Ground Motion Simulations Validations at SCEC: Process and Outcomes

Christine A. Goulet
Executive Science Director for Special Projects, SCEC

Kevin Milner, Xiaofeng Meng and many many others…

SCEC ground-motion simulation platforms

<table>
<thead>
<tr>
<th><strong>SCEC simulation computations</strong></th>
<th><strong>Seismic band</strong></th>
<th><strong>period</strong></th>
<th><strong>frequency</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>mantle waves</td>
<td>crustal waves</td>
<td>basin waves</td>
<td>strongly scattered waves</td>
</tr>
<tr>
<td>100 s 100 Hz</td>
<td>10 s 1 Hz</td>
<td>1 s 1 Hz</td>
<td>0.1 s 10 Hz</td>
</tr>
<tr>
<td>Earthquake engineering band</td>
<td>tanks, tall buildings</td>
<td>short buildings, houses</td>
<td>stiff structures, NPPs, equipment</td>
</tr>
</tbody>
</table>

- **BroadBand Platform**
  - 1D Deterministic
  - Stochastic
  - Development and production software (runs on clusters and PCs)

- **CyberShake**
  - 3D Deterministic
  - Complete physics-based PSHA (runs on HPC)

- **BroadBand CyberShake**
  - 3D Deterministic CyberShake
  - Stochastic BroadBand Platform

- **High-F**
  - 3D Deterministic
  - Physics-based development for new physics (runs on HPC and clusters)
Past validations

Needed

Quantitative validation for forward simulations in engineering problems

Broadband Platform (BBP) Validation

BBP is an open-source distribution
Broadband 0.1-20+ Hz (deterministic up to ~ 1Hz)
Simple source and path (1D)
7 alternative simulation codes

Fully validated for spectral response
- 1.5 year validation project
- Multiple rounds of validation/improvements
- Independent review panel
Continuation of work in 2018

Used for large ground motion characterization projects
- SWUS, NGA-West2, NGA-East
Focus on quantitative validation for RotD50 PSA
Key lessons learned – past validations

Need transparent validation for forward simulations!
- Need to validate against many events
- Need clear documentation of fixed and optimized parameters from modelers for each region
- Need source description that is consistent between methods
- Use unique crustal structure (V, Q) for all models, or document assumptions
- Consider multiple source realizations (50)
- Use empirical site factors, not simulated site response (yet!)
- Make all validation metrics computation and plots part of software pipeline
- Need to tie-in results to specific code version

Need fast feedback to allow for method improvements

BBP Validation Schemes

- Part A. Validation against recorded earthquake ground motions
- Part B. Validation against GMPE for generic scenarios

Validation allows for development of region-specific rules (source scaling, path)
Part A: Selection of Events and Stations

- Large dataset (>20 EQs)
- Many regions & tectonic environments
- Span wide magnitude range (Mw 4.64 to 7.62)
- Variety of mechanisms
- Well-recorded (17 EQs with > 40 records)
- Select a large subset of stations (~40) that are consistent with mean and standard deviation PSA of the full dataset.

<table>
<thead>
<tr>
<th>EQ NAME</th>
<th>REGION</th>
<th># RECORDS</th>
<th>Mag (Mw)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Mayor Cucapah</td>
<td>WGS</td>
<td>134</td>
<td>7.20</td>
<td>SS</td>
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<tr>
<td>Northridge</td>
<td>WUS</td>
<td>124</td>
<td>6.72</td>
<td>REV</td>
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<td>Hector Mine</td>
<td>WGS</td>
<td>103</td>
<td>7.15</td>
<td>SS</td>
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<tr>
<td>Landers</td>
<td>WUS</td>
<td>69</td>
<td>7.22</td>
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<td>Whittier Narrows</td>
<td>WUS</td>
<td>95</td>
<td>5.89</td>
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<td>Big Bear</td>
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<td>6.36</td>
<td>REV</td>
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<td>6.50</td>
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<td>Saguenay</td>
<td>CENA</td>
<td>24*</td>
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<td>REV OBL</td>
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<tr>
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<td>28*</td>
<td>4.64</td>
<td>REV</td>
</tr>
<tr>
<td>Mineral, VA</td>
<td>CENA</td>
<td>54*</td>
<td>5.70</td>
<td>REV</td>
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<td>Tohoku</td>
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<td>Chuetsu-Oki</td>
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<td>6.80</td>
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<td>Miyagi</td>
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<td>246</td>
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<td>REV</td>
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<td>Iwate</td>
<td>JAPAN</td>
<td>186</td>
<td>6.90</td>
<td>REV</td>
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<td>Kosai</td>
<td>TURKEY</td>
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<td>7.51</td>
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<tr>
<td>Chi-Chi</td>
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<td>257</td>
<td>6.20</td>
<td>REV OBL</td>
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<tr>
<td>L’Aquila</td>
<td>ITALY</td>
<td>40</td>
<td>6.30</td>
<td>NML</td>
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<tr>
<td>Christchurch</td>
<td>NEW ZEALAND</td>
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<tr>
<td>Darfield</td>
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<td>24</td>
<td>7.00</td>
<td>SS</td>
</tr>
</tbody>
</table>

Part A: Qualitative Evaluation Products

- Qualitative evaluation of velocity time series and Husid plot based on Arias intensity

**RECORDED**

\[ V_{s30} = 822 \text{ m/s} \]

**SIMULATED**

\[ V_{s30} = 863 \text{ m/s} \]
Part A: Qualitative Evaluation Products

PSa for station 2001-SCE, NR vs 10000034

Part A: Evaluation Products

- Goodness-of-fit measures for PSA and PGA
  - Average GOF for 50 realizations (all stations)
**Part A: Evaluation Products**

- GOF plots also developed for:
  - NGA-West GMPEs
  - Allows to see trends/event terms
  - Expectation is finite-fault representation will lead to better performance than GMPE

**Part A: Evaluation Products**

- Goodness-of-fit measures for PSa and PGA
  - Average GOF with distance (all realizations)
Part B: Evaluation Criteria

- 3 scenarios for which NGA-West1&2 GMPEs are well constrained by data: M6.2&6.6, R20&50
- Two velocity models
- Box plot represents 50 realizations of the simulations
- Dashed black lines – criteria to define pass/fail

Graves & Pitarka, Scenario: M6.2, SS, R=20 km

- AS08
- BA08
- CB08
- CY08
- Median of 4 NGA Models
- Acceptance Criteria
Summary of Findings

- The BBP objective of a version-controlled numerical test bed with common post-processing tools was successful in producing results enabling straightforward analysis and review.

- We rerun the validation parameters on all methods every time there is a new release using guidelines established by the panel for evaluation.

- Now have seven updated methods on the platform, six of which pass the validation standards.

CyberShake: PSHA from Physics-Based Simulations

- Earthquake Rupture Forecast (e.g. UCERF)
- Kinematic source models
- 3D velocity model (from F3DT)
- Seismograms and intensity measures
- Hazard Curves and fault disaggregation
- M, R, ε disaggregation
- Hazard maps
Comparison of 1D and 3D CyberShake Models for the Los Angeles Region

Calculations for 2 velocity models for each of 438 sites, 1 Hz simulations, 400,000+ earthquakes
Used OLCF Titan and NCSA Blue Waters
Averaged 1295 nodes (CPU + GPU) for 31 days, maximum of 5374
Generated 285 million two-component seismograms
43 billion intensity measures

Data Comparisons: Northridge

- Compare CyberShake simulation intensity distribution with Northridge recordings
  - Include all ruptures on the UCERF2 “Northridge” source, M6.65-6.75
    - Distribution: gray histogram
    - Mean: black line
  - Compare with nearby record(s)
    - green line
  - Contrast with GMPE log-normal distributions
    - colored distributions
**GMPE Comparisons**

- Compare CyberShake IMs to GMPE for M and R ranges where GMPEs are well constrained

Pasadena CyberShake Site
All rupture variations:
- M6.5-7
- 40-80 km source/site distance
Yellow region is a factor of 2

**Mixed effects regression**

\[
\ln y_{es} = b_1 + b_2 \cdot (m - 6) + b_3 \cdot (m - 6)^2 + (b_4 + b_5 \cdot (m - 4.5)) \cdot \ln(\sqrt{R^2 + h^2}) + b_6 \cdot R + b_7 \cdot \ln \left( \frac{V_{30}}{760} \right)
\]

GMPE is modified from Boore and Atkinson, 2008. Hereafter referred as BA.

<table>
<thead>
<tr>
<th>T=3s</th>
<th>N</th>
<th>b₁</th>
<th>b₂</th>
<th>b₃</th>
<th>b₄</th>
<th>b₅</th>
<th>b₇</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td>CyberShake (CS) 15.4</td>
<td>~10⁸</td>
<td>4.02</td>
<td>2.13</td>
<td>-0.55</td>
<td>-0.82</td>
<td>0.12</td>
<td>-0.60</td>
<td>4.47</td>
</tr>
<tr>
<td>NGA_W2 in southern California</td>
<td>2691</td>
<td>4.87</td>
<td>1.28</td>
<td>-0.27</td>
<td>-1.36</td>
<td>0.20</td>
<td>-1.18</td>
<td>4.86</td>
</tr>
</tbody>
</table>
Distance scaling

ASK14 coefficients are from Abrahamson et al., 2014

Total residuals

CS15.4

NGA_W2

GMSM Working Meeting
Location, site and path terms

CS15.4

NGA_W2

Residual partitioning

GMSM Working Meeting
Conclusions

• CyberShake shows general agreement with ground motion data and existing models;
• Similar median trend
• Similar variance partitioning

• At single site, CyberShake generates a lot data points, which allow us to dig deeper into the source of variability;

• Validation of CyberShake is still ongoing on multiple fronts.
  • Correlation among site terms between two datasets
  • Evaluate the importance of assumptions in source modeling

Lots of people involved…
