Incorporating Earthquake Source Physics into Ground Motion Models for Seismic Hazard Studies

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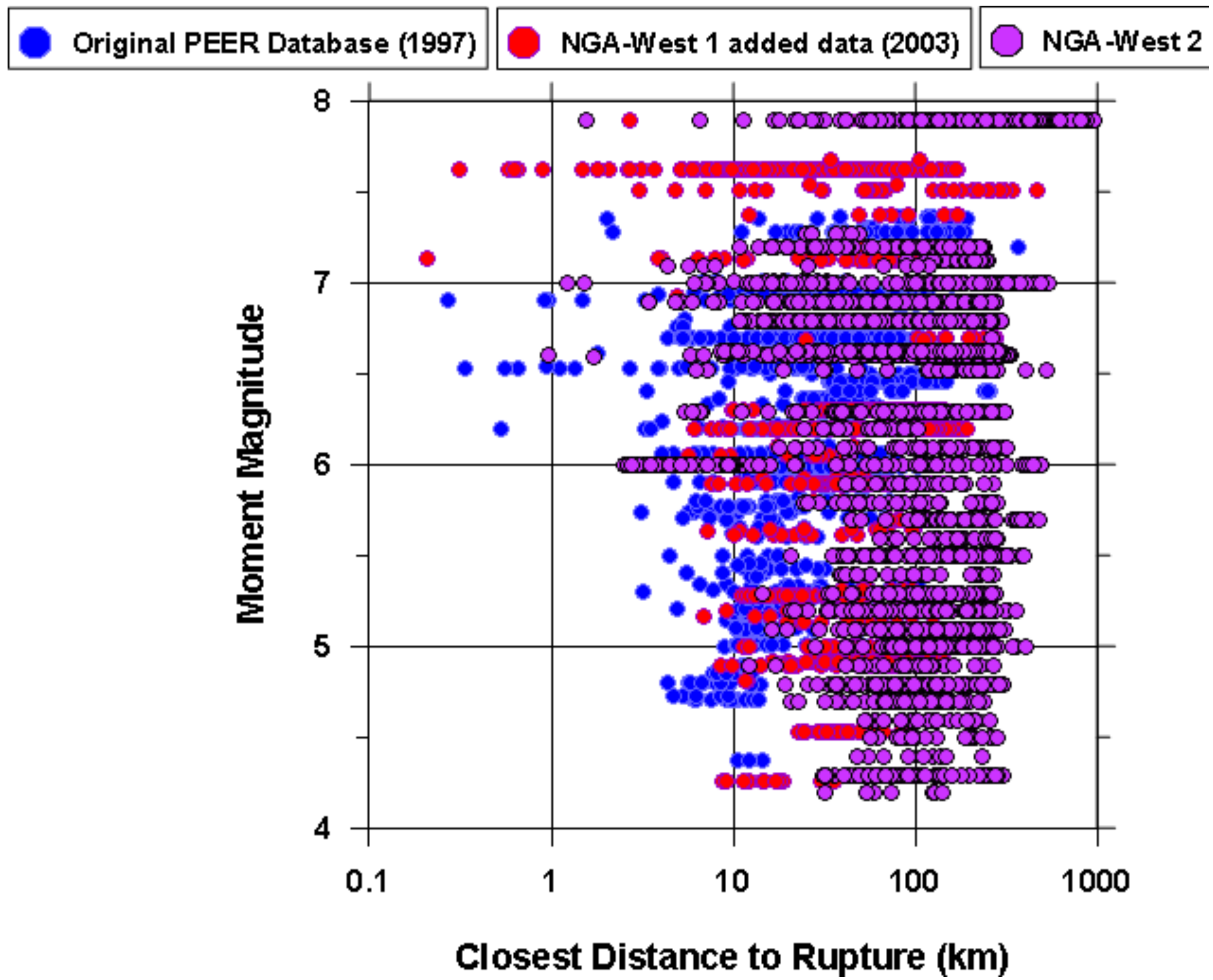
Approaches for Ground Motion Models

- Empirical models
- Point-Source simulations
- Finite-Fault Numerical simulations

Difficulties with Empirical Ground Motion Data

Data sets still sparse in the key magnitude and distance ranges



Difficulties with Empirical Ground Motion Data

- Bad properties of data sets
  - Uneven sampling of earthquakes
    - 1 to >200 recordings per event
  - Censoring of data
    - Smaller ground motions not sampled (triggering issue)
  - Limited bandwidth (long period) in older data
  - Correlation of independent parameters
    - Magnitude – distance
    - Rupture depth and focal mechanism
    - Site condition (VS30) and depth to rock
  - Correlation of dependent parameters
    - Correlation through Event term
    - Correlation through Site term

Finite-Fault Simulations (FFS)

- Physics-based
  - Accounts for site-fault specific geometries and complex crustal structure
  - No need for simplified distance metric
  - Can sample large suite of earthquakes, not just those with strong motion data
    - Define the median and variability of sources for future large magnitude earthquakes
      - Global
      - Regional
      - Fault specific
  - Avoids data sampling issues in empirical data

Uses of FFS in Seismic Hazard Studies

- Median and variability
  - FFS completely replace the empirical GMPEs (cyberShake type approach)
- Median
  - FFS replace the median, but use the empirical results for the variability
- Scaling (NGA approach)
  - Only relative differences in medians used
  - Constrain scaling in ranges not well constrained by the empirical data
    - Scaling from M7 to M8
    - Scaling to short distances
    - Scaling to long periods (from T=5 to T=20 sec)
    - Hanging wall effects
    - Directivity effects

Needs for Use of Finite-Fault Simulations in Seismic Hazard Studies

- Verification
  - Simulations are working as intended (computer program)
- Calibration/Validation
  - Optimize methods (if large enough data set used)
  - Quantitative evaluation of the accuracy of the simulation method for the optimized methods
- Robustness
  - Similar results using different simulation methods
- Transparency
  - Someone other than the author can run the simulations
- Reproducible Results
  - Fixed versions of simulation software that are readily available

Robustness

- More than one FFS method that lead to similar ground motions
  - We don't want to suppress real epistemic uncertainty
  - Need similar results for scenarios well constrained by empirical data
- Cannot rely on a single model
  - Each developer of a simulation method claims his method is correct

Transparency

- FFS computer program is publically accessible
- Validation conducted by someone other than the author of the code

Reproducible

- Forward modeling results can be reproduced by a second group
- Needs stable versions of codes

Finite-Fault Simulations

- Distribution of source parameters for future earthquakes
  - Source physics
- Wave propagation for a given source
  - Ground motions at given sites
- Past attempts at validation
  - Focused on comparing the ground motions from simulations to past earthquakes
  - Have not done a good job on the source parameters of future earthquakes

Past Attempts Using FFS

- Several project over last 20 years to compare results of Kinematic FFS
- Validation
  - Methods validated against ground motions from past earthquakes (small number of eqk)
  - Methods considered to give an acceptable fit to past ground motions
- Forward application of models
  - Define a test case: magnitude, rupture geometry, crustal model, and site locations
  - Each methods generate source parameters for a multiple realizations of the source
  - Compare median predictions
  - Compare variability

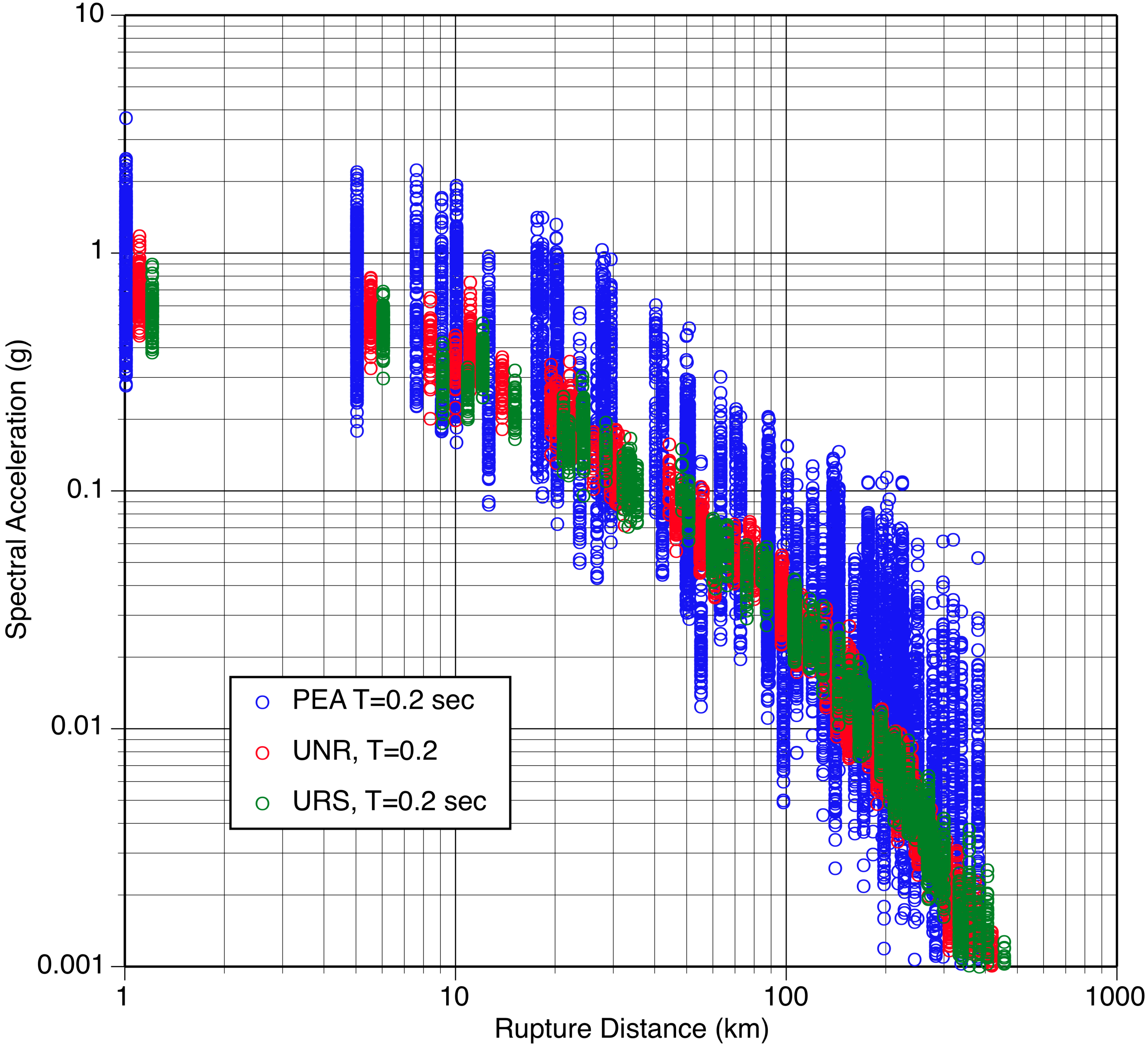
Past Attempts Using FFS (cont)

- Results: Inconsistent median results from different methods
  - Most likely due to differences in the generation of source properties for future earthquakes
  - Different methods used for the source from past earthquakes (e.g. inversions from other studies) and for the forward application
  - Are the source distributions for future earthquakes mean centered?
  - Need to consider the joint distributions of source parameters
    - Earthquake source physics
- Results: Variability not well constrained
  - Much larger or much smaller than empirical variability depending on the method and frequency band

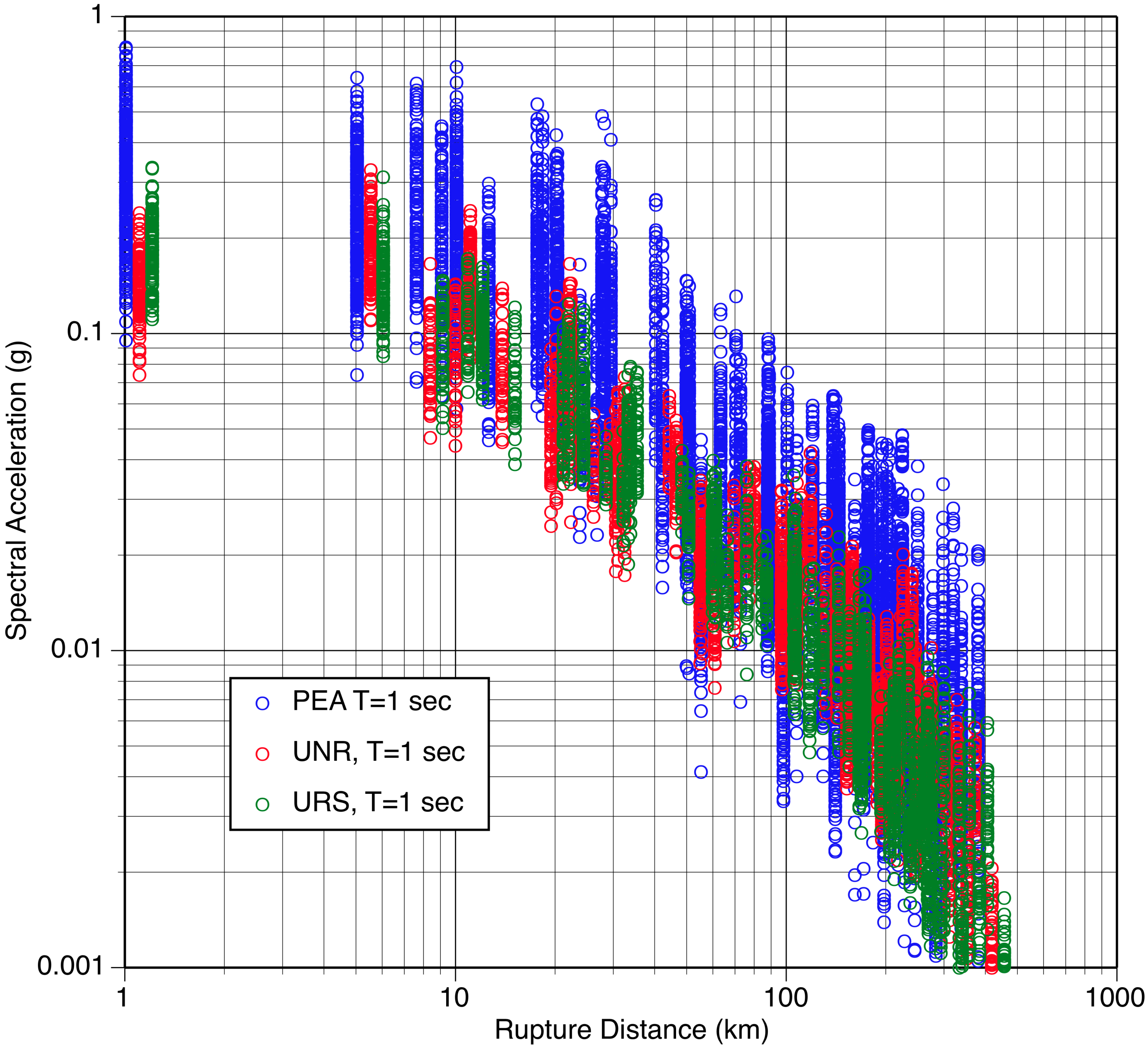
SS Scenarios: 2004 NGA FFS Project

Event Name	Mag	Area (km^2)	W (km)	L (km)	Dip	Top of Rupture (km)
SA	6.5	325	13	25	90	0
SB	6.5	480	15	32	90	0
SC	6.5	210	10	21	90	0
SD	7.0	1005	15	67	90	0
SE	7.5	3150	15	210	90	0
SF	7.5	4800	15	320	90	0
SG	7.5	2100	15	140	90	0
SH	7.8	6300	15	420	90	0
SI	7.8	3525	15	235	90	0
SJ	8.2	7050	15	470	90	0

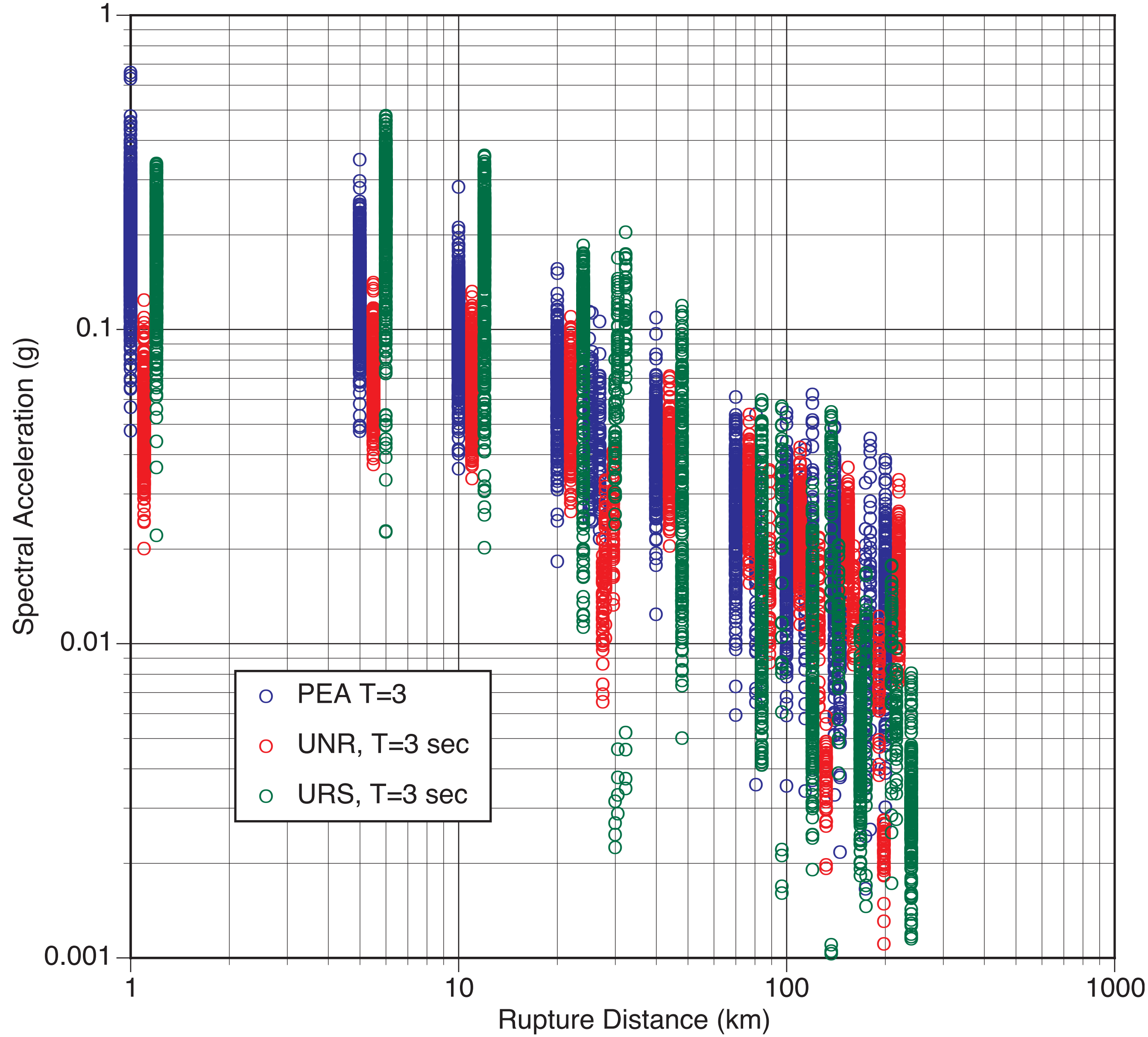
Scenario SA: M6.5, SS (T=0.2 sec)



Scenario SA: M6.5, SS (T=1 sec)

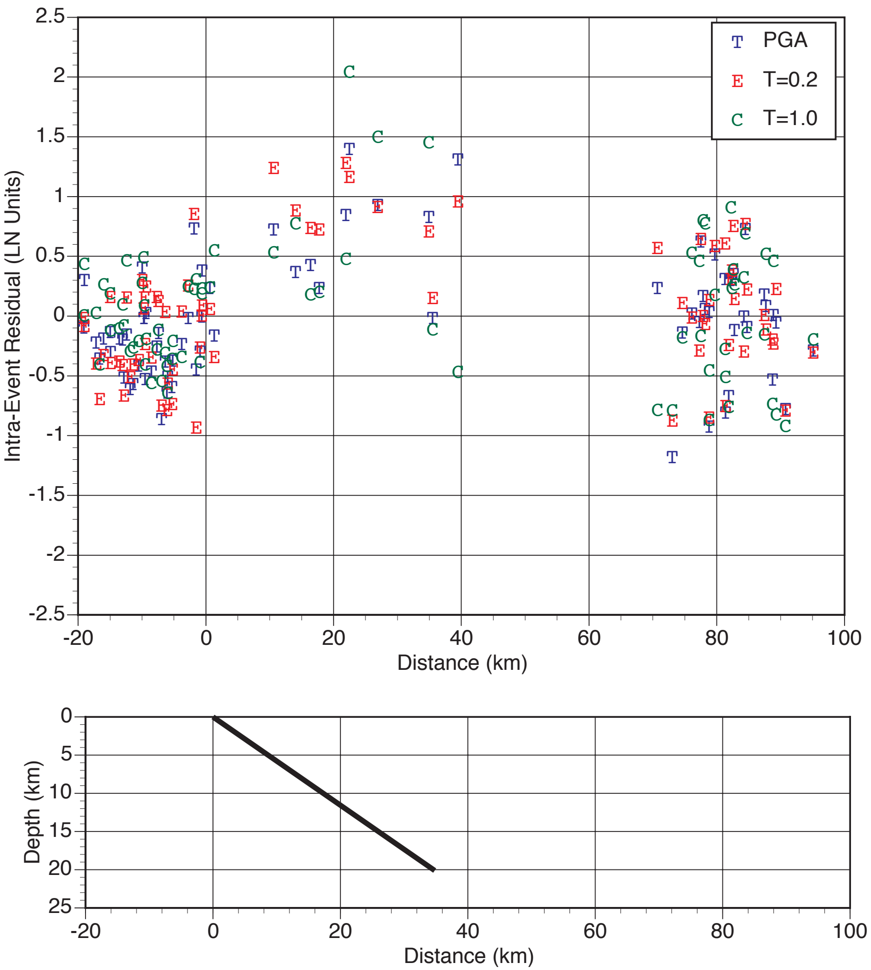


Scenario SA: M6.5, SS (T=3 sec)

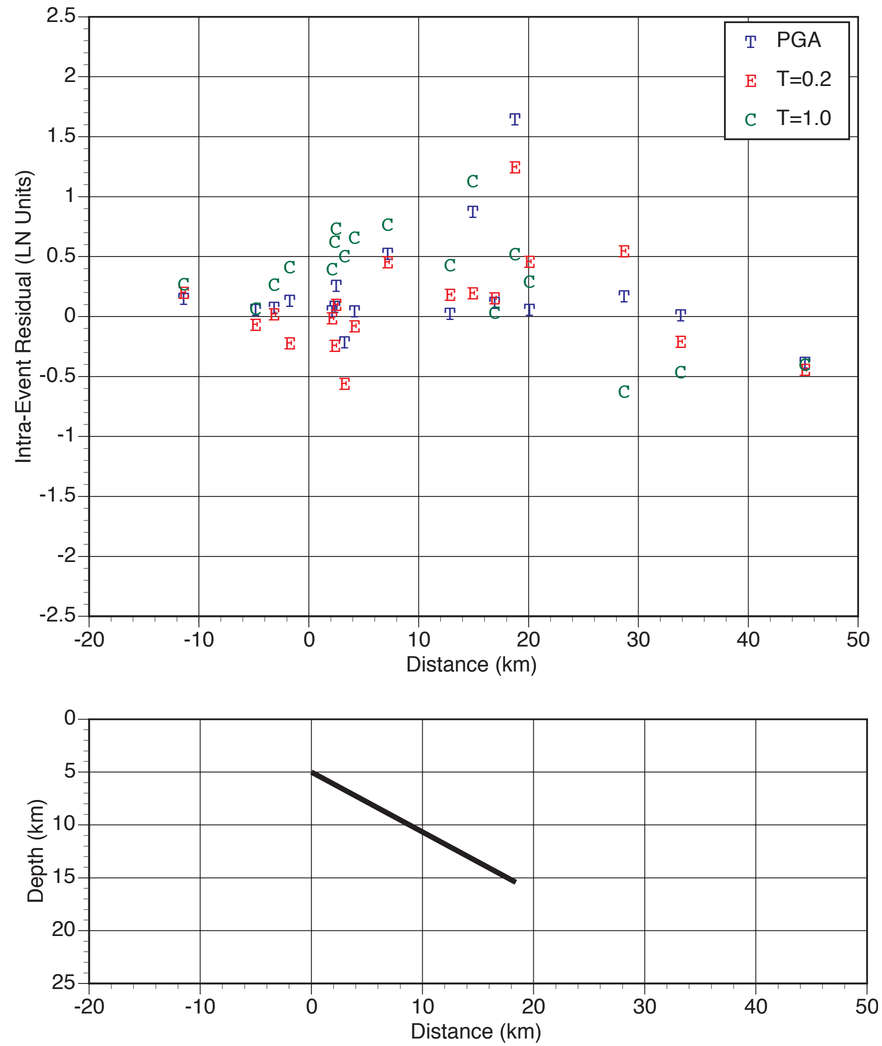


Empirical Data for HW

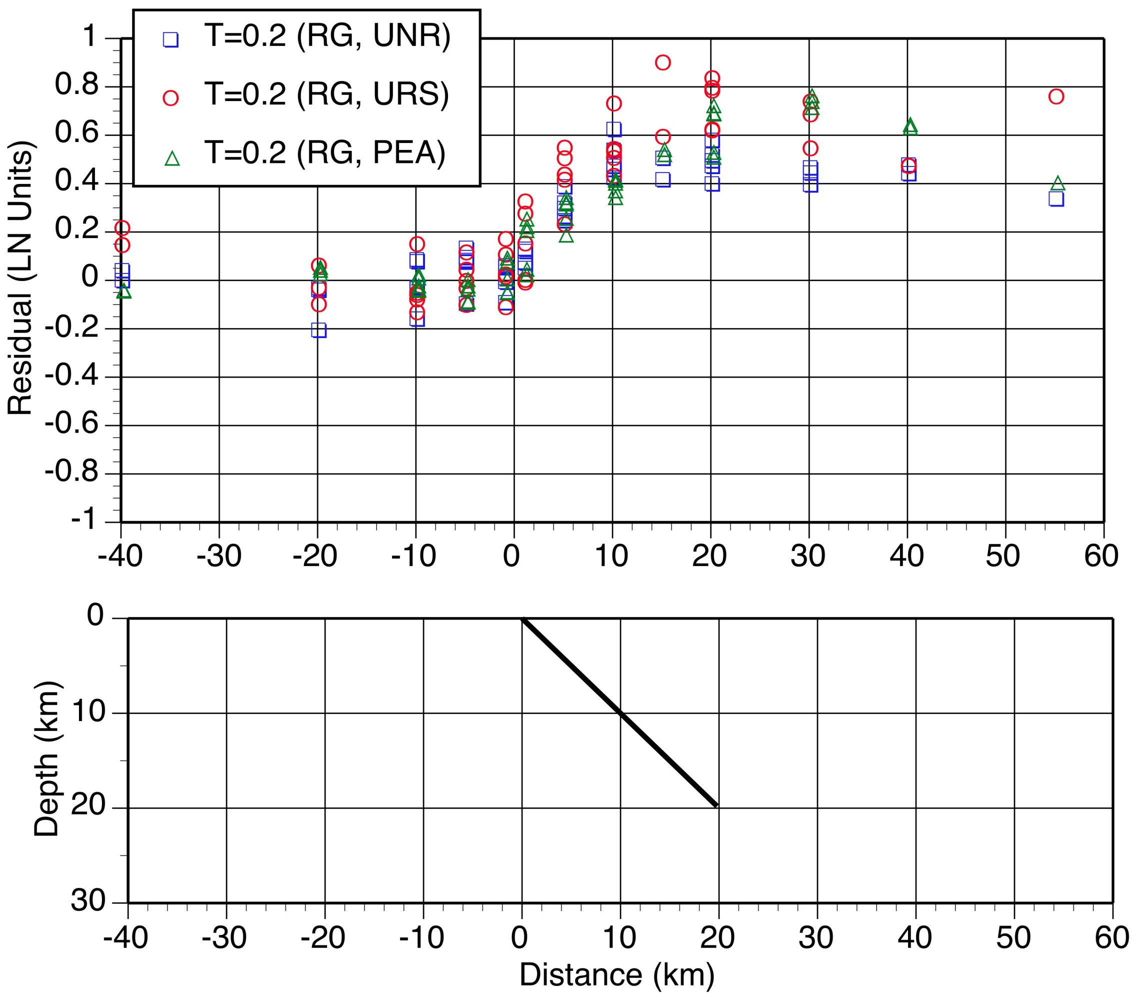
1999 Chi-Chi



1994 Northridge



M7.0, Dip=45, ZTOR=0



SCEC Broadband Platform Validation Project

- Cooperative study
  - Southern California Earthquake Center
  - Pacific Gas & Electric
  - Southern California Edison
  - Pacific Earthquake Engineering Center (NGA-east)
- Ground motion parameters of interest
  - Elastic response spectral values at 5% damping over the frequency band of 0.1-100 Hz
    - SCEC is also conducting a more extensive validation that considers many additional parameters of ground motion
  - Focus is on the median, not aleatory variability
    - Will use empirical aleatory variability models
    - In future, need to expand scope to address the variability

Needs

- Evaluation of the finite-fault simulation (FFS) methods using 1-D crustal models
  - Are they ready for engineering applications or is more research needed?
- Consider a suite of representative FFS methods for evaluation
  - Add additional modules to capture the range of candidate methods
- SCEC evaluation of the FFS methods on the Broadband platform
  - Identify the frequency and distance ranges for which the FFS methods are applicable
  - Completion date: April 2013

SCEC Validation

- Part A: Comparison with past Earthquakes
  - 20 active crustal region earthquakes
  - 3 EUS earthquakes
  - Data corrected to rock site conditions
  - Large enough data set to allow for calibration
- Part B: Comparison with Empirical GMPEs
  - 2 scenarios (M6.5 at R15-40 km; M7.0 at R15-40 km)
  - Compare median ground motions
    - Goal is to calibrate the source rupture generators
  - Rock site conditions

Proposed Active Crustal Eqk for Validation

From GMSV workshop	Additional Eqk from NGA-west2
2010 El Mayor-Cucapah, M=7.2 (EQID 280)	1999 Kocaeli, Turkey, M=7.5 (EQID 136)
1994 Northridge-01, M=6.7 (EQID 127)	1999 Chi-Chi, Taiwan, M=7.6 (EQID 137)
1999 Hector Mine, M=7.1 (EQID 158)	2000 Tottori, Japan, M=6.6 (EQID 176)
1992 Landers, M=7.3 (EQID 125)	2007 Chuetsu-Oki, Japan, M6.7 (EQID 278)
1987 Whittier, M=6.0 (EQID 113)	2004 Niigata, Japan, M=6.6 (EQID 180)
1992 Big Bear-01, M=6.5 (EQID 126)	2008 Iwate, Japan, M=6.9 (EQID 279)
2004 Parkfield, M=6.0 (EQID 179)	2009 L'Aquila, Italy, M6.3 (EQID 274)
1989 Loma Prieta, M=6.9 (EQID 118)	2010 Darfield, NZ, M=7.0 (EQID 281)
1984 Morgan Hill, M=6.2 (EQID 90)	2003 San Simeon,M6.5 (EQID 177)
1986 N. Palm Springs, M=6.1 (EQID 101)	
1983 Coalinga, M=6.5 (EQID 76)	

Consistency: Parts A and B

- Past studies have recurring inconsistency
  - Source model used in the validation (part A)
  - Method used to generate sources for future earthquakes
- Proposed approach for SCEC validation (part A)
  - Fix rupture geometry and hypocenter location for past earthquakes
  - Use the rupture generator to produce a suite (~50) of source models for the past earthquake
  - Generate ground motions at recording sites for each source model
  - Select the source model that leads to ground motions that best matches the observed ground motions

Validation for Aleatory Variability

- Source variability
  - From suite of source models for a future earthquake with a given geometry
  - "Parametric aleatory variability"
  - Source physics part
- Wave propagation variability
  - From misfit between simulated ground motions (for optimized source) and the recorded ground motions
  - "modeling aleatory variability" (related to limitation of FFS method and knowledge of crustal structure)
  - Needs to be added to the FFS variability

Aleatory Variability for Source

- How is this calibrated/validated?
- Empirical GMPEs
  - Use variability of event terms estimated from strong motion data (between-event variability)
  - Limited number of large magnitude events to use
- FFS
  - What data are available?
    - Teleseismic data to expand numbers of events beyond those events with strong ground motions?
    - Source inversion libraries?
  - Is there enough data to constrain the source variability using earthquake source physics?

Summary

- Physics-based finite-fault simulations (FFS) are clearly the future of ground motion modeling
- Finite-Fault simulations will stay as a research topic unless the key topics are adequately addressed
  - Verification
  - Calibration/Validation
  - Robustness
  - Transparency
  - Reproducibility
- Key outstanding issue limiting use of FFS in hazard studies is the distribution of source parameters for future earthquakes
  - Distribution must be mean centered
  - Variability must be validated
- SCEC broadband platform and the validation study provides a standard data set and approach to these last four topics for the median ground motion
- Validation of the variability of FFS needs to be addressed if FFS is to fully replace the empirical GMPEs