NGA-West 2: Regional Path Effects, Aftershock Effects, and Site Response

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Outline

• BSSA GMPE (Boore-Stewart-Seyhan-Atkinson)
• Path effects and their regional dependence
• Are aftershock motions different from mainshocks?
• Site response model: $V_{s30}$-scaling & basin depth effects
• Use of non-ergotic site terms for dams
• Summary
BSSA GMPE

- Database
BSSA GMPE

- Database
BSSA GMPE

• Database

4147 sites: 49% with $V_{s30}$ from measurements
BSSA GMPE

- Database
- Predictor variables
BSSA GMPE

![Graph showing PGA (g) and PGA (R_x / PGA (R_x < 0)) vs. R_x (km) for different models.

- Light grey lines: Simulation-based models
- Black lines: R_{ubr}-based model

The graph includes a note: δ = 45 deg, M 7 surface reverse]
BSSA GMPE

- Database
- Predictor variables

\[ M, R_{JB} \]

Fault type: NS, RS, SS

Site parameters: \( V_{S30}, \delta z_1 \)

![Graph showing depth vs. Vs30 for California and Japan with different site conditions.](a)
BSSA GMPE

- Database
- Predictor variables

**The equations**

\[
\ln Y = F_E (M, \text{mech}) + F_P (R_{JB}, M, \text{region}) + F_S (V_{S30}, R_{JB}, M, z_1) + \varepsilon_s \sigma (M, R_{JB}, V_{S30})
\]

- $R_{JB} = 1$ km, $V_{S30} = 760$ m/s
- Strike slip
- Reverse
- Normal
BSSA GMPE

- Database
- Predictor variables
- The equations

\[
\ln Y = F_E \left( M, mech \right) + F_P \left( R_{JB}, M, region \right) + F_S \left( V_{S30}, R_{JB}, M, z_1 \right) + \varepsilon_n \sigma \left( M, R_{JB}, V_{S30} \right)
\]
BSSA GMPE

- Database
- Predictor variables

- The equations

\[
\ln Y = F_E(M, \text{mech}) + F_p(R_{JB}, M, \text{region}) + F_S(V_{S30}, R_{JB}, M, z_1) + \epsilon_n \sigma(M, R_{JB}, V_{S30})
\]
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Path Effects

Distance attenuation

\( \ln Y \)

1 km \hspace{1cm} 10 km \hspace{1cm} 100 km

Given M

\( \ln R \)
Path Effects

**Distance attenuation**

![Graph showing distance attenuation with saturation near fault and a given magnitude](image)

*Saturation: near fault*

Given M

- InY
- 1 km
- 10 km
- 100 km

*InR*
Path Effects

**Distance attenuation**

Given M

*Constant slope: M-Dependent geometric spreading*
Path Effects

Distance attenuation

\[ \text{Given } M \]

\[ \ln Y \]

\[ \ln R \]

1 km 10 km 100 km

Large \( R \): Anelastic attenuation
Path Effects

Distance attenuation

\[ \text{InY} \]

\[ \text{InR} \]

1 km  10 km  100 km

Given M
Path Effects

Distance attenuation

\[ \text{InY} \]

\[ \text{InR} \]

1 km 10 km 100 km

Given M

High Q

Low Q
Path Effects

- CA inelastic term, $c_3$
Path Effects

- **CA inelastic term, $c_3$**

\[ \ln Y_{ij} = \eta_i' + c_1' \ln \left( \frac{R}{R_{ref}} \right) + c_3 \left( R - R_{ref} \right) \]
Path Effects

- **CA inelastic term,** \( c_3 \)

\[
\ln Y_{ij} = \eta_i' + c_1' \ln \left( \frac{R}{R_{\text{ref}}} \right) + c_3 \left( R - R_{\text{ref}} \right)
\]
Path Effects

- CA inelastic term, $c_3$
- Main regression performed with fixed $c_3$ from CA.

$$F_p(R_{JB}, M, region) = \left[ c_1 + c_2(M - M_{ref}) \right] \ln \left( \frac{R}{R_{ref}} \right) + (c_3 + \Delta c_3) \left( R - R_{ref} \right)$$
Path Effects

- CA inelastic term, $c_3$
- Main regression performed with fixed $c_3$ from CA.
- Compute residuals

**Total residual:**

$$R_{ij} = \ln Y_{ij} - \mu_{ij} \left( M, R_{JB}, V_{S30} \right)$$

**Partitioning into within- and between-event components:**

$$R_{ij} = c_k + \eta_i + \epsilon_{ij}$$
Path Effects

• CA inelastic term, $c_3$
• Main regression performed with fixed $c_3$ from CA.
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Total residual:

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$$R_{ij} = \ln Y_{ij} - \mu_{ij} \left( M, R_{JB}, V_{S30} \right)$$

Partitioning into within- and between-event components:

$$R_{ij} = c_k + \eta_i + \epsilon_{ij}$$
Within- and Between-Event Variability

- Data, $+\eta$ event
- Fit, $+\eta$ event
- GMPE mean
- Fit, $-\eta$ event
- Data, $-\eta$ event

Intensity Measure vs. Site-source distance
Path Effects

- CA inelastic term, $c_3$
- Main regression performed with fixed $c_3$ from CA.
- Compute residuals
- Evaluate regional trends from $\varepsilon_{ij}$
Faster attenuation (low $Q$)

$$\varepsilon = \Delta c_3 \left( R - R_{ref} \right) + \bar{\varepsilon}_{IR}$$
Slower attenuation (high $Q$)

$$\varepsilon = \Delta c_3 \left( R - R_{ref} \right) + \bar{e}_{IR}$$
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Aftershocks & Mainshocks

• CL1 and CL2 definition

Ref: Wooddell & Abrahamson, 2014
Aftershocks & Mainshocks

• CL1 and CL2 definition
• Base model developed with only CL1 events
Aftershocks & Mainshocks

- CL1 and CL2 definition
- Base model developed with only CL1 events
- Residuals computed using both event types

Examine between-event residuals, $\eta_i$

- Parent CL1 event: $\eta_{CL1}$
- Children CL2 events: $\eta_{CL2}$
- Mean: $\bar{\eta}_{CL2}$
Modest correlation: strongest at short periods
Aftershocks & Mainshocks

- CL1 and CL2 definition
- Base model developed with only CL1 events
- Residuals computed using both event types

Examine between-event residuals, $\eta_i$

Parent CL1 event: $\eta_{CL1}$
Children CL2 events: $\eta_{CL2}$
Mean: $\bar{\eta}_{CL2}$

Compute difference between CL1 and CL2 event terms

$$\Delta \eta = \bar{\eta}_{CL2} - \eta_{CL1}$$

13 CL1-CL2 sequences
\( \Delta \eta \) not significantly offset from zero

No trend with \( M \)

\( \therefore \) CL2 events are not more biased relative to GMPE than their CL1 parent events
Outline

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• **Site response model: \(V_{s30}\)-scaling & basin depth effects**

• Use of non-ergotic site terms for dams

• Summary
Site Response Model

$V_{S30}$-scaling

- Initial site model developed (using data analysis and simulations)
- Site coefficients fixed in GMPE regressions
- Site model checked from residuals analysis, $\varepsilon_{ij}$ terms
- Multiple iterations performed
- $V_{S30}$-scaling model used to develop updated ASCE/NEHRP site factors
Model Summary

- **Combined model**

\[
F_S(V_{S30}, M, R_{JB}, \delta z_1) = \ln(F_{lin}) + \ln(F_{nl}) + F_{\delta z_1} (\delta z_1)
\]

- **Linear term**

\[
\ln(F_{lin}) = \begin{cases} 
  c \ln \left( \frac{V_{S30}}{V_{ref}} \right) & V_{S30} \leq V_c \\
  c \ln \left( \frac{V_c}{V_{ref}} \right) & V_{S30} > V_c 
\end{cases}
\]

- **Nonlinear term**

\[
\ln(F_{nl}) = f_1 + f_2 \ln \left( \frac{PGA_r + f_3}{f_3} \right)
\]

- $V_{ref} = 760 \text{ m/s}$
- $c$ = slope term for $V_{S30}$-scaling
- $\Delta c$ = regional correction
- $V_c$ = limiting (corner) velocity for $V_{S30}$-scaling
- $f_2 = f(V_{S30}, PGA_r)$
- $f_3 = 0.1 \text{ g, } f_1 = 0$
Steps in Model Development

$V_{S30}$-scaling

• Evaluation of nonlinearity. Guided by data trends and simulation results
• Evaluation of $V_{S30}$-scaling. Considers regional effects

* Basis: Non-Reference Site Approach *

• Compute residuals between data ($\ln Y_{ij}$) and rock GMPE, $(\mu_r)_{ij}$

\[
R^c_{ij} = \ln Y_{ij} - \left[ (\mu_r)_{ij} + \eta_i \right]
\]
Nonlinearity

- Data analysis

Bin residuals \( R_{ij} \) by \( V_{S30} \):

- Class B : \( 760 < V_{S30} < 1500 \text{ m/s} \)
- Class C : \( 520 < V_{S30} < 760 \text{ m/s} \)
- Class CD : \( 310 < V_{S30} < 520 \text{ m/s} \)
- Class D : \( 200 < V_{S30} < 310 \text{ m/s} \)
- Class E : \( 200 \geq V_{S30} \text{ m/s} \)

Plot against \( PGA_r \)

Nonlinear regression

\[
\ln(F_{nl}) = f_1 + f_2 \ln\left( \frac{PGA_r + f_3}{f_3} \right)
\]
Nonlinearity
Nonlinearity

- Data analysis
- Interpretation of simulation results

Fit slope parameter to simulation results

Ref: Kamei et al. (2014)
Nonlinearity

• Data analysis
• Interpretation of simulation results
• Plot $f_2$ vs $V_{S30}$ and select model that captures trends
Nonlinearity
$V_{S30}$-Scaling

- Remove nonlinearity from residuals

$$R^{\text{lin}}_k = R^r_{ij} - \ln \left( F_{nl} \right)_{ij}$$
$V_{S30}$-Scaling

- Remove nonlinearity from residuals
- Plot against $V_{S30}$
**V_{S30}-Scaling**

- Remove nonlinearity from residuals
- Plot against $V_{S30}$
- Regional variations.
**$V_{S30}$-Scaling: Regional Variations**

NGA-West 2 data by region

Grey: all distances

Blue: $R_{jb} < 80$ km

Large difference in Japan high-frequency IMs

Not present for CA or Taiwan
**NEHRP-ASCE Site Factors**

*F*=1.0 at B-C

Average amplification computed across period ranges.

*F* increased in some cases for strong shaking

*F* generally reduced for weak shaking

*F* < 1 for Class B (only allowed if *V_s* measured)
Site Response Model

$z_1$-scaling

• Within-event residuals ($\epsilon_{ij}$) plotted against depth
• Trends identified and model developed
Model Summary

• **Combined model**

\[
F_S(V_{S30}, M, R_{JB}, \delta z_1) = \ln(F_{lin}) + \ln(F_n) + F_{\delta z_1}(\delta z_1)
\]

• **Depth model**

\[
\delta z_1 = z_1 - \mu_{z1}(V_{S30})
\]

Offset between actual depth and default for region-specific \( V_{S30} \)

\[
F_{\delta z_1}(\delta z_1) = \begin{cases} 
0 & T < 0.65 \\
 f_6 \delta z_1 & T \geq 0.65 \& \delta z_1 \leq f_7/f_6 \\
 f_7 & T \geq 0.65 \& \delta z_1 > f_7/f_6
\end{cases}
\]
Short periods: no effect
Long periods: strong trend for $\delta z_1 < \sim 0.5 \text{ km}$
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Non-Ergotic Site Terms

• **Ergotic**: GMPE used as-published (site response taken from site term).

• **Non-ergotic site term**: Evaluate true site response, which may deviate from site term in GMPE by amount $\delta S2S(T)$

• Within event standard deviation, $\phi$:
  – Ergotic: use full $\phi$; includes contribution from standard deviation of $\delta S2S(T)$, $\phi_{S2S}$
  – Non-ergotic: use $\sqrt{\phi^2 - \phi_{S2S}^2}$
Non-Ergotic Site Terms

Install sensors

Record eqks in \( M-R \) range of GMPE

Compute and partition residuals. Mean is \( \delta S2S \)

Reduced sigma impactful for PSHA
Non-Ergotic Site Terms

1. Install sensor at site
2. Record earthquakes within M-R range of GMPE
3. Compute residuals, partition into $\eta_i$, $\varepsilon_{ij}$
Non-Ergotic Site Terms

4. Compute mean and stdev of $\varepsilon_{ij}(\delta S2S, \phi_{amp})$
Non-Ergotic Site Terms

4. Compute mean and std dev of $\varepsilon_{ij}(\delta S2S, \phi_{amp})$

5. Extract $\phi_{S2S}$ from literature or region-specific analysis

6. Adjust GMPE moments, run PSHA. Site response uncertainty treated as epistemic.
Summary

• **BSSA GMPE:**
  – Relatively simple functional form
  – Considered relatively robust for scaling with respect to $M$, $R_{JB}$, and site parameters
  – Captures average hanging wall effects from dataset
  – No source depth correction required

• **Path term:**
  – Important anelastic effects at short $T$ and $R > \sim 70$ km
  – Regional variations in anelastic effects in active crustal regions
Summary

• Aftershocks and mainshocks:
  – No significant differences identified from event terms
  – GMPE considered equally applicable for both event types

• Site response model:
  – Nonlinearity from simulations and data
  – Modest regional variations in $V_{s30}$-scaling (not included in BSSA model)
  – High $V_{s30}$ limit to scaling (mid to low frequencies)
Summary

• **NEHRP/ASCE site factors. Changes caused by:**
  – Adjustments to $V_{s30}$-scaling
  – Enforcing amplification of unity at 760 m/s
  – Reduced levels of nonlinearity (esp. C & D)

• **Basin amplification model:**
  – Based on $\delta_{z1}$ term (default is $\delta_{z1} = 0$)
  – No effect at short periods; strong effect at long periods