SWUS SSHAC Workshop 1

Broadband Ground Motion Simulations

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For the Simulations team
The simulations team

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P. Somerville, R. Archuleta, N. Abrahamson, R. Graves, K. Olsen, J. Anderson,
R. Takedatsu, K. Assatourians, J. Crempien, F. Wang, G. Atkinson, M. Chapman,
J. Bayless, J. Lee, W. Silva, Y. Zeng,
T. Jordan, R. Kamai, K. Wooddell,
C. Di Alessandro, D. Boore, J. Stewart,
N. Luco, etc. and their collaborators...
Menu du jour

- Introduction
- Validation framework and schemes
  - Part A. Validation against recorded ground motions
    - Event and record selection
    - Correcting for site conditions
  - Part B. Validation against GMPEs
- Overview of simulation methods
- Example preliminary results
- Path forward to forward simulations
- Planned schedule
Interested parties and collaborations

- SWUS project

- PEER NGA-East project
  - Went through similar exercise in 2011, contributing lessons learned to this project

- PEER NGA-West3 projects
  - Made extensive use of simulations in NGA-West 1 and 2, planning to expand for next revision
  - Provide site correction factors

- SCEC & Broad Band Platform (BBP)
  - Invested lots of resources on simulations
  - Will benefit from validation

- SCEC evaluation committee includes reps from NGA-East and West 3
Lessons learned – past validations

- Need clear documentation of fixed and optimized parameters from modelers for each region
- Provide source information so it is consistent between methods
- Provide a unique definition of crustal structure to be used by all groups (Vs, Q)
- Consider multiple source realizations
- Provide uniform orientation of motions
- Run simulations for reference site conditions – correct data with empirical site factors
- Make all validation metrics and plots in uniform units/format
- Streamline the process to allow fast feedback to modelers – Use SCEC BBP
Validation schemes

- Key focus: 5% damped elastic “average” PSa [RotD50]
  - \( f=0.1-100 \text{ Hz}/ \ T=0.01-10 \text{ s} \)

- A. Validation against recorded ground motions
  - tests the models given optimized source terms

- B. Validation against GMPE prediction for generic scenarios
  - tests the generation of source terms for future earthquakes

- Validation allows for development of region-specific rules (source scaling, path)
Event and stations

Sims, TS, Ref.

Obs, TS, Surf.

Site response

Sims, TS, Surf.

IM Processors

Sims, IM, Surf.

Obs, IM, Surf.

GOF, Surf.

Previous validation exercises

Obs: observed/recorded
Sims: simulated
TS: time series
IM: Intensity measures (e.g. Sa)
Ref.: reference rock site
Surf.: surface, soil site
GOF: goodness-of-fit
This validation exercise

Part A.

Event and stations

- Sims, TS, Ref.
- Obs, TS, Surf.

Site response

- Sims, TS, Surf.
- IM Processors
- Obs, IM, Ref.
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IM Processors

- Obs, IM, Ref.
- IM Processors
- GOF, IM, Ref.
- GOF, Ref.

Part B.

- Obs: observed/recorded
- Sims: simulated
- TS: time series
- IM: Intensity measures (e.g. Sa)
- Ref.: reference rock site
- Surf.: surface, soil site
- GOF: goodness-of-fit
### Selection of events

**GOAL:** Select a representative set of earthquakes covering a variety of events (magnitude, geometry, and mechanism) and tectonic settings.

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<th>REGION</th>
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<th>Mag. (Mw)</th>
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<td>WUS</td>
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- 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)
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Table corrected after WS#1
Selection of stations

**GOAL:** Reduce the number of records (stations) per event while maintaining the mean and standard deviation of the full dataset.

**CRITERIA:**
- Site $V_{s30} \geq 300$ m/s to reduce strong non-linear site effects
- Well-Recorded Earthquakes (40 stations per event is ideal)
- Close-in records (<200 km; <1000 km for CENA)

**METHODOLOGY:**
1. Develop simple regression model for all stations for each earthquake (PGA, $T=0.2$ sec, $T=1.0$ s)
2. Randomly sample 10 stations from 4 equal distance bins (log space) to generate ~1000 to 10,000 random samples.
3. Perform regressions on samples from population.
4. Develop a penalty function to select station sample with small mean bias and standard deviation over all spectral periods (PGA, $T=0.2$ sec, $T=1.0$ s)
Selection of stations
Northridge Example

Part A (comparison with recordings)
Selection of stations
Northridge Example

Part A (comparison with recordings)

\[ \sigma_{\text{full}} = 0.442 \]
\[ \sigma_{\text{selected}} = 0.444 \]

\[ \sigma_{\text{full}} = 0.494 \]
\[ \sigma_{\text{selected}} = 0.505 \]

\[ \sigma_{\text{full}} = 0.474 \]
\[ \sigma_{\text{selected}} = 0.476 \]
Correcting data to reference condition

- Recorded data corrected to $V_{s30} = 863$ m/s
  - Empirical amplification factors from Stewart and Seyhan (Boore et al. NGA-West2 model)
    - $F_{\text{lin}} = \text{Linear scaling ($V_{s30}$ effect)}$
    - $F_{\text{nl}} = \text{Nonlinear scaling relative to $F_{\text{lin}}$}$
    - $F_{\text{site}} = 1/\exp(F_{\text{lin}} + F_{\text{nl}})$
  - Basin correction through $Z_{1.0} = f(V_{s30})$ based on Chiou and Youngs 2008 (NGA-West1 model)
    - $F_{\text{basin}} = 1/\exp(f(\Phi_5, \Phi_6, \Phi_7, \Phi_8)$

- Corrected $Psa = PSA_{\text{Rec}} * F_{\text{site}} * F_{\text{basin}}$
Correcting data to reference condition

LOMAP/SJTE2
Vs30=672 (m/s), Z10=38(m)

Amplification Factors

Spectral period, T (s)
Simulation Methodologies

Stochastic methods
- SMSIM (point source)
- EXSIM (finite fault: sub-faults = point sources)

Kinematic sources:
- Broadband using Green’s functions
  - UC Santa Barbara (UCSB) – randomness at HF in the source description, 1D-3D
  - UN Reno (UNR) – composite source model

Hybrid - Green’s functions LF, Stochastic HF
- Graves and Pitarka (G&P) – sub-fault source spectra
- Sand Diego State University (SDSU) – scattering functions (kappa, Q, intrinsic attenuation)

Deterministic source – simplified stochastic wave propagation
- Irikura
Input – Source geometry (used by all models)

src file on SCEC BBP

- MAGNITUDE
- FAULT_LENGTH
- DLEN
- FAULT_WIDTH
- DWID
- DEPTH_TO_TOP
- STRIKE
- RAKE
- DIP
- LAT_TOP_CENTER
- LON_TOP_CENTER
- HYPO_ALONG_STK
- HYPO_DOWN_DIP
- DT
- SEED
- CORNER_FREQ
- SEISMIC MOMENT
- HYPO LAT
- HYPO LONG
- HYPO DEPTH
Input - rupture models (from src)

- SMSIM and EXSIM use point sources

**srf file on SCEC BBP:**

- UCSB, SDSU, G&P
  - Spatial distribution of slip on the fault
  - Slip time function at each point on the fault (rise time)
  - Rupture time as each point on the fault
  - Slip, rupture velocity, and rise time may be correlated

- UNR uses a random distribution of sub-events

- Irikura uses G&P srf to generate asperities (basis of source in model)
Rise Time

\[ \tau = k \cdot D^{1/2} \quad \text{depth > 8 km} \]
\[ = 2 \cdot k \cdot D^{1/2} \quad \text{depth < 5 km} \]

linear transition between 5-8 km

Scales with square root of local slip (D) with constant (k) set so average rise time is given by the Somerville et al (1999, 2009) relations:

\[ \tau_A = 1.6 \cdot 10^{-9} \cdot M_o^{1/3} \quad \text{(WUS)} \]
\[ t_A = 3.0 \cdot 10^{-9} \cdot M_o^{1/3} \quad \text{(CEUS)} \]

Sample srf (G&P) – 1 realization
Input – Path (region-specific)

- For Greens’ functions
  - LF: 1D velocity structures: $V_s$, $V_p$, rho, Q
  - UCSB & UNR: Modified “equivalent” profile to account for $Q(f)$
  - All use a standard shallow velocity profile with $V_{s30} = 863$ m/s

- Stochastic methods
  - Use region-specific empirical models for $Q(f)$, geometrical spreading and duration
Process and nomenclature

For each scenario, specification of:

Source (from src)
- Kinematic models: rules for slip, rise time, rake, etc.
- Stochastic models: sub-faults as point sources with time-dependent $f_c$

Path (consistent with 1D velocity model)
- Kinematic models: Green’s functions computed with velocity models
- Stochastic models: Empirical geometrical spreading, $Q(f)$ duration

For each scenario, seismograms generated for:
- 50 source realizations $X \sim 40$ stations
Evaluation criteria

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

NR vs. run 10000034, station 2001-SCE
Evaluation criteria

PSa for station 2001-SCE, NR vs 10000034

NR, N/S

NR, E/W

NR, rotd50
Evaluation criteria

- Goodness-of-fit measures for PSa and PGA
  - GOF with T at each station
  - Average GOF with T for all stations within an event

Part A (comparison with recordings)
Evaluation criteria

- Goodness-of-fit measures for PSa and PGA
  - GOF with T at each station
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  - Average GOF for all realizations (all stations)
Evaluation criteria

- Goodness-of-fit measures for PSa and PGA
  - GOF with T at each station
  - Average GOF with T for all stations within an event
  - Average GOF for all realizations (all stations)
  - GOF with distance for each event for a subset of T
Evaluation criteria

- PSa controlling factor in evaluation
- Other measures may be considered
- “Verdict” for each methodology
  - Applicable for a given region?
  - Applicable for a certain bandwidth?
  - Needs refinement?
- Also check against GMPEs – is there a benefit to use finite fault parameters Vs. strike, dip, distance?
Validation schemes

- Key focus: 5% damped elastic Psa (0.1 to 100 Hz)
- A. Validation against recorded ground motions (time series)
- B. Validation against GMPE prediction for generic scenarios – “model centering”
  - 3 scenarios in well constrained range of GMPEs (Mw~6.0-7.0, R~20-50 km)
  - Use as global check of models, also test the generation of source terms for future earthquakes (e.g. development of inputs for new scenarios)
Scenario selection

- Selected 3 scenarios for which NGA-West1&2 GMPEs are well constrained by data:
  - M6.2 SS, 20 and 50 km
  - M6.6 SS, 20 and 50 km
  - M6.6 REV, 20 and 50 km
- 50 realizations of the source, WITH randomized hypocenter location for each
- Simulations for two velocity models: NorCal and SoCal
Station selection

6.2 SS, NorCal
Evaluation criteria

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

- AS08
- BA08
- CB08
- CY08
- Median of 4 NGA Models
- Acceptance Criteria
Sample parameters (G&P)

- **Region Specific**
  - Velocity structure, attenuation factors, kappa and GFs
  - Mag-Area, stress parameter and rise time/corner frequency
  - Site amplification factors

- **Event Specific**
  - Magnitude, fault geometry, fault dimensions, mechanism and hypocenter

- **Rule Based**
  - Rupture parameters (correlation of slip distribution, average rise time, average rupture speed perturbations) scale with moment
  - Rise time, rupture speed scale with depth
  - Rise time/corner frequency adjusted for buried thrust ($\alpha_T$)
  - Local rise time and rupture speed perturbations scale with local slip

- **Possible Adjustments**
  - Magnitude/Mag-Area for validation events
  - Deep slow slip/background water level on slip
  - Shape of the slip function (longer tail)
  - Sample rise time/rupture speed perturbations from PDF (instead of direct correlation with slip)
  - Off-fault damage
From validation to forward simulations

- Modelers to select best fitting realization(s) and path forward:
  
  **PATH 1**
  - Find the best fitting source (srf) realization
  - Use its goodness of fit to represent modeling uncertainty
  - Include uncertainty in srf specification when forward modeling future scenarios

  **PATH 2**
  - Use the average goodness of fit of 50 srf’s to represent modeling uncertainty
  - No need to include uncertainty in srf specification when forward modeling future scenarios
Schedule summary – completion dates

- Today – define forward simulation scenarios
- April 2013 – method impl. On SCEC BBP
  - Completed: G&P, EXSIM  Later: SMSIM
  - In progress: UCSB, SDSU, Irikura, UNR
- May 2013 - Validation
  - Part A: 7 scenarios, all methods
  - Part B: all methods
- June 2013 – Documentation & forward sims
  - Modelers self-evaluation and documentation
  - Initial forward simulation test
- August 2013 - Evaluation
  - SCEC evaluation of methods report
  - Initial forward simulations
Schedule summary – completion dates

- September 2013 - SCEC AM
  - Review initial forward sims results
- October 2013 – SWUS SSHAC WS 2
  - Review results, adjust scenarios if needed
- January 2014 – Forward sims, final set
- February 2014 – Review forward sims
- March 2014 - SWUS SSHAC WS 3
  - Incorporation of sims in GMPE logic tree
References

- Mai, P.M., Imperatori, W., Olsen, K.B. (2010), Hybrid Broadband Ground-Motion Simulations: Combining Long-Period Deterministic Synthetics with High-Frequency Multiple S-to-S Backscattering, BSSA, 100(SA), pp. 2124-2142.