Simulation of near-fault ground motions for randomized hypocenter and site locations

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Motivation

- Recorded near-fault (NF) ground motions (GM) remain scarce
- Their characteristics are different from far-field GMs
- NF effects are not (yet) properly represented in modern codes and current ground motion prediction equations (GMPEs)
Rupture directivity effects (is a pulse observed? what are its amplitude and period?) depend on directivity parameters

- that describe the geometry of the rupture relative to the site.
- We use:
  - $s$: length (along strike) of rupture between epicenter and site
  - $d$: width of rupture between hypocenter and site
  - $\theta$: horizontal angle between rupture plane and epicenter to site direction
  - $\phi$: vertical angle between rupture plane and hypocenter to site direction
Motivation

- Ongoing effort to understand, model, and simulate NF GMs and their effects on the response of long period structures

- E.g., procedure for simulation of NF GMs for specified $\left( F, M_w, Z_{TOR}, R_{RUP}, V_{S30}, s_{or}d, \theta_{or}\phi \right)$ (Dabaghi and Der Kiureghian, 2014, 2017, 2018)
  - Accounts for rupture directivity effect
  - Produces relative number of pulse-like and non-pulse-like GMs consistent with recorded GMs
  - Useful to generate synthetic GMs for seismic assessment studies

For SS faults ($F = 0$):
$$s_{or}d = s, \quad \theta_{or}\phi = \theta$$

For REV faults ($F = 1$):
$$s_{or}d = d, \quad \theta_{or}\phi = \phi$$
Motivation

For seismic assessment studies, site specific GMs are selected based on deaggregation results:

- Information about faults contributing to the hazard + \((M_w, R_{RUP})\)
- No information about the location of the hypocenter \((s_{or} d, \theta_{or} \phi)\)
Outline – Simulation of NF GMs ...

- ... for specified \((F, M_w, Z_{TOR}, R_{RUP}, V_{s30}, s_{ord}, \theta_{or} \phi)\)
  - Stochastic model of NF GM
  - Simulation procedure

- ... for a specified site with known \((V_{s30})\) and a specified fault with known \((F, M_w)\)
  - Randomized rupture geometry
  - Randomized hypocenter location

- ... for comparison with NGA West 2 models (for specified \(F, M_w, Z_{TOR}, R_{RUP}, V_{s30}\))
  - Randomized rupture geometry and hypocenter location
  - Randomized site location
SYNTHETIC NF GMS FOR SPECIFIED
\( (F, M_w, Z_{TOR}, R_{RUP}, V_{s30}, s_{ord}, \theta_{ord}, \phi) \)

- Stochastic model of NF GM
- Simulation procedure

Site-based stochastic model in two orthogonal horizontal directions:

- Pulse-like motion
- Non-pulse like motion
Pulse-like GM model

- Pulse in at least one direction, due to rupture directivity, ...

- Model formulated in:
  - Direction of the largest pulse: \( a_{pp}(t) \)
  - Corresponding orthogonal direction: \( a_{PO}(t) \)

\[
\begin{align*}
  a_{pp}(t) & \\
  a_{pulse}(t) & \\
  a_{res}(t) & \\
  a_{PO}(t) & \\
\end{align*}
\]

19 physically meaningful parameters

<table>
<thead>
<tr>
<th>Pulse</th>
<th>( \alpha_{p,1} )</th>
<th>( \alpha_{p,2} )</th>
<th>( \alpha_{p,3} )</th>
<th>( \alpha_{p,4} )</th>
<th>( \alpha_{p,5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_p(\text{cm/s}) )</td>
<td>( T_p(\text{s}) )</td>
<td>( \gamma )</td>
<td>( \nu/\pi(\text{rad}) )</td>
<td>( t_{\text{max,}p}(\text{s}) )</td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>( \alpha_{p,6} )</td>
<td>( \alpha_{p,7} )</td>
<td>( \alpha_{p,8} )</td>
<td>( \alpha_{p,9} )</td>
<td>( \alpha_{p,10} )</td>
</tr>
<tr>
<td>( I_{a,\text{res}}(\text{cm/s}) )</td>
<td>( D_{5-95,\text{res}}(\text{s}) )</td>
<td>( D_{0-5,\text{res}}(\text{s}) )</td>
<td>( D_{0-30,\text{res}}(\text{s}) )</td>
<td>( f_{\text{mid,}\text{res}}(\text{Hz}) )</td>
<td>( f'_{\text{res}}(\text{Hz/s}) )</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>( \alpha_{p,13} )</td>
<td>( \alpha_{p,14} )</td>
<td>( \alpha_{p,15} )</td>
<td>( \alpha_{p,16} )</td>
<td>( \alpha_{p,17} )</td>
</tr>
<tr>
<td>( I_{a,\text{PO}}(\text{cm/s}) )</td>
<td>( D_{5-95,\text{PO}}(\text{s}) )</td>
<td>( D_{0-5,\text{PO}}(\text{s}) )</td>
<td>( D_{0-30,\text{PO}}(\text{s}) )</td>
<td>( f_{\text{mid,}p_0}(\text{Hz}) )</td>
<td>( f'_{p_0}(\text{Hz/s}) )</td>
</tr>
</tbody>
</table>
Non-pulse-like GM model

- No pulse in any horizontal direction

- Formulated in:
  - Major principal direction: $a_{NP1}(t)$
  - Intermediate principal direction: $a_{NP2}(t)$

<table>
<thead>
<tr>
<th>Major</th>
<th>$\alpha_{NP,1}$</th>
<th>$\alpha_{NP,2}$</th>
<th>$\alpha_{NP,3}$</th>
<th>$\alpha_{NP,4}$</th>
<th>$\alpha_{NP,5}$</th>
<th>$\alpha_{NP,6}$</th>
<th>$\alpha_{NP,7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{0,NP1}(\text{cm/s})$</td>
<td>$D_{5-95,NP1}(\text{s})$</td>
<td>$D_{0-5,NP1}(\text{s})$</td>
<td>$D_{0-30,NP1}(\text{s})$</td>
<td>$f_{mid,NP1}(\text{Hz})$</td>
<td>$f'_{NP1}(\text{Hz/s})$</td>
<td>$\zeta_{NP1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intermediate</th>
<th>$\alpha_{NP,8}$</th>
<th>$\alpha_{NP,9}$</th>
<th>$\alpha_{NP,10}$</th>
<th>$\alpha_{NP,11}$</th>
<th>$\alpha_{NP,12}$</th>
<th>$\alpha_{NP,13}$</th>
<th>$\alpha_{NP,14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{0,NP2}(\text{cm/s})$</td>
<td>$D_{5-95,NP2}(\text{s})$</td>
<td>$D_{0-5,NP2}(\text{s})$</td>
<td>$D_{0-30,NP2}(\text{s})$</td>
<td>$f_{mid,NP2}(\text{Hz})$</td>
<td>$f'_{NP2}(\text{Hz/s})$</td>
<td>$\zeta_{NP2}$</td>
</tr>
</tbody>
</table>
Simulation procedure using the stochastic model

+ input variables: \((F, M, Z_{TDA}, R_{RUP}, V_{SSD}, \sigma_d, \theta_{or}, \phi)\)

(Shahi and Baker, 2014)
Simulation procedure

\[ E[z] = \beta_0 + \beta_1 M_w + \beta_2 (M_w - 6.5) \mathbb{I}(M_w > 6.5) + \beta_3 F_{f_{\text{flt,Z}}} + \beta_4 \ln \left( \sqrt{R_{\text{RUP}}^2 + h^2} \right) + \beta_5 M_w \ln \left( \sqrt{R_{\text{RUP}}^2 + h^2} \right) + \beta_6 \ln(\hat{V}_{s30}) + \beta_7 s_{or,d} \]

Empirical predictive relations for model parameters (Dabaghi and Der Kiureghian, 2014, 2018)
Simulation procedure

Pulse Probability Model

Pulselike GM Model

Non-Pulselike GM Model

Pulselike Predictive Relations

mMP Pulse Model

MFW Model

Model Parameters

Motion in Direction of Largest Pulse

Pulse Motion

Residual Motion

Orthogonal Motion
Simulation procedure
SYNTHETIC NF GMS FOR A SPECIFIED SITE WITH KNOWN \( (V_{s30}) \) AND A SPECIFIED FAULT WITH KNOWN \( (F, M_w) \)

- Randomized rupture geometry
- Randomized hypocenter location
rupture dimensions and hypocenter location are unknown
<table>
<thead>
<tr>
<th>Fault</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>- M</td>
<td>- Location</td>
</tr>
<tr>
<td>- F</td>
<td>- Vs30</td>
</tr>
<tr>
<td>- Top Points</td>
<td>Lmax</td>
</tr>
<tr>
<td>- Dip</td>
<td>strike</td>
</tr>
<tr>
<td>- Wmax (opt.)</td>
<td></td>
</tr>
</tbody>
</table>

Ztor

Campbell et al. (2009)
Depth to top of rupture $Z_{tor}$

- A median estimate of $Z_{tor}$ derived from the NGA database is used (Campbell et al., 2009):

<table>
<thead>
<tr>
<th>$M$</th>
<th>$Z_{tor}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M \leq 5$</td>
<td>6</td>
</tr>
<tr>
<td>$5 &lt; M \leq 6$</td>
<td>3</td>
</tr>
<tr>
<td>$6 &lt; M \leq 7$</td>
<td>1</td>
</tr>
<tr>
<td>$M &gt; 7$</td>
<td>0</td>
</tr>
<tr>
<td>Fault</td>
<td>Site</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>- M</td>
<td>- Location</td>
</tr>
<tr>
<td>- F</td>
<td>- Vs30</td>
</tr>
<tr>
<td>- Top Points</td>
<td></td>
</tr>
<tr>
<td>- Dip</td>
<td></td>
</tr>
<tr>
<td>- W\text{max} (opt.)</td>
<td></td>
</tr>
</tbody>
</table>

W > W_{\text{max}} or L > L_{\text{max}}

- M

- F, M

Ztor

L, W

Campbell et al. (2009)

Wells and Coppersmith (1994)
Fault rupture dimensions $L_R$ and $W_R$

- Wells and Coppersmith (1994) mean relations

- For SS faults:
  \[
  E[\log_{10} L_R] = -2.57 + 0.62M_w, \quad \sigma = 0.165 \\
  E[\log_{10} W_R] = -0.76 + 0.27M_w, \quad \sigma = 0.115
  \]

- For Reverse faults:
  \[
  E[\log_{10} L_R] = -2.42 + 0.58M_w, \quad \sigma = 0.18 \\
  E[\log_{10} W_R] = -1.61 + 0.41M_w, \quad \sigma = 0.151
  \]

Empirical estimates from subset of NGA-W2 database
Fault rupture dimensions $L_R$ and $W_R$

- $\log_{10} L_R$ and $\log_{10} W_R$ are simulated as correlated normal random variables

<table>
<thead>
<tr>
<th>Correlations</th>
<th>All Faults</th>
<th>SS Faults</th>
<th>Reverse Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log_{10} A_R$, $\log_{10} L_R$</td>
<td>0.7840</td>
<td>0.8242</td>
<td>0.8021</td>
</tr>
<tr>
<td>$\log_{10} L_R$, $\log_{10} W_R$</td>
<td>0.0351</td>
<td><strong>0.0680</strong></td>
<td><strong>0.0958</strong></td>
</tr>
<tr>
<td>$\log_{10} A_R$, $\log_{10} W_R$</td>
<td>0.6377</td>
<td>0.5981</td>
<td>0.6666</td>
</tr>
</tbody>
</table>
within the fault plane
Example randomized ruptures - SS Fault

**Input:**
- $M = 6.45$
- Dip = 90°
- Strike = 128°
- $L_{max} = 37$ km
- $W_{max} = 20$ km

Ztor = 1 km
Fault
- M
- F
- Top Points
- Dip
- Wmax (opt.)

Site
- Location
- Vs30

M → Ztor

W > Wmax or L > Lmax

F, M → L, W

Top points
Strike
Dip

Rupture Plane Coordinates

Campbell et al. (2009)
Wells and Coppersmith (1994)

Relative Hypocenter Location

Mai et al. (2005)

Campbell et al. (2009)
Wells and Coppersmith (1994)
Hypocenter location (Mai et al. 2005)

- $HypX$: along-strike hypocenter position normalized by fault length [0 to 1]

Truncated Normal RV

$\mu = 0.5$

$\sigma = 0.23$
Hypocenter location (Mai et al. 2005)

- $HypZ$: down-dip hypocenter position normalized by fault width [0 to 1]

Weibull: Strike-Slip Gamma: Dip-Slip

Scale = 0.626  Shape = 3.921

Scale = 7.364  Shape = 0.072

(from Mai et al. 2005)
Fault
- M
- F
- Top Points
- Dip
- Wmax (opt.)

Site
- Location
- Vs30

M
Ztor
W>Wmax or L>Lmax

F, M
L, W
Top points
Strike
Dip

Relative Hypocenter Location
Mai et al. (2005)

Wells and Coppersmith
(1994)

Rupture Plane Coordinates

F

Hypocenter Coordinates

Campbell et al. (2009)
Example randomized hypocenter location – SS Fault (F = 0)

**Input:**
- $M = 6.45$
- Dip = 90°
- Strike = 128°
- $L_{\text{max}} = 37$ km
- $W_{\text{max}} = 20$ km

(Top View)
Example randomized hypocenter location – REV Fault (F = 1)

**Input:**

- $M = 6.45$
- Dip = 60°
- $L_{\text{max}} = 37\, \text{km}$
- Strike = 128°
- $W_{\text{max}} = 20\, \text{km}$
### Fault
- M
- F
- Top Points
- Dip
- Wmax (opt.)

### Site
- Location
- Vs30

#### Top points
- Strike
- Dip

#### Rupture Plane Coordinates
- Rrup, s, d, θ, φ

#### Hypocenter Coordinates
- Relative Hypocenter Location
  - Mai et al. (2005)
- Wells and Coppersmith (1994)

#### Site Location
- Ztor
  - Campbell et al. (2009)
- L, W
  - W > Wmax or L > Lmax
Fault
- M
- F
- Top Points
- Dip
- Wmax (opt.)

Site
- Location
- Vs30

Rupture Plane Coordinates
Hypocenter Coordinates

Ztor
Campbell et al. (2009)

W > Wmax
or
L > Lmax

L, W
Wells and Coppersmith (1994)

Relative Hypocenter Location
Mai et al. (2005)

Top points
Strike
Dip

Site Location

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Simulation procedure

Simulated for given $(F, M_w)$ and site location

Pulse Probability Model

Pulselike GM Model

Non-Pulselike GM Model

Pulselike Predictive Relations

Non-Pulselike Predictive Relations

mMP Pulse Model

MFW Model

Simulated for given $(F, M, Z_{TOR}, R_{SUP}, V_{S30}, s_{sur})$
SYNTHETIC NF GMS FOR COMPARISON WITH NGA WEST2 MODELS
i.e., for specified \((F, M_w, Z_{TOR}, R_{RUP}, V_{S30})\)

- Randomized rupture geometry and hypocenter location
- Randomized site location
NGA West2 GMPEs...

- ... don’t include directivity parameters \((s_{ord}, \theta_{ord}, \phi)\) as input
- To compare synthetic NF GMs with NGA West2 models, should simulate GMs for specified \((F, M_w, Z_{TOR}, R_{RUP}, V_{S30})\)
- Randomize rupture geometry and hypocenter location (given \(F, M_w\))
- Also randomize site location
  - sample from a uniform distribution along the circumference located at a distance \(R_{RUP}\) from the simulated fault rupture
Examples – vertical SS EQs

- Use MCS to generate any desired number of realizations of $L_R$, hypocenter location, and site location for $F = 0$, $M_w = 6.5$, $Z_{TOR} = 0$ (assumed for $M_w \geq 6.5$), $R_{RUP} = 10km$

- For each realization, calculate $s_{ord}$ and $\theta_{ord}$
600 simulations vs. NGA-W2 GMPEs (RotD50)

Scenario \( M_w = 6.5, \ V_{s30} = 400 \text{m/s} \)

\( \Pr(\text{pulse-like}) \sim 20\% \)

At most periods, simulated GMs fall within the median \( \pm 1\sigma \) levels predicted by the NGA-West2 model

Proportion of pulse- and non-pulse-like GMs consistent with that of recorded GMs
600 simulations vs. NGA-W2 GMPEs (RotD50)

Scenario $M_w = 7$, $V_{s30} = 400 m/s$ and $R_{rup} = 20 km$ – SS Fault
600 simulations vs. NGA-W2 GMPEs (RotD50)

Scenario $M_w = 7$, $V_{s30} = 525 m/s$ and $R_{rup} = 20 km$ – SS Fault
Scenario $M_w = 7$, $V_{s30} = 760\text{m/s}$ and $R_{rup} = 20\text{km}$ – SS Fault

600 simulations vs. NGA-W2 GMPEs (RotD50)
600 simulations vs. NGA-W2 GMPEs (RotD50)

Scenario $M_w = 6.5$, $V_{s30} = 760\, m/s$ and $R_{rup} = 20\, km$ – SS Fault
600 simulations vs. NGA-W2 GMPEs (RotD50)

Scenario $M_w = 7$, $V_{s30} = 760m/s$ and $R_{Rup} = 20km$ – SS Fault
600 simulations vs. NGA-W2 GMPEs (RotD50)

Scenario $M_w = 7.5$, $V_{s30} = 760m/s$ and $R_{Rup} = 20km$ – SS Fault
Summary

- New procedure to simulate NF GMs for a specified site with known \( V_{s30} \) and a specified fault with known \( (F, M_w) \), by randomizing rupture dimensions and hypocenter location.

- By also randomizing site location, can compare simulations with NGA West2 GMPEs.
References


Thank You

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