Directionality of ground motions in the NGA-West2 database

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Motivation

• “Maximum-direction” spectral accelerations have received increasing attention in the engineering community in recent years (e.g., 2009 NEHRP Provisions)

• NGA-West2 models will provide predictions of “$\text{Sa}_{\text{RotD50}}$” spectra

• We provide a modification to convert those predictions to maximum-direction spectra

• We also report on orientations of the maximum direction motions, and suggest how to use these models for engineering analysis
Example 1-second oscillator responses to multi-component motions

- $S_{a(1s)} / S_{a_{\text{RotD}100}(1s)}$
- Displacement / Maximum displacement

HWA031 recording from Chi-Chi-04, 1999 earthquake

Gilroy Array #6 recording from Morgan Hill, 1984 earthquake
Model formulation for $Sa_{RotD100}$ at a specified period

$$Sa_{RotD100} = \frac{Sa_{RotD100}}{Sa_{RotD50}} \cdot Sa_{RotD50}$$

$$\ln Sa_{RotD100} = \ln \left( \frac{Sa_{RotD100}}{Sa_{RotD50}} \right) + \ln (Sa_{RotD50})$$

This study

$$\ln \left( \frac{Sa_{RotD100}}{Sa_{RotD50}} \right) = a + \eta' + \varepsilon'$$

Primary GMPE

$$\ln (Sa_{RotD50}) = f(M, R, V_{S30}, ...) + \eta + \varepsilon$$

Simple prediction (constant?)

Complex prediction

Independent of primary GMPE
Results to discuss today

- $\text{Sa}_{\text{RotD100}} / \text{Sa}_{\text{RotD50}}$ ratios
- Orientation of $\text{Sa}_{\text{RotD100}}$ relative to strike
- Difference in orientation of $\text{Sa}_{\text{RotD100}}(T_1)$ and $\text{Sa}_{\text{RotD100}}(T_2)$
- Change in $\text{Sa}(T)$ at angles away from the $\text{Sa}_{\text{RotD100}}$ orientation
- Amplitude of $\text{Sa}(T)$ in a specified direction

Oscillator responses to 1979 Imperial Valley-06, El Centro Differential Array recording
Data set

- NGA-West2 database

- We used subsets of the data chosen by the modelers (as of 11/1/2011), to ensure use of appropriate data and to be compatible with NGA West 2 models for $S_{a_{RotD50}}$

- $S_a$ values computed for
  - 5% damping only
  - 21 periods
  - All orientations in 1° increments
Histograms of $\text{Sa}_{\text{RotD100}}/\text{Sa}_{\text{RotD50}}$

- $T = 0.2$ s
- $T = 1.0$ s

Number of ground motions

Geometric mean $\text{Sa}_{\text{RotD100}}/\text{Sa}_{\text{RotD50}}$
Median $S_{a_{\text{RotD100}}}/S_{a_{\text{GMRotl50}}}$ ratios, versus previous models

There is a clear period dependence in these ratios.
These ratios differ from the NEHRP Provisions ratios
Variation in $\text{Sa}_{\text{RotD100}} / \text{Sa}_{\text{GMRotI50}}$ with closest distance ($R_{rup}$)?

Other variables ($M$, directivity parameters) had less strong effects.
Model with $R_{rup}$ dependence

\[
\ln\left(\frac{S_{a_{RotD100}}}{S_{a_{RotD50}}}\right) = a_0 + a_1 \cdot (R_{rup} - 60) + \eta + \varepsilon
\]
Standard deviations (example numbers for $\text{Sa}(1\text{s})$)

\[ \sigma' = 0.629 \]
\[ \ln \text{Sa}_{\text{RotD100}} = \ln(\text{Sa}_{\text{RotD100}} / \text{Sa}_{\text{RotD50}}) + \ln(\text{Sa}_{\text{RotD50}}) \]

This study

\[ \ln(\text{Sa}_{\text{RotD100}} / \text{Sa}_{\text{RotD50}}) = a + \eta' + \epsilon' \]

Primary GMPE

\[ \ln(\text{Sa}_{\text{RotD50}}) = f(M, R, V_{S30}, ...) + \eta + \epsilon \]

This study:
\[ \tau = 0.010 \quad \phi = 0.083 \]

Campbell Bozorgnia (2008) NGA:
\[ \tau = 0.255 \quad \phi = 0.568 \]
Orientation of $S_{a,\text{RotD100}}$ (using $\alpha$ as angle to strike parallel)

- Dependence of $\alpha$ on various parameters was studied
- A parametric model to predict the distribution of $\alpha$ is proposed

Oscillator responses to 1979 Imperial Valley-06, El Centro Differential Array recording
Dependence of $\alpha$ on $M$ and $R_{rup}$
Distribution of $\alpha$ for varying $T$, with $R_{rup}$ between 0 and 5 km

Apparent division at 0.5 or 1 second
Observations regarding distributions of $\alpha$

Some dependence on distance and period (consistent with previous work)

- The distribution tends towards fault normal for $R < 5$ km and $T \geq 0.5$ s
  (This is not the same as saying $\alpha$ is *always* fault normal)

- The distribution is apparently uniform otherwise

No obvious dependence on magnitude, directivity parameters, etc.
Other models for directionality

The direction of $\text{Sa}_{\text{RotD100}}(T)$ will vary with period

1. By how much will the azimuths of $\text{Sa}_{\text{RotD100}}(T^*)$ and $\text{Sa}_{\text{RotD100}}(T')$ vary?

2. If we identify a target $\text{Sa}_{\text{RotD100}}$ at one period ($T^*$), what will the spectral value be at some other period ($T'$)?

Oscillator responses to 1979 Imperial Valley-06, El Centro Differential Array recording
Distribution of $\alpha^* - \alpha'$ for various $T^*$ and $T'$

- $T^* = 1 \text{ s}, T' = 2 \text{ s}$
- $T^* = 0.1 \text{ s}, T' = 0.2 \text{ s}$
- $T^* = 1 \text{ s}, T' = 5 \text{ s}$
- $T^* = 0.1 \text{ s}, T' = 0.5 \text{ s}$
Median ratio of $S_{a\varphi}/S_{a_{\text{RotD50}}}$, as a function of distance from $S_{a_{\text{RotD100}}}$ orientation

Example 1's response case:

$\varphi = \text{Angle relative to } S_{a_{\text{RotD100}}} \text{ (degrees)}$
Individual ground motion example

TCU076 station, 1999 Chi-Chi earthquake
$R_{rup} = 3$ km, $M = 7.6$
Example predictions using above results

M = 7, R_{clst} = 2.5 km, V_{S30} = 760 m/s
Conclusions

• Observed ratios of $S_{a_{\text{RotD100}}}/S_{a_{\text{RotD50}}}$ are consistent with previous studies
  – Dependent on period and (weakly) on distance
  – No clear dependence on other properties (magnitude, directivity-related parameters)

• Orientations of $S_{a_{\text{RotD100}}}$ appear to be uniform beyond 5 km closest distance
  – Within 5 km and for $T \geq 0.5s$, there is a tendency towards fault-normal orientation

• Orientations of $S_{a_{\text{RotD100}}}$ vary with period, for a given ground motion, which complicates target spectrum calculation and ground motion selection

• We aim to address that problem by providing models for:
  – Difference in orientation of $S_{a_{\text{RotD100}}}$ at two periods
  – Deviation from $S_{a_{\text{RotD100}}}$ as a function of the above orientation difference
Thanks to the project technical review team:

- Brian Chiou
- Nicolas Luco
- Mahmoud Hachem
- Tom Shantz
- Paul Somerville
- Paul Spudich
- Jon Stewart
- Badie Rowshandel
Fault normal spectra versus $S_{a_{\text{RotD50}}}$

![Graph showing fault normal spectra versus $S_{a_{\text{RotD50}}}$]
Is $S_{ar_{rotD100}} = S_{a_{FN}}$ for directivity ground motions?

- Each ground motion in the NGA West 2 database classified as pulse or non-pulse
  - Improved pulse-classification algorithm (Shahi and Baker)
  - Documentation in progress

- Source-site geometry used to manually identify Pulse-like ground motions caused by directivity
$S_{\text{RotD100}}$ orientation for directivity ground motions

Data pooled from 21 periods
$S_{a_{\text{RotD100}}}$ orientation for directivity ground motions

Data for period closest to $T_p$
Effect of Chi-Chi

Geometric mean $\frac{S_{a_{RotD100}}}{S_{a_{RotD50}}}$

- NGA-West2 data
- NGA-West2 without Chi Chi
Effect of changing the dataset
Any variation in this ratio with distance ($M$)?

- $T = 0.1\ s$
- $T = 1\ s$
- $T = 3\ s$
- $T = 7.5\ s$
Any variation in this ratio with \( s \)? (Strike slip only)

- \( T = 0.1 \ s \)
- \( T = 1 \ s \)
- \( T = 3 \ s \)
- \( T = 7.5 \ s \)
Any variation in this ratio with $\theta$? (Strike slip only)

- $T = 0.1\ s$
- $T = 1\ s$
- $T = 3\ s$
- $T = 7.5\ s$
Any variation in this ratio with D? (Non-strike-slip only)
Regression analysis to evaluate significance of above parameters

- Both forward and backward step-wise regression was used to select statistically significant parameters

- Some dependence on M and R (depends upon period)

- Some dependence on directivity parameters at higher periods

- Our recommendation: a simple model dependent on R only
Distribution of $\alpha$ for different M-R bins

$T = 1 \text{ s}$

Distance range (km)

<table>
<thead>
<tr>
<th>Magnitude range</th>
<th>0-3</th>
<th>3-5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
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<tbody>
<tr>
<td>5.6</td>
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<td>7.8</td>
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</tbody>
</table>

Dir

count
Distribution of $\alpha$ for different M-R bins

Data pooled from all periods
Distribution of $\alpha$ for different R bins

Data pooled from all periods

Distance range (km)

<table>
<thead>
<tr>
<th>Distance range (km)</th>
<th>Density</th>
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<tbody>
<tr>
<td>0-3</td>
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<td>30-40</td>
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Models for $\alpha$? Two options:

1. Parametric model for distribution of $\alpha$ (i.e., equation for a probability distribution)
   - Linearly-varying distribution of $\alpha$ for $R < 5$ km (function of $T$)
   - Uniform distribution for $R > 5$ km

2. Just report histogram values at different $T$ for $R < 5$ km
   - Simpler, but hard to do calculations with

R < 5 km, $T = 0.1s$

R < 5 km, $T = 7.5s$
Direction of RotD100 with $\theta$

$T = 0.1 \text{ s}$

$T = 1 \text{ s}$

$T = 3 \text{ s}$

$T = 7.5 \text{ s}$
Zooming in towards high $\theta$

<table>
<thead>
<tr>
<th>$T = 0.1\ s$</th>
<th>$T = 1\ s$</th>
<th>$T = 3\ s$</th>
<th>$T = 7.5\ s$</th>
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<th>$75-80$</th>
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![Graphs showing data distribution for different $T$ values](image-url)
Only records with high amplification

\(T = 0.1 \text{ s}\)

\(T = 1 \text{ s}\)

\(T = 3 \text{ s}\)

\(T = 7.5 \text{ s}\)
• When $\theta$ is high some $S_{a,RotD100}$ values are found in fault parallel orientation. This may be due to the radiation patterns

• Due to low sample size and presence of randomness we cant make confident conclusions.
Distribution of $\alpha^*-\alpha'$ for different $T^*, T'$

- $T^* = 1 \text{ s}, T' = 2 \text{ s}$
- $T^* = 0.1 \text{ s}, T' = 0.2 \text{ s}$
- $T^* = 1 \text{ s}, T' = 5 \text{ s}$
- $T^* = 0.1 \text{ s}, T' = 0.5 \text{ s}$
Median ratio of $\text{Sa}(\Phi)/\text{Sa}_{\text{RotD50}}$, as a function of distance from $\text{Sa}_{\text{RotD100}}$ orientation