Engineering Characterization of Spatially Variable Ground Motion

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ESG4 Conference
Santa Barbara, CA. August 26 2011
Acknowledgements to:

Robert L. Nigbor and Jamie Steidl for providing access to Borrego Valley Differential Array data

CEA for project funding
Outline

• Motivation
• Metrics of spatial variability in ground motions (SVGM)
• Simulation procedure for generating SVGMs
• Investigation of seismic ground strains
• Conclusions
Motivation

Kato et al., 1998
Example applications

Seismic demands on buried structures (pipelines, tunnels) e.g., Hashash et al., 2001 O’Rourke and Deyoe, 2004
Example applications

Seismic demands on buried structures (pipelines, tunnels)

Multi-support excitation for extended structures (bridges)

e.g., Der Kiureghian & Neuenhofer, 2004
**Example applications**

Seismic demands on buried structures (pipelines, tunnels)

Multi-support excitation for extended structures (bridges)

Foundation – level ground motion reduction from kinematic soil-structure interaction e.g., ASCE-41
Rancho Cucamonga Law &
Justice Center
1987 Whittier Earthquake
Outline

• Motivation
• **Metrics of spatial variability in ground motions (SVGM)**
• Simulation procedure for generating SVGMs
• Investigation of seismic ground strains
• Conclusions
Metrics of SVGM

• Wave passage
• Lagged coherency
• Amplitude variability
• Correlations
Wave passage

(a) Wave Passage Effect

$V_{app,\theta} = \frac{V_{app}}{\sin \theta}$

Zerva, 2009
Wave passage

![Graph showing stacked cross correlation coefficients and separation distances over time lags.](image)

(a) Stacked Cross Correlation Coefficient
- Main
- A
- B
- C
- D
- E

(b) Separation Distance vs. Time Lag
- Points indicating separation distances at various time lags.
Wave passage

(a) Stacked Cross Correlation Coefficient

Main
A
B
C
D
E

Peak Cross-Corr.

(b) Separation Distance (m)

V_{app,θ}

Time Lag (sec)
Wave passage

Arrival time perturbation, ATP
Wave passage

Sensitive to waveform duration – full signal or S-window

Can have poor results if varying site conditions
Wave passage

Lotung SMART 1 data: Boissiere and Vanmarcke (1995)

- Estimated Horizontal Propagation Velocity: 3893 m/s
- Standard deviation of the residuals: 14.7 $\frac{1}{100}$ s
- $R^2 = 0.762$

Slope ranges from 2.8-6.7 km/s
Wave passage

Lotung SMART 1 data: Boissieres and Vanmarcke (1995)

Estimated Horizontal Propagation Velocity: 3893 m/s
Standard deviation of the residuals: 14.7 \( \frac{1}{100} \) s

\( R^2 = 0.762 \)

Std dev reflects arrival time perturbations
Wave passage

BVDA and LSST Data (this study)

<table>
<thead>
<tr>
<th>BVDA Event</th>
<th>θ (deg.)</th>
<th>$V_{app,\theta}$ (m/sec)</th>
<th>$V_{app}$ (m/sec)</th>
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<td>31</td>
<td>2999</td>
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<td></td>
<td>$\sigma_{lnV}$ = 0.62</td>
<td>0.54</td>
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<tr>
<td></td>
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<td>Med. = 4408</td>
<td>2580</td>
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<table>
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<tr>
<th>LSST Event</th>
<th>θ (deg.)</th>
<th>$V_{app,\theta}$ (m/sec)</th>
<th>$V_{app}$ (m/sec)</th>
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<td>$\sigma_{lnV}$ = 0.84</td>
<td>0.54</td>
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<tr>
<td></td>
<td></td>
<td>Med. = 2260</td>
<td>2110</td>
</tr>
</tbody>
</table>

Lower $\sigma_{lnV}$ for $V_{app}$ :: preferred to $V_{app,\theta}$

$V_{app} = 2.1-2.6$ km/s

$\sigma_{lnV} = 0.5-0.6$
Wave passage

BVDA and LSST Residuals (this study)

Negligible ATP for $\xi < 50 \text{ m}$
Lagged Coherency

Reflects phase variability that remains after aligning stations (removing wave passage and ATP).
Lagged Coherency

Derived from smoothed power spectral density functions

\[
\gamma_{jk}(f) = \frac{S_{jk}(f)}{\left[ S_{jj}(f)S_{kk}(f) \right]^{\frac{1}{2}}}
\]

\[
\gamma(\xi, f)_{jk} = \left| \gamma(\xi, f)_{jk} \right| \exp \left[ i \theta(\xi, f)_{jk} \right]
\]

Sensitive to level of smoothing, windowing procedures, etc.
Lagged Coherency

Complex statistical properties

Kernal density estimate of PDF
Lagged Coherency

Complex statistical properties

Transformation using $\tanh^{-1}$ produces normal distribution
Lagged Coherency

Trends with frequency and distance (BVDA data)

Model bias for $f < 10$ Hz and $\zeta < 30$ m
Lagged Coherency

Chiba and LSST array data

Bias for Chiba; no bias for LSST
Lagged Coherency

Model adjustment

\[
\tanh^{-1} \gamma(f, \xi) = a(\xi) \exp\left\{b(\xi) f\right\} + d(\xi) f^{c(\xi)} + k
\]
Lagged Coherency

Model adjustment

\[
tanh^{-1} |\gamma(f, \xi)| = a(\xi) \exp\left\{b(\xi) f \right\} - d(\xi) e^{c(\xi)} + k
\]

No change in \(b, c, d\)
Lagged Coherency

Adjusted model compared to data

\[ \xi = 10 \text{ m} \]

BVDA 10 m
LSST 0-10 m

\[ \xi = 20 \text{ m} \]

BVDA 20 m
LSST 10-30 m
Lagged Coherency

Adjusted model compared to data
Amplitude Variability

Fourier amplitude variation in pair, $\Delta A(\xi, f)$
Amplitude Variability

Fourier amplitude variation in pair, $\Delta A(\xi, f)$

Distribution of $\Delta A(\xi, f)$ has mean zero and $\sigma_{\Delta A}$
Amplitude Variability

BVDA & LSST data

\[ \sigma_{\Delta A}(f) = A \left(1 - e^{Bf}\right) \]

\[ B = b_1 + b_2 \zeta \]
Correlations

Frequency-to-frequency correlations for coherency or amplitude variability

Calculated for frequency steps

Weak correlation
Correlations

Frequency-to-frequency correlations for coherency or amplitude variability

Amplitude variability – coherency correlation

No apparent correlation
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• Motivation
• Metrics of spatial variability in ground motions (SVGM)
• **Simulation procedure for generating SVGMs**
• Investigation of seismic ground strains
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SVGM Simulations

• Objective
• Phase modification
• Amplitude modification
• Frequency-dependent windowing
Objective

Given seed accelerogram, generate simulated motion compatible with $|\gamma|$ and $\Delta A$ models

Useful for response history analysis of structures

Useful for estimation of ground strains
Phase Modification

\[ \phi_j(f, \xi) = \phi_i(f) + \varepsilon_{ij}^n(f, \xi) + 2\pi f \Delta t \]

Phase of seed record
Phase Modification

$$\phi_j(f, \xi) = \phi_i(f) + \varepsilon_{ij}^n(f, \xi) + 2\pi f \Delta t$$

Random phase change.
Zero Mean
Standard deviation $\sigma_\phi$
Normal distribution
Appears uniform at high frequency due to wrapping
Phase Modification

\[ \phi_j(f, \xi) = \phi_i(f) + \varepsilon_{ij}^n(f, \xi) + 2\pi f \Delta t \]

Wave passage.

\( \Delta t \) from \( \xi \) and \( V_{app, \theta} \)
Phase Modification

Result of phase modification (full duration):

Unrealistic high frequency energy at start and end of record
Amplitude Modification

\[ A_j (f) = \exp \left\{ \ln \left[ A_i (f) \right] + \varepsilon_{ij}(f) g \frac{1}{\sqrt{2}} \sigma_{\Delta A} (f) \right\} \]

Amplitude of seed record
Amplitude Modification

\[
A_j(f) = \exp \left\{ \ln \left[ A_i(f) \right] + \varepsilon_{ij}^A(f) g \frac{1}{\sqrt{2}} \sigma_{\Delta A}(f) \right\}
\]

Gaussian random number.
Mean zero
Standard deviation of unity
Amplitude Modification

\[ A_j (f) = \exp \left\{ \ln [ A_i (f)] + \varepsilon_{ij}^A (f) g \frac{1}{\sqrt{2}} \sigma_{\Delta A} (f) \right\} \]

From amplitude variability model
Amplitude Modification

\[ A_j(f) = \exp \left\{ \ln \left[ A_i(f) \right] + \varepsilon_{ij}^A(f) \frac{1}{\sqrt{2}} \sigma_{\Delta A}(f) \right\} \]

To represent single station amplitude variability
Amplitude Modification

Result of amplitude modification (full duration):

Pronounced time-domain leakage effect
**Frequency Dependent Windowing**

- **A**
  - Time - t (sec)
  - Acceleration - a (g)
  - Fourier Amp. - |A| (g-sec)

- **B**
  - Time - t (sec)
  - Acceleration - a (g)
  - Fourier Amp. - |A| (g-sec)

- **C**
  - Frequency - f (Hz)
  - Acceleration - a (g)
  - Fourier Amp. - |A| (g-sec)

- **Equations**
  - L<sub>w</sub>= full duration, T
  - b<sub>5</sub>&gt;0.12 Hz
  - R<sub>3</sub> (hop size)
  - L<sub>4</sub>&#8710~10s
  - b<sub>4</sub>=0.5~1 Hz
  - R<sub>4</sub>
  - L<sub>1</sub>&#8710~1s
  - b<sub>1</sub>=2-Nyq. Hz
  - b<sub>5</sub>, b<sub>4</sub>, b<sub>3</sub>, b<sub>2</sub>
Frequency Dependent Windowing

Seed Motion

(a)

(b)

(c)
Frequency Dependent Windowing

Window Time Series

Window length related to freq. band

S.T. Fourier trans.

Modify A & φ
Frequency Dependent Windowing

Stitch together modified A & $\phi$

Inverse Fourier trans. to time domain
Frequency Dependent Windowing

Critical details:

• Windowing procedure

• Recombination procedure

Details in Ancheta et al. (2011, Earthquake Spectra, in review)
Frequency Dependent Windowing

Leakage removed
Frequency Dependent Windowing

Compare simulations to underlying models

![Graphs showing frequency-dependent windowing comparisons](Image)
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Seismic Ground Strains

- Previous work
- Procedure for simulation-based strain estimation
- Simulation results & prediction equations
- Verification using array data
Previous Work

Strains from wave passage

\[ PGS = A \frac{PGV}{V_{app}} \]

Newmark, 1967
Yeh (1974)
St. John and Zahrah (1987)
Trifunac and Lee (1996)
Hashash et al. (2001)
Previous Work

Strains from wave passage

Inference of strains from arrays using geodetic approach

O’Rourke et al. (1984)
Bodin et al. (1997)
Gomberg et al. (1999)
Paolucci and Smerzini (2008)
Previous Work

Paolucci and Smerzini (2008)

Strains much higher than anticipated from wave passage.

Limited to modest PGV levels
Strain Estimation from Simulations

1. $N_i$ seed motions selected for $j=1..N_e$ events
2. For each seed motion, simulate $N_s$ motions for suites of separation distances ($\xi = 6, 10, 20, 40, 80$ m) and apparent velocities ($V_{app}$).
3. Each seed-simulated motion integrated twice to displacement & normalized by $\xi$ to calculate strain history. Peak is PGS.
Strain Estimation from Simulations

Events

M 4.9 Anza, CA
M 4.9 Big Bear City, CA
M 6.0 Whittier, CA
M 6.1 North Palm Springs, CA
M 6.5 Big Bear City, CA
M 6.7 Northridge, CA
M 6.9 Loma Prieta, CA
M 7.5 Kocaeli, Turkey
M 7.6 Chi Chi, Taiwan
M 7.9 Denali, AL

Soil sites selected

135 motions
Results of Simulations

Affected by $\xi$

Saturation effect for PGV $> \sim 80$ cm/s
Fitting of Model

\[
\ln PGS_{ijk} \mid \xi = \begin{cases} 
\alpha + \beta \ln PGV_{ijk} + \epsilon_{ijk} & \text{for } PGV < PGV_L \\
\psi & \text{otherwise}
\end{cases}
\]

<table>
<thead>
<tr>
<th>$\xi$ (m)</th>
<th>$\alpha$ ($\xi$)</th>
<th>SE($\alpha$)</th>
<th>$\beta$ ($\xi$)</th>
<th>SE($\beta$)</th>
<th>$\psi$ ($\xi$)</th>
<th>SE($\psi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>-10.92</td>
<td>0.0092</td>
<td>0.866</td>
<td>0.0035</td>
<td>-7.02</td>
<td>0.059</td>
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<tr>
<td>10</td>
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<td>0.0034</td>
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<td>0.0092</td>
<td>0.959</td>
<td>0.0035</td>
<td>-8.25</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Final coefficients from random effects analysis.

FOSM used to represent range of $V_{\text{app}}$ in data set.
Fitting of Model
Verification of $\xi$-Dependence

LSST data

Calculate differential displacement from pairs & normalize by $\xi$.

Statistically significant difference for low $\xi$; not for $\xi > 20$ m.
Outline

• Motivation
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Summary of Key Results

• Three key metrics of SVGM.
  – Wave passage: Recommendations on $V_{app}$, $\sigma_{lnV}$, and importance of ATP
  – Modest adjustment of previous $|\gamma|$ model
  – Model for amplitude variability

• Simulation procedure provides realistic spatially variable waveforms including amplitude variability.

• New insights on ground strain:
  – Separation distance dependence
  – Saturation at large PGV
More Information

• Metrics of SVGM: this conference
• SVGM simulations: Ancheta et al., Earthquake Spectra, in review
• Ground strains: Ancheta (2010) dissertation; soon in PEER report