Diablo Canyon Seismic Hazard Reevaluation

Presentation to Nuclear Regulatory Commission Public Meeting Bethesda, Maryland

April 28, 2015

AGENDA

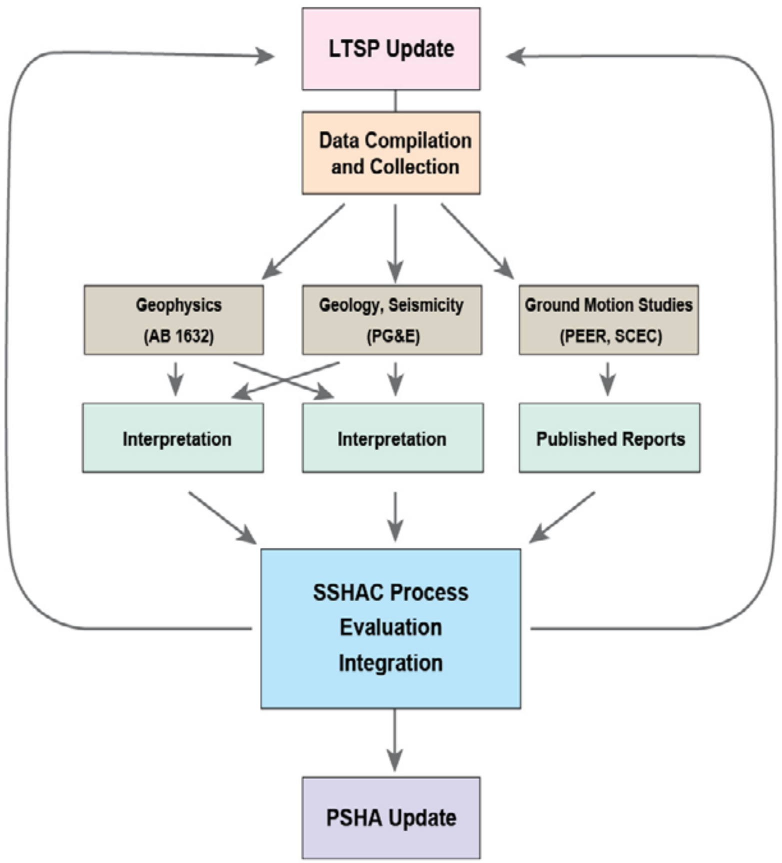
Time	Topic	Speaker
1:00 - 1:15	Introductions	NRC/PG&E Co.
1:15 - 1:45	Overview of R2.1 Seismic	NRC
	- Discussion on meeting goals and expected outcome	
	- General Background on 50.54(f) and NTTF 2.1 Seismic	
	- Introduction of seismic hazard PSHA methods and	
	Senior Seismic Hazard Analysis Committee (SSHAC) process	
1:45 - 3:45	Presentation of Seismic Reevaluation Report, Overview	Jearl Strickland
	- SSHAC Activities	Norm Abrahamson
	- Seismic Sources	Norm Abrahamson
	- Ground Motion Model	Norm Abrahamson
	- Interim Actions or Evaluations	Nozar Jahangir
	- Technical Focus Areas and Discussions	All
3:45 - 4:05	Planned Break	
4:05 - 4:20	NRC Meeting Wrap up	NRC
	- Technical wrap-up, review focus area, and next steps	
4:20 - 5:00	Public Questions or Comments	Public/NRC

Overview

Safety is and always will be a core value for PG&E and Diablo Canyon Power Plant.

- New and extensive seismic hazard re-evaluation continues to show plant can safely withstand earthquakes.
- Seismic re-evaluation was performed with independent experts in a transparent and open public process.
- Using new regulatory guidance, the latest scientific methodologies and site-specific information, the analysis demonstrates the plant's earthquake design is appropriate and safe.
- PG&E maintains a Long Term Seismic Program (LTSP) for Diablo Canyon, a unique program in the industry that continually assesses seismic safety.
- Safety commitment will continue to be reflected through ongoing seismic study.

SSHAC - Objectives



- Update the seismic source characterization (SSC) and ground motion characterization (GMC) models for use in an updated site-specific probabilistic seismic hazard assessment (PSHA)
- Develop a methodology for obtaining reproducible, stable estimates of probabilistic seismic hazard at a site, including *explicit* quantification of uncertainty.
- SSHAC guidelines are summarized in NRC documents NUREG/CR-6372 and NUREG-2117.
- DCPP incorporated new geophysical data into the SSC model, acquired as part of the State mandated AB1632 studies.

SSHAC - Workshops

SSC/GMC Workshop 1 – Nov. 29 – Dec. 1, 2011

SWUS GMC Workshop 1 – Mar. 19 – 21, 2013

- Significant Issues, Available Data, Data Needs
- Included Resource Expert Presentations
- Following March 12, 2012 50.54(f) letter, split SSC and GMC into separate SSHAC studies.

SSC Workshop 2 – Nov. 6 – 8, 2012

SWUS GMC Workshop 2 – Oct 22 – 24, 2013

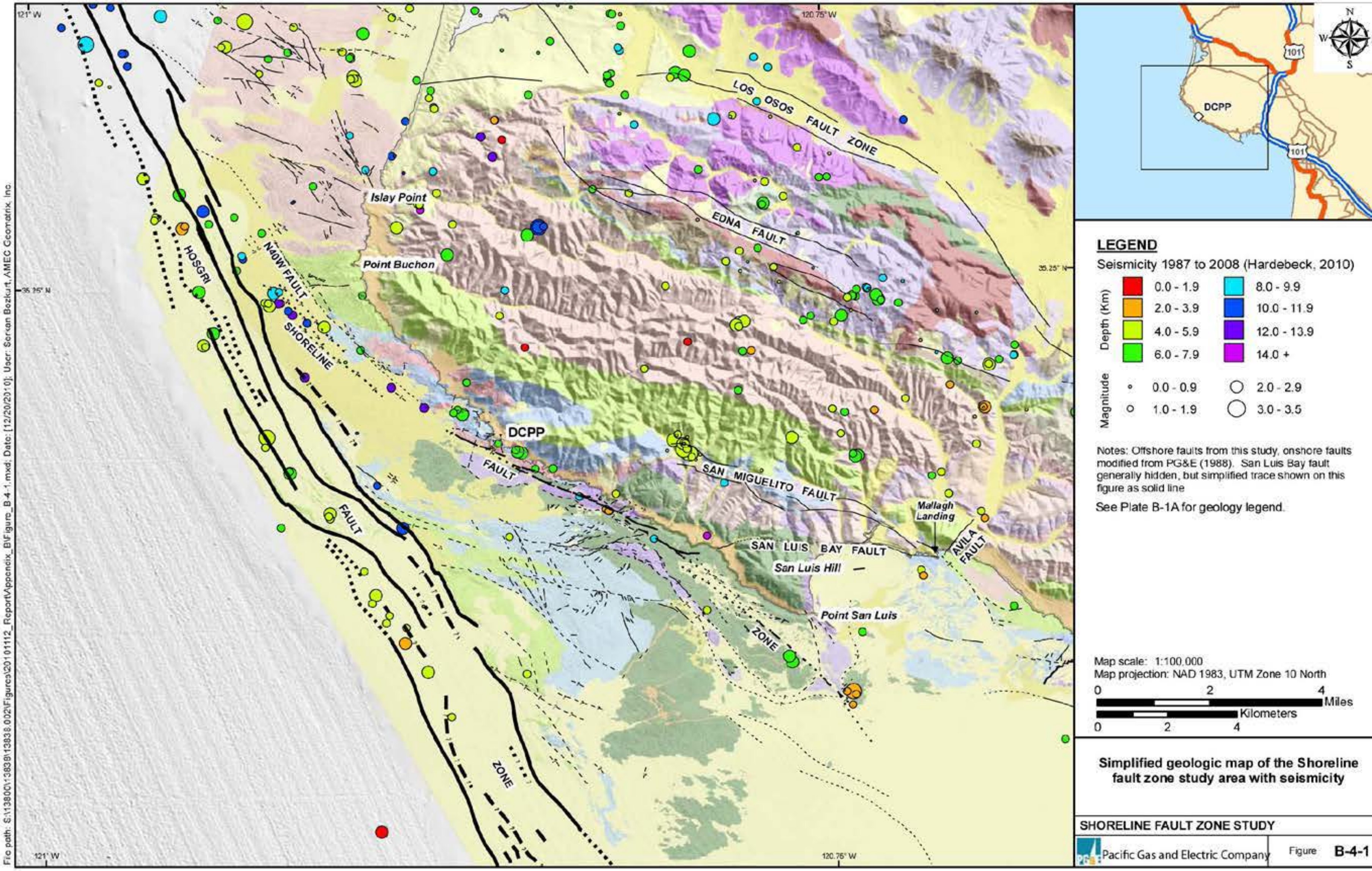
- Alternative Models and Proponent Interpretations
- Included Proponent and Resource Expert Presentations

SSC Workshop 3 – Mar. 25 – 27, 2014

SWUS GMC Workshop 3 – Mar 10 – 12, 2014

- Preliminary Model and Hazard Sensitivity
- Included Proponent Expert Presentations

Diablo Canyon Tectonic Setting



Seismic Source Characterization (SSC) Model – New Data

CCCSIP Study (PG&E)

- Offshore 2D/3D Seismic-Reflection Data
- Onshore 2D/3D Seismic-Reflection Data
- Updated Geologic Map Data

Relocated Seismicity Catalog (J. Hardebeck, USGS)

Offshore 2D Seismic-Reflection Data (S. Johnson, USGS)

Offshore high-resolution bathymetry data (R. Kvitek, CSUMB and S. Johnson, USGS)

GPS Velocity Field (J. Murray, USGS and C. DeMets, UW)

SSC Models and Methods

New Models

- Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) – USGS, CGS, SCEC
- Offshore Hosgri fault slip rates

New Methods

- Rupture Sources: Incorporate earthquake ruptures that involve multiple faults
- Composite earthquake magnitude-frequency distributions (Wooddell et al, 2015)
- Fault geometry models that correlate geometric uncertainty
- Capture time-dependent behavior and uncertainties
- Virtual faults within the host areal source zone

Types of Seismic Sources

Primary fault sources

- Contribute most of the hazard
- Hosgri, Los Osos, San Luis Bay, Shoreline faults

Connected fault sources

- Can link (rupture with) Primary fault sources
- E.g., San Gregorio, San Simeon, Wilmar Avenue, Oceano faults

Regional fault source

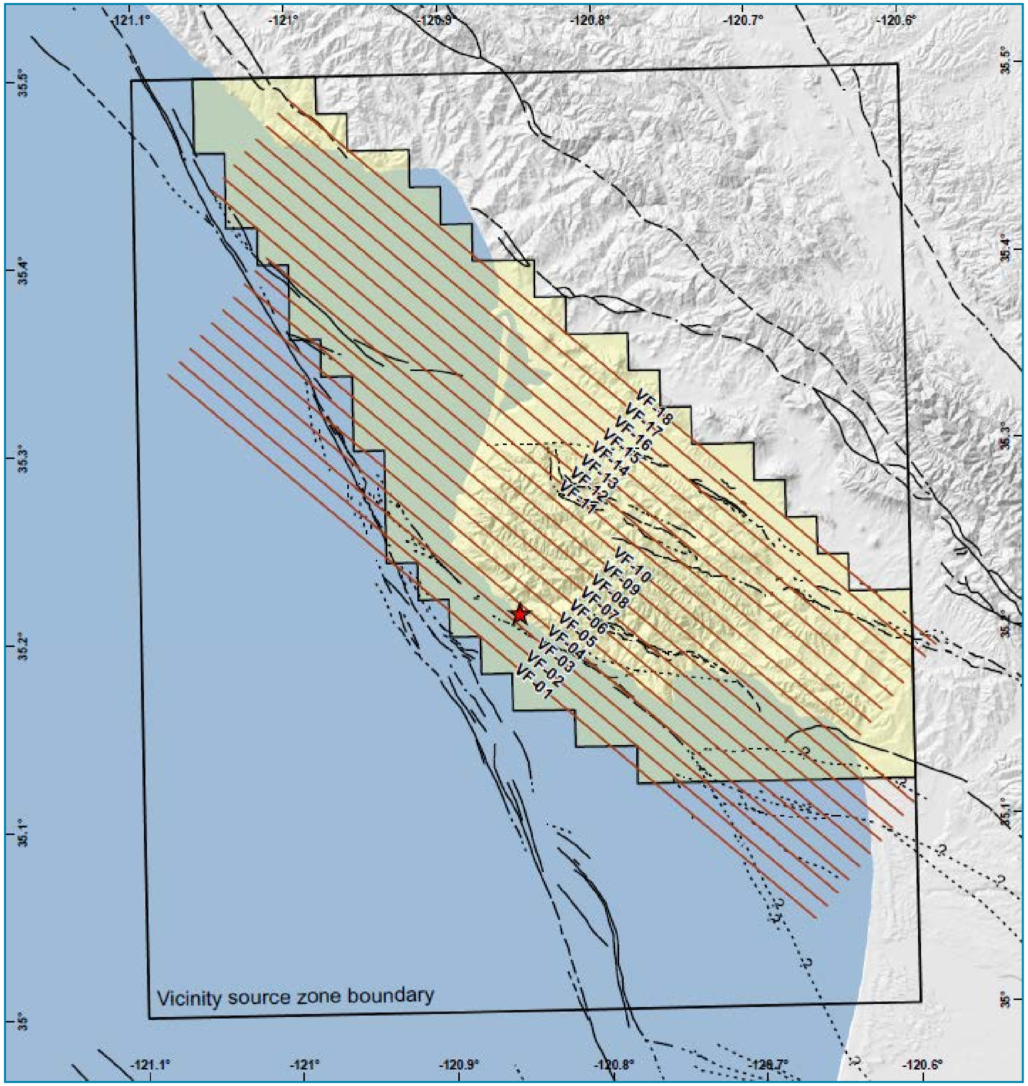
- San Andreas
- UCERF3 faults
- Additional non-UCERF3 faults

Areal Source Zones

- Regional source zone
- Vicinity source zone
- Local source zone

Local Areal Source Zone

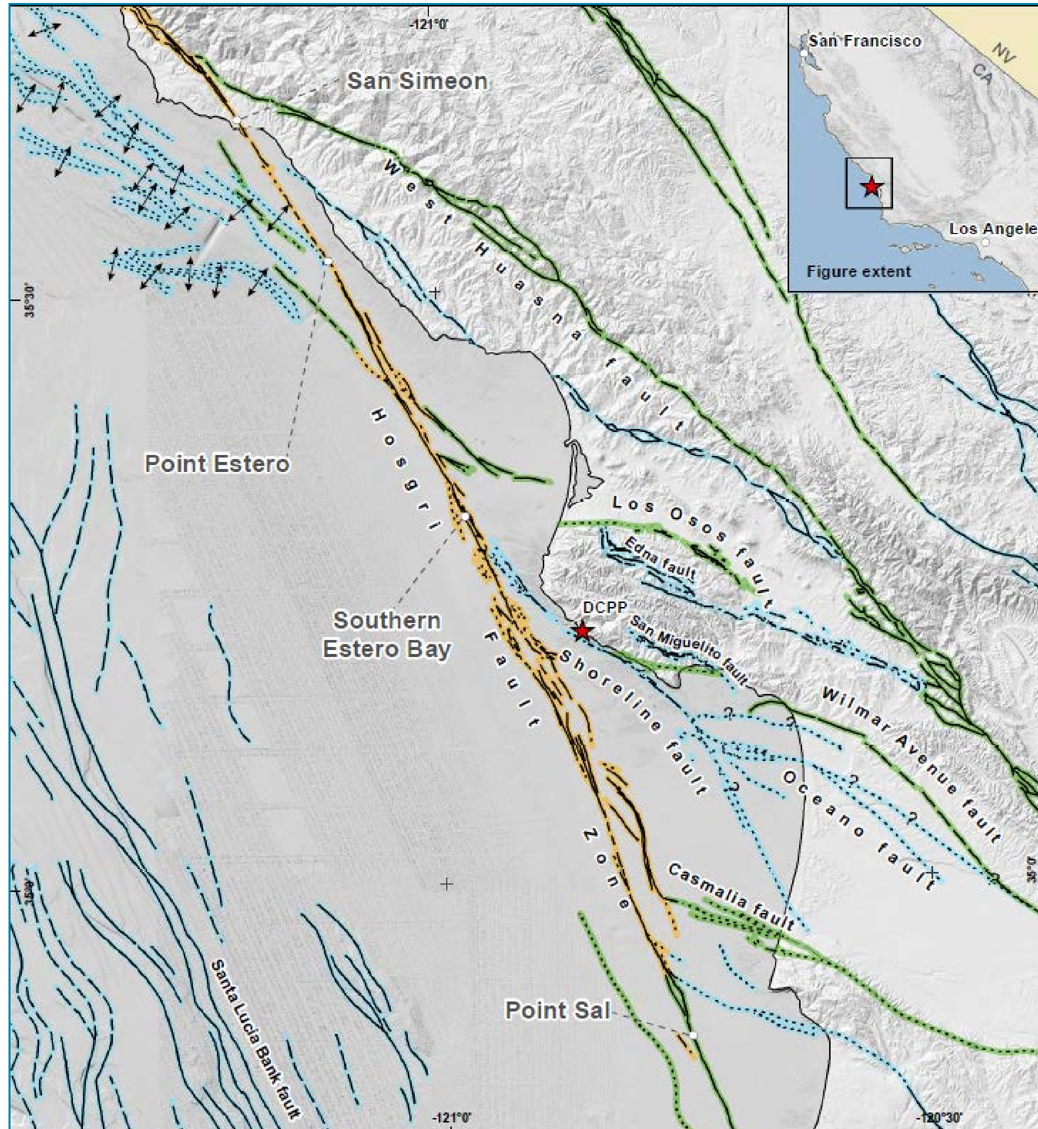
Virtual faults capture uncertainty in location, dip, sense of slip for other known and possible faults



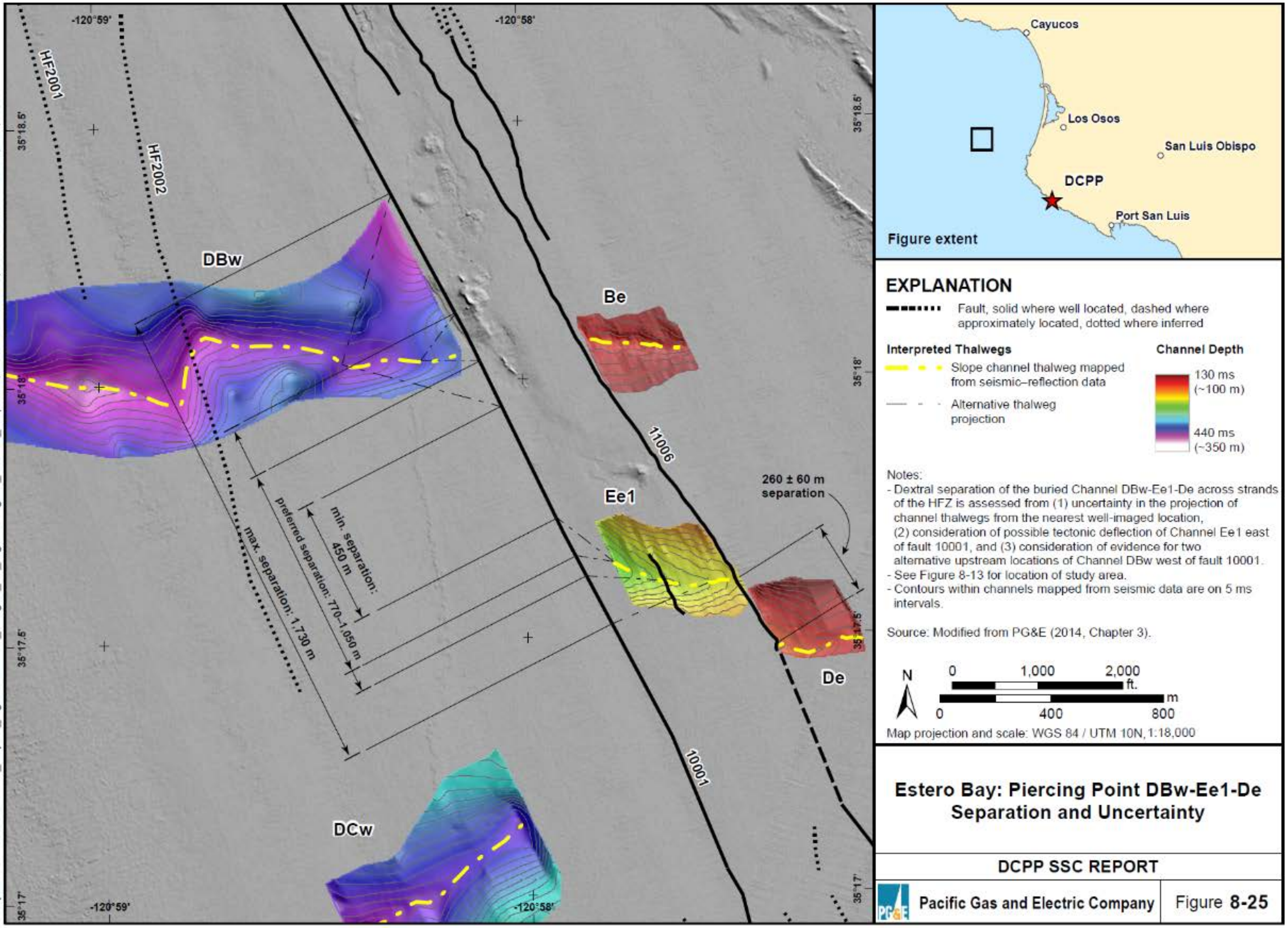
Seismic Source Characterization Focus Areas

<u>NRC SSC Topic 1</u>: Summarize the key data used to constrain the slip rate of the Hosgri fault, including associated uncertainties.

- Four slip rate sites
- Three new sites offshore
- Uncertainties developed for each site
- Sites are weighted for final uncertainty



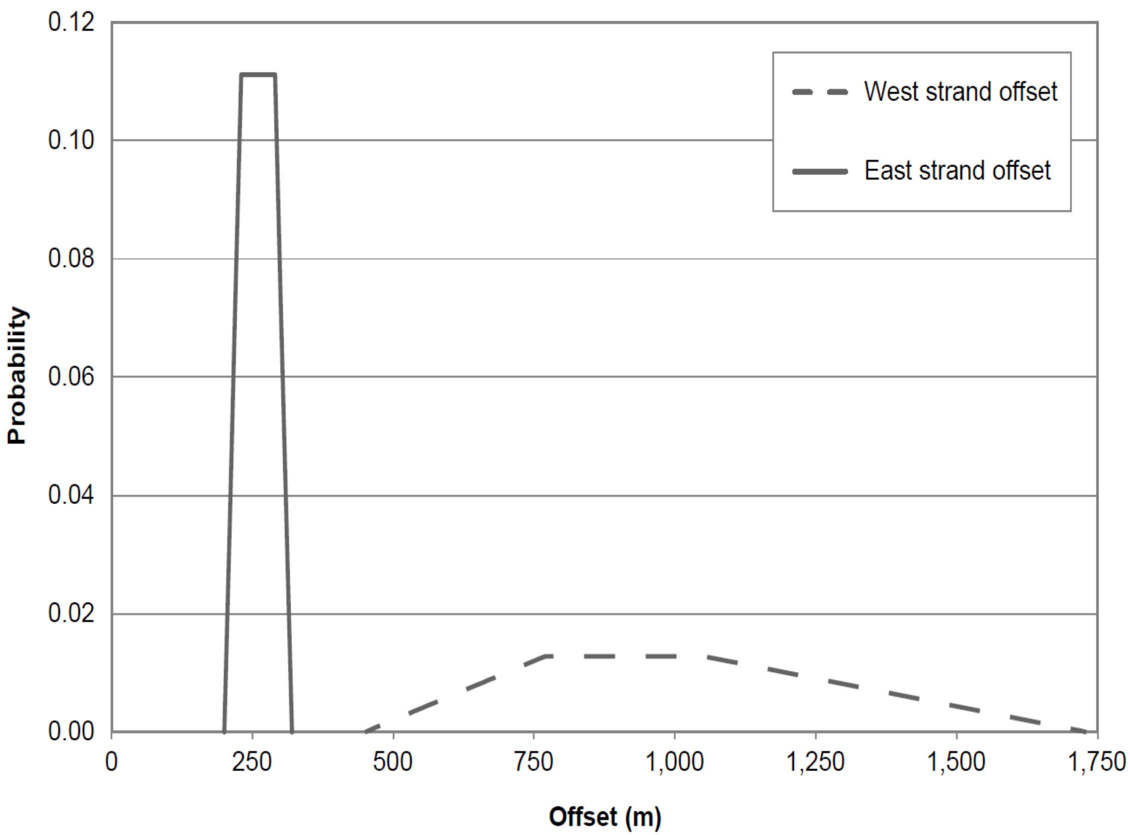
Hosgri Fault Slip Rate: Estero Bay Site



Hosgri Fault Slip Rate Models

Documentation of Offset Uncertainty

(a) Offset PDF



(b) Justification for offset PDF

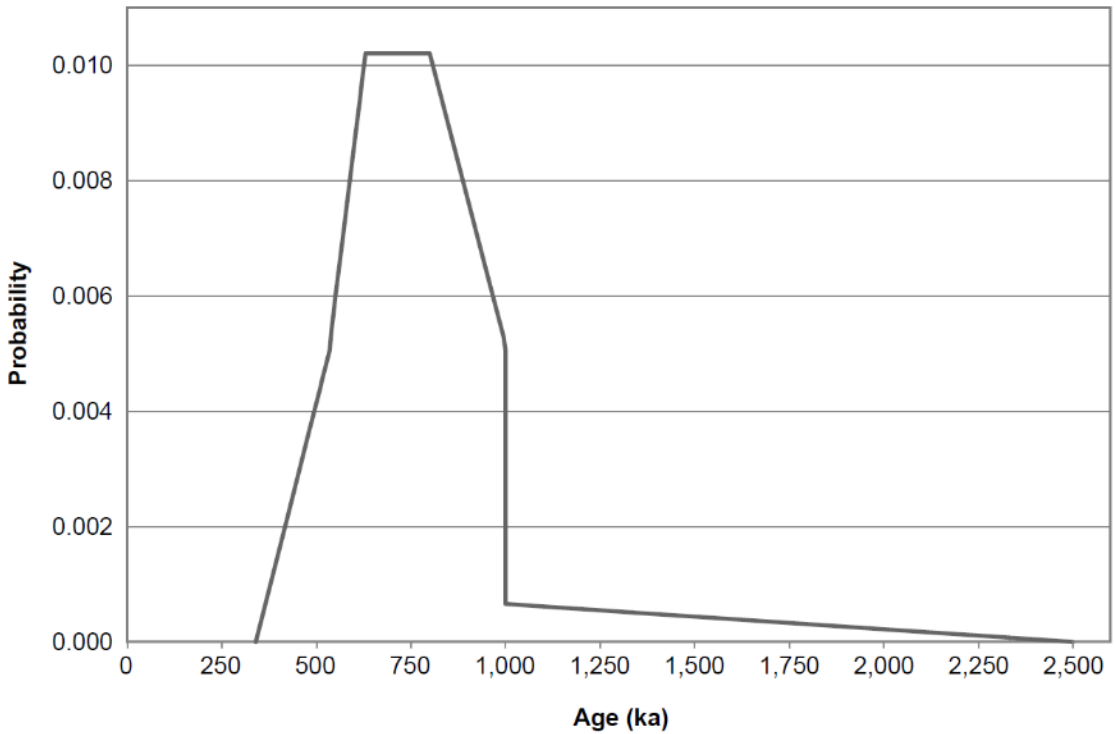
Value	West Strand Offset (m)	Basis
Min.	450	South margin of the shallow channel-like feature and the limits of uncertainty in the projection of Channel Ee1
Preferred	770	Range estimated from direct projection of Channel Ee1 and margins of shallow channel-like feature west of fault 10001
Preferred	1,050	
Max.	1,730	North margin of the deep channel- like feature and the limits of uncertainty in the projection of Channel Ee1

Value	East Strand Offset (m)	Basis
Min.	200	Estimated from incorporating uncertainty in projections
Preferred	230	Range estimated from the direct projection of Channel Ee1 and De thalwegs
Preferred	290	
Max.	320	Estimated from incorporating uncertainty in projections

Hosgri Fault Slip Rate Models

Documentation of Age Uncertainty

(c) Age PDF



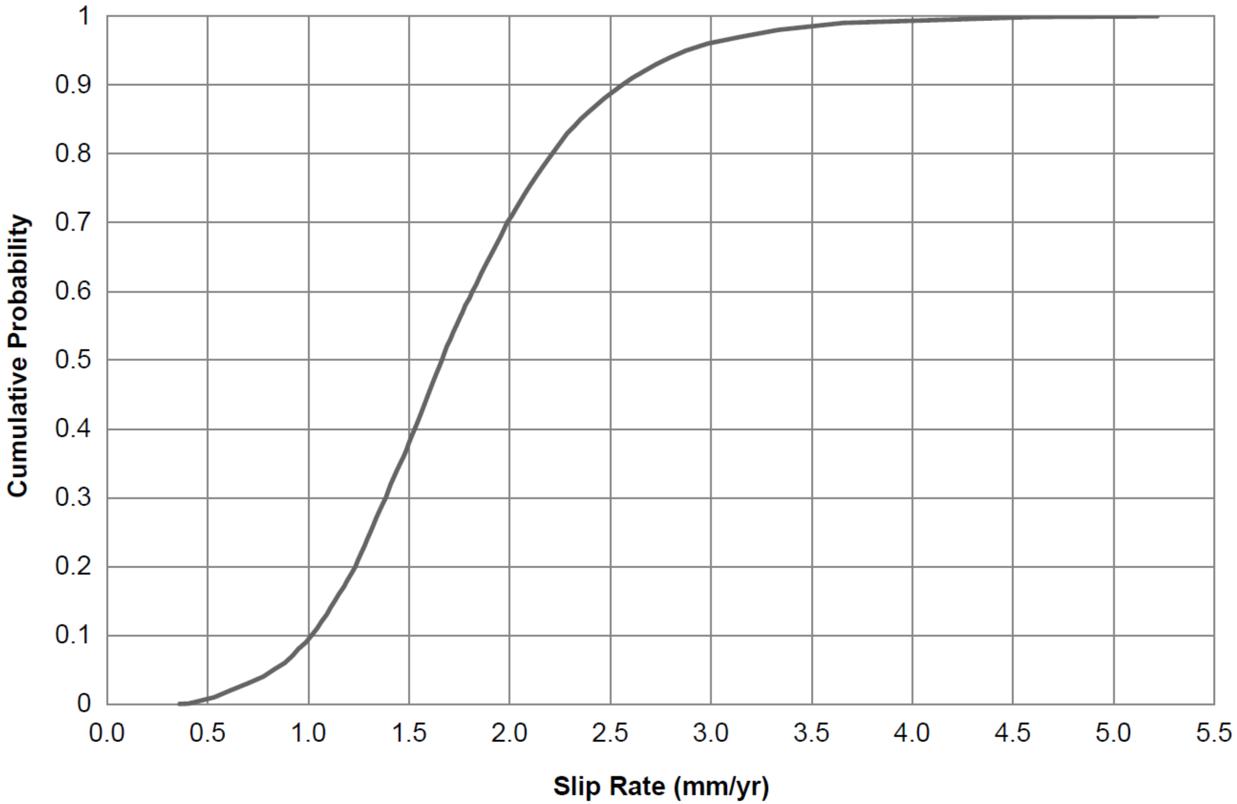
(d) Justification for Age PDF

Value	Age (ka)	Basis
Min	340	MIS 10; youngest age of overlying unconformity
Pref. Low End	535	MIS 14; ≥5 transgressive uncon. in strata above channel
Preferred	630	MIS 16; probable end of MPT
Preferred	800	MIS 20; shelf progradation deeper sea level during late stage MPT
Pref. High End	1,000	High end of uncertainty in shelf progadation
Max.	2,500	Max. age of NTN unconformity (PG&E, 2014 Chapter 3)

Hosgri Fault Slip Rate Models

Slip Rate CDF for Estero Bay Site

(e) Slip Rate CDF



(f) Summary Statistics

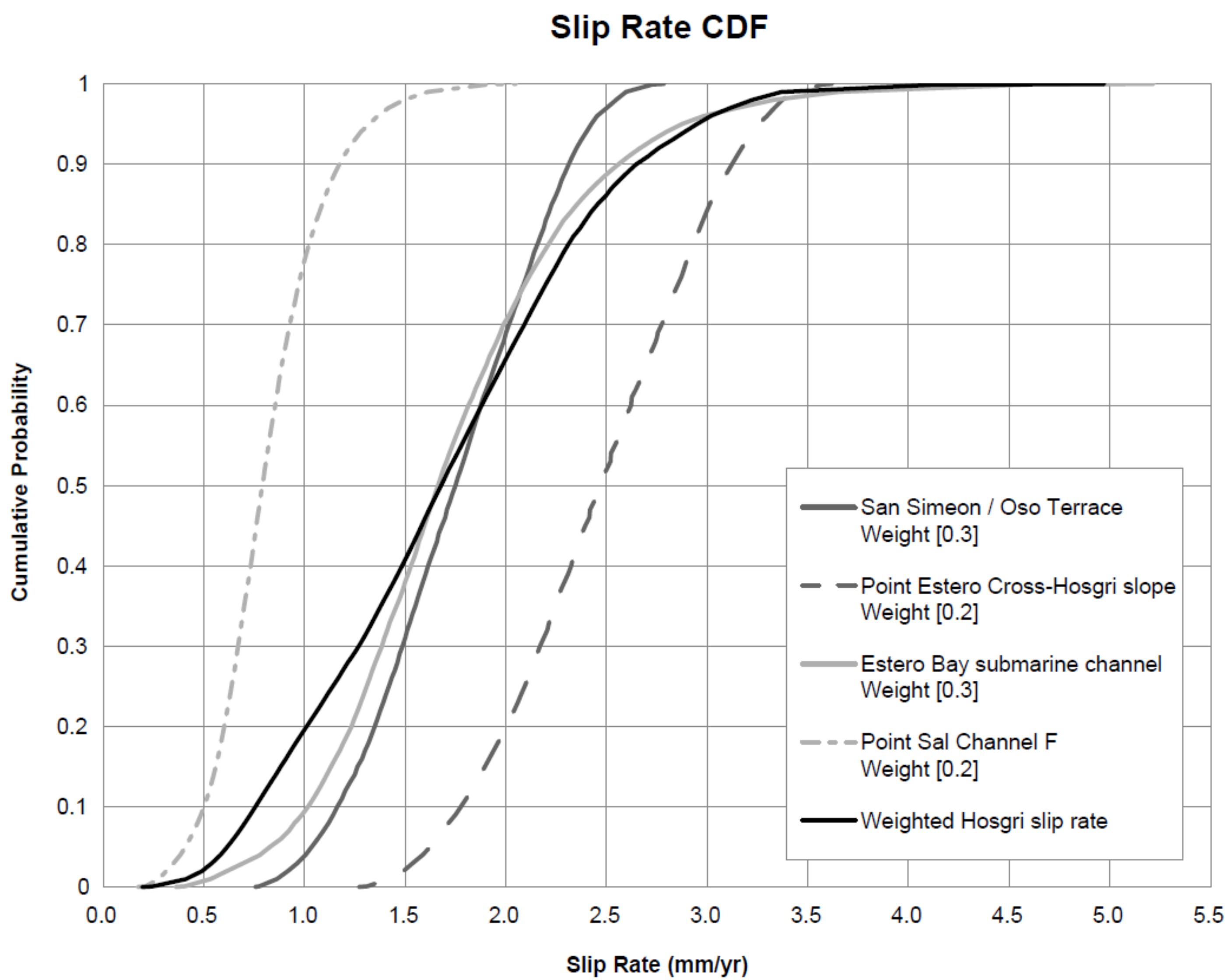
Cumulative Probability	Slip Rate (mm/yr)
0.05	0.8
0.1	1.0
0.2	1.2
0.5	1.7
0.8	2.2
0.9	2.6
0.95	2.9
Minimum	0.3
Maximum	5.3
Mean	1.7

Hosgri Fault Slip Rate Models

Weighting of Four Study Sites

CBR of TDI (in mm/yr):

Center: 1.7 (wtd. mean)
Body: 0.8 to 2.6 (10%, 90%)
Range: 0.4 to 3.4 (1%, 99%)



Seismic Source Characterization Focus Areas

***NRC SSC Topic 2*: Clarify how elements of the thrust/ reverse interpretation for the San Luis Range Thrust are incorporated into the SSC.**

•San Luis Range thrust model proposes that the Irish Hills are uplifted by a northeast-dipping thrust fault

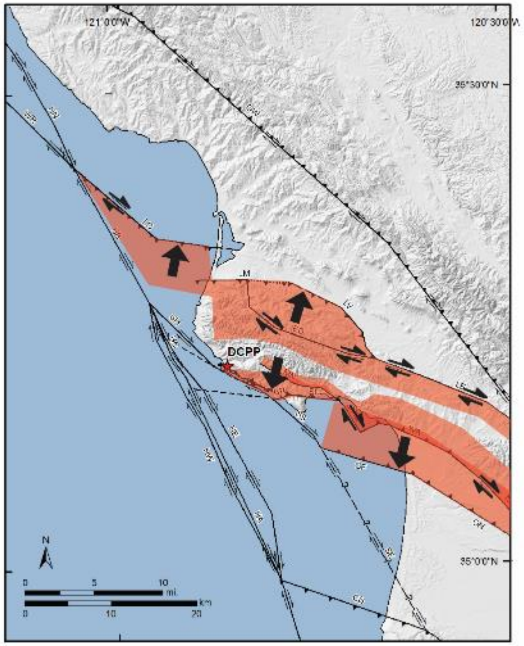
•SSC model incorporates this model as one of three alternatives of uplifting the Irish Hills

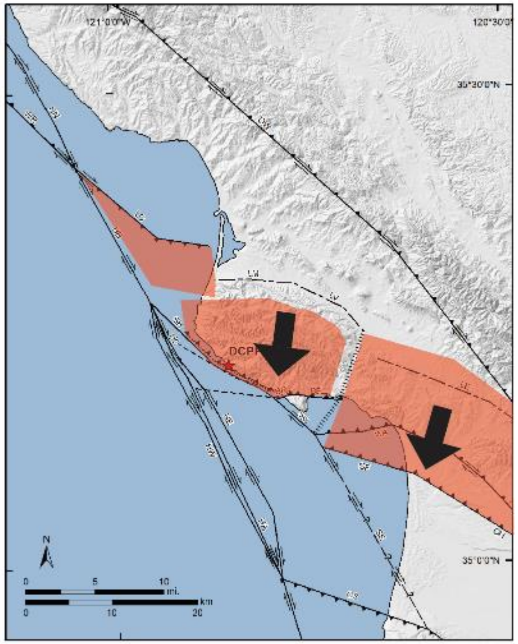
Fault Geometry Models

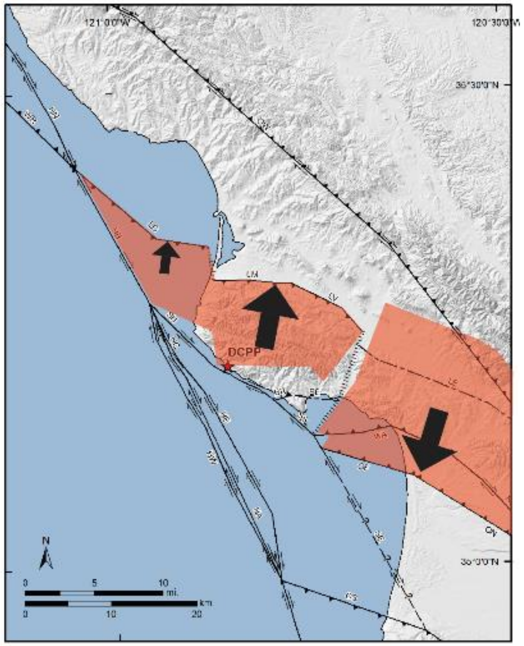
3 for Hosgri; 3 for San Luis-Pismo Block

Alternative Fault Models:

- Describe the fault geometry for each tectonic model in a correlated way
- Dip variability is achieved through the differences between tectonic models







Seismic Source Characterization Focus Areas

***NRC SSC Topic 3:* Clarify how the rupture models are derived from the fault source geometry models.**

Fault Geometry Models (FGMs) describe the fault locations, dips, and senses of slip

Rupture Models describe the alternative locations on the FGMs where maximum earthquake ruptures and smaller, floating ruptures occur.

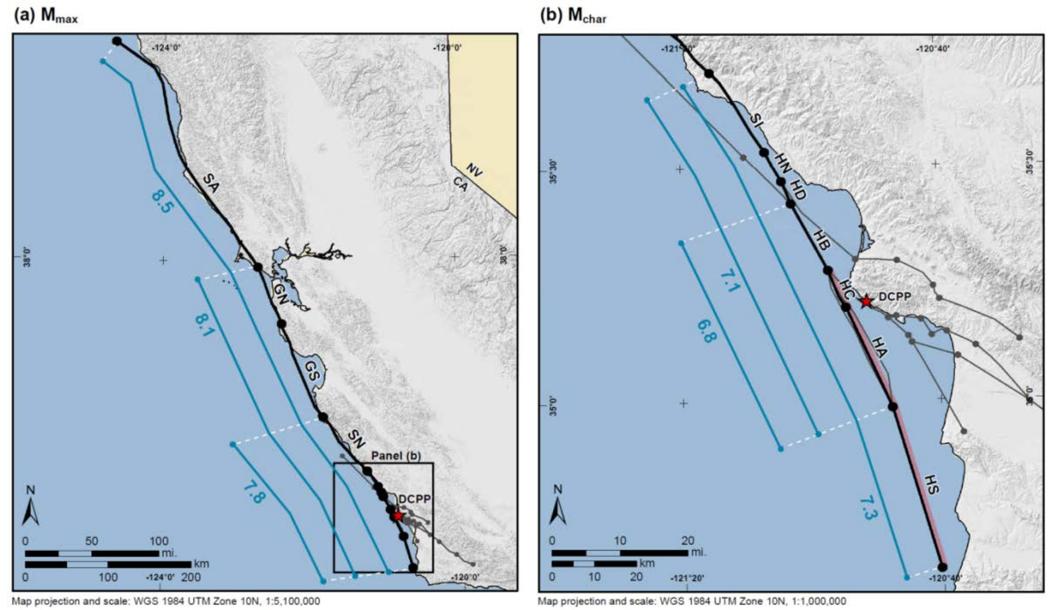
- Represents aleatory variability in how earthquakes rupture the fault network
- Allows single- and multi-fault rupture in a standard, forward model
- Rupture models include sufficient *rupture sources* such that the range of alternative types of ruptures are sampled for adequate source and ground motion variability

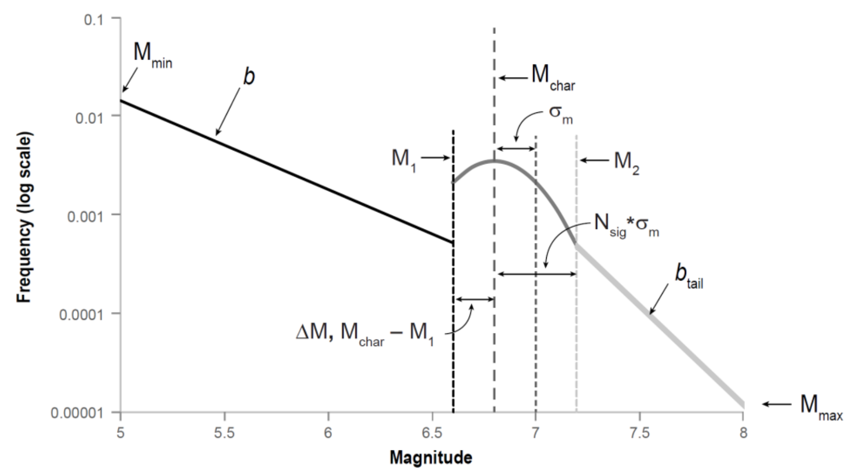
New Methods, Models in DCPP SSC Model

Rupture Models

Allow multi-fault ruptures

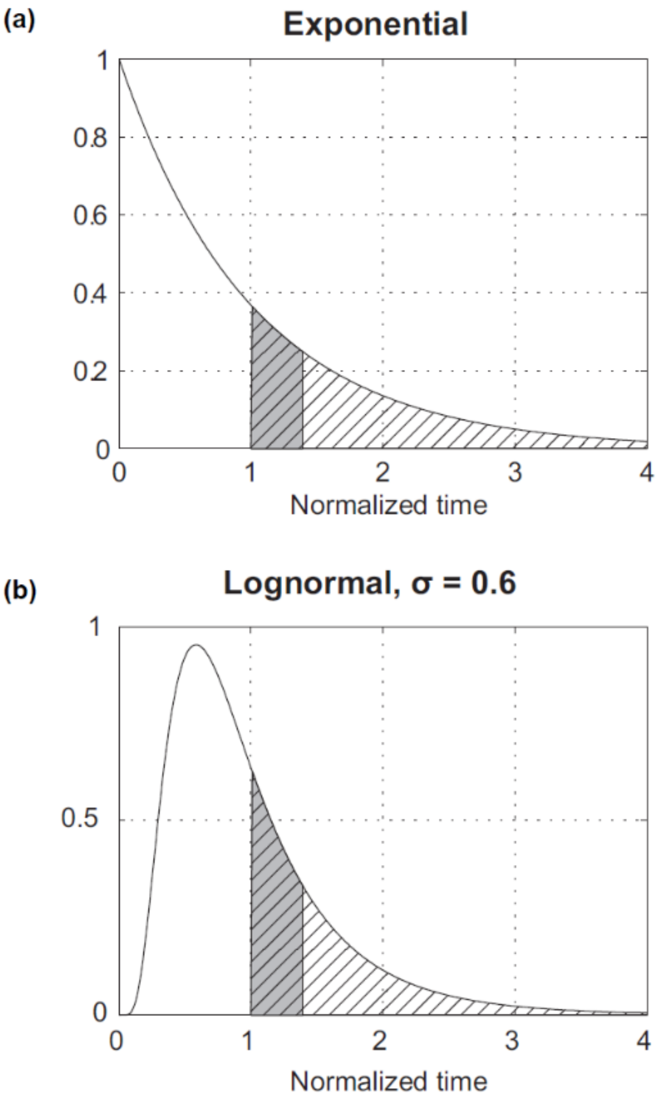
New composite magnitude-frequency distribution





Seismic Source Characterization Focus Areas

<u>NRC SSC Topic 4</u>: Summarize the Methodology Used to Define the Equivalent Poisson Rates.



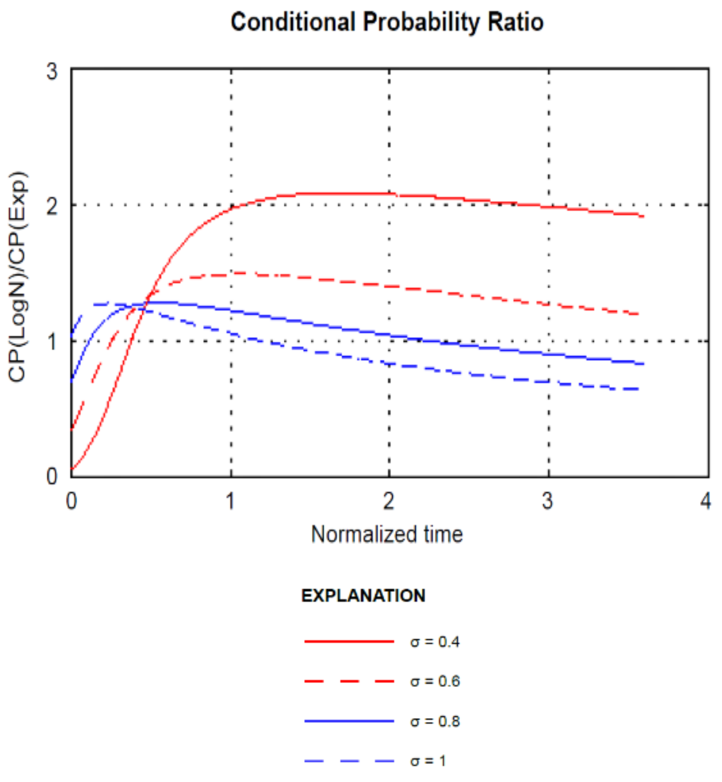
Motivation: Non-Poisson Recurrence Behavior is Likely

- In some cases, paleoseismic recurrence records are inconsistent with a Poisson process
- Renewal process includes intuitive physics (elastic strain accumulation and release)
- Simple models available that simulate renewal-type behavior

Methodology to Define the Equivalent Poisson Ratio (EPR)

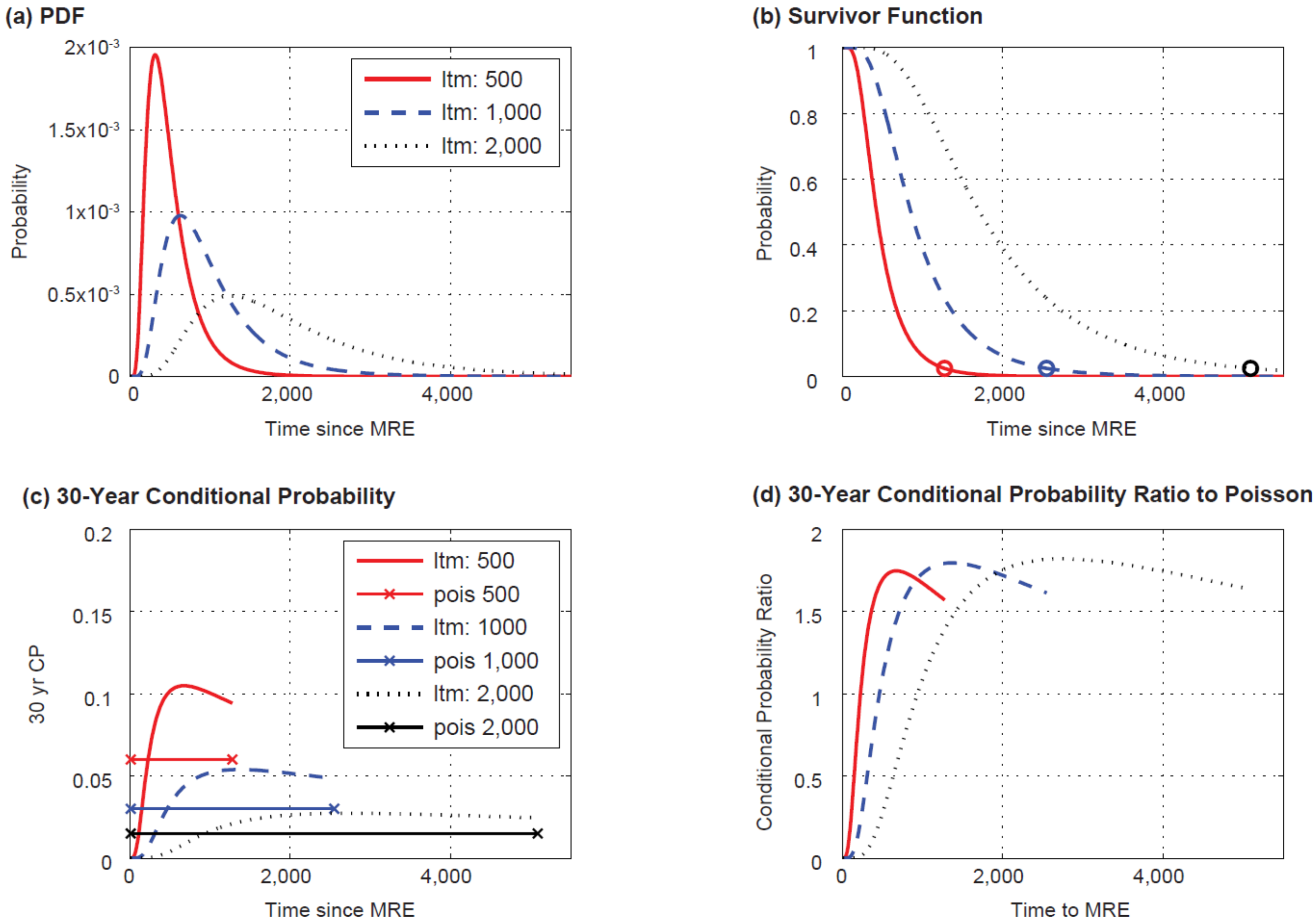
Methodology:

1. Lognormal model for recurrence (also BPT, Weibull)
2. Requires estimates of long-term mean (LTM), coefficient of variation (CV), and time since the most recent event (Tmre)
   - CV range from global paleoseismic data (mostly California)
   - T_{min} constraint on Tmre from historical record (SLO Mission)
   - LTM from slip rate and simple slip/event model
3. For each CV and slip rate, model considers joint probabilities of correct LTM and Tmre
4. 3-pt. approximation of resulting CDF is used in the logic tree for an EPR

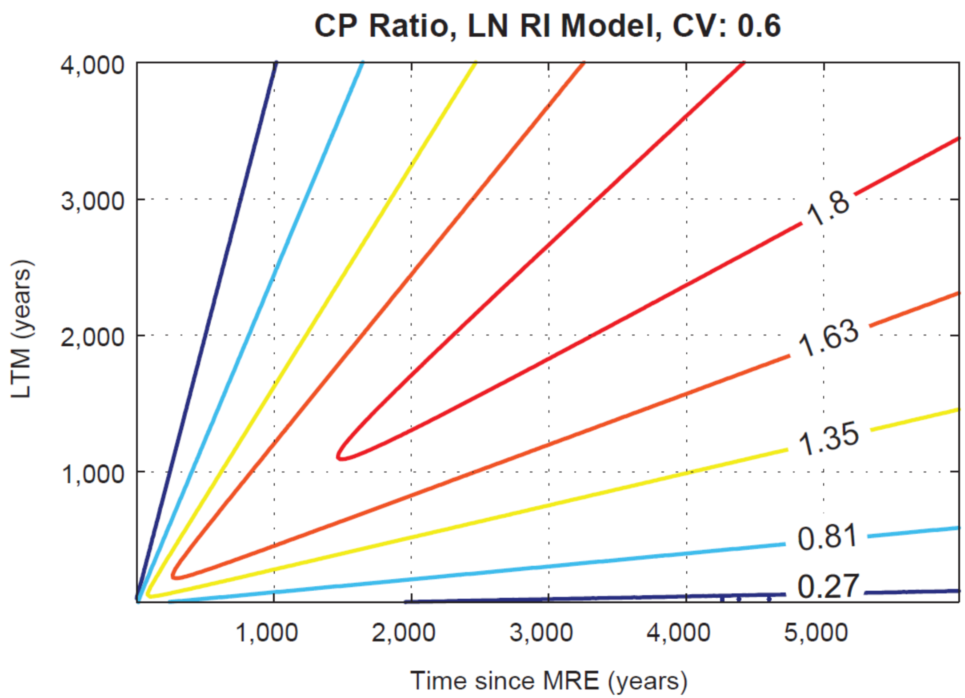


EPR Methodology

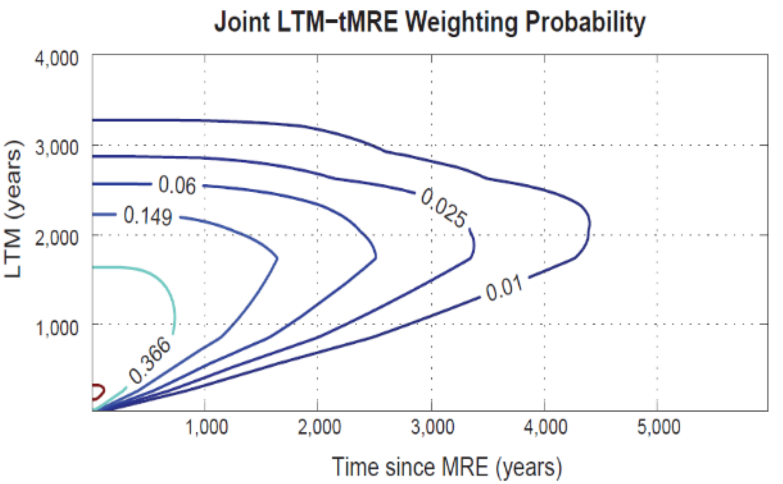
Use of survivor function to constrain LTM, Tmre joint probability (CV=0.6 shown)



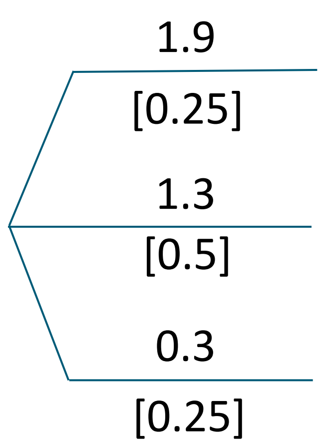
EPR Methodology



Note: Contours are the ratio of time-dependent rate to time-independent rate.
The long-term mean distribution is uniform on the range shown.



EPR Logic Tree, Hosgri fault



Ground Motion Models

Reference rock ground motion model (SSHAC GMC)

- Median ground motion
- Aleatory Variability

Site Amplification

- How the ground motion at the control point differs from the reference rock ground motion

Capture Uncertainties in each part

- Epistemic uncertainties

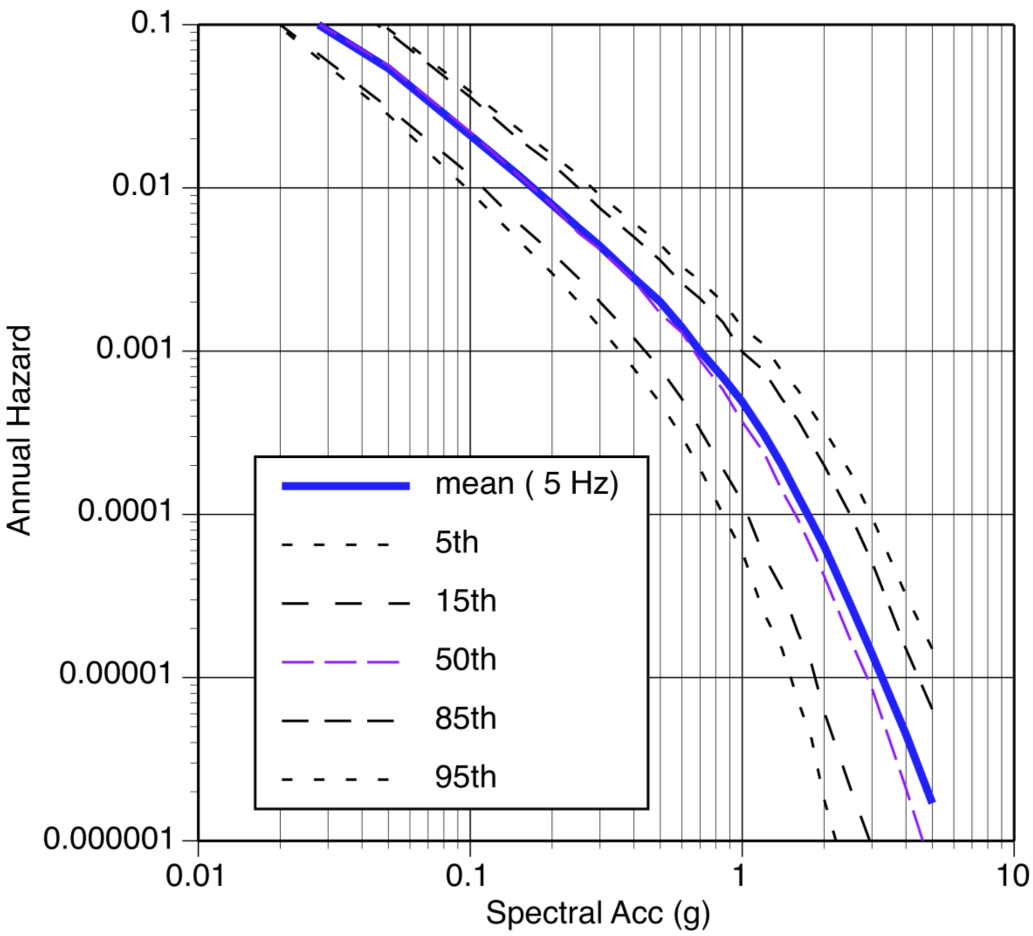
New Data, Models, Methods for GMC

Data
- NGA-W2 strong motion data set (PEER)
- European strong motion data set (RESORSE)
- Finite-fault simulations close to large earthquakes (SCEC)

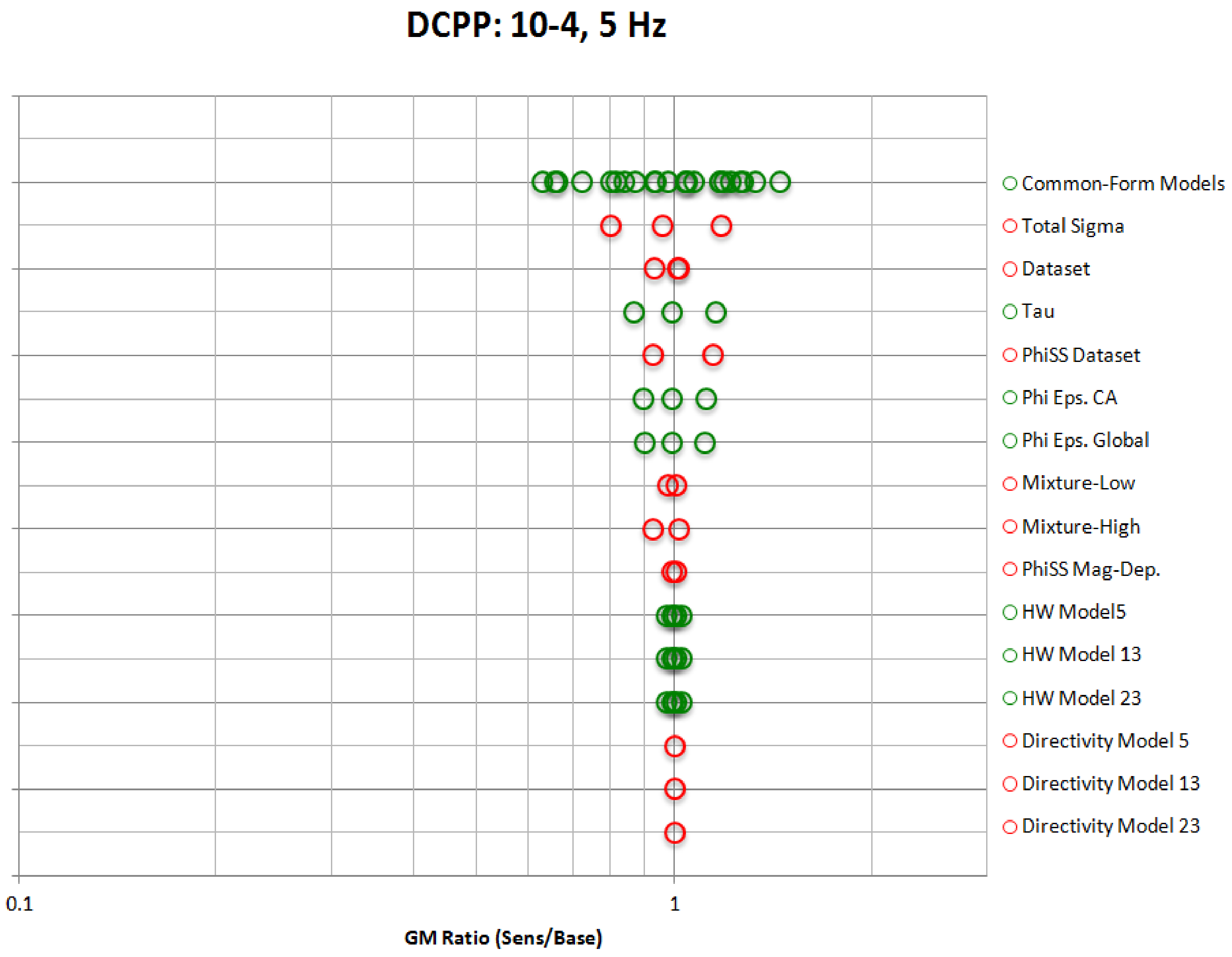
Models
- Median GMPE: NGA-W2 GMPEs
- Median GMPE: European and Japanese GMPEs
- Aleatory variability: Mixture model

Methods
- Sammons map approach to develop weights for GMPEs
- Additional epistemic uncertainty added to all GMPEs
- Included comparisons with empirical data and finite-fault simulations (SCEC) as part of the evaluation of the weights
- Single-station sigma approach
- Improved treatment of uncertainty for empirical DCPP site terms

Example Hazard Curves at Control Point with Uncertainty



Hazard Sensitivity to GM Model 5 Hz: 1E-4



Ground Motion Characterization Focus Areas

***NRC GMC Topic 1:** Provide additional detail in the criterion used for the selection of candidate Ground Motion Prediction Equations (GMPEs) for development of the common form median ground motion models for DCPP. Specifically, please elaborate on the basis for including GMPEs based on data sets other than NGA West-2.*

Selected Candidate GMPEs

NGA-W2	Abrahamson et al. (2014), referred to as ASK14
NGA-W2	Boore et al. (2014), referred to as BSSA14
NGA-W2	Campbell and Bozorgnia (2014) , referred to as CB14
NGA-W2	Chiou and Youngs (2014), referred to as CY14
NGA-W2	Idriss (2014), referred to as Id14
Europe & ME	Akkar et al. (2014a, 2014b), referred to as ASB14
Japan & CA	Zhao et al. (2006), referred to as ZH06
Japan & CA	TI Team implementation of Zhao and Lu (2011), referred to as ZL11

Selection Criteria

Consider all modern GMPEs from active crustal regions

- Assumes that the magnitude and distance scaling in active crustal regions is similar around the world
- Selected GMPEs had to meet 7 criteria (SWUS, section 5.5.2)
  - Most recent version
  - Not an adjustment of another model
  - Functional form extrapolates in a reasonable manner
  - Do not combine data from active crustal and subduction earthquakes
  - Not just a research tool
  - Not developed for a very small region
  - Peer reviewed

Why Select GMPEs not from NGA-W2 data

- The objective is to capture the uncertainty
- GMPEs from other regions may provide alternative credible scaling for ground motions in CA
- Early feedback from PPRP recommended that we not limit the GMPEs to NGA models because there models may not capture the full range of uncertainty
- Some of the large magnitude data in the non-NGA GMPEs are contained in the NGA data set, so there is overlap, but also different modeling approaches used
- The weights for the final models are developed considering how well the models fit the NGA data

Ground Motion Characterization Focus Areas

***NRC GMC Topic 2*: Provide additional detail on the development of the common functional form used to fit the candidate GMPEs. Specifically, please discuss how model parameters such as depth to Vs equals to 1 km/s and 2.5 km/s (which are present in some of the candidate GMPEs) are accounted for in the functional form.**

Common-Form Model

The common-form models

- Developed for a single reference rock condition of VS30=760 m/s
- Footwall side only to keep the functional form simple
- Hanging-wall effects added to the common-form model

The other site parameters, Z1.0 and Z2.5, are set to their default values for VS30=760 m/s

- Basin depth is not a significant issue for soft-rock sites

Ground Motion Characterization Focus Areas

***NRC GMC Topic 3*: Provide additional detail on the approach for weighting the selected common form models as well as the criteria used to verify the physicality of the final model.**

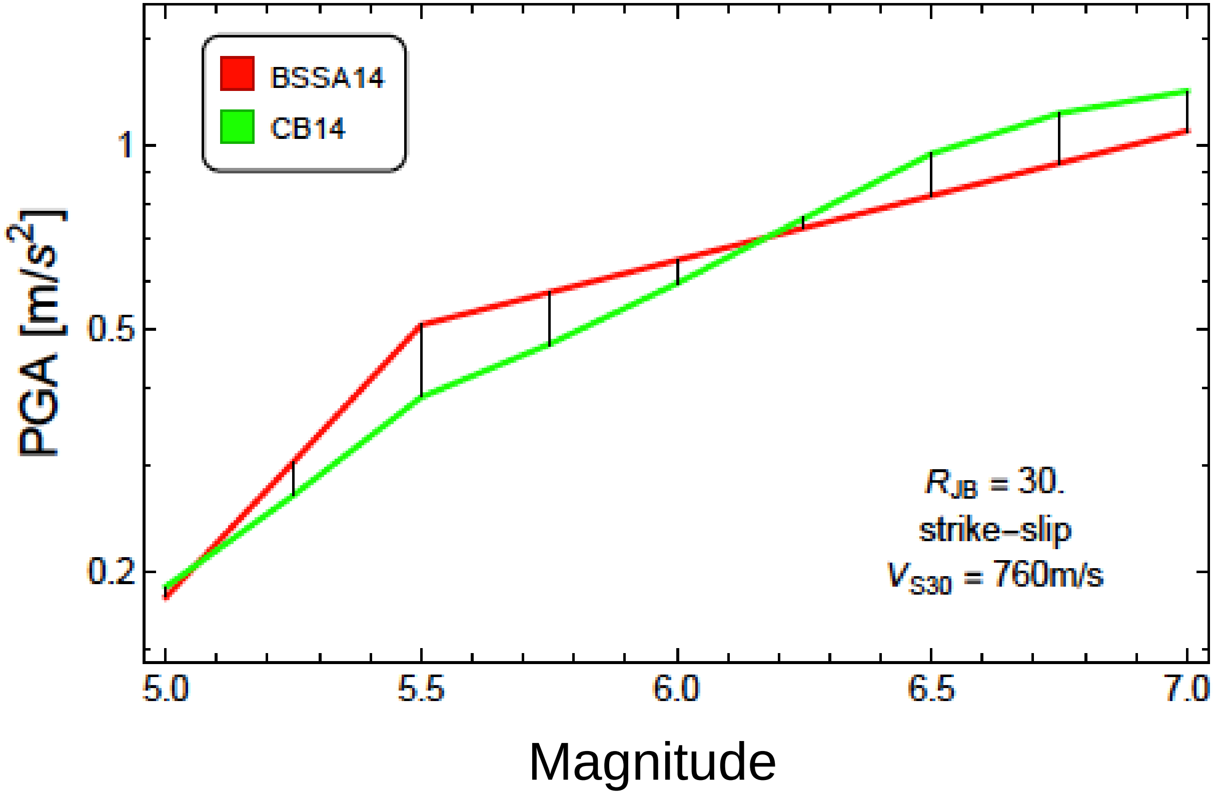
2000 models generated to fill in the space of possible GMPEs

- Sampled the covariance of the coefficients
- Treats the correlations of the coefficients

Non-physical models

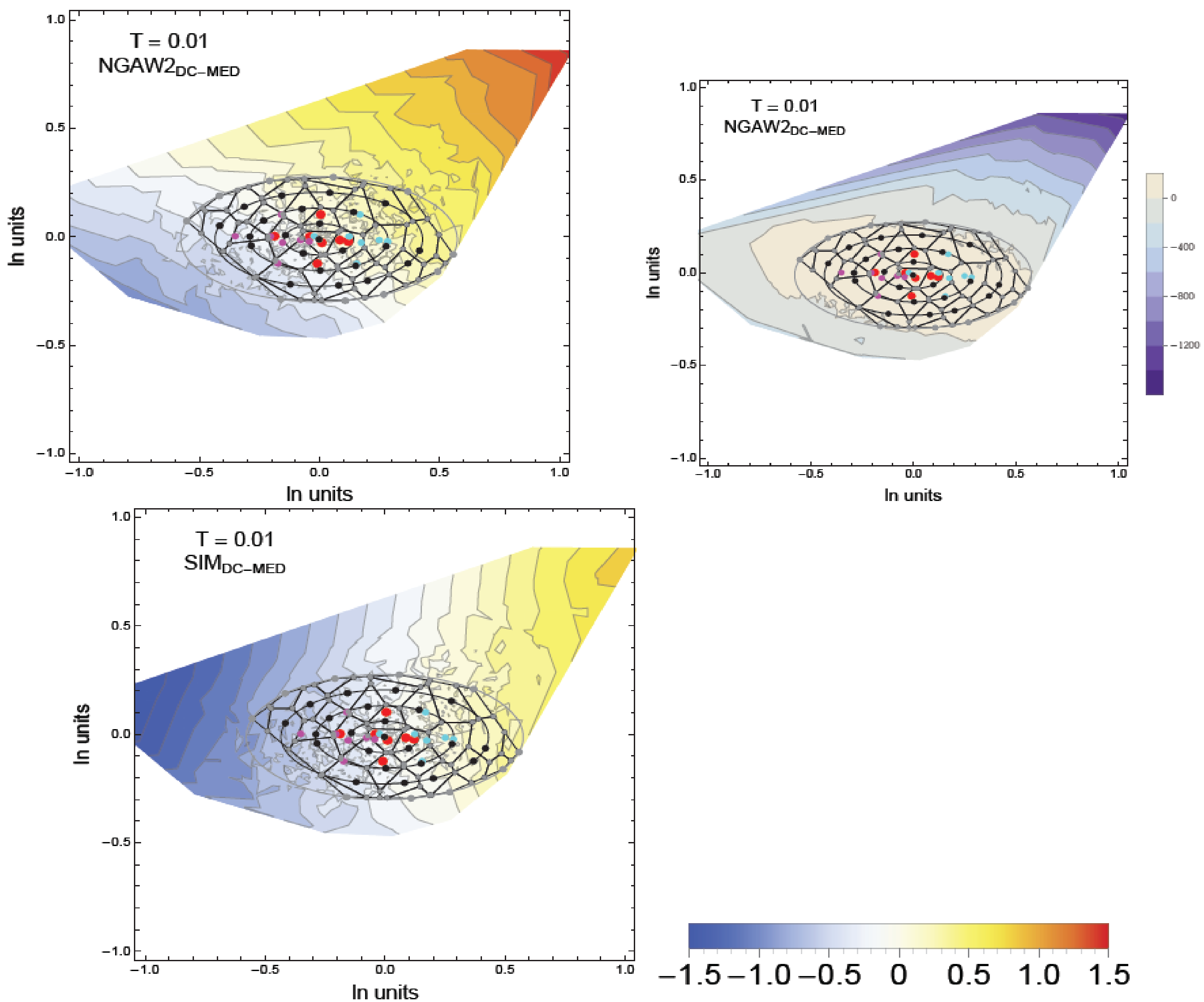
- Tails of distributions of coefficients may lead to sampled models that are “unphysical”
- Defined as models for which the magnitude or distance scaling is not monotonically increasing (M) or decreasing (R)

Mapping GMPE Differences

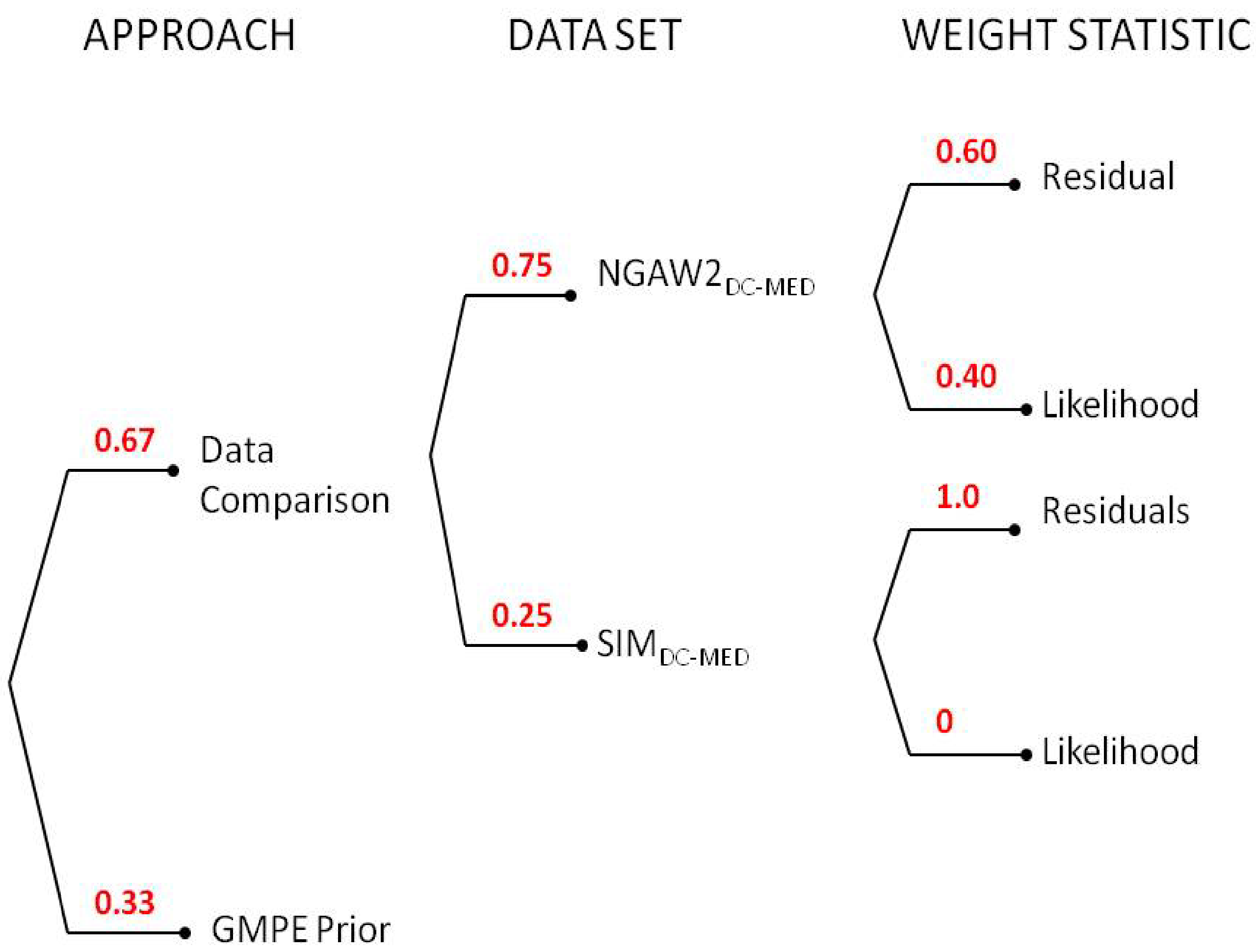


Measure the Standard Deviation of Difference in GMPEs for a Range of M,R

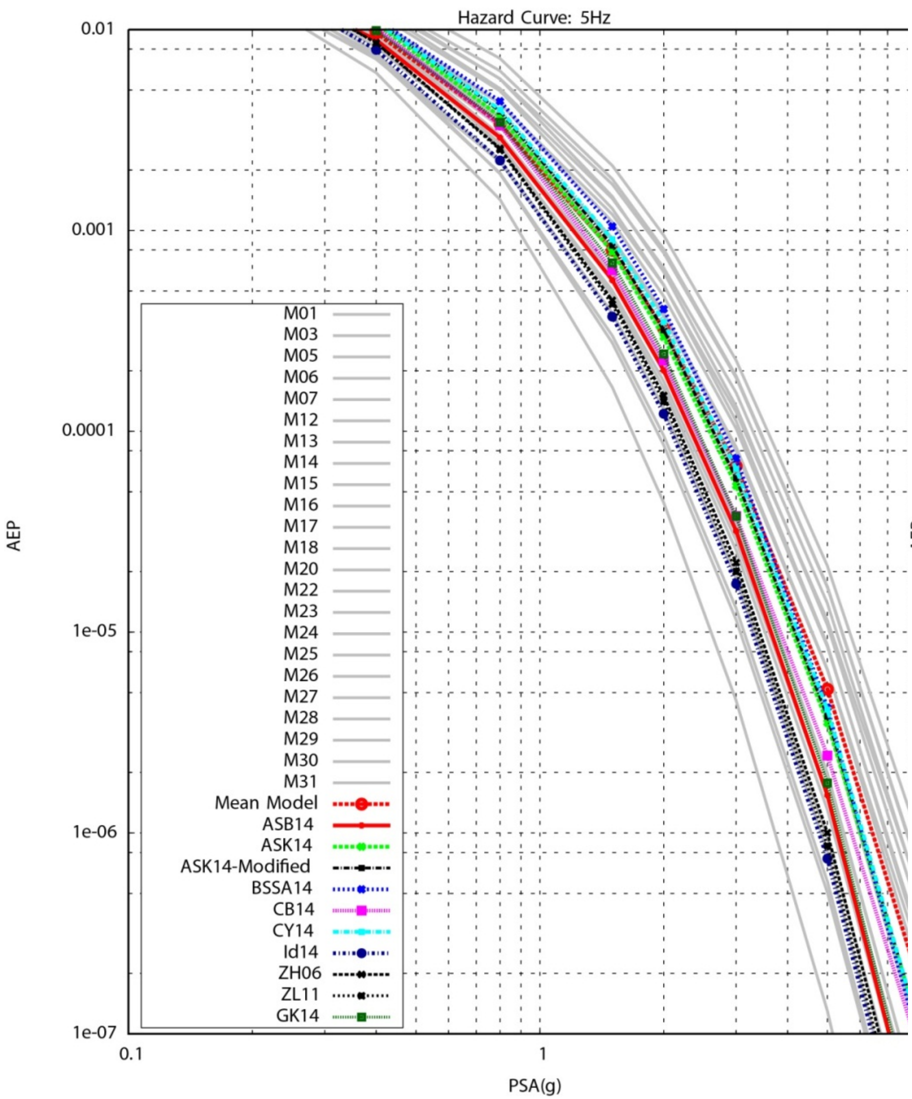
Use Sammons Maps to Describe Space of Median GMPEs and Develop Weights

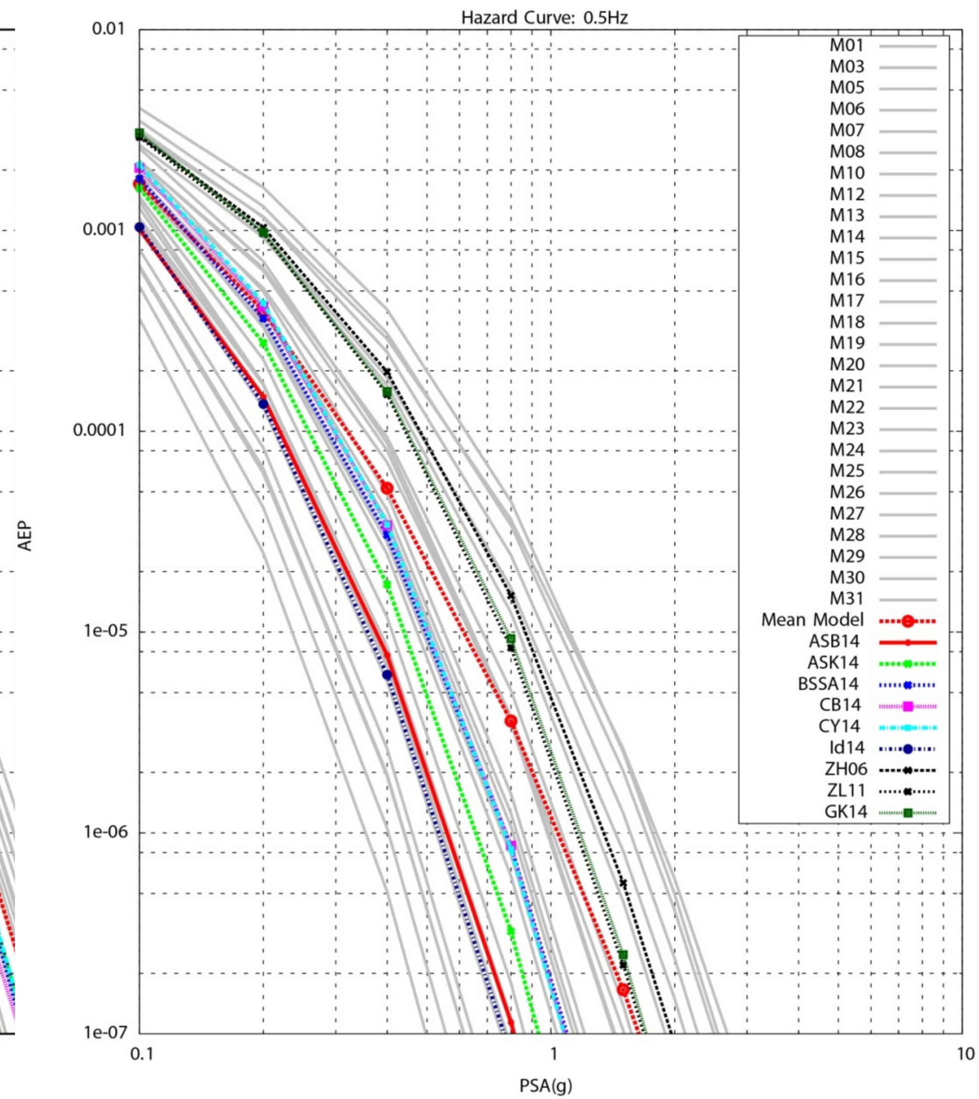


Weights for the Common-Form Models



Hazard Sensitivity to Median GMPE



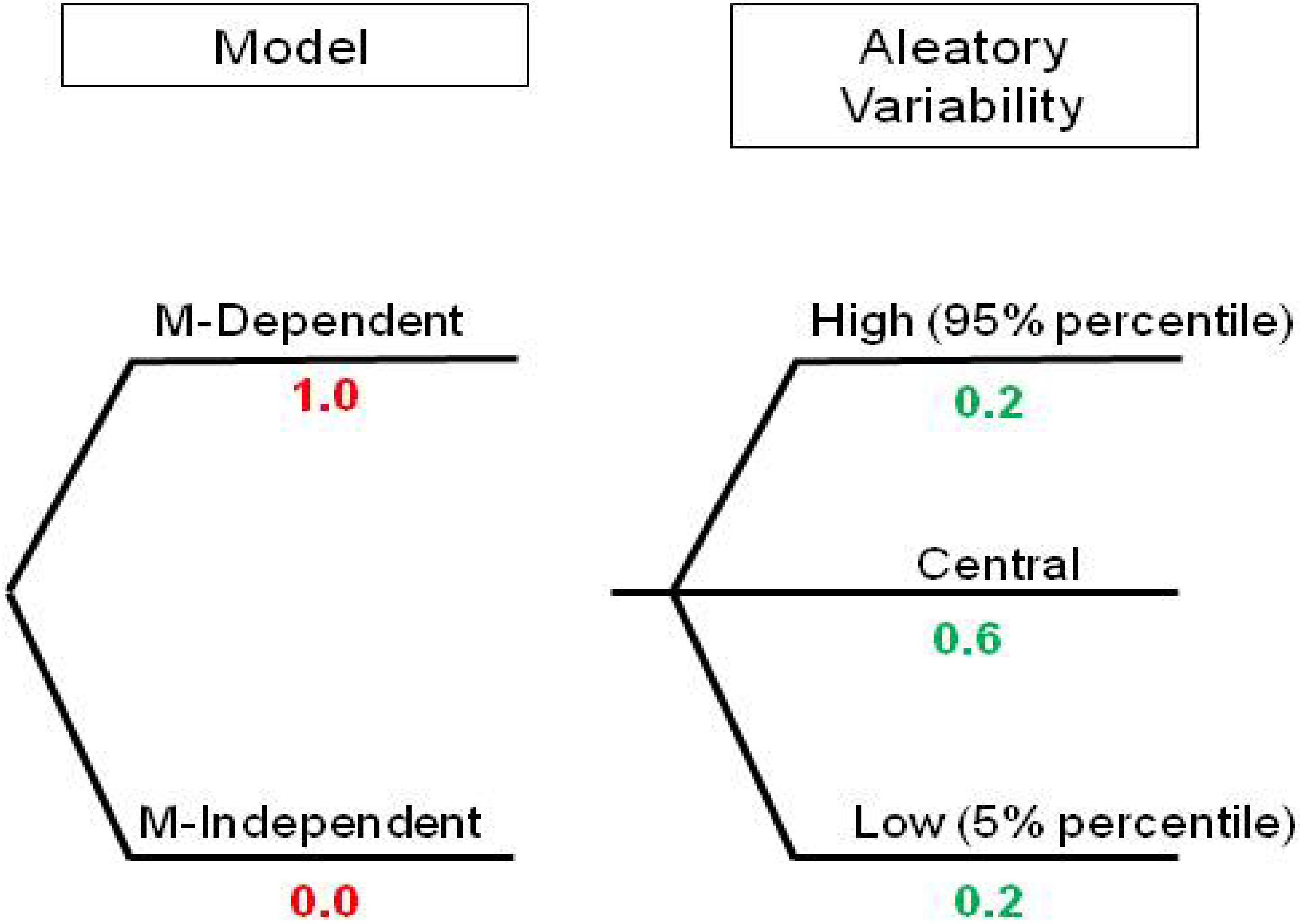


Ground Motion Characterization Focus Areas

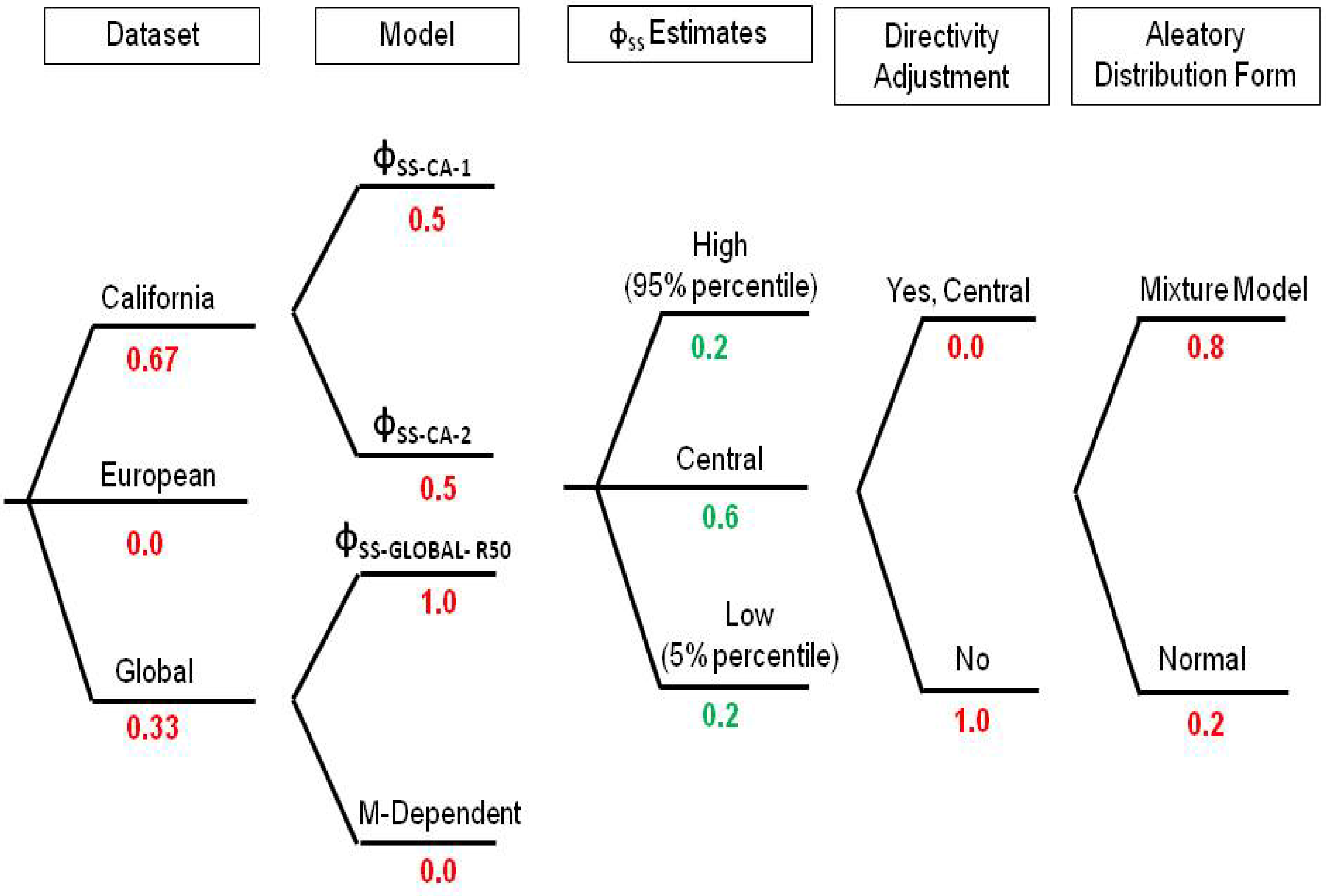
<u>NRC GMC Topic 4</u>*: Provide additional detail on how the continuous distribution for total sigma was developed by combining the between-event and within-event aleatory variabilities*.

$$\sigma_{SS}(M,T) = \sqrt{\phi_{SS}^2(M,T) + \tau^2(M,T)}$$

Example of Tau Models for 1 Hz



PhiSS Logic Tree



Combining PhiSS and Tau into Total Sigma

Use Chi-Squared distribution for phiSS^2 and Tau^2

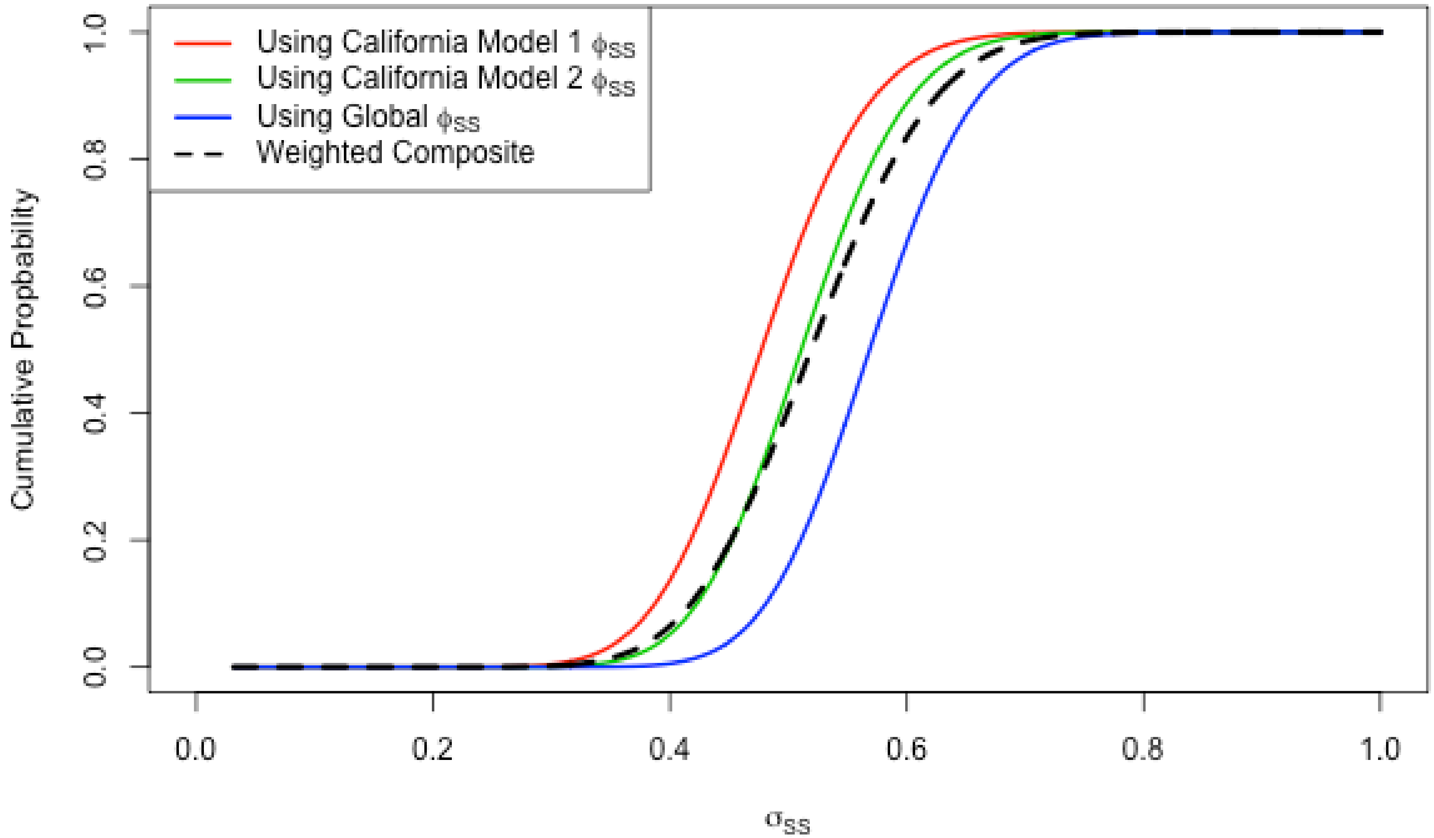
For each model (branch 2) of phiSS logic tree, sample the three PhiSS values and the three tau values

Develop a cumulative distribution function (CDF)

Average the CDF using the logic tree weights for the alternative PhiSS models (branch 2) and data sets (branch 1)

Sample the total CDF at the 5^{th}, 50^{th}, and 95^{th} fractile levels

Combining Phi and Tau into Total Sigma



Site Amplifications Focus Areas

***NRC SA Topic 1*: Section 2.3.2.1 of 50.54(f) Submittal states that shear modulus and damping curves are not directly applicable to DCPP since analytical modeling is not used and that non-linear site effects are implicitly included in the empirical GM,PEs for Vs30 = 760 m/sec. However the NGA West 2 data base has a limited amount of data for sites with Vs30 near 760 m/sec and for earthquake with magnitude and source to site distance similar to those dominating the hazard for DCPP.**

Please provide additional information on how these limitations in the NGA West 2 data base are accounted for in site response model for DCPP?

Limitations of the Data Base for Hard Rock Sites

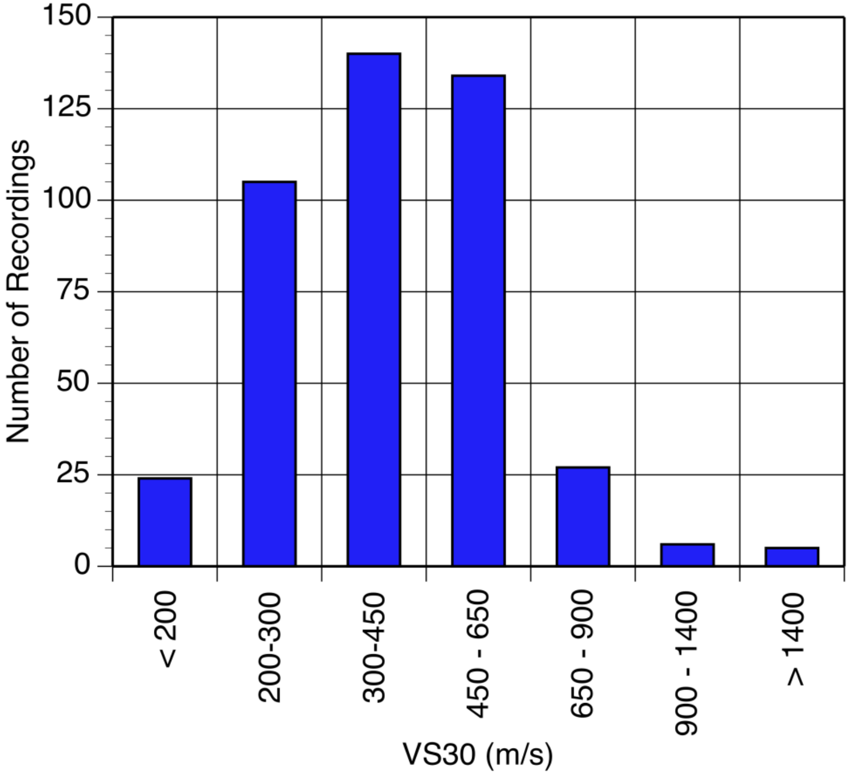
Select a reference rock site condition

- Range with data, but not too low VS to avoid strong non-linear site effects
- Selected VS30=760 m/s for the reference rock site condition

Nonlinear Site Response in NGA-W2 GMPEs

Some GMPEs used analytical modeling for noninearity.

NGA-West2 data set used by ASK14 (M>6, R<20 km)



Site Amplifications Focus Areas

***NRC SA Topic 2*: Section 2.3.6 of the 50.54(f) Submittal describes the development of the site terms for DCPP. For the calculations of between-event residuals, provide additional information on the criteria used to determine the appropriate distance range (+ and – Rrup) to the sample station. Please discuss the sensitivity of this distance range on between-event residual values. Please provide an example calculation that uses site specific values to determine the values for Phi s2s including the epistemic uncertainty in the site term.**

Estimation of DCPP Site Terms

Non-ergodic ground-motion model

$$\ln SA_{obs}(M_i, Loc_i, Site_j) = \ln GMPE(M_i, R_{ij}, VS30_j)$$
$$+ \delta L2L_l + \delta S2S_j + \delta P2P_{lj} + \delta B_i^0 + \delta W_{ij}^0$$

Estimate the combined source and path terms for each earthquake using observations from other sites (not DCPP)

$$\delta L2L_l + \delta B_i^0 + \delta P2P_{lj}$$

Estimation of DCPP Site Terms

$$\delta S2S_j = \ln SA_{obs}(M_i, Loc_i, Site_j) - \ln GMPE(M_i, R_{ij}, VS30_j)$$
$$-\left(\delta L2L_l + \delta B_i^0 + \delta P2P_{lj}\right) + \delta W_{ij}^0$$

Sources of Uncertainty of Site Term

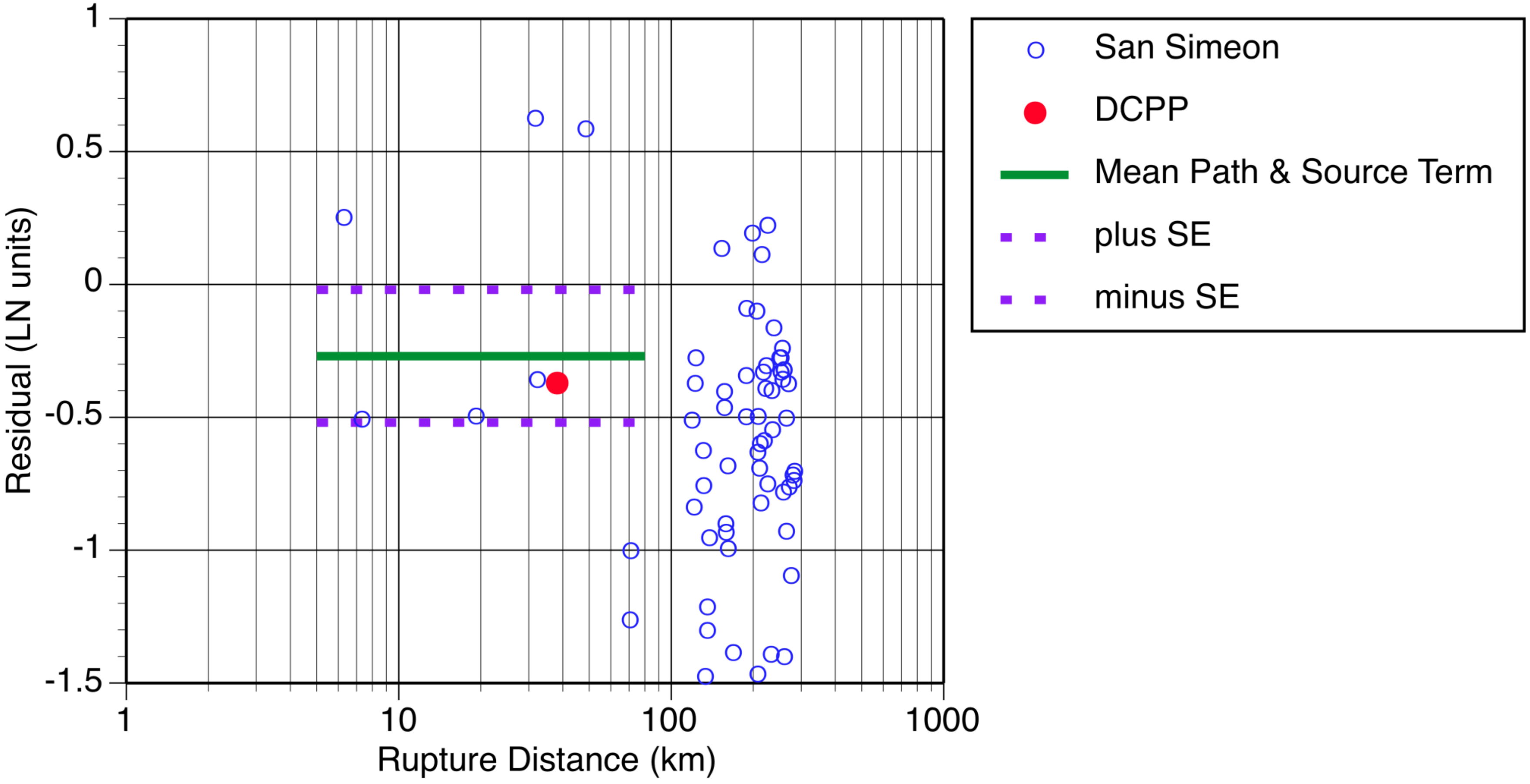
- Uncertainty in the Event-specific source and path term:
- Randomness of the remaining aleatory variability of the within-event term

Selection of Distance Range for Residuals

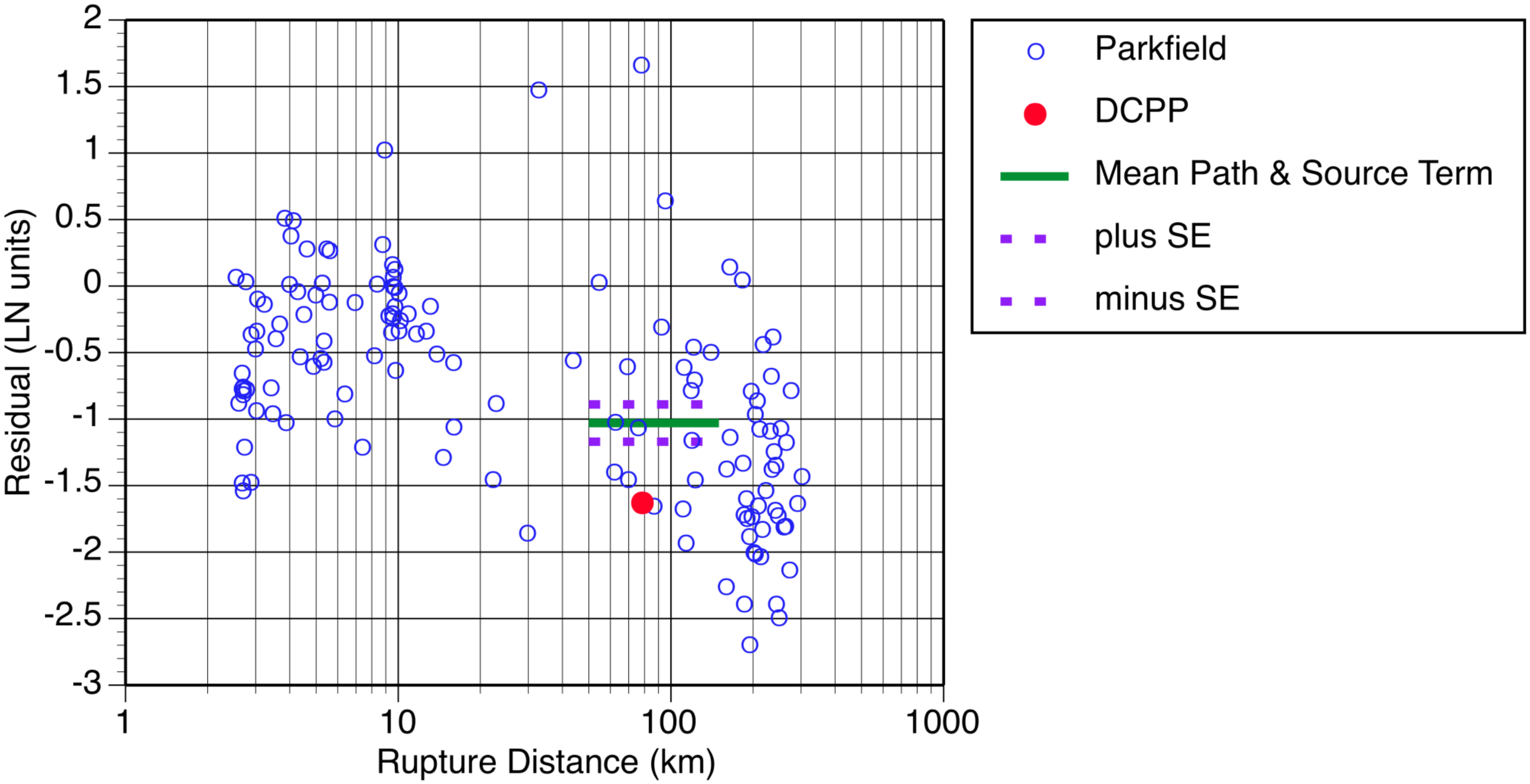
Two factors

- Distance range that includes the DCPP distance
- Distance range for which the residuals do not have a strong distance slope

Example: BSSA14 model, 5 Hz San Simeon



Example: BSSA14 model, 5 Hz Parkfield



Uncertainty in the Event-specific Source and Path Term

Computed from the standard deviation and number of recordings used to estimate the term

- San Simeon: 8 recordings, Sigma = 0.68 ln units
- Parkfield: 16 recordings, Sigma = 0.55 ln units

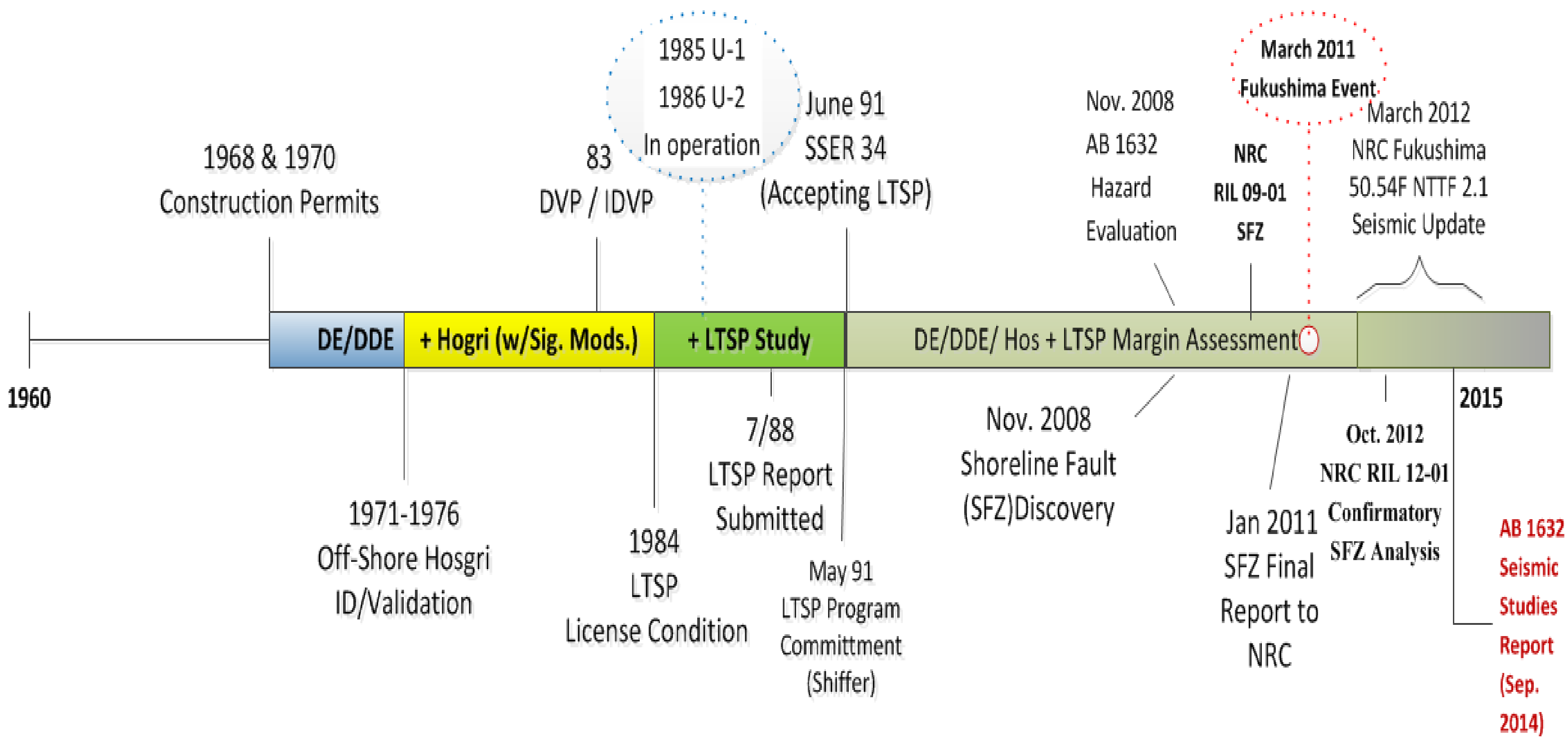
Epistemic uncertainty is the standard error of the mean

- Sigma / sqrt(N)
  - 0.25 for San Simeon
  - 0.14 for Parkfield

$$\text{Std Error of } \delta S2S_{DCPP} = \frac{\sqrt{\sum_{i=1}^{NEQK} SE(Source+Path)_i^2 + \phi_0^2}}{NEQK} = 0.22$$

Interim Evaluations and Actions

DCPP Seismic Design/Licensing Basis History



DCPP Design / Licensing Basis

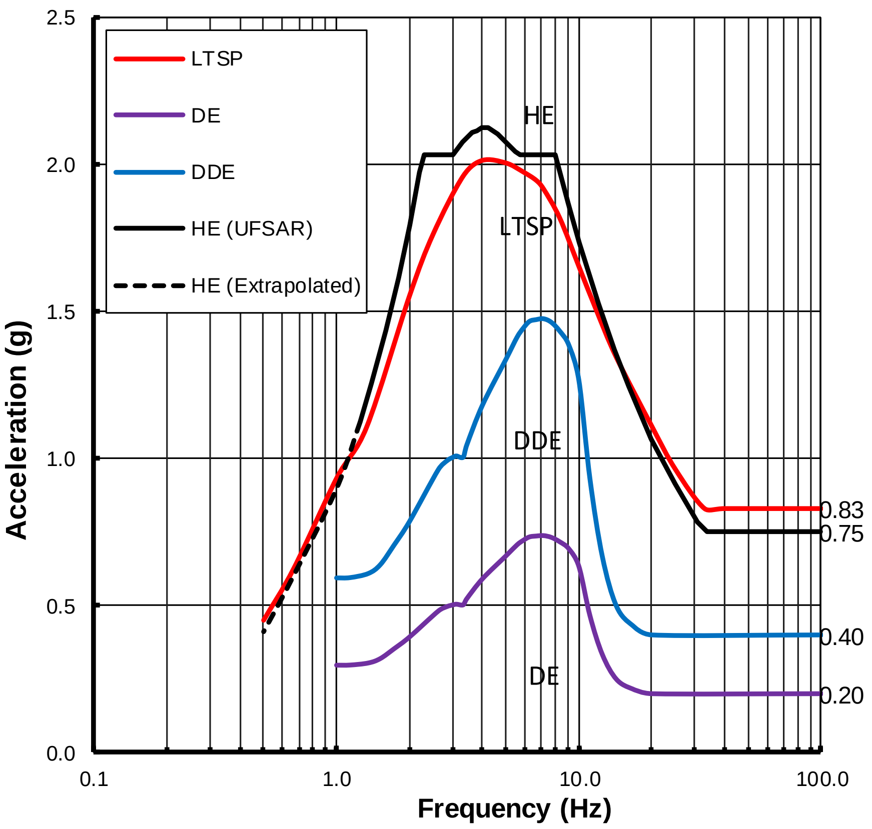
DCPP was licensed prior to App. A to 10 CFR Part 100 (Introduced "OBE& SSE" terms)

DE: OBE Equivalent = 0.2 g

DDE: SSE equivalent = 0.4 g

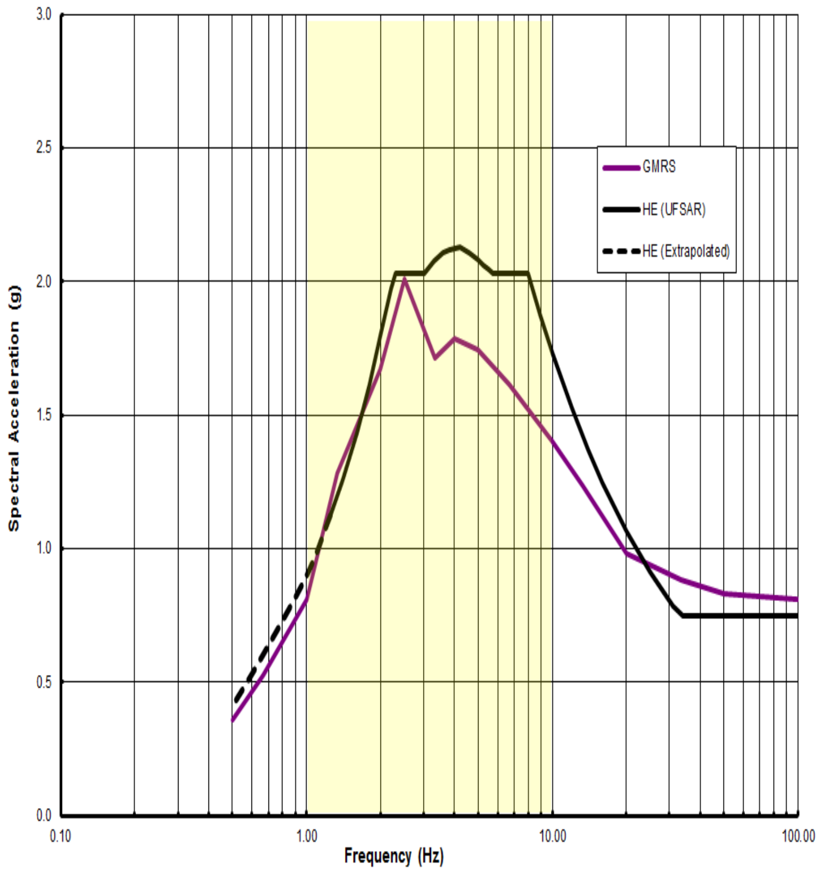
HE: Largest design ground motion = 0.75 g

LTSP: Seismic Margin /LTSP Spectra = 0.83 g

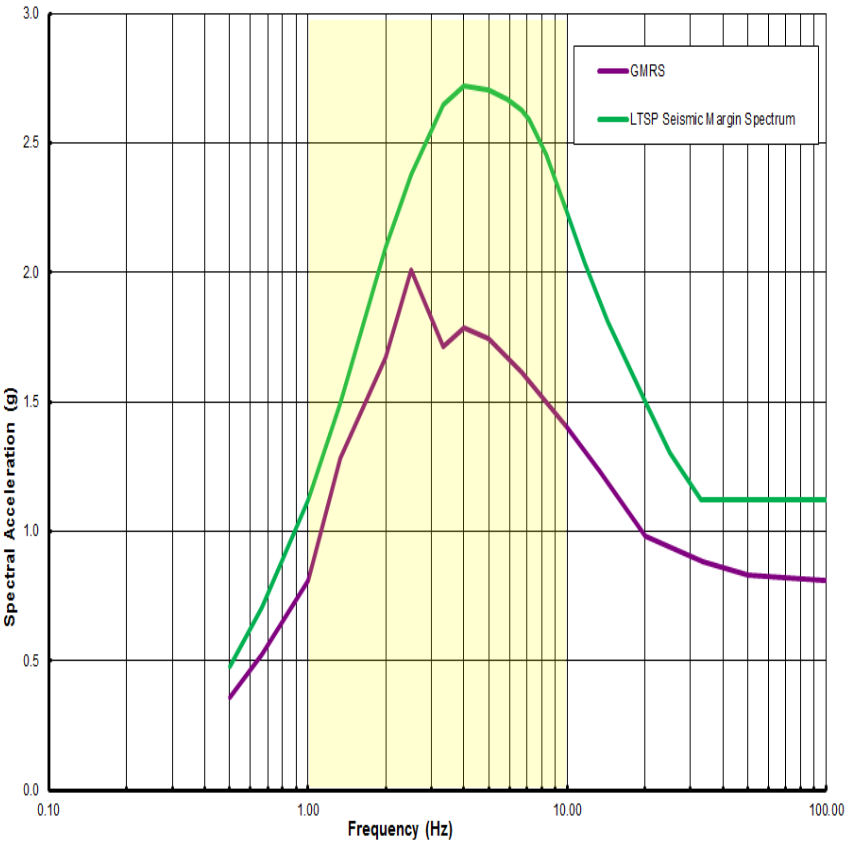


GMRS Comparisons

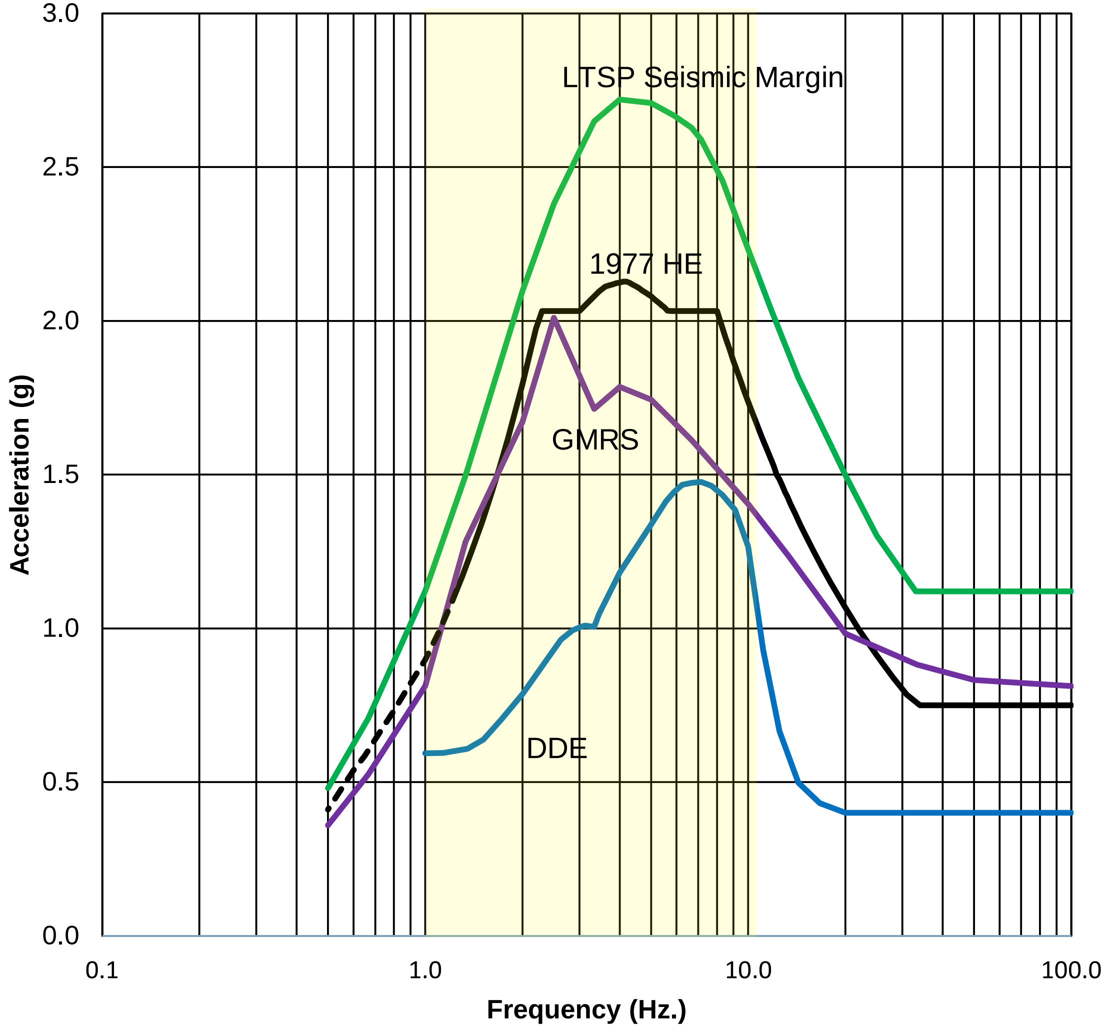
GMRS Vs. 1977 HE Design



GMRS Vs. LTSP Seismic Margin



GMRS Comparisons (continued)



LTSP Seismic Margin

LTSP Licensing Background

- DCPP License condition No. 2.C.(7) required in part “PG&E shall develop and implement a program to reevaluate the seismic design bases used for the DCPP”
- Seismic reevaluation effort was titled Long Term Seismic Program (LTSP); issued in 1988 with 1991 addendums to address the LC and committed to maintain the program going forward.
- LTSP deliverables were Seismic Probabilistic Risk Assessment (SPRA) and Seismic Margin Assessment (SMA)
- NRC’s comprehensive assessment and acceptance are documented in Supplement 34 to Safety Evaluation Report (SSER-34)

LTSP Seismic Margin (continued)

- Key Points
  - From SPRA; Mean Seismic Core Damage Frequency (SCDF) was calculated to be $3.7x10^{-5}$
    - Current SCDF (including updated; data, logic model, HRA) is $2.66x10^{-5}$
    - SCDF sensitivity review considering updated Hazard (with the original Fragilities) is ~ $2.06x10^{-5}$. The fragilities will be revised to get updated risk values.
  - The fragilities and HCLPF capacities are based on 5% damped horizontal spectral acceleration values, averaged over 3.0-8.5 Hz. (~ 1.94gs)
  - From Seismic Margin evaluation; the Lowest, High Confidence Of Low Probability of Failure (HCLPF) of SSCs was determined to be 2.62g **resulting in a minimum seismic margin of 1.35.**
  - NRC reviewed and acknowledged the significant seismic margin in SSER-34 .

ESEP, SFP Evaluation

Expedited Seismic Evaluation Program (ESEP):

- The GMRS is recognized as beyond design basis. However there needs to be reasonable assurance of plant safety while new/updated risk evaluations are in-progress
- Developed to address where significant exceedance beyond design basis are identified in the 1-10Hz. frequency range.
- The GMRS is effectively bounded by the 1977 HE design spectra in 1-10 Hz. Minor high frequency exceedance is well within the LTSP seismic margins and adequately considered in the SPRA analysis. Therefore there is reasonable assurance of plant safety.

Spent Fuel Pool Evaluation:

- SFP structure is an integral part of the Auxiliary building, which has been designed and evaluated as a seismic Design Class I structure in accordance with the DE, DDE, HE design criteria, and considered in the SPRA (Building fragility). Therefore, there is reasonable assurance of structural integrity. DCPP will perform rapid drain down evaluation activities, as required per SPID and will reevaluate the fragilities for the Auxiliary building as part of SPRA update.

Current and Next Actions

Proceeding with SPRA Update/Upgrade

- Updating building models (3D FEA)
- Updating SSI models
- Developing Building FIRS
- Fragility evaluation preparation
- Updating/upgrading the SPRA model

Next Actions

- Determine Risk evaluation Prioritization (NRC)
- Obtain agreed upon Hazard (GMRS) to proceed with the SPRA (NRC)
- Complete Seismic Risk Assessment (PG&E)