Seismology and the Structure of the Earth

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Literature


Software

INTRODUCTION

to
Seismometry
&
Restitution of Ground Motions
&
Interpretation of Seismograms

SEISMIC SOURCE ➔ EARTH ➔ RECORDING SYSTEM ➔ SEISMOGRAM

- seismic source parameters
- tomography
- types of instruments, transfer function
- interpretation

prediction

known only in Applied Geophysics
largely unknown
known
known

INPUT ➔ SYSTEM ➔ OUTPUT

Lenhardt 3 Introduction
WHAT'S MISSING?

1. special seismic source models
2. site response
   ray tracing
   absorption
   scattering
   reflectivity
   macroseismology
3. noise
   coupling effects
   simulating other instruments
   world wide networks
4. archiving concepts
   data formats
   evaluation routines
OBJECTIVES

Major Topics of Global Seismology

<table>
<thead>
<tr>
<th>Source topics</th>
<th>Earth structure topics</th>
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<tbody>
<tr>
<td><strong>Classical objectives</strong></td>
<td></td>
</tr>
<tr>
<td>A. Source location</td>
<td>A. Basic layering (crust, mantle, core)</td>
</tr>
<tr>
<td>B. Energy release</td>
<td>B. Continent-ocean differences</td>
</tr>
<tr>
<td>C. Source type</td>
<td>C. Subduction zone geometry</td>
</tr>
<tr>
<td>D. Faulting geometry, area, displacement</td>
<td>D. Crustal layering, structure</td>
</tr>
<tr>
<td>E. Earthquake distribution</td>
<td>E. Physical state of layers</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Current research objectives</th>
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<tbody>
<tr>
<td>A. Slip distribution on faults</td>
<td>A. Lateral variations in crust, mantle, core</td>
</tr>
<tr>
<td>B. Stresses on faults and in Earth</td>
<td>B. Topography of internal boundaries</td>
</tr>
<tr>
<td>C. Faulting initiation/termination</td>
<td>C. Inelastic properties of the interior</td>
</tr>
<tr>
<td>D. Earthquake prediction</td>
<td>D. Compositional/thermal interpretations</td>
</tr>
<tr>
<td>E. Analysis of landslides, eruptions, etc.</td>
<td>E. Anisotropy</td>
</tr>
</tbody>
</table>

Primary Sources of Seismic Waves

<table>
<thead>
<tr>
<th>Internal</th>
<th>External</th>
<th>Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake faulting</td>
<td>Wind, atmospheric pressure</td>
<td>Volcanic eruptions</td>
</tr>
<tr>
<td>Buried explosions</td>
<td>Waves and tides</td>
<td>Landslides</td>
</tr>
<tr>
<td>Hydrological circulation</td>
<td>Cultural noise</td>
<td></td>
</tr>
<tr>
<td>Magma movements</td>
<td>Meteorite impacts</td>
<td></td>
</tr>
<tr>
<td>Abrupt phase changes</td>
<td>Rocket launches, jet planes</td>
<td></td>
</tr>
<tr>
<td>Mine bursts, rock spalliation</td>
<td></td>
<td></td>
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</tbody>
</table>

Characteristic Seismic Wave Periods

<table>
<thead>
<tr>
<th>Wave type</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body waves</td>
<td>0.01 - 50</td>
</tr>
<tr>
<td>Surface waves</td>
<td>10 - 350</td>
</tr>
<tr>
<td>Free oscillations</td>
<td>350 - 3600</td>
</tr>
</tbody>
</table>

To achieve these goals, different instruments need to be employed.
DISTORTION OF SEISMIC SOURCE SPECTRUM

\[ S(\omega) = A(\omega) I(\omega) R(\omega) B(\omega) G(\omega) \]

with

- \( S(\omega) \)... observed displacement spectrum
- \( A(\omega) \)... spectrum of actual source signal
- \( I(\omega) \)... instrument response
- \( R(\omega) \)... site response incl. the effect of the free surface
- \( B(\omega) \)... attenuation
- \( G(\omega) \)... geometrical decay
PRINCIPLE

OF DISTORTION OF THE SEISMIC SOURCE SPECTRUM

Interpretation

Source mechanism

Earth structure

Instrument

Seismic record

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The Brune earthquake model consists of a circular fault of radius 'r' along which a constant shear stress drop 'Δσ' takes place:

\[ M_0 = c \int_{-\infty}^{\infty} u(t) dt = c\Omega(0), \quad r^3 = \frac{7M_0}{16\Delta\sigma}, \quad f_0 = \frac{kV_s}{2\pi r} \]

with

- \( M_0 \) ... seismic moment (= G A D; G = modulus of rigidity, A = size of fault plane, D = average displacement)
- \( V_s \) ... shear wave velocity
- \( f_0 \) ... corner frequency of s-wave
- \( k \) ... constant, describes shape of source model (~ 2.34 for ‘Brune’ model)

The moment magnitude 'Mw' is given by:\n
\[ M_w = \frac{2}{3} \log(M_0) - 6.1 \quad ; \quad M_0 \text{ given in Nm} \]

Expected source radius and corner frequency as function of moment and stress drop. Frequencies between \( f_0/2 \) and \( 5f_0 \) must be recorded for seismic moment and energy determinations (from Mendecki, A.J. 1997).

EFFECT OF RECORDING INSTRUMENTS
SEISMOMETERS

Depending on the instrument deployed, recorded waveforms appear different. Short-period instruments allow the detection of high frequent seismic signals (e.g. PKP phases of remote earthquakes), whereas long-period instruments permit the detection of signals with lower frequencies (e.g. pPKP phases). Broad-band instruments are a compromise and combine both advantages.

FIJI ISLANDS: 1990/06/26 08:00

1.9491e-16

-2.0883e-16
3.9545e-17

-7.5048e-17
8.4066e-16

-1.1518e-15

PKP
pPKP

TIME [min]

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

top: ‘SPZ’ short period instrument (WWSSN)
centre: ‘BBZ’ broad band instrument (KIRNOS)
bottom: ‘LPZ’ long period seismometer (WWSSN)

remark: PKP = core phase of P-wave from distant earthquake (Fiji Islands, distance ~ 151°)
pPKP = surface reflection of PKP (can be used for focal depth determination)

(see also Scherbaum, F. 1996)
Converting seismic traces from e.g. velocity to displacement traces often leads to distinct onsets, which would have been difficult to detect on the original trace.

(see also Scherbaum, F. 1996)
EFFECT OF NOISE ON DETERMINING SPECTRA
Geophone versus Accelerometer

To create acceleration-seismograms from velocity records, differentiating velocity records may enhance unwanted high frequent noise, thus obscuring the seismic spectrum.

x-axis: frequency (Hz), y-axis: amplitude

top: pseudo-acceleration spectra (differentiated velocity record of geophone)
bottom: acceleration spectra from accelerometer
(see also Mendecki, A.J. 1997)
Displacement spectrum for P-wave after instrument correction (from Scherbaum, F. 1996).

The seismic moment is given by the flat portion of the spectrum $\Omega(0)$, with 'c' being a factor taking account of distance, attenuation and radiation:

$$M_o = c \int_{-\infty}^{\infty} u(t) dt = c\Omega(0)$$
FOURIER ANALYSIS – A BRIEF REVIEW

Every periodic and non-harmonic process can be represented by a sum of harmonic time-series. The frequency-dependent amplitude of each harmonic time-series depends on the shape of the non-harmonic process.

A time-series \( f(t) \) can be approximated by the sum of 1st and higher harmonics ‘a’ and ‘b’.

\[
f(t) = a_0 + a_1 \cos \omega t + a_2 \cos 2\omega t + \ldots + b_1 \sin \omega t + b_2 \sin 2\omega t + \ldots
\]

The latter parameters constitute the frequency dependent amplitudes \((a^2+b^2)^{1/2}\) and phases \(\arctan(a/b)\) of the desired ‘Fourier’ spectrum.

The Fourier-transform for a time series \( f(t) \) is

\[
f(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(\omega) e^{i\omega t} d\omega =
\]

\[
a_0 + a_1 \cos \omega t + a_2 \cos 2\omega t + \ldots + b_1 \sin \omega t + b_2 \sin 2\omega t + \ldots
\]

\[
F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t)(\cos \omega t - i \sin \omega t)dt
\]

Consider effects of limited bandwidth, clipping and/or dynamic range and the sampling rate!

Which influence would they have on spectral analysis?

Which wrong conclusions could be drawn?

\[\text{remember that } e^{i\omega t} = \cos(\omega t) + i \sin(\omega t) \text{ and } e^{-i\omega t} = \cos(\omega t) - i \sin(\omega t), i = \sqrt{-1}.\]
Various parameters are necessary to describe and evaluate seismic onsets (from Scherbaum, F. 1996).

The seismic moment of the signal is given by integration of the displacement pulse 'u(t)', with 'c' being a factor taking account of distance, attenuation and radiation:

\[ M_s = c \int_{-\infty}^{\infty} u(t) dt = c\Omega(0) \]

Other parameters in the time domain are:
1. \( t_{01}, t_{01}, t_{01}\) ... arrival time with error margin (depending on noise level!)
2. \( a_{1\text{extr}}, t_{1\text{extr}}\) ... amplitude and time of first extremum
3. \( a_{\text{max}}, t_{\text{max}}\) ... amplitude and time of maximum amplitude
4. \( a_{\text{min}}, t_{\text{min}}\) ... amplitude and time of minimum amplitude
5. \( t_{\text{end}}\) ... end of signal (depending on noise level!)
6. \( t_{01}, t_{02}, t_r\) ... start and end-time of signal used to determine the signal moment, rise time
7. envelope ... affected by attenuation
8. \& other onsets and extremes with different periods.