Extracting the response from complicated waveforms

Roel Snieder, Nori Nakata, Masatoshi Miyazawa, Kurang Mehta, Rodney Calvert, Jon Sheiman, Kees Wapenaar

Center for Wave Phenomena
Colorado School of Mines
Fluctuation-dissipation theorem

\[ D = \frac{kT}{m\gamma} \]

Very Long Baseline Interferometry

Distance between USA and Germany

http://www.lupus.gsfc.nasa.gov/brochure/btoday2.html
Pseudo-random source

Piezo-electric vibrator from CGG
General scalar linear system

$$\left( a_N \frac{\partial^N}{\partial t^N} + \cdots + a_1 \frac{\partial}{\partial t} \right) u(\mathbf{r}, t) = H \ast u(\mathbf{r}, t) + q(\mathbf{r}, t)$$

eamples

diffusion equation

$$\frac{\partial u}{\partial t} = \nabla \cdot (D\nabla u) + q$$

Schrodinger’s eq.

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V \psi$$

(Snieder, Wapenaar, and Wegler, Phys. Rev. E., 75, 036103, 2007)
Master equation

\[
G(\mathbf{r}_A, \mathbf{r}_B) - G^*(\mathbf{r}_A, \mathbf{r}_B) = 2 \sum_{n \text{ odd}} (i\omega)^n \int a_n(\mathbf{r}) G(\mathbf{r}_A, \mathbf{r}) G^*(\mathbf{r}_B, \mathbf{r}) \, dV \\
+ \oint L(G^*(\mathbf{r}_B, \mathbf{r}), G(\mathbf{r}_A, \mathbf{r})) \, dS \\
+ 2i \int G(\mathbf{r}_A, \mathbf{r}) \text{Im}(H) G^*(\mathbf{r}_B, \mathbf{r}) \, dV
\]
Wave field reconstruction

(Lin, Ritzwoller and Snieder, Geophys. J. Int., 177, 1091–1110, 2009)
Surface-wave

(Forghani and Snieder, The Leading Edge, 29, 790-794, 2010)
amplitude $\propto R(-R^2) = -R^3$
amplitude $\propto R(-R^2) + T(-TR) = -R$
A new low-quality source
Geometry of L08-pad

(Miyazawa, Snieder & Venkataraman, Geophysics, 73, D35-D40, 2008)
from Noise to Signal

Top station

Bottom station
Cross-Correlation
Cycle 1

UD

EW

NS

Depth [m]

-0.4 s  0.0 s  0.4 s

ST1

ST8
• 364 shots divided into 9 shot windows (missing shots shown by the horizontal bar)

• shot spacing = 25 m

• receiver spacing = 50 m
Mars OBC : VS gather
Mars OBC : VS gather
Mars OBC : VS gather

receiver

receiver

receiver

20 40 60 80 100

FSM

0 1

time (s)

total ⊗ total
down ⊗ up
dir(down) ⊗ up

res

res

?”

?”
Near-surface structure from Kik-Net

Free surface

Borehole (few hundred m deep)

Complicated earthquake signal
Data at station NIGH13

- UD2: surface
- UD1: borehole
- NS2: surface
- NS1: borehole
- EW2: surface
- EW1: borehole
Annual stacks at station NIGH13

Correlation

Deconvolution
Arrival time of shear wave

From logging data
(Nakata and Snieder, JGR, 117, B01308, 2012)
S-waves in Niigata and earthquakes

![Graph showing S-waves in Niigata and earthquakes](image)
Time-lapse change

Tohoku-Oki earthquake

Before

After

Difference

2005 - 2008

Before - after the Tohoku EQ

Change in velocity (%)
S-velocity changes with seasons
Rainfall/$v_s$ for soft-rock sites
Rainfall/\(v_s\) for hard-rock sites
Shear-wave splitting
Number of earthquakes:
- Before: 61
- After: 61
- Total: 162

Isotropic velocity (m/s):
- Before: 763–777
- After: 714–732
- Total: 739–747

Anisotropy coefficient (%):
- Before: 7.2–8.4
- After: 11.7–13.3
- Total: 10.3–11.3
Seismic interferometry in Millikan Library

Deconvolution with top floor
Deconvolution with bottom floor
traveling waves  
  normal mode
Vibrations in building
Recorded motion

East-West

Floor

Time (s)

Elevation (m)
After deconvolution

East-West
Response to different earthquakes
Stiffness vs. acceleration

Velocity (m/s)

Acceleration (m/s²)

○ traveling wave
○ coda wave