Strong Motion Seismology
- Broadband Acceleration Time Histories-

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> Introduction to Strong Motion Seismology

> Deterministic Simulations at Low Frequencies
  • 1999 Izmit, Turkey, earthquake (Mw7.3)
  • 2007 Chuetsu-oki, Japan, earthquake (Mw6.6)

> Stochastic Simulation at High Frequencies
  • 2007 Chuetsu-oki, Japan, earthquake (Mw6.6)

> Perspective – Conclusion
Observed strong motions

PGA = Peak Ground Acceleration (1g = 9.8 m/s/s)

PGV = Peak Ground Velocity (m/s)

> 1971 San Fernando, CA (6.6)
> ... 
> 1985 Nahanni, Canada (6.8)
> ... 
> 1999 Chi-chi, Taiwan (7.6)
> ... 
> 2008 Iwate-Miyagi Nairiku, Japan (6.8)

Strasser and Bommer (2009), Strong ground motions – Have we seen the worst?
1994 M6.7 Northridge earthquake
Wald and Heaton (1994): The slip history of the 1994 Northridge, California, earthquake determined from strong-motion, teleseismic, GPS, and leveling data.
Irikura et al. (1997), Lesson from the 1995 Hyogo-ken Nanbu earthquake: Why were such destructive motions generated to buildings?
Pitarka et al. (1998), Three-dimensional simulation of the near-fault ground motion for the 1995 Hyogo-ken Nanbu (Kobe), Japan, earthquake.
What is « Strong Motion Seismology »?

» Study on « strong ground motion data »

» = Near-field ground motion of large earthquake

» = towards Quantitative Seismic Hazard Analysis (QSHA)

» = Source effect (wave radiation) + path effect (« attenuation ») + site effect (non-linearity)

» = Seismology + engineering seismology
Empirical attenuation laws ($Y = \text{PGA, PGV, PSAs}$)

$$\ln Y = F_M(M) + F_D(R_{JB}, M) + F_S(V_{S30}, R_{JB}, M) + \epsilon \sigma_T$$


$$F_M(M) = \begin{cases} e_1 U + e_2 SS + e_3 NS + e_4 RS + e_5 (M - M_h) & M \leq M_h \\ e_1 U + e_2 SS + e_3 NS + e_4 RS + e_7 (M - M_h) & M > M_h \end{cases}$$

$$F_D(R_{JB}, M) = (c_1 + c_2 (M - M_{ref})) \ln(R / R_{ref}) + c_3 (R - R_{ref})$$

$$R = \sqrt{R_{JB}^2 + h^2}$$

$$F_S(V_{S30}, R_{JB}, M) = F_{LIN} + F_{NL}$$

$$F_{LIN} = b_{lin} \ln(V_{S30} / V_{ref}); \quad V_{ref} = 760 \text{ m/s}$$

$$F_{NL} = \begin{cases} b_{nl} \ln(pga\_low / 0.1); & pgalnl \leq a_1 (= 0.03 \text{ g}) \\ b_{nl} \ln(pga\_low / 0.1) + c(\ln(pga\_nl / a_1)^2 + d(\ln(pga\_nl / a_1))^3); & a_1 < pgalnl \leq a_2 \\ b_{nl} \ln(pga\_nl / 0.1); & a_2 (= 0.09 \text{ g}) < pgalnl \end{cases}$$

$$M = 5-8, R_{JB} < 200 \text{ km}, V_s = 180-1300 \text{ m/s}$$
Near Field Ground Motion

> Have we understood near field ground motion?

\[ \text{residual} = \log_{10}(\frac{\text{PGV}_{\text{emp}}}{\text{PGV}_{\text{syn}}}) \]

Aochi & Douglas (2006), Testing the validity of simulated strong ground motion from the dynamic rupture of a finite fault, by using empirical equations
Finite Difference for Wave Propagation

> Stress-velocity formulation

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

\[ \rho \frac{\partial}{\partial t} v_x = \frac{\partial}{\partial x} \tau_{x x} + \frac{\partial}{\partial y} \tau_{x y} + \frac{\partial}{\partial z} \tau_{x z} + F_x \] and two other equations.

\[ \frac{\partial}{\partial t} \tau_{xx} = \lambda \left( \frac{\partial}{\partial x} v_x + \frac{\partial}{\partial y} v_y + \frac{\partial}{\partial z} v_z \right) + 2\mu \frac{\partial}{\partial x} v_x \] and five other equations.

UNIT STAGGERED-GRID
Virieux & Madariaga (1982)

PARTIALLY-STAGGERED-GRID
Saenger et al. (2000)
Finite difference scheme

> In most case, structural grid = easy domain decomposition.
> 4th order in space = good cost performance.

\[
\frac{\partial}{\partial x} f(x) = \frac{1}{h} \left( \frac{9}{8} \left( f\left( x + \frac{h}{2} \right) - f\left( x - \frac{h}{2} \right) \right) - \frac{1}{24} \left( f\left( x + \frac{3}{2} h \right) + f\left( x - \frac{3}{2} h \right) \right) \right)
\]

Free surface (traction = 0)
Absorbing boundary condition (No reflection. No inward wave)
Earthquake source (pre-described or simultaneously to be calculated) … factor varies
Finite difference simulation 15 years ago

> Kinematic source on finite fault segments

> 51.2x25.6x25.6 km$^3$ (0.2 km) = 256 x 128 x 128 grids

> A duration of 25s = 55 hours on 8 procs CRAY CS6400.

Furumura & Koketsu (1998)
Simulation Strategy from Source to Site

1. Initial Condition
   - Fault Geometry, Tectonic Stress
   - Rupture Criterion

2. Dynamic Rupture Propagation
   - Boundary Integral Equation Method

3. Seismic Wave Propagation
   - FDM

4. (Non-linear) Soil Behavior
   - Finite Element Method
Moyenne Durance

5 Segments with different mechanisms

1. Direction of maximum principal stress
   - N180°E
   - N170°E
   - N160°E
   - N150°E
   - N140°E

2. Level of absolute stress
   - High
   - Low

3. Hypocenter location
   - Segment 1
   - Segment 2
   - Segment 3
   - Segment 4
   - Segment 5

Hypothesis (unknown)

Tectonic Stress (uni-axi)
\( \sigma_1 = N160° \pm \alpha \)

Aochi et al. (GJI, 2006)

20/11/2012
2004 Les Saintes

- Flat topography and elastic
- GEBCO topography and elastic
- GEBCO topography and viscoelastic

Salichon et al. (2009)

Jousset & Aochi (2006)
Nice region

Modèle 50 x 50 x 30 km$^3$ autour de Nice

Faille étendu (18x9km) cinématique

ANR QSHA (2006-2008)
Interpretation of tectonics of 1887 Ligure earthquake

Macroseismic Intensity Date from SisFrance
(http://www.sisfrance.net)

North

South

Reverse or normal faulting?
Different position / depth

Aochi et al. (2011)
20/11/2012
Grenoble basin

Aochi et al. (2006)
Variation and uncertainty in strong ground motion

Rhine (with soft layer, shallow earthquake)

Douglas et al. (2007)

Campbell (1997)
2009 l’Aquila, Italy

Unpublished works
History of ground-motion prediction

Douglas & Aochi (2008)

Boxes indicate those methods often used in research and/or practice
DEvelopment of Broadband Time histories for Engineers

Hybrid Method

Mechanics

Source Effect

Temporal Heterogeneity

Spatial Heterogeneity

Radiation Coefficient

Empirical Green's functions

Full Simulation of Complex Source + Complex Wave Propagation

Scattering Theory

Spatial Heterogeneity

Low cost

High cost

Purely stochastic

Physical-based (finite source) stochastic method

Inspired by Douglas and Aochi (2008)

20/11/2012
2007 Mw6.6 Chuetsu-oki earthquake

Kashiwazaki – Kariwa NPP

Japan Sea

Kashiwazaki town
Near-field Ground Motion and Fault Model

> Seismological Inversion

- Adequate solutions are found for both fault orientations.

Aoi et al. (2008)
Near-field Ground Motion and Fault Model

[Diagram showing a map with study area, depth and cross-section plots, and data points labeled NE, CT, SW.]

Courtesy of Dr. A. Kato (ERI)(2008)
Station nucléaire Kashiwazaki-Kariwa a subi des accélérations (680 gal) dépassant le critère (450 gal)

Hikima and Koketsu (2008)
3D Structure Model x Finite Source Model
Aftershock simulation (Mw4.5)

FDM simulation
110 x 120 x 70 km
Grid 200 m
Step 0.01 sec
Fmax = 1.6 Hz

ERI
NIED
GSJ
Observation
Main shock simulation (Model Hikima & Koketsu)

FDM simulation
110 x 120 x 70 km
Grid 200 m
Step 0.01 sec
Fmax = 1.6 Hz

ERI
NIED
GSJ
Observation
SMGA (Strong Motion Generation Area) models

> Three SMGAs are identified (Irikura et al.)

Aochi and Dupros (2011)
Dynamic cross-cutting fault model

(5)

Slip Rate [m/s]
t=1.3s  2.7s  4.0s  5.3s  6.7s

Change in Shear Stress [MPa]
t=1.3s  2.7s  4.0s  5.3s  6.7s
Kashiwazaki-Kariwa NPP

> Dynamic source models are not calibrated though, …

Borehole receiver (260m)

5 models

Kinematic 1
Kinematic 2
SMGA 1
SMGA 2
Dynamic conjugate faults
NPP borehole record

- Lacks of power at intermediate frequencies in kinematic models
- Dynamic model on conjugate faults provides better result??

![Graph showing seismic data and frequency analysis](image)
Stochastic High Frequency Generation

> **Mechanical-base Hypothesis**
  - High freq. generation area = Low freq. generation area
  - All fluctuations at source (not in propagation)
  - Extention of low frequency deterministic description

> **Advantage**
  - La finiteness of source taken into account
  - Coarse sub-fault division + temporal fluctuation
  - Consistent in low frequency (velocity, displacement)

Hisada (2008), Broadband strong motion in layered half-space using stochastic Green’s function technique.
High frequency generation – Basic idea

> We adopt Hisada (2008)’s method so that the stochastic description is consistent with the deterministic one at low frequencies

Source time function in time domain

Phase - frequency

Coherent phase in low frequency
Random phase for high frequency

Note: Green function based on reflectivity (scattering not included).

Hisada (2008)
Localisation of high-frequency sources

Process: Apply a function exponentially decreasing on the original function, so as to the energy of high-frequency sources are localised at the beginning of the waveform. (e.g. attenuation factor calibrated on the observation from Jin and Aki, 2005).

\[ E_a \neq E_b \]

We adjust the initial amplitude so that the total energy is conserved.
Correction of energy

Original Hisada’s method

Applying a decay function

NS

UD
An example at station NIG004
Stochastic simulation of the 2007 Chuetsu-oki earthquake

Observation
Synthetic

20/11/2012
Hybrid ground motion generation for NIG018

For Source 5

Stochastic

Hybrid

FDM

1.5 Hz

> Coherent in low frequency, 3-components.
Stochastic simulation of the 2007 Chuetsu-oki Earthquake

Courtesy of Dr. F. Bonilla (Ifsttar) by DEBATE project
Conclusion/Perspective

> Strong Motion Seismology = Comprehension of mixed effect of source x structure (x site effect).

> Quantitative prediction of ground motion is essential for seismic hazard analysis. = It is important to show how well the past earthquake can be modelled.

> Mechanical-based deterministic/stochastic simulations are applicable in the near field of finite source, completing kinematic approach and GMPEs.

> It remains unsolved:

  • Large amplitude de ground motion (extreme ground motion) should be physically constrained.
  • Incoherent wave propagation (stochastic Green function) could be better.
Thank you for your attention.

Seeking an 1-year-postdoc for ANR S4 (Subduction Standard & Slow Seismology).

Call for papers: 3rd International Workshop on Advances in High-Performance Computational Earth Sciences: Applications and Frameworks – 13th ICCS, 5-7 June 2013, Barcelona, Spain.

Call for abstracts: "S201 Earthquake scenarios" in « strong ground motion » - IASPEI 2013, 22-26 July 2013, Gothenburg, Sweden.