Do Scaled Ground Motion Records Cause Biased Nonlinear Structural Responses?

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Problem Statement

Given:

1) A nonlinear structural model to be dynamically analyzed (design or evaluation) at a specific site.

2) A ground motion target response spectrum.

3) An earthquake magnitude (M), source-to-site distance (R), and other ground motion prediction equation (a.k.a., attenuation) input parameters of interest. e.g.,
   - M = 7.5
   - R = 3 km
   - Forward rupture directivity region
   - Strike-normal orientation
   - SD NEHRP site condition
Possible Genesis of a Target Response Spectrum

2%/50yr Uniform Hazard Spectrum for San Francisco

Disaggregation

Prob. Seismic Hazard Disaggregation
Downtown_San_Fra 122.399° W, 37.798 N.
Mean period 1.00 sec, Accel.=0.8397 g
Median Return Time of GM 2275 yrs
Mean (R,Ms) 14.1 km, 7.67, 1.57
Model (R,Ms): =13.9 km, 7.94, 1.60 (from peak R,Ms bin)
Model (R,Ms): =13.9 km, 7.94, 1.57 (from peak R,Ms bin)
Binning: DeltaR=1.0 km, delMa=0.2, DeltaMs=1.0

M~7.8
R~15km

Problem Statement (cont’ed)

**Given:**

1) A nonlinear structural model to be dynamically analyzed.

2) An earthquake magnitude (M), source-to-site distance (R), and $S_a(T_1)$ level

**Find:**

- The “average” (geometric mean) nonlinear structural response for the target ground motion.

  e.g., story drift ratios $\equiv$ differential horizontal displ. of floors
Next Generation Attenuation (NGA) Project has about 3,500 “uniformly” processed three-component recordings.

In many practical applications:
- M large
- R is short
- $S_a(T_1)$ is high

“Right” records are scarce.
Alternative No 1: Spectrum matching

- Spectrum match earthquake records to “appropriate” target spectrum of given M, R, and $S_a(T_1)$, e.g.,

- Perform nonlinear dynamic analyses and calculate the geometric mean response
Alternative No 2: Amplitude Scaling

- Scale (in amplitude only) the earthquake records to $S_a(T_1)$, e.g., when $T_1 = 1.0$ sec.

- Perform nonlinear dynamic analyses and calculate the geometric mean response
Use of Scaled Records for NL Dynamic Analyses

- Is that a legitimate operation or does it introduce bias in median and dispersion of the structural response?

  \[
  \text{Bias} = \frac{\text{median structural response to scaled records}}{\text{median structural response to unscaled records naturally at target } S_a}
  \]

- If there is a bias, does it depend
  - Scale factor
  - characteristics of the target ground motion scenario (e.g., M and R),
  - characteristics of the source records
  - vibration period(s) of the structure of interest
  - strength of the structure (i.e., level of response nonlinearity)
  - contribution of higher (than the first) vibration modes to the structural response.

- Are there records that are better candidate than others for scaling?
Analyses Setup: Bins of Ground Motion Records

- **Intra-bin Scaling**: “right” M and R but “wrong” (i.e., lower) $S_a(T_1)$ level

<table>
<thead>
<tr>
<th>Bin Label</th>
<th>$M_w$</th>
<th>$R_{close}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6.4 to 6.8</td>
<td>0 to 15km</td>
</tr>
<tr>
<td>II</td>
<td>6.4 to 6.8</td>
<td>15 to 30km</td>
</tr>
<tr>
<td>III</td>
<td>6.4 to 6.8</td>
<td>30 to 50km</td>
</tr>
<tr>
<td>IV</td>
<td>6.9 to 7.6</td>
<td>0 to 15km</td>
</tr>
<tr>
<td>V</td>
<td>6.9 to 7.6</td>
<td>15 to 30km</td>
</tr>
<tr>
<td>VI</td>
<td>6.9 to 7.6</td>
<td>30 to 50km</td>
</tr>
</tbody>
</table>

  73 records each

- **Inter-bin Scaling**: “wrong” M, and/or R, and/or $S_a(T_1)$ level

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Source Bin</th>
<th>Target Bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>IV</td>
</tr>
<tr>
<td>2</td>
<td>II</td>
<td>IV</td>
</tr>
<tr>
<td>3</td>
<td>V</td>
<td>IV</td>
</tr>
<tr>
<td>4</td>
<td>II</td>
<td>V</td>
</tr>
<tr>
<td>5</td>
<td>III</td>
<td>V</td>
</tr>
<tr>
<td>6</td>
<td>VI</td>
<td>V</td>
</tr>
<tr>
<td>7</td>
<td>III</td>
<td>VI</td>
</tr>
<tr>
<td>8</td>
<td>III</td>
<td>I</td>
</tr>
<tr>
<td>9</td>
<td>I</td>
<td>Near-Source</td>
</tr>
<tr>
<td>10</td>
<td>Near-Source</td>
<td>I</td>
</tr>
</tbody>
</table>

31 records
48 Single-Degree-of-Freedom (SDOF) NL Oscillators
- 8 Periods: \( T = 0.1, 0.2, 0.3, 0.5, 1, 2, 3, \) and 4 s.
- 6 Strength Reduction Factors: \( R = 1, 2, 4, 6, 8, \) and 10
- Force-displacement hysteretic behavior is bilinear with 2% hardening (no strength or stiffness degradation)

9-story, 5-bay Steel Moment Resisting Frame
- Elastic model
- Ductile model

\[
F = S_a \cdot m
\]
\[
R = \frac{S_a}{S_a} \cdot m
\]
Measures of Structural Response

- SDOF systems: peak inelastic displacement (inelastic spectral displacement), $S_d^i$

- MDOF Building ($T_1=2.3\text{s}$, $\nu_1=2\%$ of critical):
  - the peak roof drift ratio, $\theta_{\text{roof}}$ (i.e., peak roof displacement normalized by the building height),
  - the maximum peak (over time) inter-story drift ratio over all stories, $\theta_{\text{max}}$

- NOTES:
  - SDOF results are for constant R (yield strength varies from record to record). About 2M runs
  - MDOF results are for a fixed strength (about 6,500 runs)
Procedure for Quantifying Bias due to Scaling

- Select first target $S_a$ for scaling and compute response
- Scale all other records in the “source” bin to the target $S_a$ and keep track of scaling factor, SF, values

**NOTE:** results shown are for intra bin scaling: Near Source Record Bin, Moderate Strength (R=4) and Period (T=1s)
Response Plotted vs. Elastic $S_d$

Intra-Bin Scaling Example

- Unscaled Accelerogram
- Target

Scale Factor = 29.1

Response lower than average. Biased?
Ratio of Responses Plotted vs. Scale Factor

BIAS = \( a \cdot SF^b \)

fitted line that gives the bias in median \( S_d^i \) for a given scale factor

Bias if different than 1

Target record

Scaled record

Scaled/Unscaled \( S_d \) (\( T, \xi = 5\% \), \( R, \alpha = 2\% \))

No bias for \( SF = 1 \)

Bias proportional to \( SF \)

Bias = 2.1

Bias = 0.70

Bias = 0.35

Bias = a \( SF^b \)

\( a = 1.00 \)

\( b = 0.88 \)
Yes, There Is Bias? Why?

- Difference in spectral shape. On average
  - “valley” records are scaled up
  - “peak” records are scaled down

31 "Near-Source" Recordings

- Scaled up by 6.8
- Scaled down by 0.35

More aggressive at $T>T_1$

More benign at $T>T_1$
Three Meanings for This Response Bias

- This response bias applies to the median response of
  - Randomly selected record scaled by a $SF=x$
  - A suite of records all scaled by the same $SF=x$
  - A suite of records that, on average, are scaled by the same $SF=x$ but with different scaling factors for each single record (à la Cornell)
Intra-Bin Scaling: Bias for $T=1\text{s}$, $R=4$ SDOF, All Bins

- Largest for Near-Source Bin
- Smallest for Bin III
Intra-Bin Scaling: Bias for All SDOFs, Near-Source Bin

Bias increases with inelasticity

Bias decreases at longer periods

Peak due to predominant period of pulse-like records in this bin

NOTE: $a=1$ for all SDOFs in equation $BIAS=a \cdot SF^b$
Inter-Bin Scaling: $T=1s$, $R=4$ SDOF, Bin III to Bin I

- Bin III ($M=6.4$ to $6.8$; $R=30$ to $50$km) is weaker than Bin I ($M=6.4$ to $6.8$; $R=0$ to $15$km)

$$SF_{\text{inter-bin}} = r(m[S_a]) * SF_{\text{remaining}}$$

- Ratio of median $S_a$'s target/source
- Remaining scaling factor (as in the intra-bin case)
Inter-Bin Scaling: $T=1\text{s}, R=4$ SDOF, Bin III to Bin I

Residual bias at SF=1
Bias similar to intra-bin case for same target bin (0.38 before)

Target Records more aggressive at $T>T_1$

Source records more benign at $T>T_1$
MDOF Structure: Intra Bin Scaling, Near-Source Bin

\( \theta_{\text{roof}} \) is first-mode dominated
No bias in the elastic range.
Small bias in the post-elastic range

\( \theta_{\text{max}} \) is sensitive to higher modes
Bias is larger and is in the elastic case too due to differences in spectral shapes (at \( T<T_1 \) this time!)
How Can the Bias be reduced?

Most similar 10 only!

Bias virtually gone
Conclusions

- Scaling a randomly selected record induces bias in nonlinear response (conditional on M, R, and $S_a$ level)

- Bias depends on
  - Scale factor
  - The fundamental period of the structure
  - The overall strength of the structure
  - The sensitivity of the response measure to higher modes
  - The ground motion scenario (e.g., $M$ and $R$) of the records that are scaled

- Inter-bin scaling bias is comparable to intra-bin scaling bias for the target $M$ and $R$ bin case. However, there is usually an additional bias due to pre-scaling to median $S_a$ of target bin

- **Judicious** selection of source records reduces considerably the response bias

- The results of this study can serve as a basis to place limits on the amount of scaling that is acceptable for a given structure (alternatively, correct response for bias)