Why structural engineers need to be involved in seismic hazard representation

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OUTLINE

WHAT WE NEED TO UNDERSTAND

HOW WE AIM TO UNDERSTAND THE PROBLEM

WHAT STILL NEEDS TO BE DONE

INFLUENCE OF RESPONSE SPECTRA DEFINITIONS ON THE RESPONSE OF RC BRIDGE COLUMNS
Recall Response Spectrum

- **ACCELERATION**
- **VELOCITY**
- **DISPLACEMENT**

Adapted from Source: https://sites.google.com/site/quakemanagerwiki/record-manager/spectra/what-is-a-response-spectrum
How are ground motions recorded?

- **Seismic activity is recorded in the field by accelerometers.**
- **Accelerometers measure acceleration in 3 orthogonal directions.**
  - Horizontal 1
  - Horizontal 2
  - Vertical

Response Spectrum for each component? Bidirectional Response Spectrum?
Design Spectrum

\[ S_d = \frac{S_a}{w^2} \]

- **Bidirectional hazard representation**
- **Considers:**
  - Probabilistic Seismic Hazard Analysis
  - Historical seismicity.
  - Ground Motion Prediction Equations (GMPEs)
    - NGA-West2 Models:
      - Two horizontal components with RotD50 definition
Response Spectra Definitions

**Response Spectra Definitions**

\[ a_{\text{ROT}}(t; \theta) = a_1(t) \cos(\theta) + a_2(t) \sin(\theta) \]

### DISPLACEMENT SPECTRUM

**Christchurch 2011**

<table>
<thead>
<tr>
<th>PERIOD [S]</th>
<th>T = 1s</th>
<th>T = 2s</th>
<th>T = 3s</th>
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<tbody>
<tr>
<td>0</td>
<td>35.23</td>
<td>69.27</td>
<td>75.83</td>
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<tr>
<td>0.5</td>
<td>35.01</td>
<td>69.02</td>
<td>75.69</td>
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<td>36.18</td>
<td>77.07</td>
<td>76.5</td>
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<td>79.72</td>
<td>77.26</td>
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<td>2</td>
<td>41.55</td>
<td>125.62</td>
<td>104.9</td>
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<tr>
<td>2.5</td>
<td>42.19</td>
<td>128.32</td>
<td>105.83</td>
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<tr>
<td>3</td>
<td>43.61</td>
<td>151.66</td>
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<tr>
<td>3.5</td>
<td>44.26</td>
<td>154.36</td>
<td>105.83</td>
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<tr>
<td>4</td>
<td>45.02</td>
<td>123.61</td>
<td>76.5</td>
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<tr>
<td>4.5</td>
<td>45.80</td>
<td>126.60</td>
<td>77.26</td>
</tr>
<tr>
<td>5</td>
<td>46.57</td>
<td>129.57</td>
<td>78.32</td>
</tr>
</tbody>
</table>

**RotD00**: Minimum
**RotD50**: Median
**RotD100**: Maximum

**SD [MM]**

\[ SD(\theta) = \sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \]

**Christchurch 2011**
How have the definitions been adapted?

NGA-West1

RotD50

RotD100

RotD50 SPECTRA OR RotD100 SPECTRA?

OR ...

NGA-West2

RotD100

Shahi et al. (2012)

RotD100

ASCE 7 (2016)

SA_{ROTD100}/SA_{ROT50} \quad \xi = 5\%

FACTOR = 1.2

FACTOR = 1.1

AASHTO

GMRotI50

WHAT WE NEED TO UNDERSTAND
The Question:
What response spectra definition should we use?

The Problem:
Decisions are being made without consultation of structural engineers

The Complication:
We (as engineers) “don’t know what we don’t know.”

Our position:
Decisions should only be made after non-linear analysis quantifies impact
Research Objectives

1. **Determine the impact of response spectra definitions on the seismic response of SDOF bridge systems.**
   - Specifically evaluating RotD50 designs versus RotD100 designs.

2. **Validation of the direct displacement-based design method (DDBD) for bidirectional spectra.**
Application of Direct Displacement-Based Design (DDBD)

**For each ground motion record:**

\[ \Delta_t_i \rightarrow T_{eff} \]

\[ \xi = 5\% \rightarrow \mu = 1 \]

\[ \Delta y = \frac{\Delta_i}{\mu} \]

\[ \phi_y = \frac{3}{H^2} \left( \frac{\Delta_i}{\mu} \right) \]

\[ \xi = 0.05 + 0.444 \left( \frac{\mu - 1}{\mu \pi} \right) \]

(Takeda Thin Hysteresis)
Application of Direct Displacement-Based Design (DDBD)

FOR EACH CHOSEN TARGET DISPLACEMENT:

\[ k_{\text{eff}} = \frac{4\pi^2 \cdot W}{g \cdot T_{\text{eff}}^2} \]

**BASE SHEAR:**

\[ F_N = V_b = k_{\text{eff}} \cdot \Delta t_i \]

**MOMENT CAPACITY:**

\[ M_N = V_b \cdot H \]

\[ M_y = \frac{M_N}{r_\Delta \mu - r_\Delta + 1} \]

\[ I_{CR} = \frac{M_y}{E \phi_y} \]
Application of Direct Displacement-Based Design (DDBD)

FOR EACH GROUND MOTION RECORD:

**DISPLACEMENT SPECTRUM**

\[ T_{\text{eff}} \rightarrow k_{\text{eff}} \rightarrow V_b \rightarrow M_N \rightarrow M_y \rightarrow I_{\text{CR}} \]

FOR ALL DESIGNS:

- SDOF BRIDGE SYSTEMS ARE RC CIRCULAR COLUMNS.
- MATERIAL PROPERTIES ARE CONSTANT FOR ALL COLUMN DESIGNS.
- HEIGHT IS CONSTANT.
- FORCE-DISPLACEMENT BILINEAR FACTOR \((r_\Delta)\) EQUAL TO 5%.
Ground Motion Data Selection

All records were obtained from PEER NGA-West2 database

### Magnitude

- $7 \leq M < 8$: 33.3%
- $6 \leq M < 7$: 51.7%
- $5.7 < M < 6$: 15.0%

### Soil Condition

- D: Soft Soil Deposits: 3.33%
- C: Medium-Dense...: 58.33%
- B: Stiff Soils: 28.33%
- A: Rock: 1.67%

### Epicentral Distance [km]

- $R > 100$: 11.67%
- $50 \leq R < ...$: 16.67%
- $20 \leq R < ...$: 30.00%
- $10 \leq R ...$: 25.00%
- $R < 10$: 16.67%

### Hypocenter Depth [km]

- $15 \leq ...$: 21.67%
- $10 \leq ...$: 18.33%
- $5 \leq HD ...$: 55.00%
- $0 < HD < ...$: 0.00%
Ground Motion Response Spectra

**ROTD100 SPECTRA**

**GROUND MOTION PAIR**

**H1**

**H2**

**Displacement [cm]**

**Period [s]**
Nonlinear Time History Analysis with Ruaumoko

For each design:

→ Section Properties

→ Material Properties

→ Design Values

\[ \Delta_{\text{max}} \]

- 61 ground motion records used in analysis
- 700 designs per ground motion pair
  - 350 using RotD50 spectra
  - 350 using RotD100 spectra
- NLTHA performed for each design as shown on the left.

Ruaumoko 3D
NLTHA Results example: 1992 Landers EQ – RotD100 Designs

\[
\frac{\Delta_{\text{max}}}{\Delta_t} = \frac{752 \text{ mm}}{751 \text{ mm}} = 1.00
\]

\[
\mu = 1 \quad T_{\text{eff}} = 3 \text{s}
\]

\[
\frac{\Delta_{\text{max}}}{\Delta_t} = \frac{471 \text{ mm}}{572 \text{ mm}} = 0.82
\]

\[
\Delta_{\text{max}} = 752 \text{ mm}
\]

\[
\Delta_{\text{max}} = 471 \text{ mm}
\]
**NLTHA Results example: 1992 Landers EQ – RotD50 Designs**

\[
\begin{align*}
\mu &= 1 \\
T_{\text{eff}} &= 3s \\
\frac{\Delta_{\text{max}}}{\Delta_t} &= \frac{785 \text{ mm}}{532 \text{ mm}} = 1.48 \\
\mu &= 8 \\
T_{\text{eff}} &= 3s \\
\frac{\Delta_{\text{max}}}{\Delta_t} &= \frac{565 \text{ mm}}{406 \text{ mm}} = 1.39
\end{align*}
\]
Displacement Ratios Comparison: 1992 Landers EQ

If Ratio = 1 \therefore \Delta_{max} = \Delta_{target} \rightarrow \text{Intended performance}
Displacement Ratios Comparison: 2018 Anchorage EQ

If Ratio = 1 ∴ \( \Delta_{\text{max}} = \Delta_{\text{target}} \) → Intended performance
RESULTS

Displacement Ratio – 61 GM

\[ \mu_1 \]
Mean = 1.27
Mean = 1.00

\[ \mu_{1.5} \]
Mean = 1.31
Mean = 1.03

\[ \mu_2 \]
Mean = 1.29
Mean = 1.00

\[ \mu_3 \]
Mean = 1.25
Mean = 0.95

\[ \mu_4 \]
Mean = 1.22
Mean = 0.92

\[ \mu_6 \]
Mean = 1.21
Mean = 0.88

\[ \mu_8 \]
Mean = 1.20
Mean = 0.87

Across all \( \mu \)
Mean = 1.25
Mean = 0.95

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Overall Results – 61 GM

- **TOTAL OF 21,350 STRUCTURES PER RotDNN DEFINITION**
- **NLTHA USING SECANT STIFFNESS DAMPING MODEL**

**RESULTS**

**CDF FOR ALL DISPLACEMENT RATIOS**

- RotD50 Mean
- RotD50 COV
- RotD100 Mean
- RotD100 COV

**Axes:**
- Δ_{max} / Δ_T [m/m]
- Mean / COV

**Percentiles:**
- 58.52
- 0.948
- 1.25
- 18.03

**Ductility level:**
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
Damping Model Importance

**EQUATION OF MOTION:** \( m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g \)

**RAYLEIGH DAMPING:** \( c = \alpha[m] + \beta[k] \)

\[ \begin{align*}
\text{WITH INITIAL STIFFNESS:} & \quad c = \alpha[m] + \beta[k_i] \\
\text{WITH SECANT STIFFNESS:} & \quad c = \alpha[m] + \beta[k_s]
\end{align*} \]

Experiment

Secant Stiffness

Initial Stiffness

Petrini et al. (2008)
Damping Model Comparison – 50 GM

**WITH INITIAL STIFFNESS**

Ratio of NTHA to Target Displacement

\[ \frac{\Delta_{\text{Max}}}{\Delta_T} \text{ [m/m]} \]

- COV = 0.231
- COV = 0.268

**WITH SECANT STIFFNESS**

Ratio of NTHA to Target Displacement

\[ \frac{\Delta_{\text{Max}}}{\Delta_T} \text{ [m/m]} \]

- COV = 0.214
- COV = 0.259

- **EACH POINT CORRESPONDS TO 7 DUCTILITY LEVELS X 50 GM RECORDS = 350 STRUCTURES**

- **TOTAL OF 17,500 STRUCTURES PER RotDnn DEFINITION**
Damping Model Comparison – 50 GM

**WHAT WE NEED TO KNOW**

- Each point corresponds to 7 ductility levels x 50 GM records = 350 structures
- Total of 17,500 structures per RotDNN definition
Damping Model Comparison – 50 GM

WITH INITIAL STIFFNESS

Displacement Ratio $\mu_g$

WITH SECANT STIFFNESS

Displacement Ratio $\mu_g$

- EACH POINT CORRESPONDS TO 7 DUCTILITY LEVELS X 50 GM RECORDS = 350 STRUCTURES
- TOTAL OF 17,500 STRUCTURES PER ROTDNN DEFINITION
Damping Model Comparison – 50 GM

- EACH CURVE CORRESPONDS TO A DUCTILITY LEVEL = 50 TARGETS X 61 GM RECORDS = 3,050 STRUCTURES
What we understand so far...

✓ On average, RC circular columns designed to the maximum hazard definition, ROTD100, on average show 5% less deformation than expected in design.

✓ On average, RC circular columns designed using the median hazard definition, ROTD50, show deformations 25% greater than specified during design.

✓ Structures designed to ROTD100 spectra are in agreement with expected response for SDOF systems, and verifies the use of DDBD method for bidirectional loading.

✓ Damping model definition has significant impact on results and their variability.
What still needs to be done…

- SDOF SYSTEMS → RotD100 DEFINITION
- MDOF SYSTEMS → ? DEFINITION

Source: "
Taken at Umi Hotaru, Chiba, Japan www.umihotaru.com/en/
What still needs to be done

- 20-POINT RESPONSE SPECTRUM
THANK YOU
SUMMARY

What we need to understand:

- Ground motion directionality
- Response spectra definitions

How we aim to understand the problem:

- Analysis with real pair of acceleration records
- SDOF designs using DDBD approach
- NLTHA to verify SDOF designs
- Comparison of ROTDNN definitions

What still needs to be done:

- Additional SDOF parameters
- Evaluate definitions for MDOF systems accounting for increase in complexity

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