- **E**

Radial component:
- **N**
- **E**

Transverse component:
- **Radial**
- **Transverse**

Direction of earthquake:
- **Source**
- **Receiver**

Wave propagation direction \( \hat{k} \)

- **SV**
- **P**
- **SH**
Example body wave arrivals

North–south

East–west

Vertical

Radial

Transverse

PKiKP

SKP

SP

PKKP

SKKP

PKS

SKKS

PS

pPS

SS

sSdiff

Sdiff

500 s
The contemplations of a body wave seismologists
Signals of Interest

- travel times
  - velocity anomaly along the ray path
  - Incorrect ray path

- amplitudes
  - radiated energy from earthquake
  - focussing and defocussing
  - energy scattered away - reflection and transmission coefficients
  - inelasticity
Use in tomographic models

- How to combine many, many observations to make an image of the variations in the Earth?

Ved Lekic’s lecture on inverse theory
Seismology #3
Waveform complexities

- triplications or multi-pathing
- Measure direction, differential travel-time, amplitude and frequency content of arrivals
Targeting boundaries - triplications

\[ \text{time} = 2 \times \text{distance} \]

- '410' triplication
- '660' triplication

Ray parameter (s/dg)
Targeting boundaries - multi-pathing

- multi-pathing
- guided waves

Interpreting anomalies causing multi-pathing often takes initial knowledge from a tomographic model.

What is the amplitude of the anomaly causing the multi-pathing?
Targeting boundaries - impedance contrast

- What is the amplitude and sharpness of the seismic discontinuity? -> reflection coefficients

- What is the topography of the discontinuity?  -> (differential) travel times

- Need reference phase not affected by boundary, e.g.:
Targeting boundaries - converted phases

P-to-S conversions

- What is the amplitude and sharpness of the seismic discontinuity? -> measure frequency sensitive conversion coefficients
- What is the topography of the discontinuity? -> differential travel times
Scattering - or *Coda*

- What are the sizes of the heterogeneity?
  -> ~ Wavelength of scattered waves

- Where is this heterogeneity present?
  -> Incoming direction of waves

- What are amplitudes of the heterogeneity?
  -> Energy of scattered waves is sensitive to impedance contrast
  -> Sometimes individual scatterers can be constrained.
  -> Otherwise statistical properties of scatterers are studied
Scattering

Earthquake at station CCM

Moonquake at Apollo 12
Body wave seismologists: First contemplations

- What phase can be used for target area?
- What reference phase can be used?
- What event-station geometry works to target the area of interest? Sometimes an array of stations is needed.

- Or

There is this new geometry available, I have the setup to look at and analyse specific seismic phases, why don’t I get the data ... I am sure there will be something interesting in the data set.
Body wave study 101: Seismic experiments

Neala Creasy

Maureen Long

just keep digging
Body wave study 101: Downloading the data

- One database is www.iris.edu. Data available for Mw 5.5+ earthquakes since 1990.
Body wave study 101: Processing the data

- Removing instrument response
- Rotation from North-East to Radial - Transverse
- Compute predicted arrivals to find phases of interest
- Potentially creating reference synthetics
- Applying some sorts of automated or manual quality control:
Body wave study 101: Software highlight

- Obspy -> www.obspy.org
- Open source python toolkit
- Handles
  - downloading
  - removing instrument response
  - general signal processing routines
  - plotting functions

Will be used in the 2nd seismology practical
Body wave study 101: Data analyses

- Frequency band to choose resolution of interest
- Deconvolution of the assumed source (i.e. creating ‘receiver functions’)
- Stacking to bring out smaller arrivals (array seismology techniques)
Body wave study 101: Data analyses

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Software highlight: FuncLab

- Matlab GUI
- Receiver functions
  - download
  - processing
  - stacking

[https://seiscode.iris.washington.edu/], Porritt & Miller, 2018]
Body wave study 101: Data analyses

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And now, on to some cool studies…
Inner Core phases

PKP/PKPbc
PKIKP/PKPd

Jessica Irving & Deuss, 2011

[Jessica Irving & Deuss, 2011]
To investigate anisotropy, use ray angle, $\zeta$.

$\zeta$: angle between the wave in the inner core and Earth's rotational axis.

Inner Core phases

rotational axis
Inner core hemispherical anisotropy

PKP/PKPbc
PKIKP/PKPdf

Mantle
Inner core
Outer core

Jessica Irving & Deuss, 2011
Inner core hemispheres

PKiKP

PKIKP

Outer core

Inner core

Mantle

[Lauren Waszek & Deuss, 2011]
Inner core hemispheres

PKiKP

Outer core

PKIKP

Inner core

Mantle

[Lauren Waszek & Deuss, 2011]
Outer Core anomalous layer?  
SmKS data

[Hellfrich & Kaneshima 2010]
Outer Core anomalous layer? SmKS data

[Jessica Irving, Sanne Cottaar & Ved Lekic, 2018]
Large Low (Shear) Velocity Provinces LL(S)VPs

Ved Lekic et al. 2012

[Image: Maps of Large Low (Shear) Velocity Provinces LL(S)VPs]
Large Low Shear Velocity Provinces: multi-pathing

[Background: Sanne Cottaar & Ved Lekic, 2016]
Large Low Shear Velocity Provinces: multi-pathing

Pierce points at 2800 km
- entry
- exit

[To et al. 2005]
Large Low Velocity Provinces: P waves

[Dan Frost & Rost, 2014]
Ultra-low Velocity Zone (ULVZ)- guided wave

[Sanne Cottaar & Romanowicz, 2012]
Ultra-low Velocity Zone (ULVZ)- guided wave

Sanne Cottaar & Romanowicz, 2012
Ultra-low Velocity Zone (ULVZ)- guided wave

[Sanne Cottaar & Romanowicz, 2012]
Post PKKP scatterers

- slowness (s/dg)
- backazimuth (dg)
- time (s)
PKP scattering - array stacking

[Nick Mancinelli et al. 2016]
SS pre-cursors

[Zheng & Romanowicz, 2012]
Mantle Transition Zone

SS
S410S
S660S

[Deuss, 2007]

[Christine Houser, 2016]
Mantle Transition Zone

[Deuss, 2007]

[Christine Houser, 2016]
Mid-mantle scatterers
Mid-mantle scatterers

MiMOSA’s
Mid-Mantle Observed Seismic Anomalies

Neala Creasy et al. CIDER 2016

[Lauren Waszek, Schmerr, Ballmer, 2018]
Guided waves - slow material

[Sun, Meghan Miller, Holt, Thorsten Becker 2014]
Guided waves - in a subducted slab

$\text{f > 1 Hz}$

[Image - 95x15 to 1016x697]

[Wu & Jessica Irving, 2018]
Guided waves - in a subducted slab

\[ f > 20 \text{ Hz} \]

[Wu & Jessica Irving, 2018]