Introduction to Strong Motion Seismology

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SSA/EERI Tutorial

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Probabilistic Methods

Deterministic Approach

- Select a small number of individual earthquake scenarios: M,R(Location) pairs
- Compute the ground motion for each scenario (typically use ground motion with 50% or 16% chance of being exceeded if the selected scenario earthquake occurs
- Select the largest ground motion from any of the scenarios

Probabilistic Approach

- Source Characterization
  - Develop a comprehensive set of possible scenario earthquakes: M, R(location)
  - Specify the rate at which each scenario earthquake (M,R) occurs
- Ground Motion Characterization
  - Develop a full range of possible ground motions for each earthquake scenario (ε=number of std dev above or below the median)
  - Specify the probability of each ground motion for each scenario

Probabilistic Approach (cont)

- Hazard Calculation
  - Rank scenarios (M,R, ε) in order of decreasing severity of shaking (Here, use Sa)
  - Result: Table of ranked scenarios with ground motions and rates
  - Sum up rates of scenarios with ground motion above a specified level (hazard curve)
- Select a ground motion for the design hazard level
  - Back off from worst case ground motion until either:
    - The ground motion is does not lead to excessive costs, <u>or</u>
    - The hazard level is not too small (e.g. not too rare) to ignore (e.g. the design hazard level)

PSHA Calculation

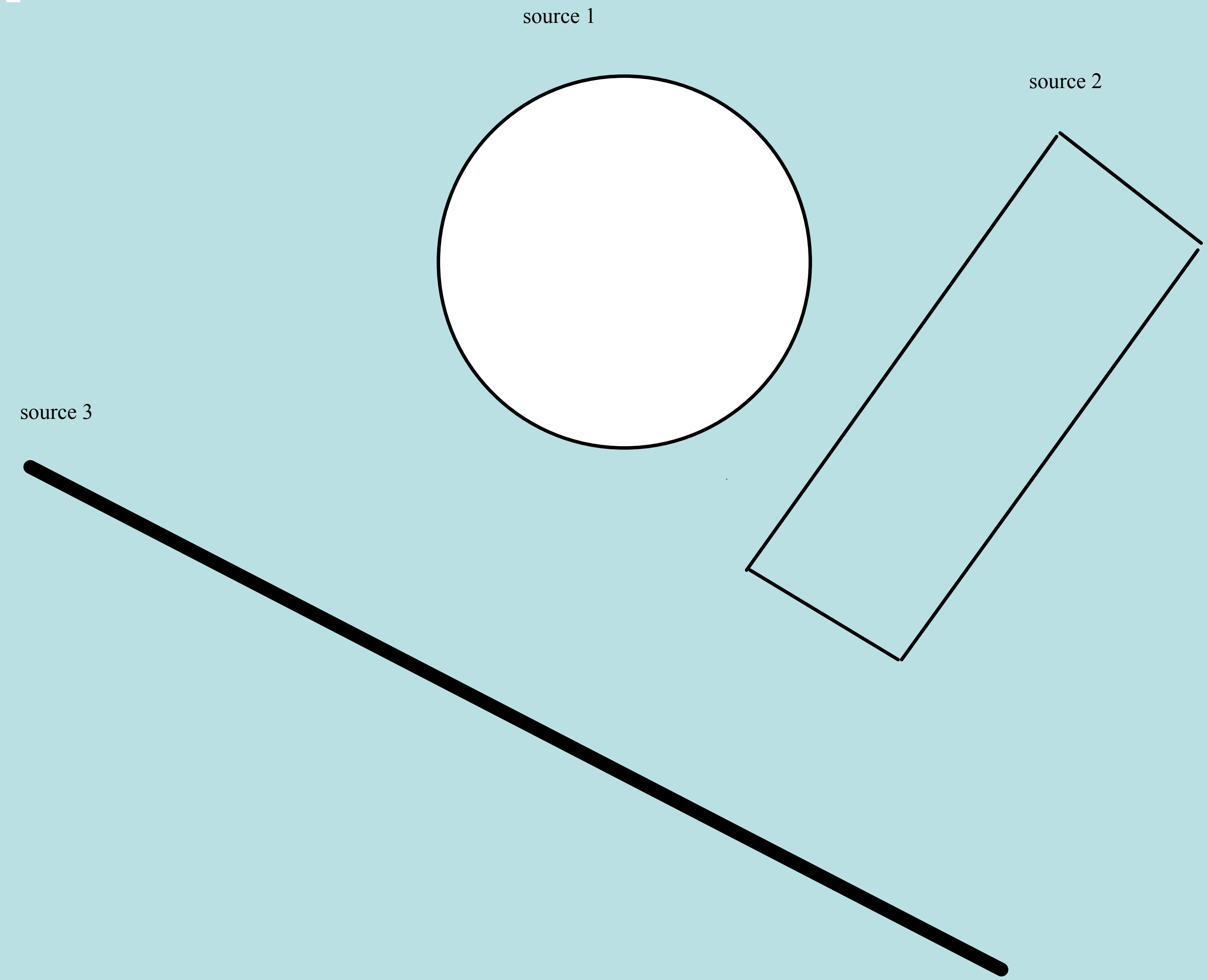
- Standard form of hazard

$$v(Sa > z) = \sum_{i=1}^{nSource} N_i(M_{\min}) \int_M \int_R f_{mi}(M)\, f_{Ri}(r,M)\, P(Sa > z \mid m,R)\, dR\, dM$$

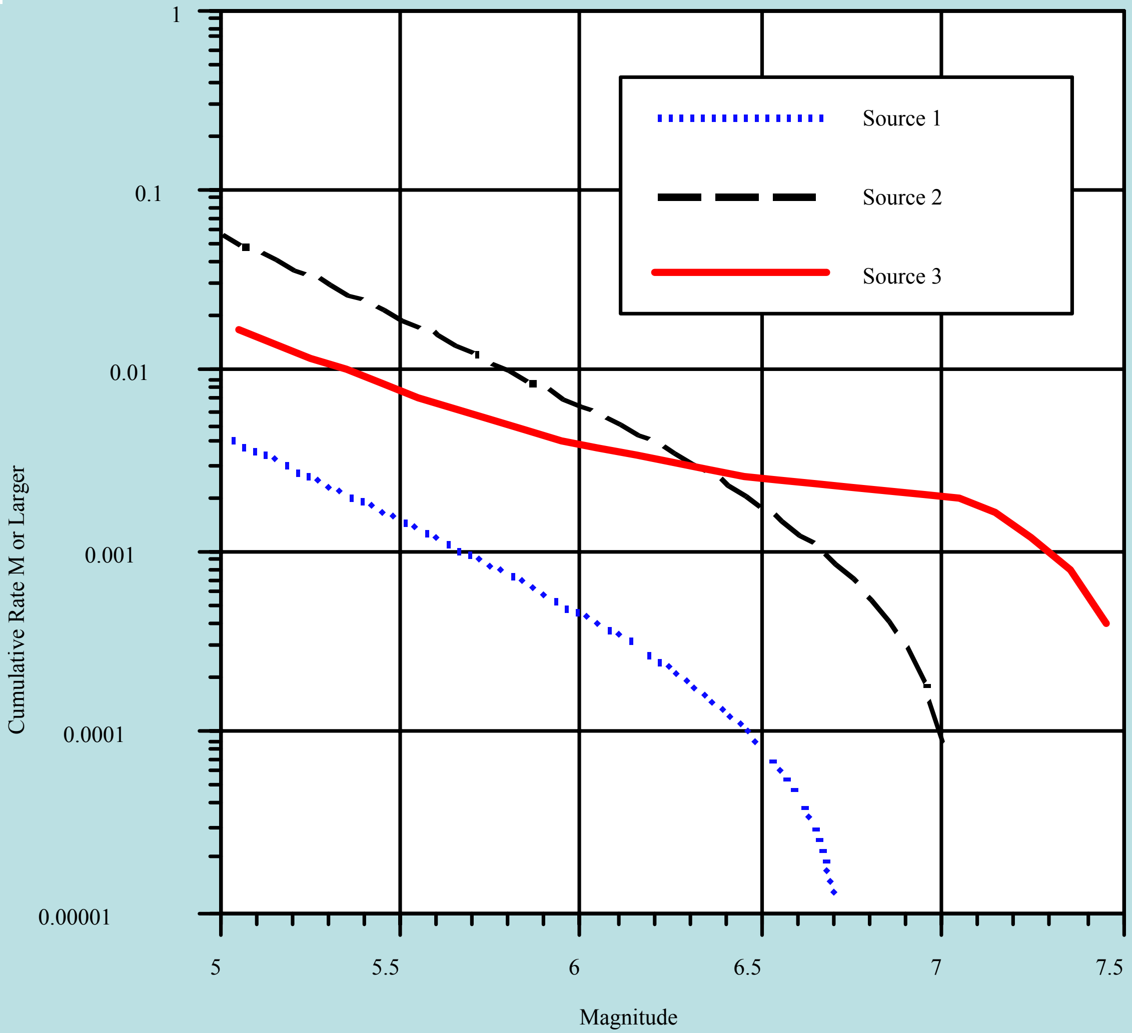
- Alternative form (explicit ground motion aleatory variability)

$$v(Sa > z) = \sum_{i=1}^{nSource} N_i(M_{\min}) \int_M \int_R \int_\varepsilon f_{mi}(M)\, f_{Ri}(r,M)\, f_\varepsilon(\varepsilon) P(Sa > z \mid m,R,\varepsilon)\, d\varepsilon\, dR\, dM$$

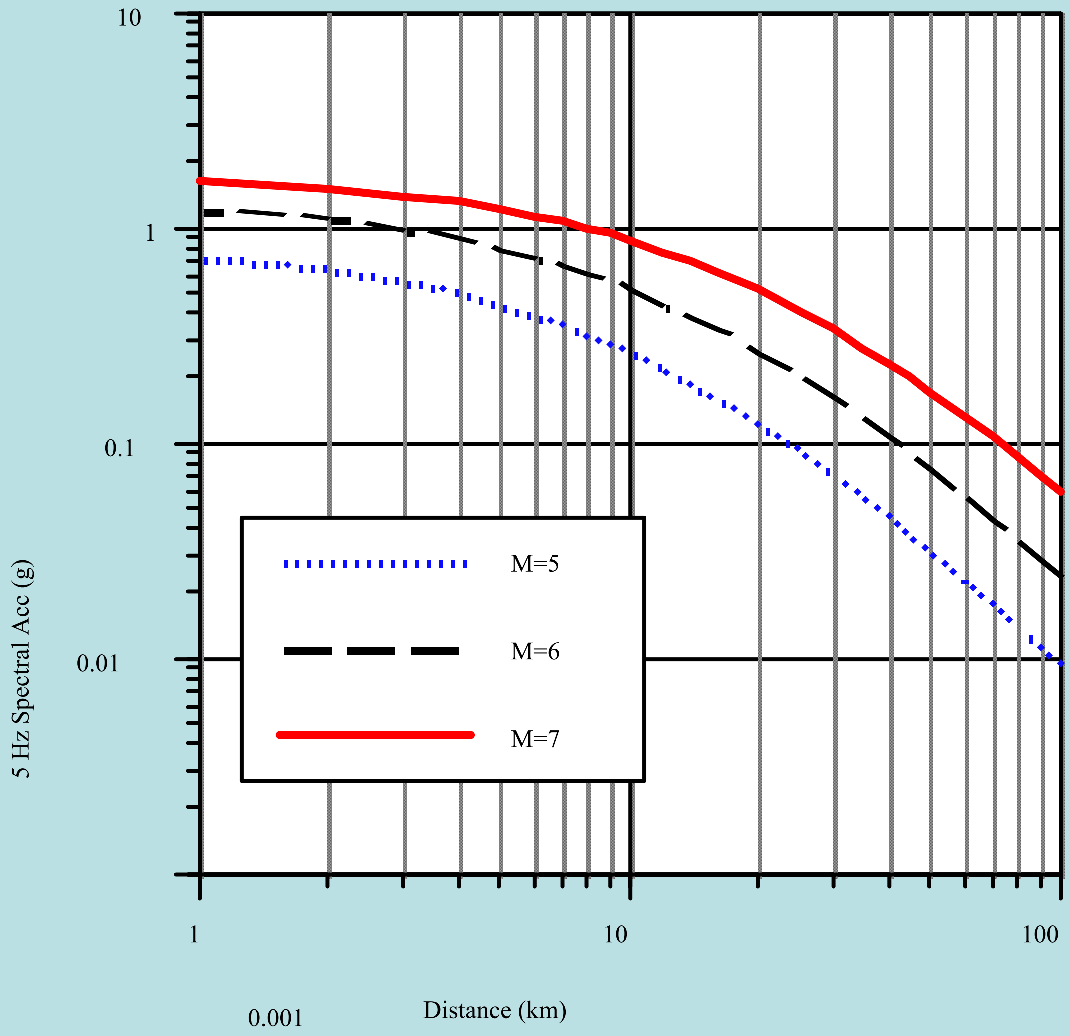
Example Sources



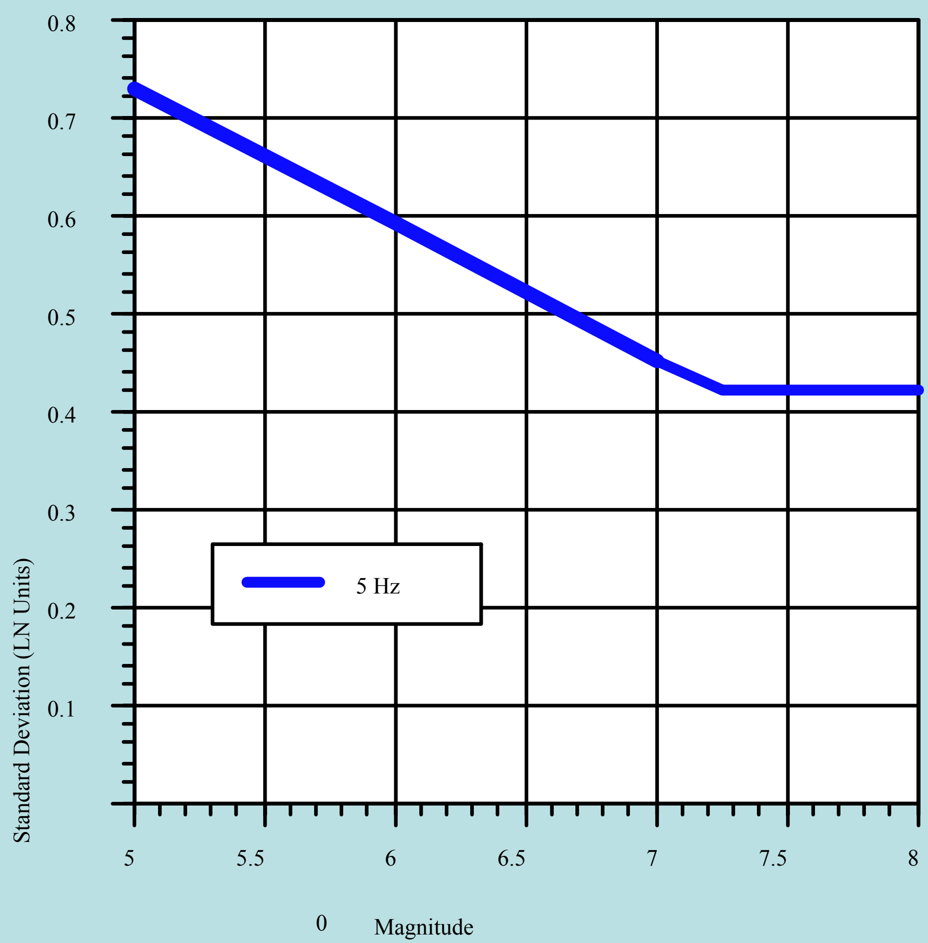
Example Source Characterization



Median Ground Motion



Standard Deviation of Ground Motion



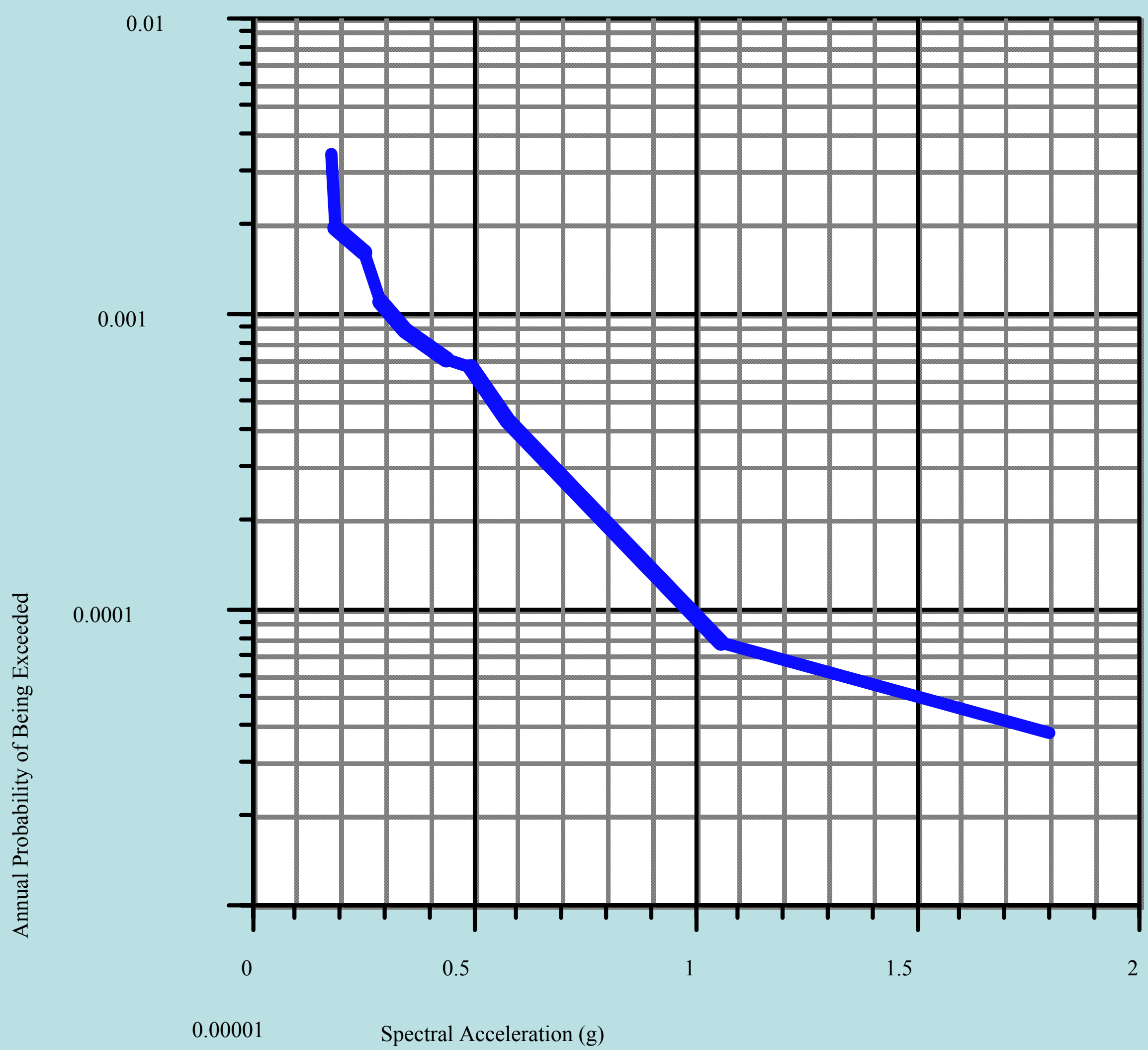
Partial List of Scenarios

Source	Mag	R (km)	Rate of Sa	Median Sa	Std Dev	ε	P(e)	Sa(g)	Rate
1	6.50	2	0.00022	1.38	0.53	0.5	0.175	1.80	0.000038
1	6.50	2	0.00022	1.38	0.53	-0.5	0.175	1.06	0.000038
1	5.00	2	0.00180	0.58	0.73	0.0	0.197	0.58	0.000355
1	5.00	10	0.00180	0.24	0.73	1.0	0.121	0.49	0.000218
2	5.50	40	0.02216	0.07	0.66	1.5	0.066	0.18	0.001453
2	6.00	40	0.00786	0.10	0.59	1.5	0.066	0.25	0.000516
2	6.50	40	0.00279	0.16	0.52	1.5	0.066	0.35	0.000183
3	7.25	60	0.00170	0.19	0.42	2.0	0.028	0.44	0.000047
3	7.25	60	0.00170	0.19	0.42	1.0	0.121	0.29	0.000206
3	7.25	60	0.00170	0.19	0.42	0.0	0.197	0.19	0.000336

Rank Scenarios by Ground Motion

Source	Mag	R (km)	ε	Sa(g)	Rate	Hazard
1	6.50	2	0.5	1.80	0.000038	0.000038
1	6.50	2	-0.5	1.06	0.000038	0.000076
1	5.00	10	0.0	0.58	0.000355	0.000432
3	7.25	60	1.0	0.49	0.000218	0.000649
2	6.50	40	1.5	0.44	0.000047	0.000697
3	7.25	60	1.5	0.35	0.000183	0.000880
1	5.00	2	1.5	0.29	0.000206	0.001085
2	6.00	40	2.0	0.25	0.000516	0.001601
3	7.25	60	1.0	0.19	0.000336	0.001937
2	5.50	40	0.0	0.18	0.001453	0.003390

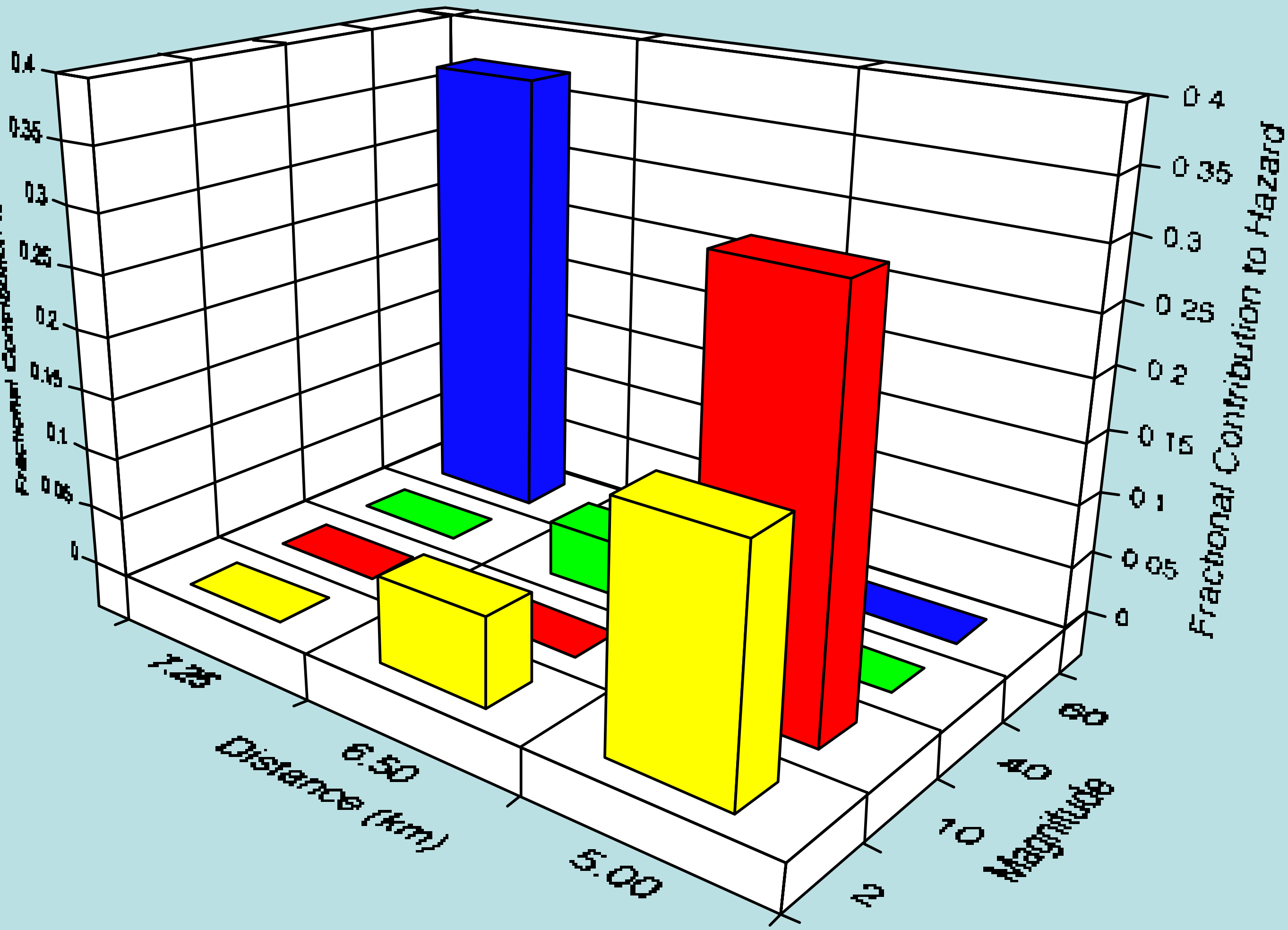
Hazard Curve



Deaggregation at 10^{-3} Hazard

Source	Mag	R (km)	ε	Sa(g)	Rate	Hazard	Deagg
1	6.50	2	0.5	1.80	0.000038	0.000038	0.035
1	6.50	2	-0.5	1.06	0.000038	0.000076	0.035
1	5.00	10	0.0	0.58	0.000355	0.000432	0.327
3	7.25	60	1.0	0.49	0.000218	0.000649	0.201
2	6.50	40	1.5	0.44	0.000047	0.000697	0.044
3	7.25	60	1.5	0.35	0.000183	0.000880	0.169
1	5.00	2	1.5	0.29	0.000206	0.001085	0.190
2	6.00	40	2.0	0.25	0.000516	0.001601	
3	7.25	60	1.0	0.19	0.000336	0.001937	
2	5.50	40	0.0	0.18	0.001453	0.003390	

Group Similar Scenarios for Deaggregation Plots



Aleatory Variability and Epistemic Uncertainty

- Scientific Uncertainty (epistemic)
  - Due to lack of information
  - Incorporated in PSHA using logic trees (leads to alternative hazard curves)
  - Impacts the mean hazard
- Random Variability (aleatory)
  - Randomness in M, location, ground motion (ε)
  - Incorporated in hazard calculation directly

Epistemic Uncertainty

- Due to lack of data
  - Sparse data implies large uncertainty

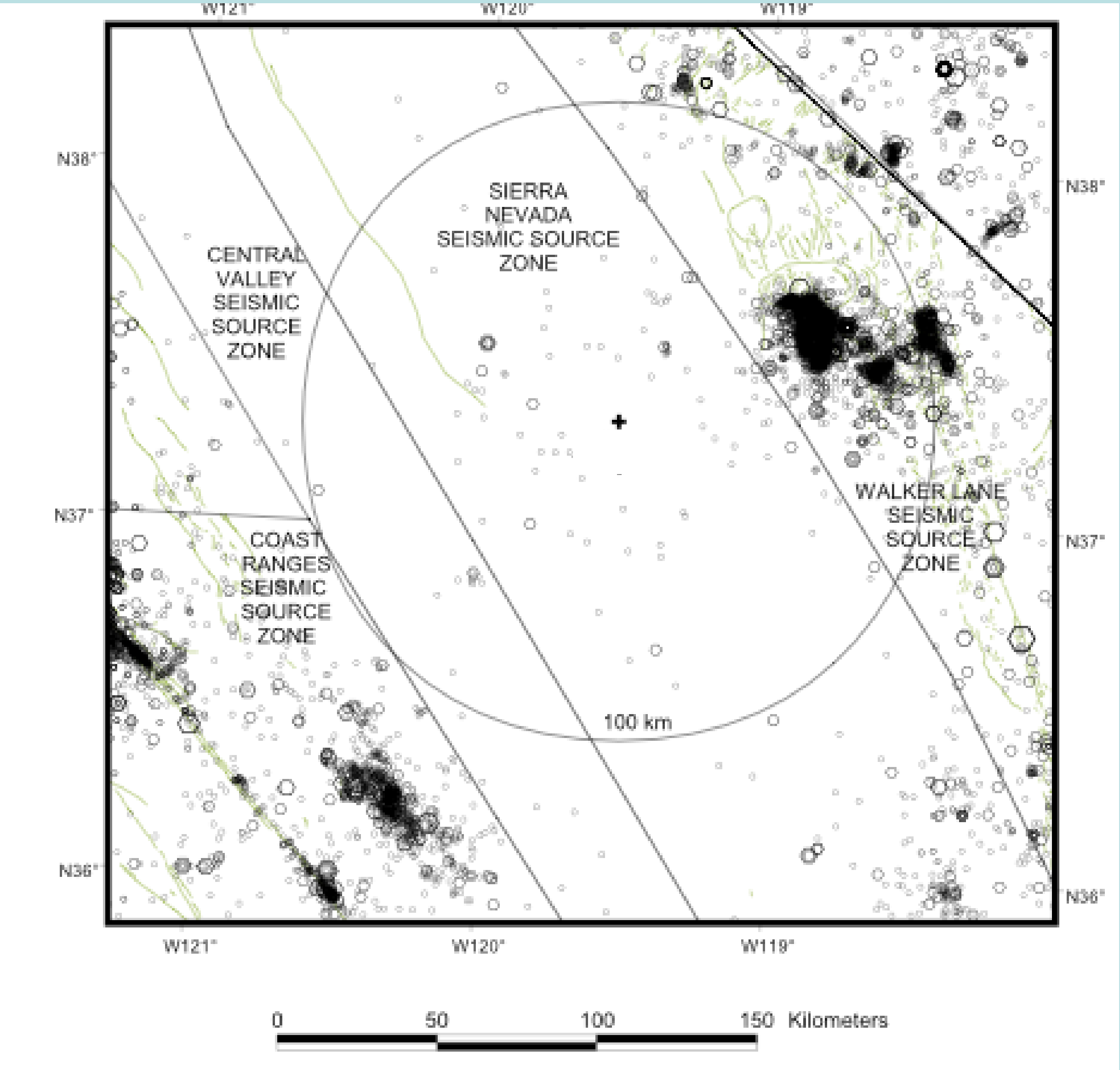
- In practice, not always the case

  Estimated using alternative available models/data
  - Few available studies leads to small uncertainty (few alternatives available)
  - Many available studies leads to larger uncertainty (more alternatives available)

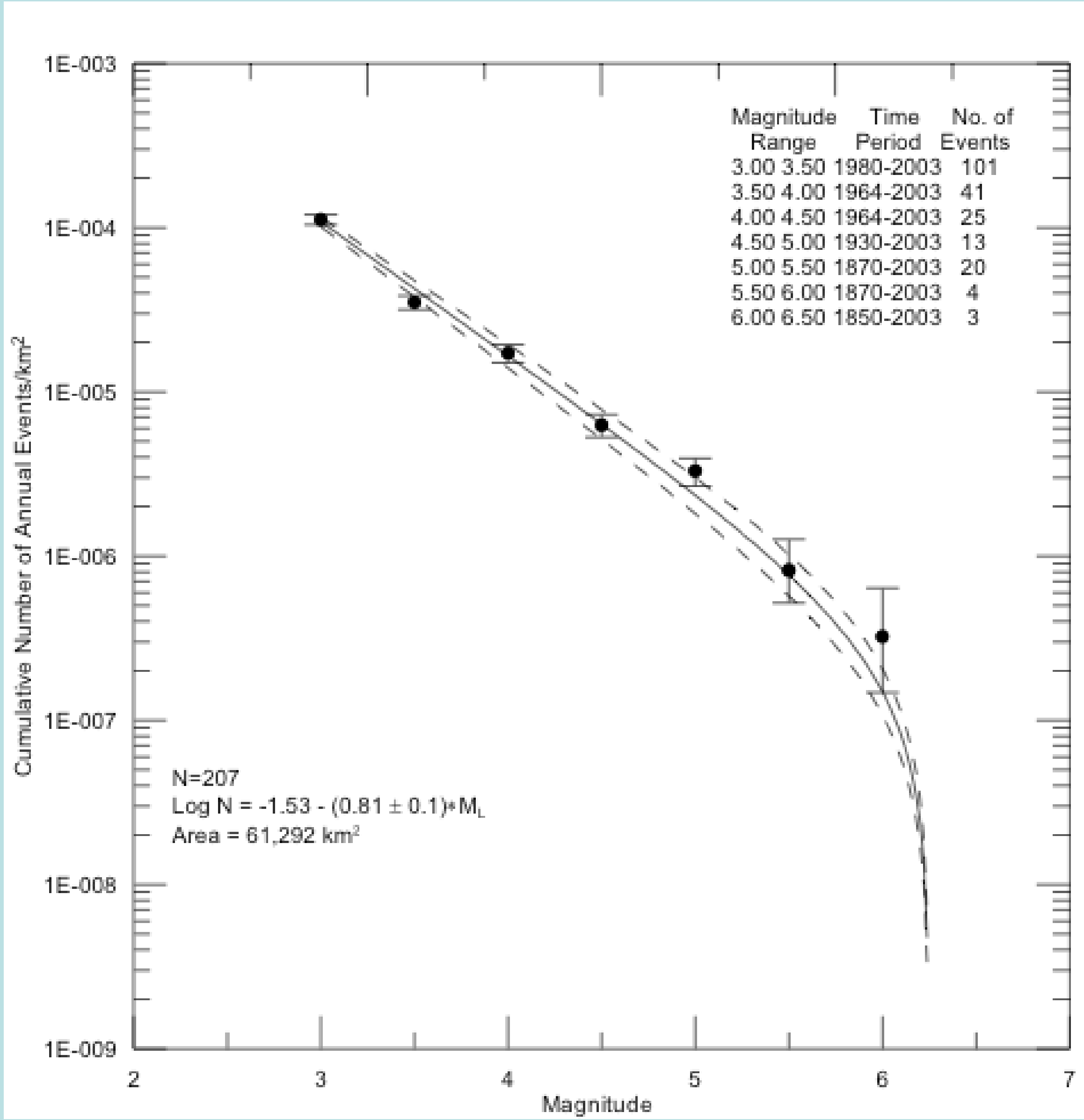
Common Misunderstandings in PSHA

- PSHA combines ground motions from different earthquakes
  - No, PSHA <u>ranks</u> ground motions from different earthquakes, it does not combine ground motions
    - UHS does combine ground motions, but not required in PHSA
  - PSHA combines the chance of getting a specified level of ground motion from different earthquakes
    - - There is more than one earthquake that can lead to a specified ground motion at the site
- PSHA does not give earthquake scenarios
  - Deaggregation provides descriptions of scenarios

Example Hazard



Background Rate



Fault Sources

- Mean Characteristic Magnitude
  - M = log(fault area) + 4
- Usually balance moment-rate on fault
  - $M_o(M) = 10^{1.5M+16.05}$
  - Moment-rate = μAS

    μ = shear modulus (3E11 dyne/cm^2)

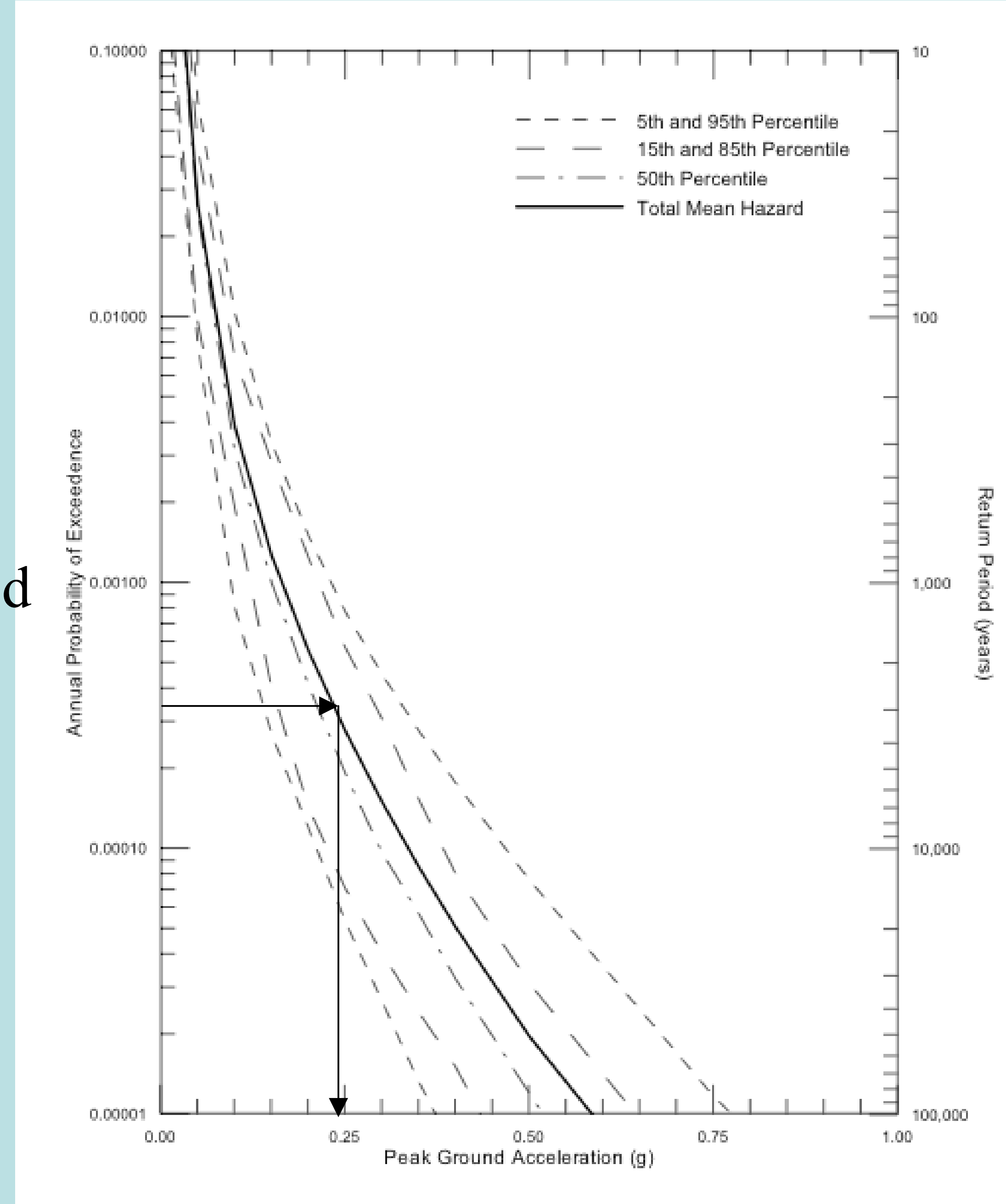
    A = fault area in cm^2

    S = slip-rate in cm/yr

$$Eqk\,rate = \frac{Moment\ Rate}{Moment\,/\,Eqk}$$

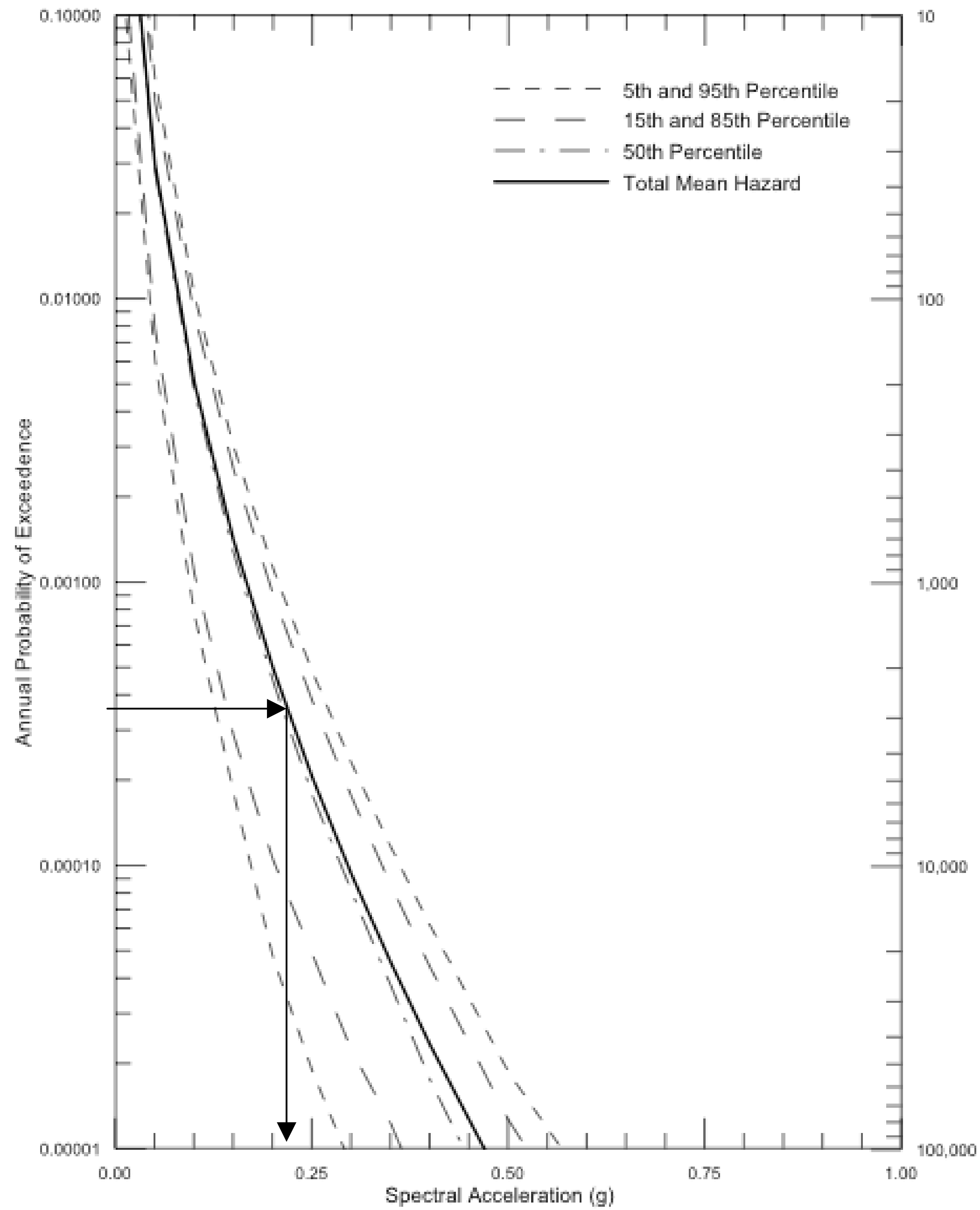
PGA Hazard

3000 yr return period
PGA = 0.24g

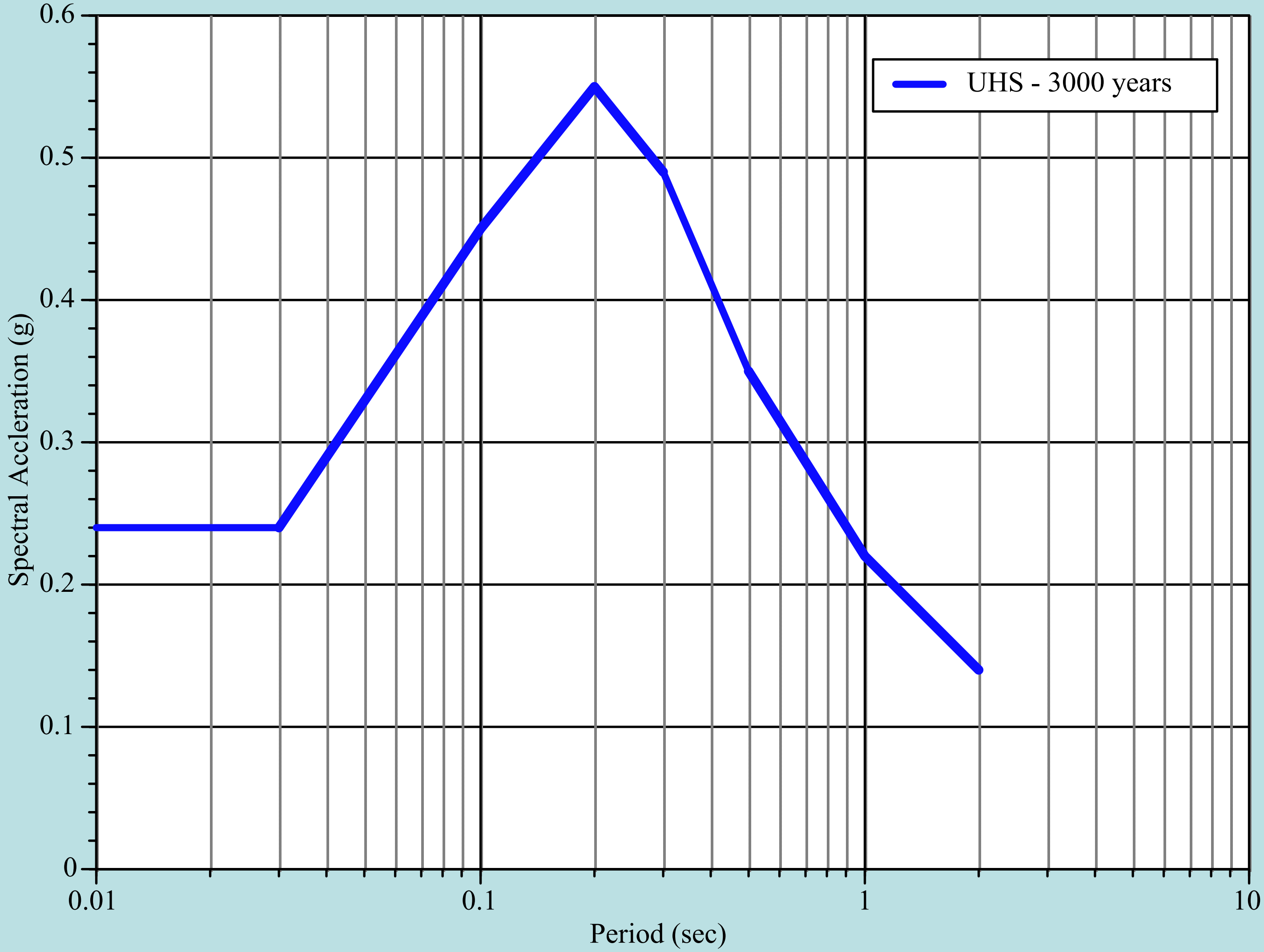


T=1 sec Hazard

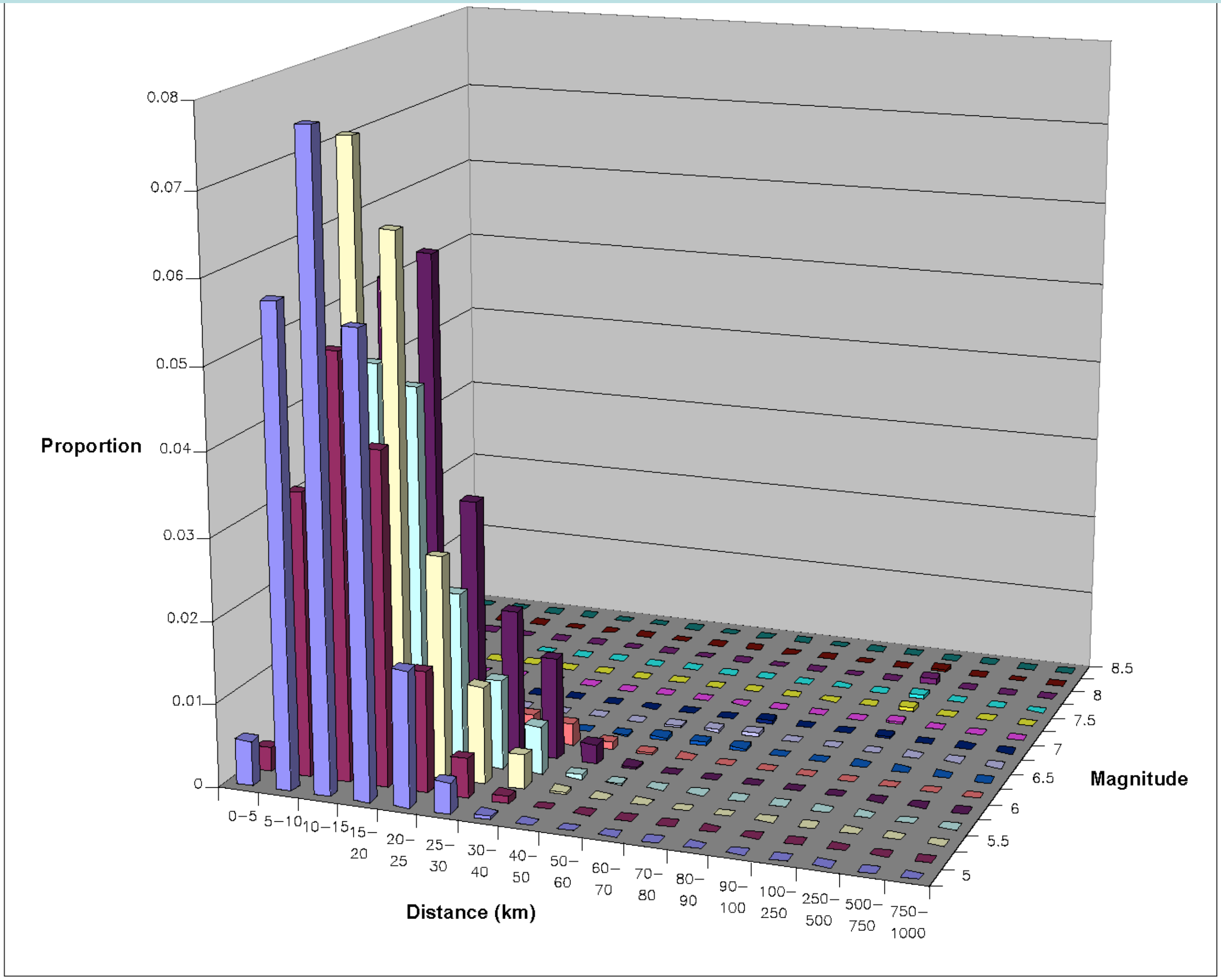
3000 yr return period
Sa(T=1) = 0.22g



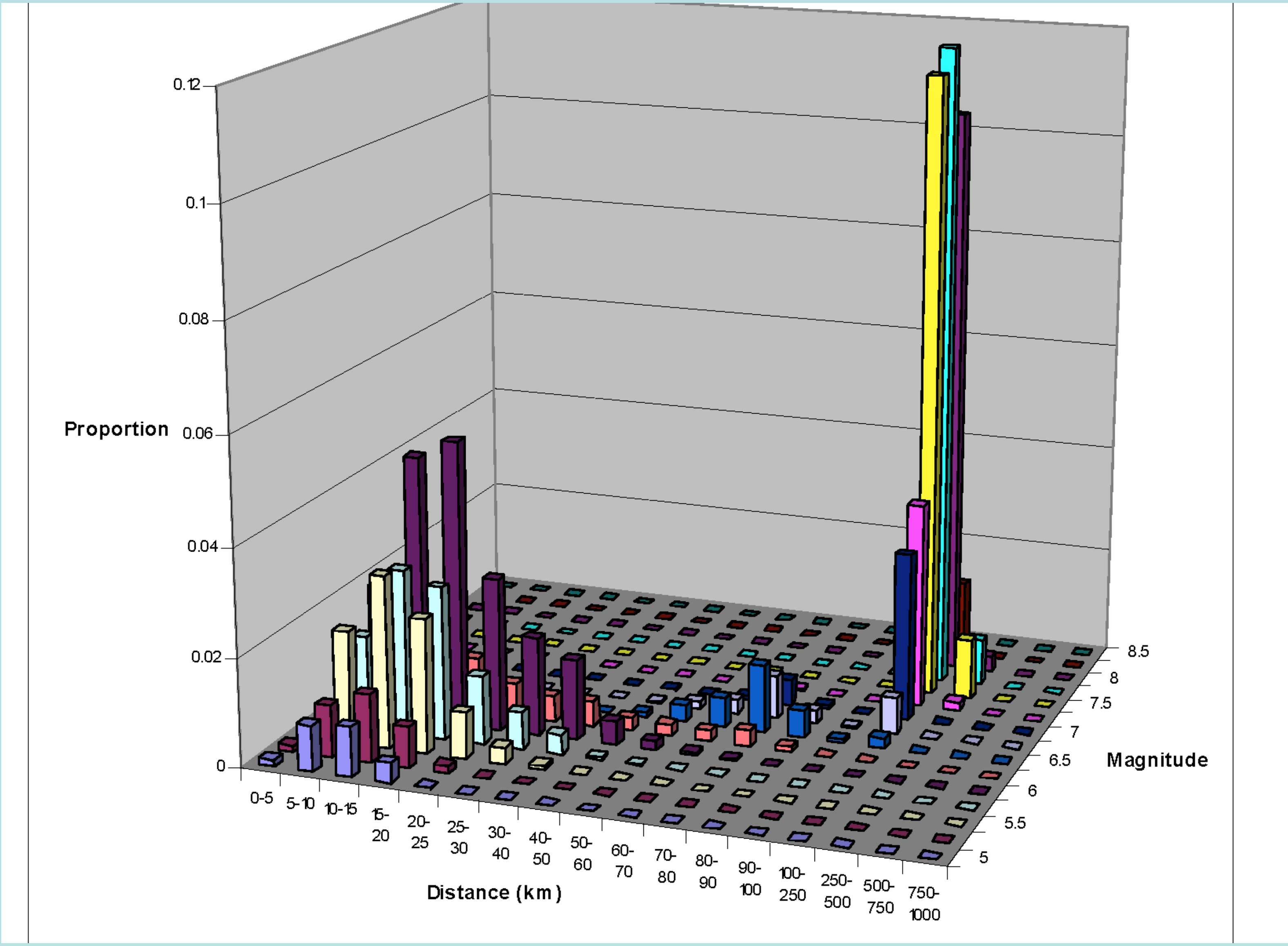
Uniform Hazard Spectrum



Deaggregation for PGA=0.24g



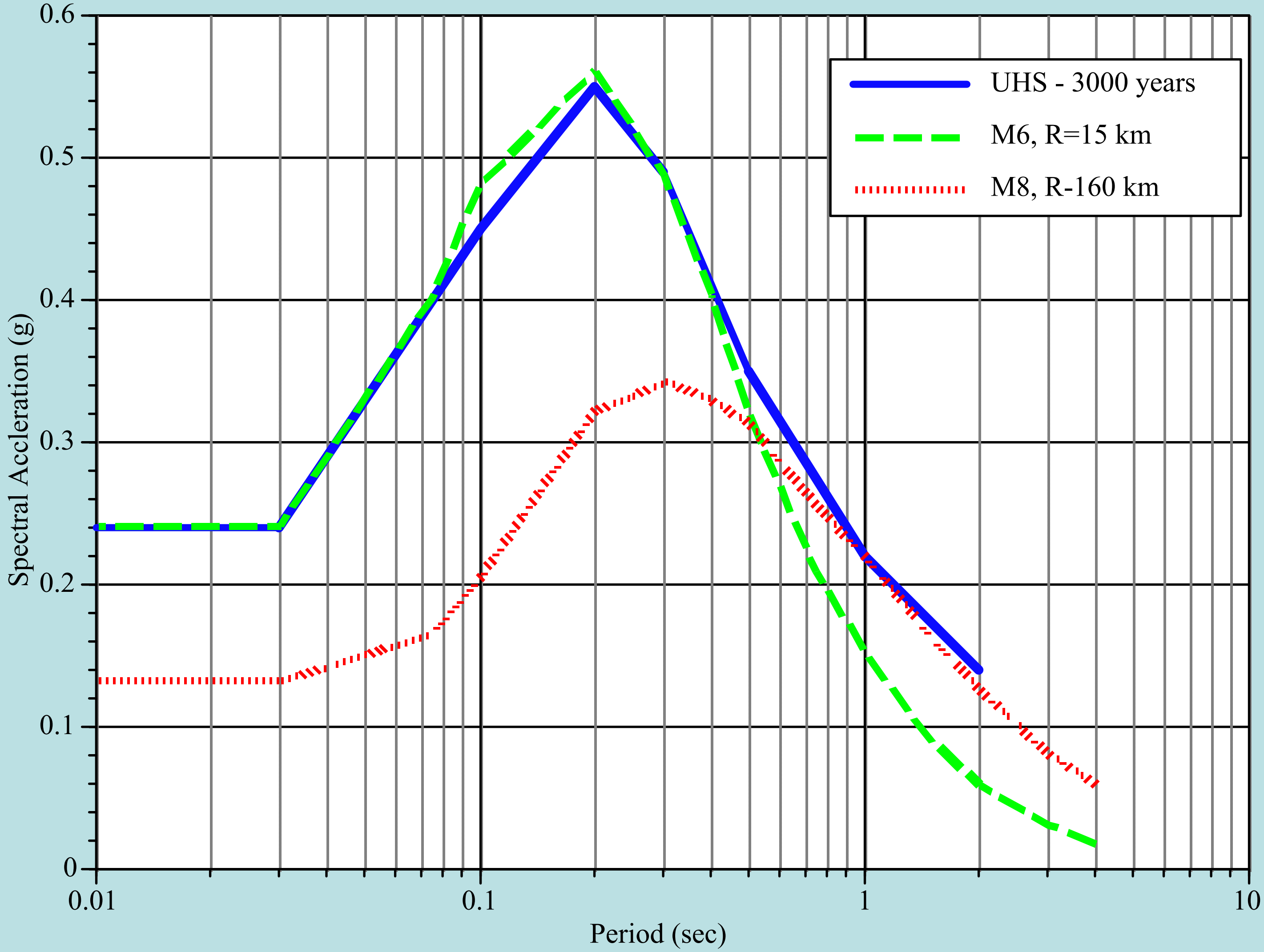
Deaggregation for Sa(T=1)=0.22g



Controlling Scenarios

- For 3000 years:
  - PGA: M=6.0, R=15 km
  - Sa(T=1): M=8.0, R=160 km

UHS Scenarios



UHS

- Hazard reports should provide spectra for scenarios that control the UHS
- UHS envelopes the alternative scenarios
  - used to reduce engineering analysis costs by reducing number of scenarios to consider, it is not required in PSHA
- Decision to use UHS or individual scenarios should be made by engineers involved in the analysis of structure, not by hazard analyst

Rate of Occurrence

- Hazard curve gives rate of exceeding a ground motion
- Hazard reports should also provide a table with the rate of occurrence:

$$\nu(a_1 > Sa > a_2) = Haz(a_1) - Haz(a_2)$$

Rate of Occurrence - by Mag-Dist-GM

Rate of Occurrence for a specific magnitude, distance and ground motion range is given by:

$$
\begin{aligned}
v(M_1 < M < M_2, R_1 < R < R_2, A_1, Sa < A_2) = \\
& Haz(A_1) Deag(M_1 < M < M_2, R_1 < R < R_2, A_1) \\
- \quad & Haz(A_2) Deag(M_1 < M < M_2, R_1 < R < R_2, A_2)
\end{aligned}
$$

This provides information needed for risk calculations

Ground Motion Prediction Equations

(Attenuation Relationships)

Ground Motion Regions

- Three main tectonic categories
  - Shallow crustal earthquakes in active tectonic regions
  - Shallow crustal earthquakes in stable continental regions
  - Subduction earthquakes
    - Interface
    - Intraslab

Ground Motion Models

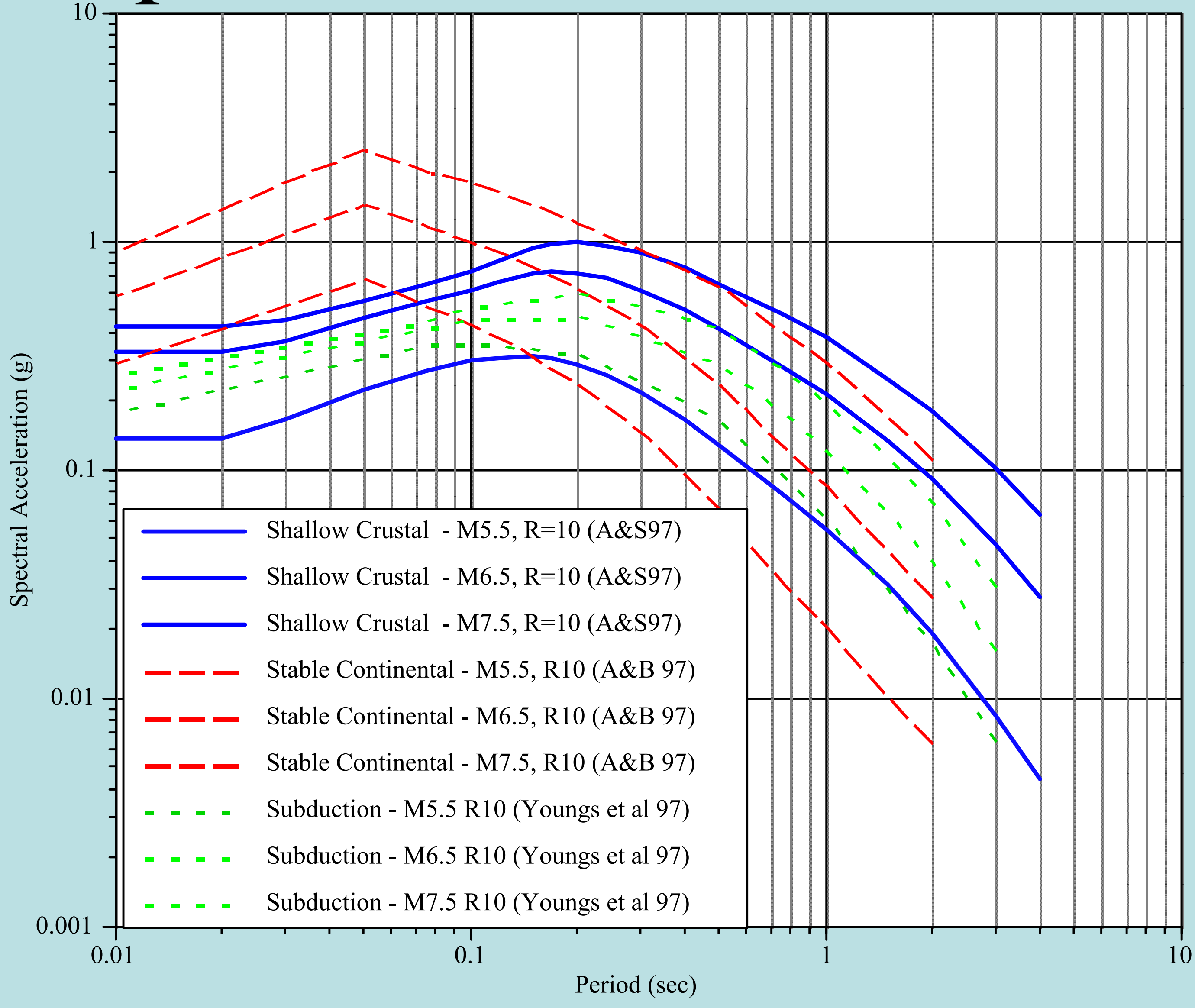
Shallow crustal earthquakes in stable continental regions

- Subduction earthquakes
  - Interface
  - Intraslab

Ground Motion Models

- Shallow Crustal in Active Regions
  - Primarily empirically based models
- Shallow Crustal in Stable Continental Regions
  - Seismological simulations
    - Point source stochastic model
- Subduction
  - Primarily empirically based models
  - Some simulations for very large magnitudes (M9)

Example of Tectonic Differences



Numerical Simulations

- Separate Effects
  - Source
  - Path
  - Site
- Low frequencies (f < 1 Hz)
  - Theoretical seismological models work well
- High frequencies (f>1 Hz)
  - A stochastic or empirical element is required

Point Source Stochastic Model

- Source Parameters

  M Moment magnitude

  $\Delta\sigma$ Stress-drop

- Path Parameters

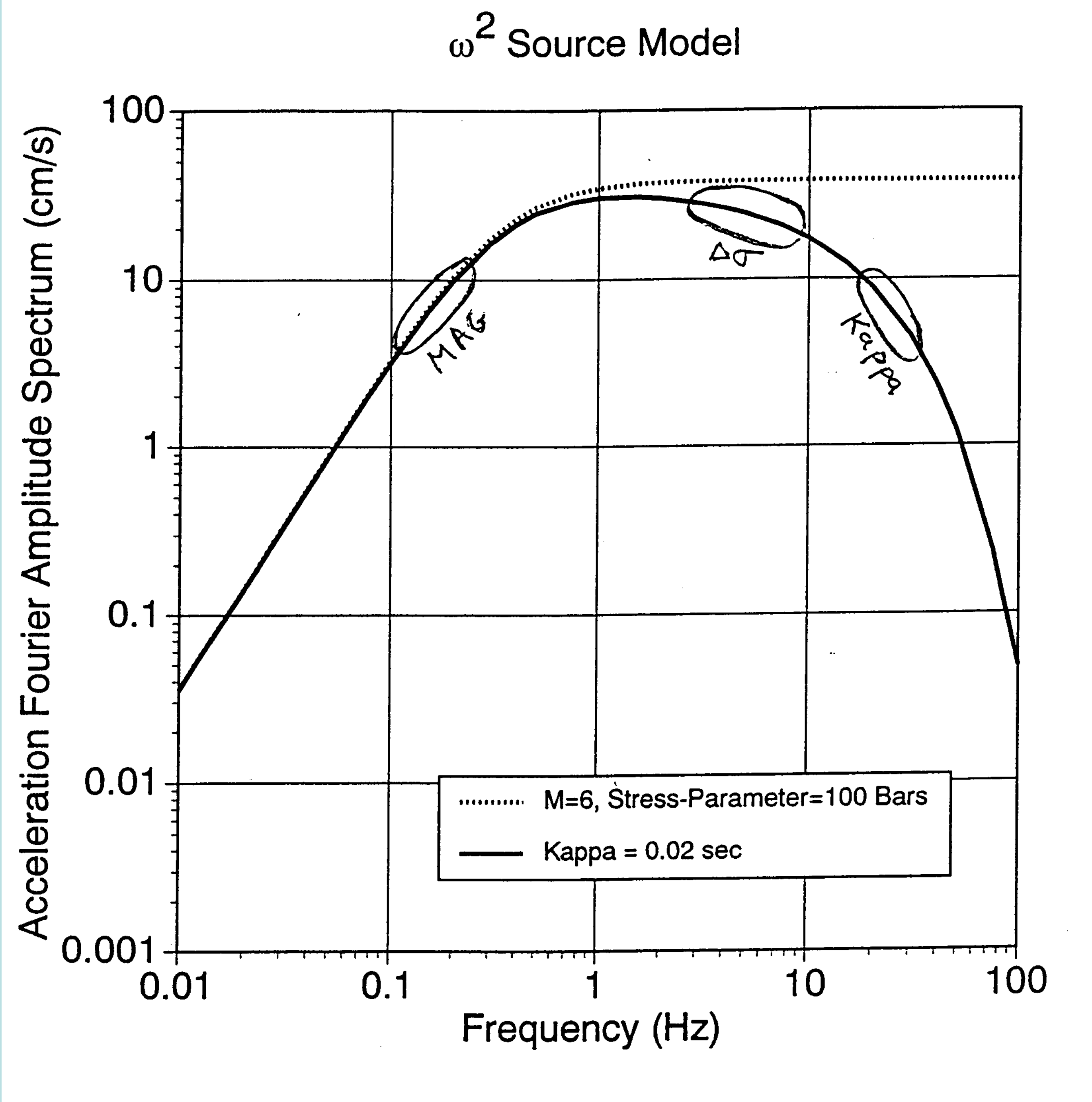
  N Geometical spreading coefficient

  Q(f) Anelastic attenuation along ray path

- Site Parameters

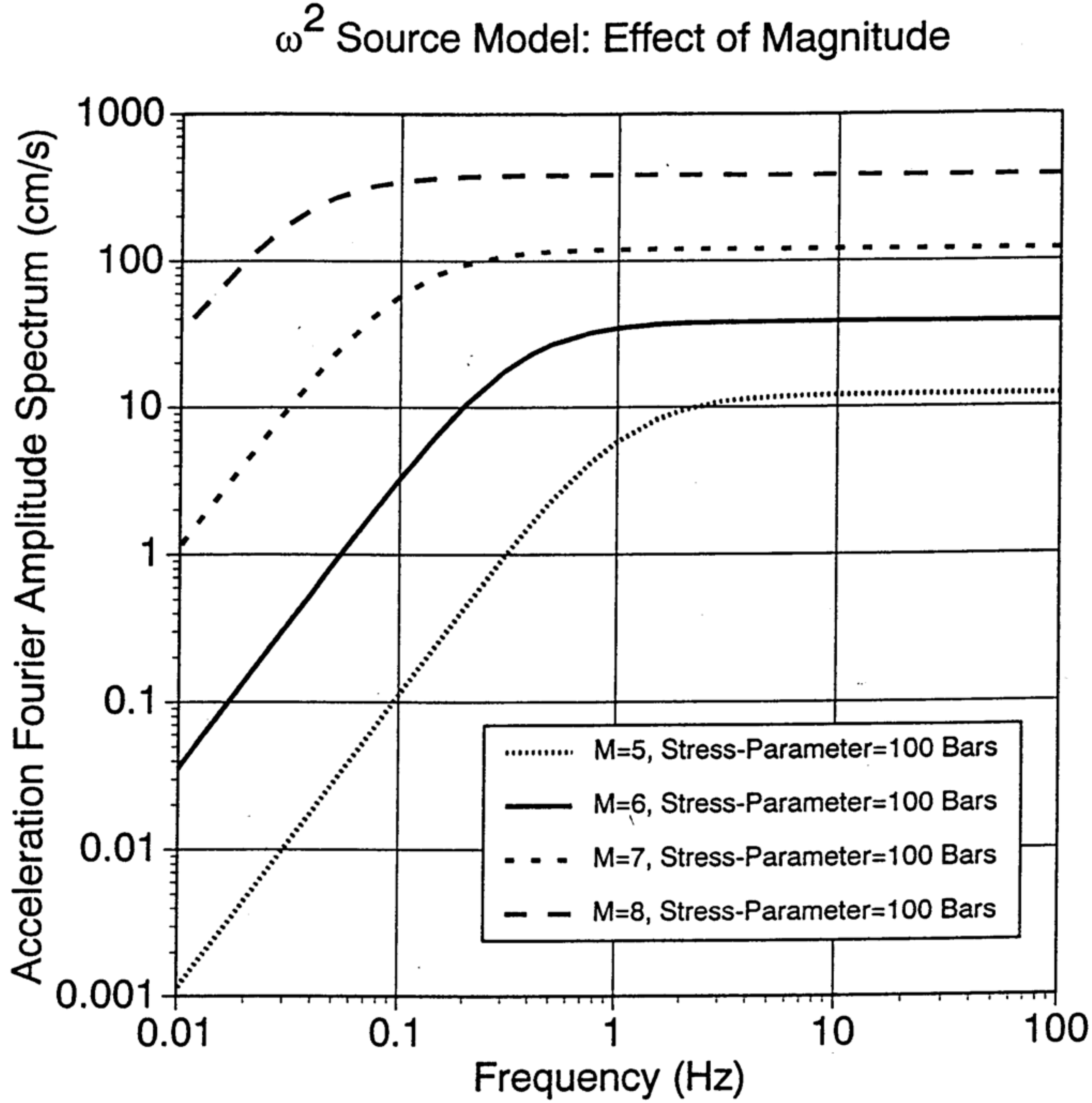
  κ Accounts for damping in shallow rock

  A(f) Amplification factor for the impedance contrast from source to site

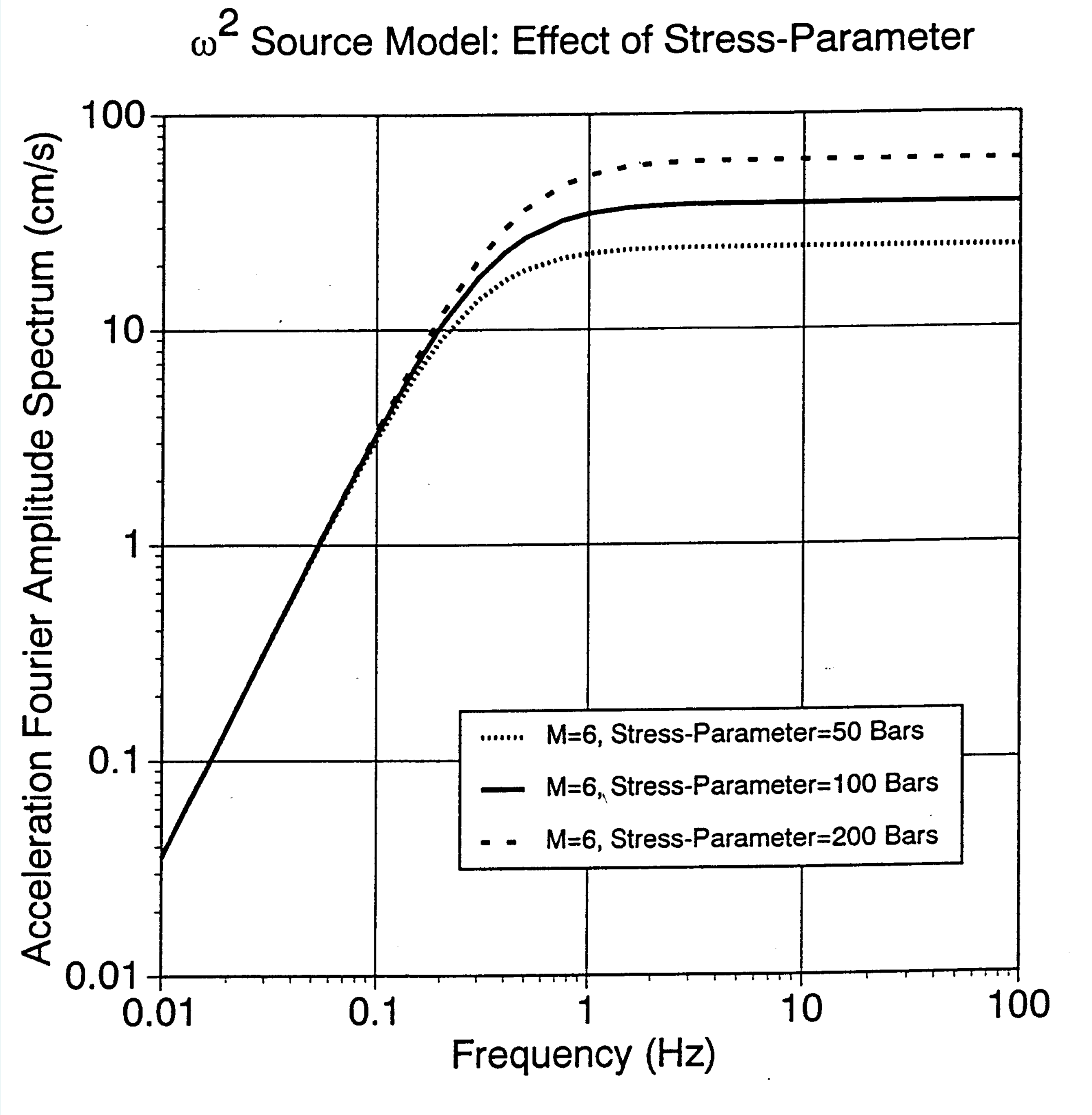

ω2 Source Model
Acceleration Fourier Amplitude Spectrum (cm/s)
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
Frequency (Hz)
MAG
Δσ
Kappa
M=6, Stress-Parameter=100 Bars
Kappa = 0.02 sec

Source Parameters

- Moment Magnitude
  - Measures total energy in earthquake
- Stress-drop
  - Measures the compactness of the source in space and/or time
  - High stress-drop leads to larger high frequency ground motions



ω2 Source Model: Effect of Magnitude
Acceleration Fourier Amplitude Spectrum (cm/s)
1000
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
Frequency (Hz)
M=5, Stress-Parameter=100 Bars
M=6, Stress-Parameter=100 Bars
M=7, Stress-Parameter=100 Bars
M=8, Stress-Parameter=100 Bars

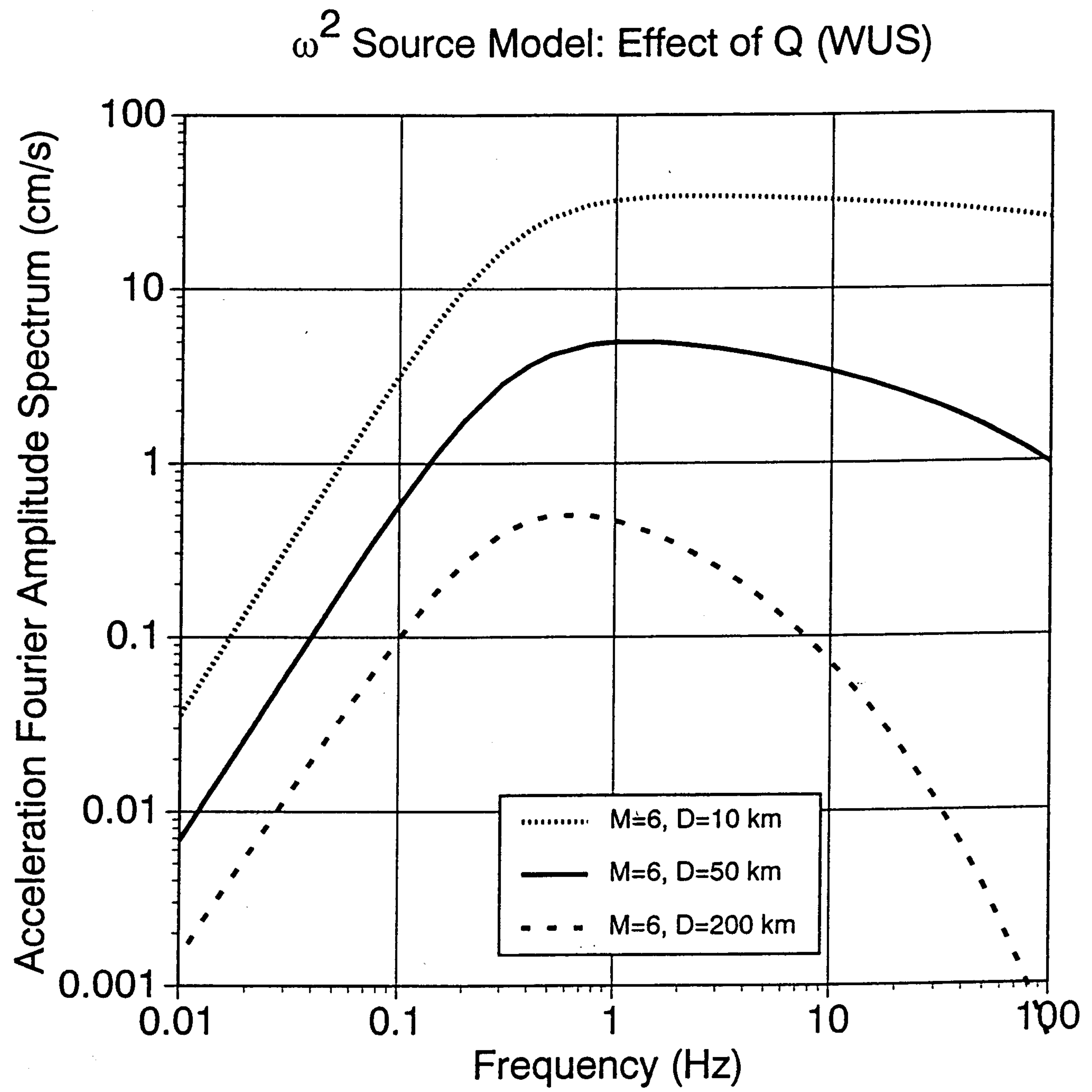


ω² Source Model: Effect of Stress-Parameter
Acceleration Fourier Amplitude Spectrum (cm/s)
100
10
1
0.1
0.01
0.01
0.1
1
10
100
Frequency (Hz)
M=6, Stress-Parameter=50 Bars
M=6, Stress-Parameter=100 Bars
M=6, Stress-Parameter=200 Bars

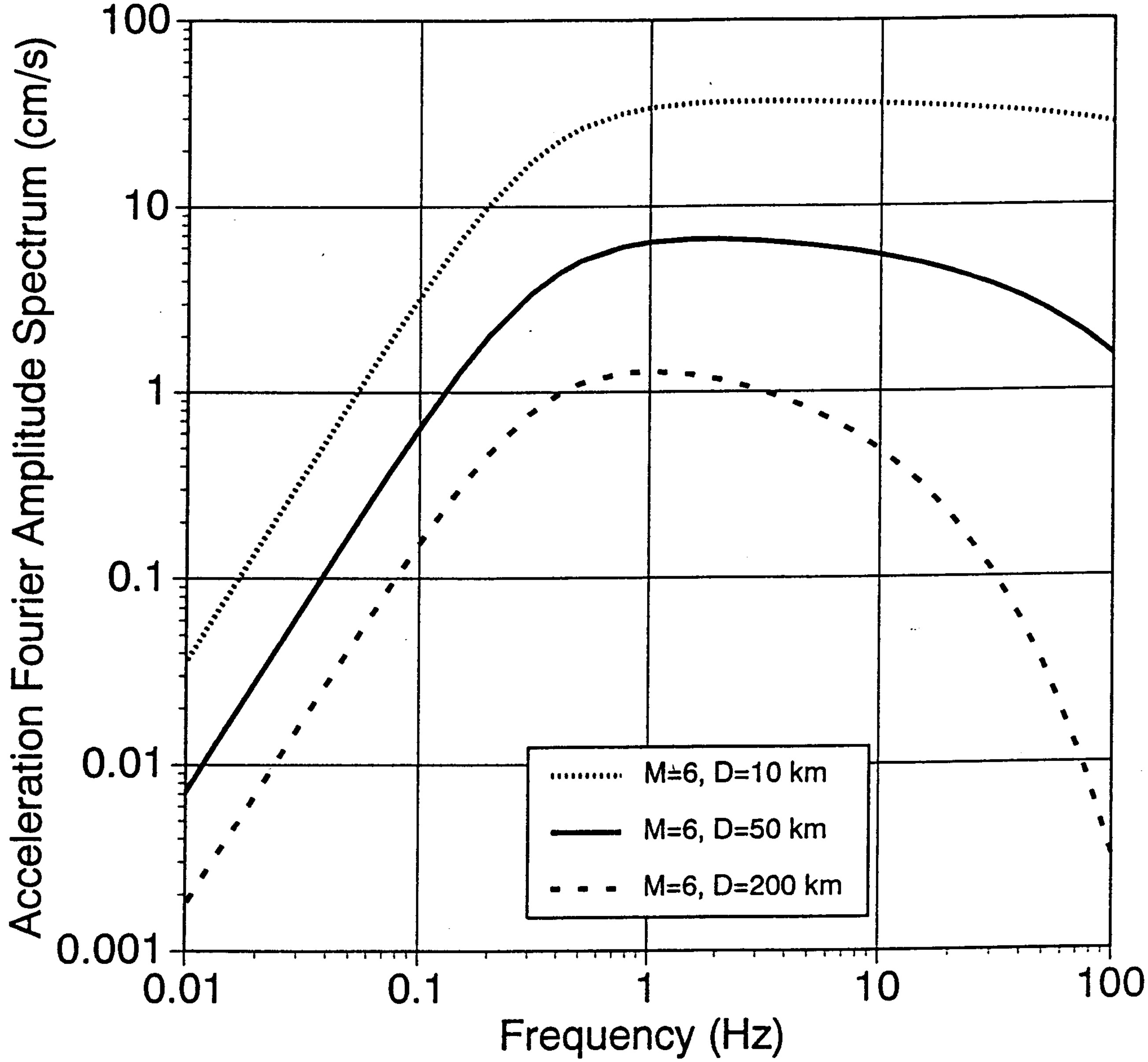
Path Parameters

$$R^{-N} \exp\left(\frac{-\pi f R}{V_S Q(f)}\right)$$

- Geometrical Spreading (N)
  - Describes distance attenuation from a point source
- Q
  - In practice, Q accounts for all source of attenuation not modeled by the geometrical speading
  - Q model must be consistent with geometrical spreading model


ω² Source Model: Effect of Q (WUS)
Acceleration Fourier Amplitude Spectrum (cm/s)
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
Frequency (Hz)
M=6, D=10 km
M=6, D=50 km
M=6, D=200 km

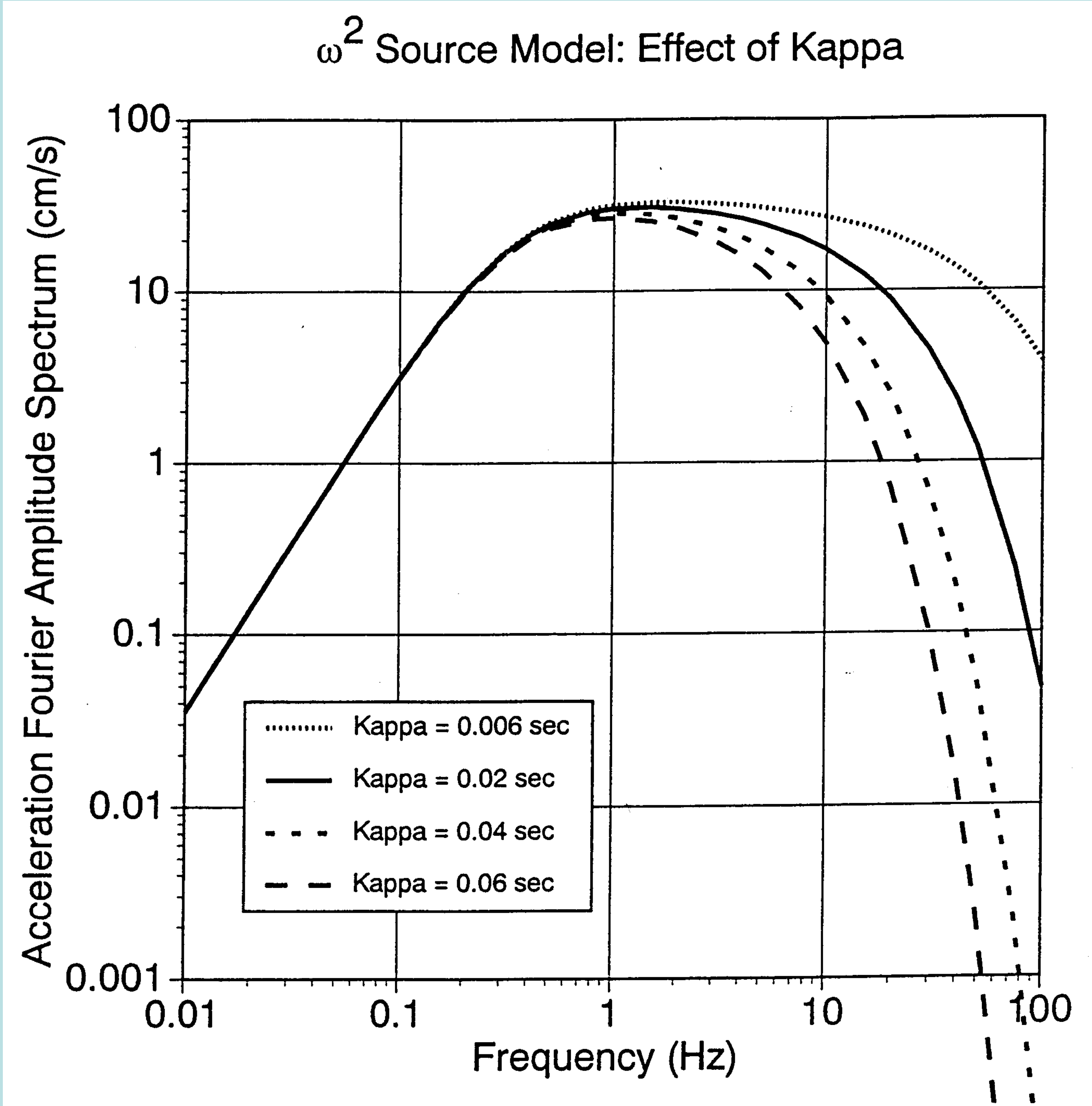
ω^2 Source Model: Effect of Q (EUS)



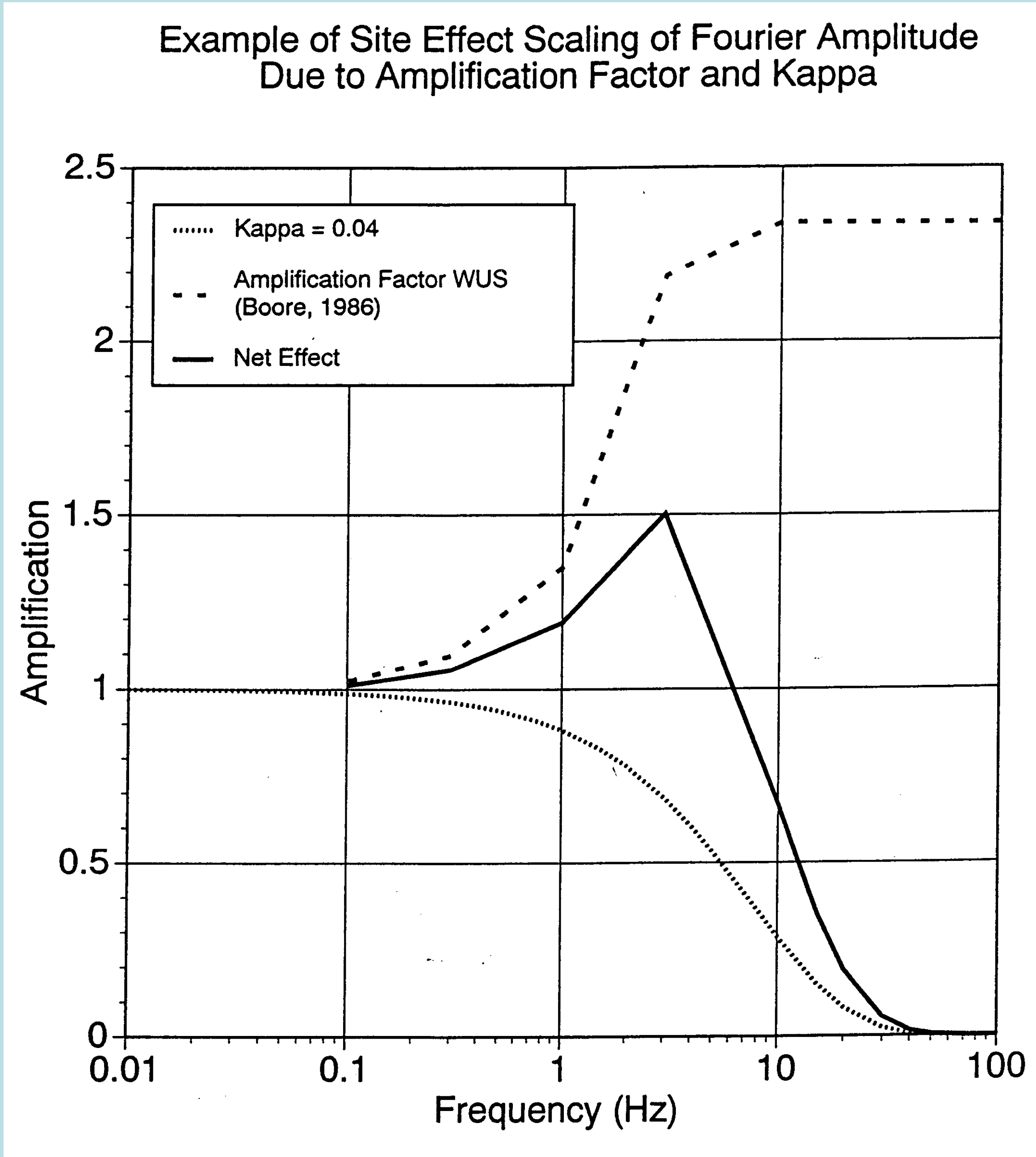
(rock) Site Parameters

$$A(f)\exp(-\pi\kappa f)$$

- A(f)
  - Accounts for amplification due to impedance contrast in crust
- Kappa
  - Accounts for attenuation of the high frequency (related to material damping in the shallow crustal rock)
  - In practice, accounts for high frequency differences between point source model and observations
    - May be due to source effects as well as site effects
  - Same effect also modeled by f_{max}



ω² Source Model: Effect of Kappa
Acceleration Fourier Amplitude Spectrum (cm/s)
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
Frequency (Hz)
Kappa = 0.006 sec
Kappa = 0.02 sec
Kappa = 0.04 sec
Kappa = 0.06 sec



Example of Site Effect Scaling of Fourier Amplitude
Due to Amplification Factor and Kappa
Kappa = 0.04
Amplification Factor WUS
(Boore, 1986)
Net Effect
Amplification
2.5
2
1.5
1
0.5
0
0.01
0.1
1
10
100
Frequency (Hz)

Shallow Crustal Earthquakes in Active Tectonic Regions

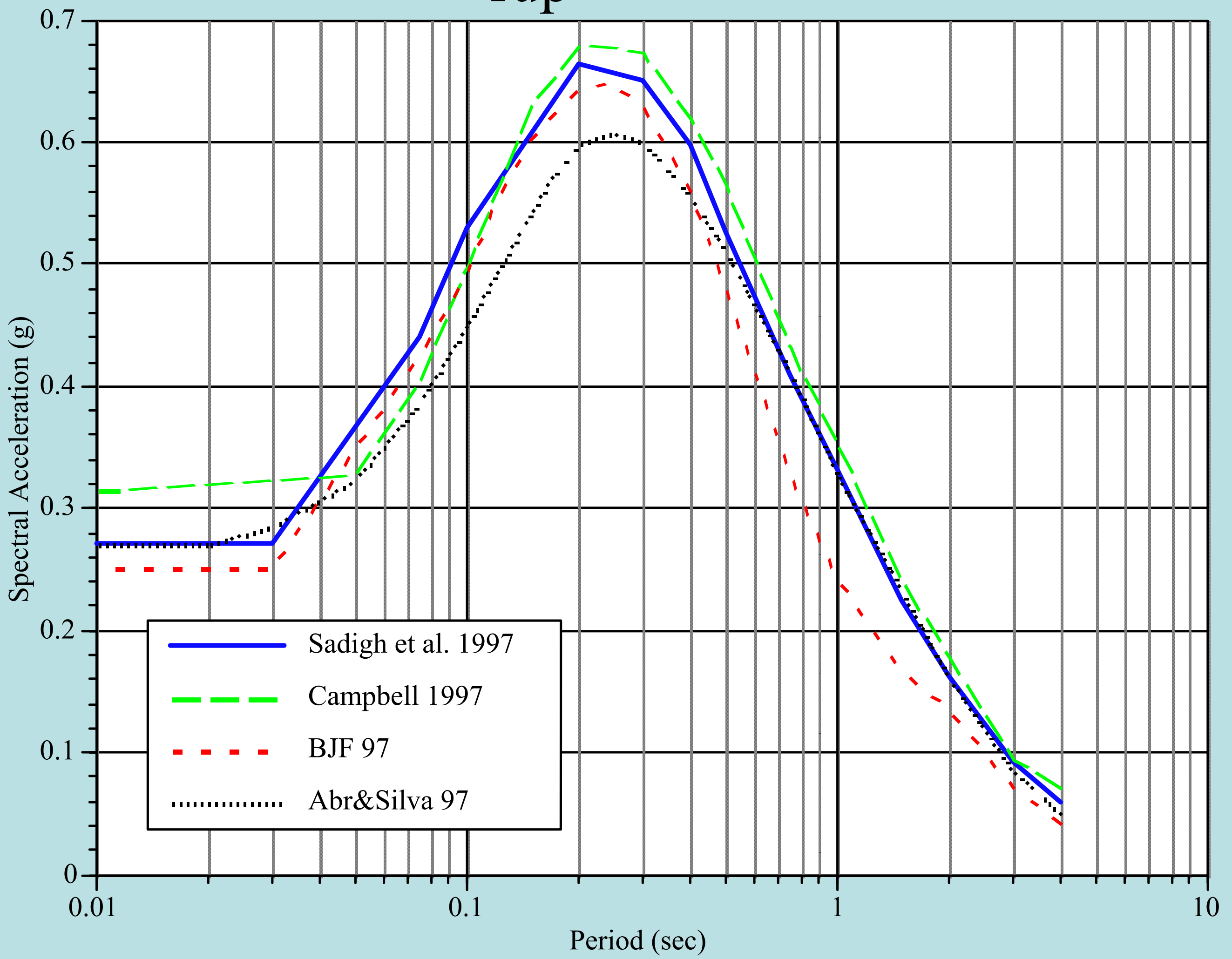
- Empirically Based Models
  - Summary of models in 1997 Seismological Research Letters
    - Abrahamson & Silva (1997)
    - Boore et al (1997)
    - Campbell (1997)
      - Updated model by Campbell and Bozorgnia (2002)
    - Sadigh et al (1997)
    - Spudich et al (1997)
      - - for extensional regimes
  - Other Models commonly used
    - Idriss (1994)

Different Parameters Used

Model	Distance	Site	Style-of-faulting	Other Param
A&S	Rrup	Rock Soil	SS, RV/OBL, RV	HW
BJF	RJB	VS30	SS, RV	
Campbell	Rseis	Hard-rock Soft-rock Soil	SS RV+RV/OBL	Depth to basement rock
Idriss	Rrup	Rock Soil	SS, RV/OBL, RV	
Sadigh	Rrup	Rock Deep Soil	SS, RV/OBL, RV	

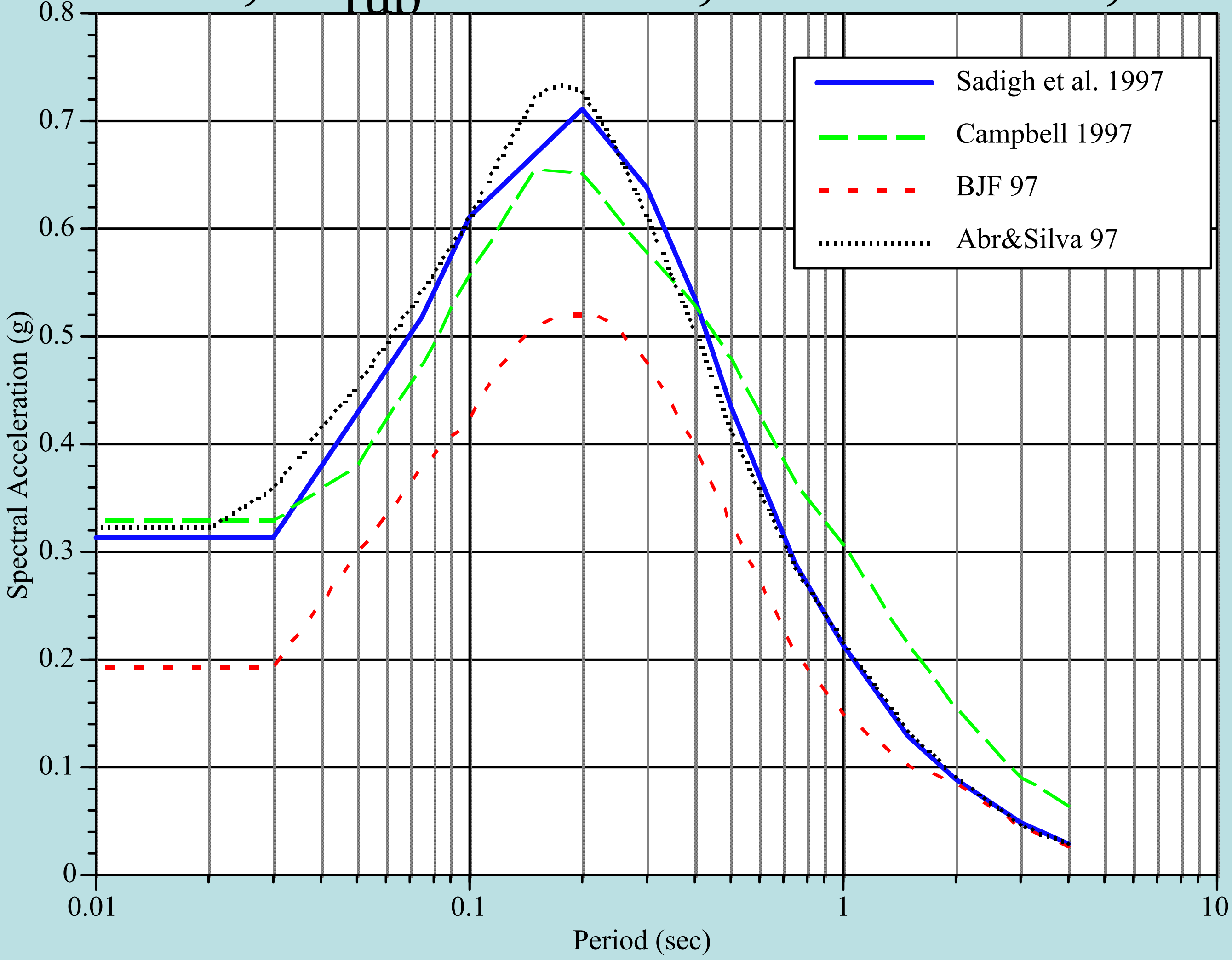
Comparison of Median Sa

M=6.5, R_{rup}=10 km, SS, Soil



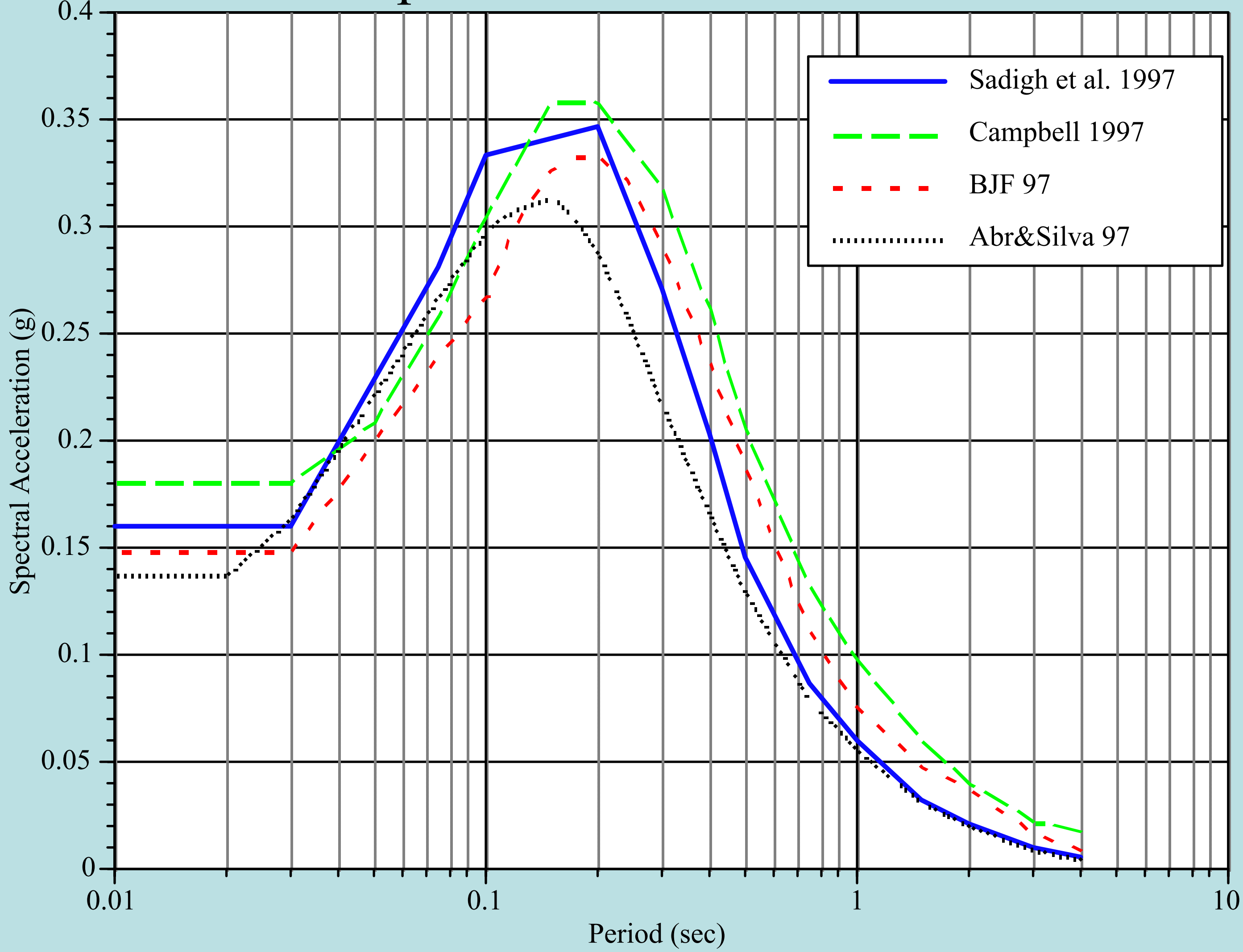
Comparison of Median Sa

M=6.5, R_{rup}=10 km, Soft-Rock, SS



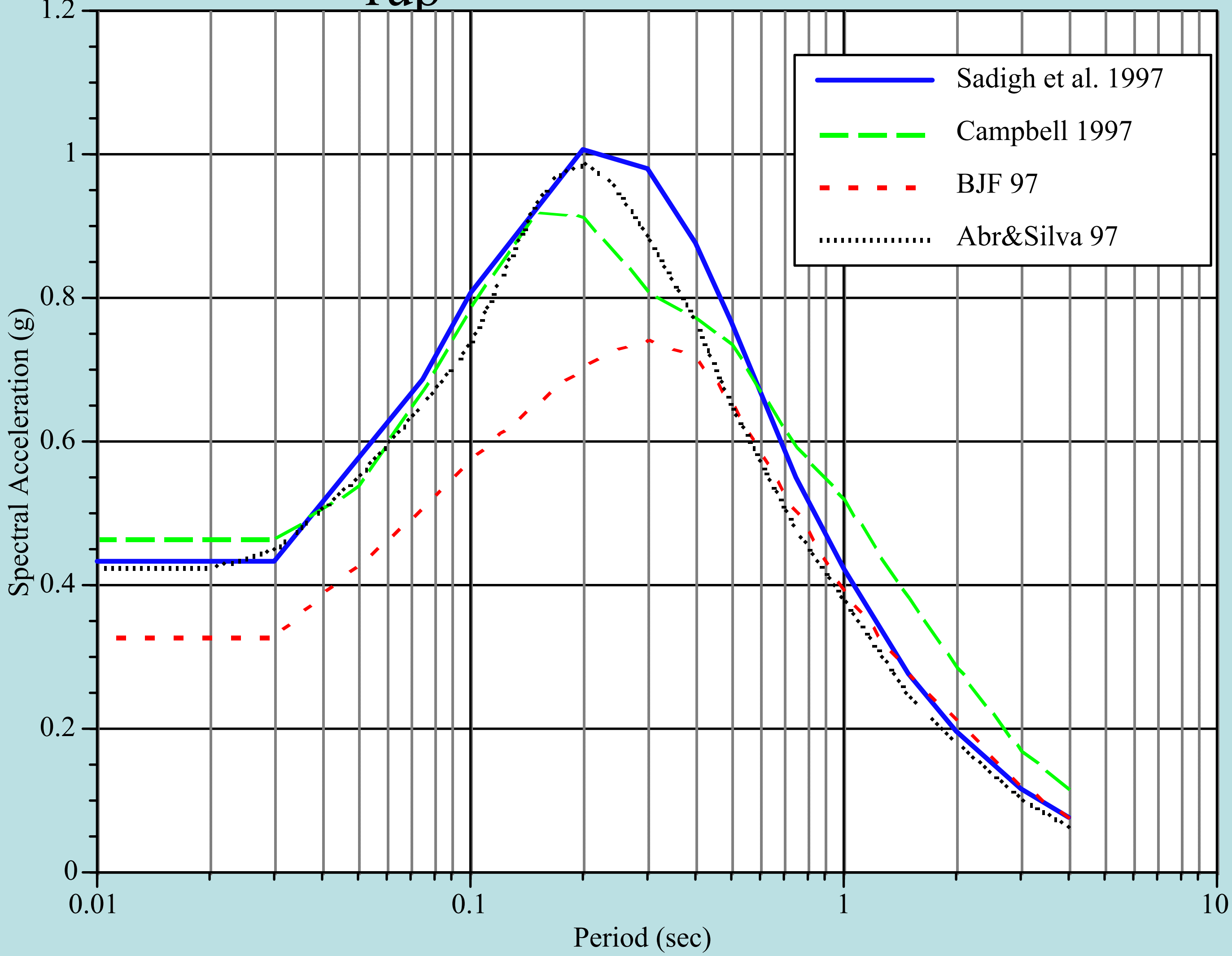
Comparison of Median Sa

M=5.5, R_{rup}=10 km, Soft-Rock, SS



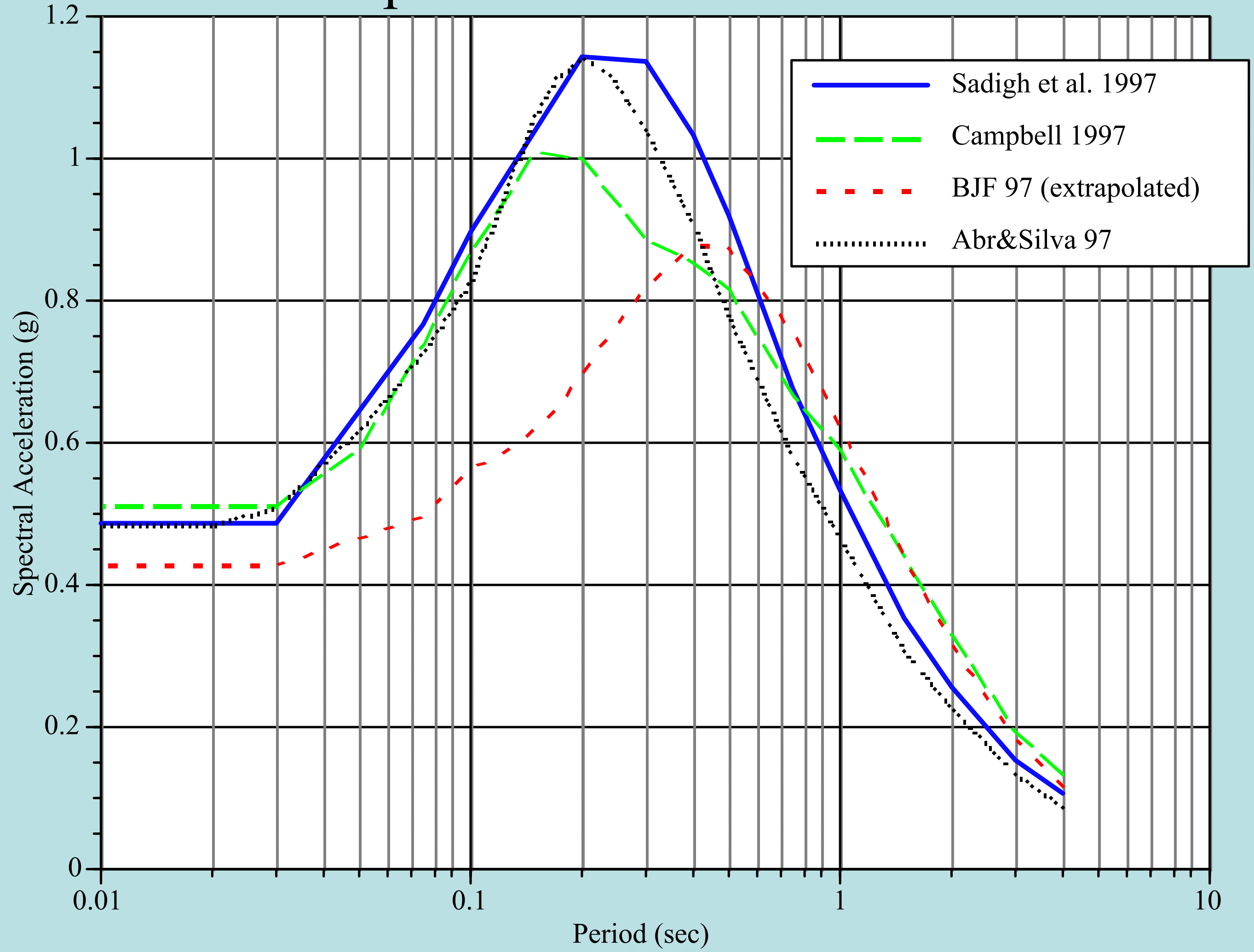
Comparison of Median Sa

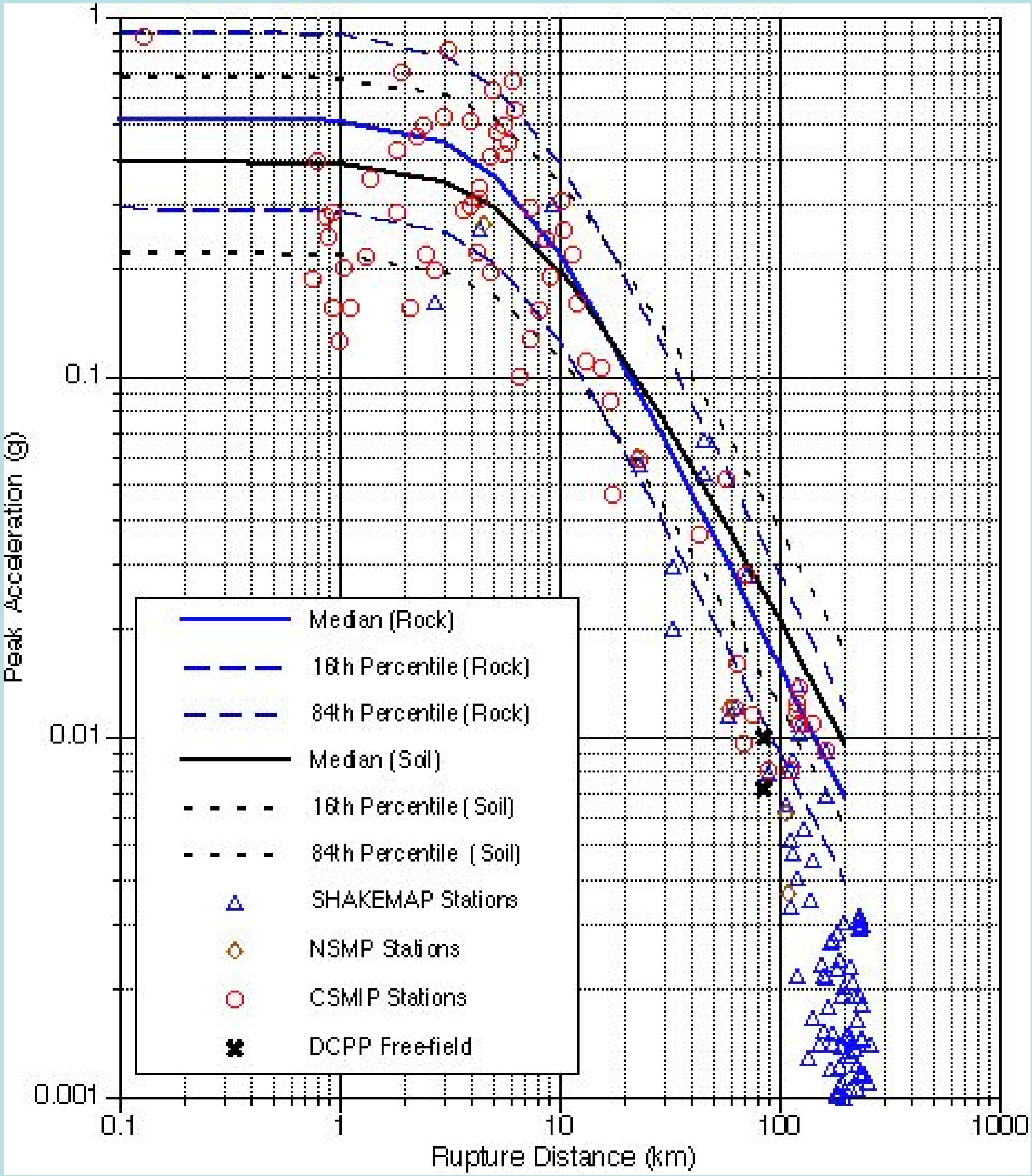
M=7.5, R_{rup}=10 km, Soft-Rock, SS



Comparison of Median Sa

M=8.0, R_{rup}=10 km, Soft-Rock, SS





2004 Parkfield Attenuation

Comparison with A&S 97

Next Generation Attenuation (NGA) Project

- Joint Project
  - PEER/Lifelines Program
    - PEER
    - Caltrans
    - CEC
    - PG&E
  - SCEC
  - USGS

NGA Project

- NGA-E (empirical)
  - New ground motion models based primarily on empirical data
  - Use analytical models (seismological and geotechnical) to guide extrapolation outside of empirical data
    - Results used only in terms of scaling
- NGA-H (hybrid)
  - New ground motion models based on both empirical data and numerically simulated data
    - Uses the values of the ground motion from the simulations, not just scaling

NGA-E Project

- Ground motion models for crustal earthquakes in California
- Must be applicable to all design cases in California (excludes subduction)
  - Ground Motion Parameters:
    - Horizontal components (Ave Horiz, FN, and FP)
    - PGA, PGV, PGD
    - Pseudo spectral acc at 5% damping: 0-10 sec
  - Applicable Magnitude Range:
    - 5.0 - 8.5 (SS)
    - 5.0 - 8.0 (RV)
  - Applicable Distance Range:
    - 0 - 200 km
  - Fault Types
    - Strike-slip, Reverse, Normal

Ground Motion Model Developers

- Abrahamson & Silva
- Boore and Atkinson
- Campbell & Bozorgnia
- Chiou & Youngs
- Idriss

Empirical Data Set

- Common data set provided to developers
  - 175 earthquakes
  - 3548 recordings
- Each developer selects applicable subset of data
  - Justify the exclusion of earthquakes and recording sites
  - Document any modification of independent parameters from PEER recommended values
  - Ground motion values are not modified (e.g. common set used by all developers), but developers select applicable period range of each recording

Developer Scope

- Evaluate new predictive parameters
  - Directivity parameters
  - Hanging wall / foot wall
  - Static stress-drop
  - Asperity depth
  - Depth to “rock” (Vs 1.0, 1.5, or 2.0 km/s)
  - Basin parameters
- Each developer decides if new predictive parameter is to be included in their model
  - Justify the selection or rejection of each parameter evaluated

Independent Parameters

- Magnitude definition
  - All developers use moment magnitude
- Distance definition
  - Developers select appropriate distance metric
- Site classification
  - Developers select site classification
    - Clear definition of site classes
  - Provide a translation scheme to NERHP categories

Supporting Simulations

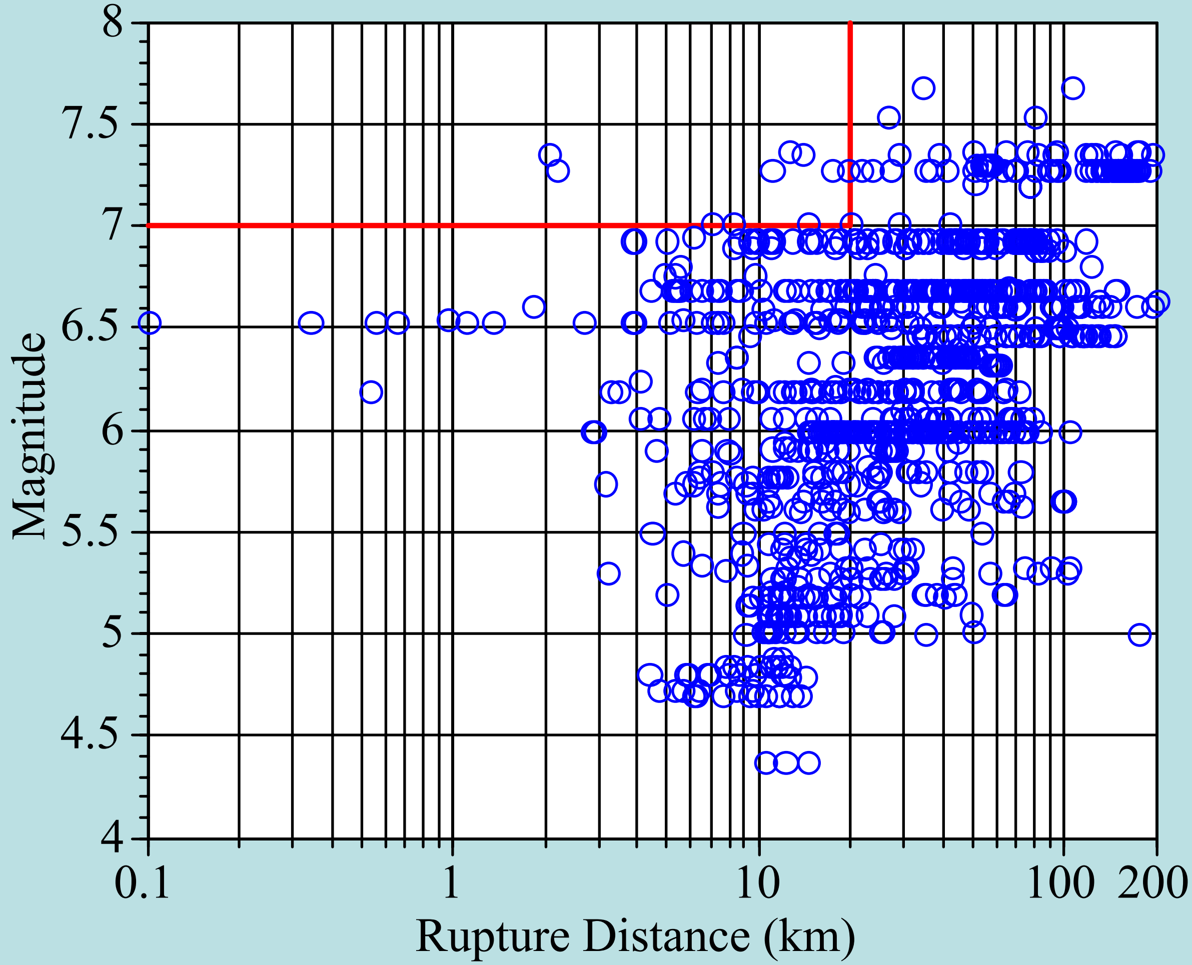
- 1-D Rock simulations
- 3-D basin simulations
- Isochron simulations
- Site amplification calculations

1-D Rock simulations

- Simulations by three groups
  - Zeng
  - URS
  - Pacific Engineering
- Simulations can be used for:
  - Magnitude scaling above M7
  - Distance scaling 0-15 km and 70-200 km
  - Period extrapolation to 10 seconds
  - Directivity scaling
  - Hanging wall footwall scaling
  - Asperity depth (shallow vs buried slip)
  - Stress-drop scaling

Empirical Models, Pre-1995

Shallow Crustal Earthquakes in Active Regions



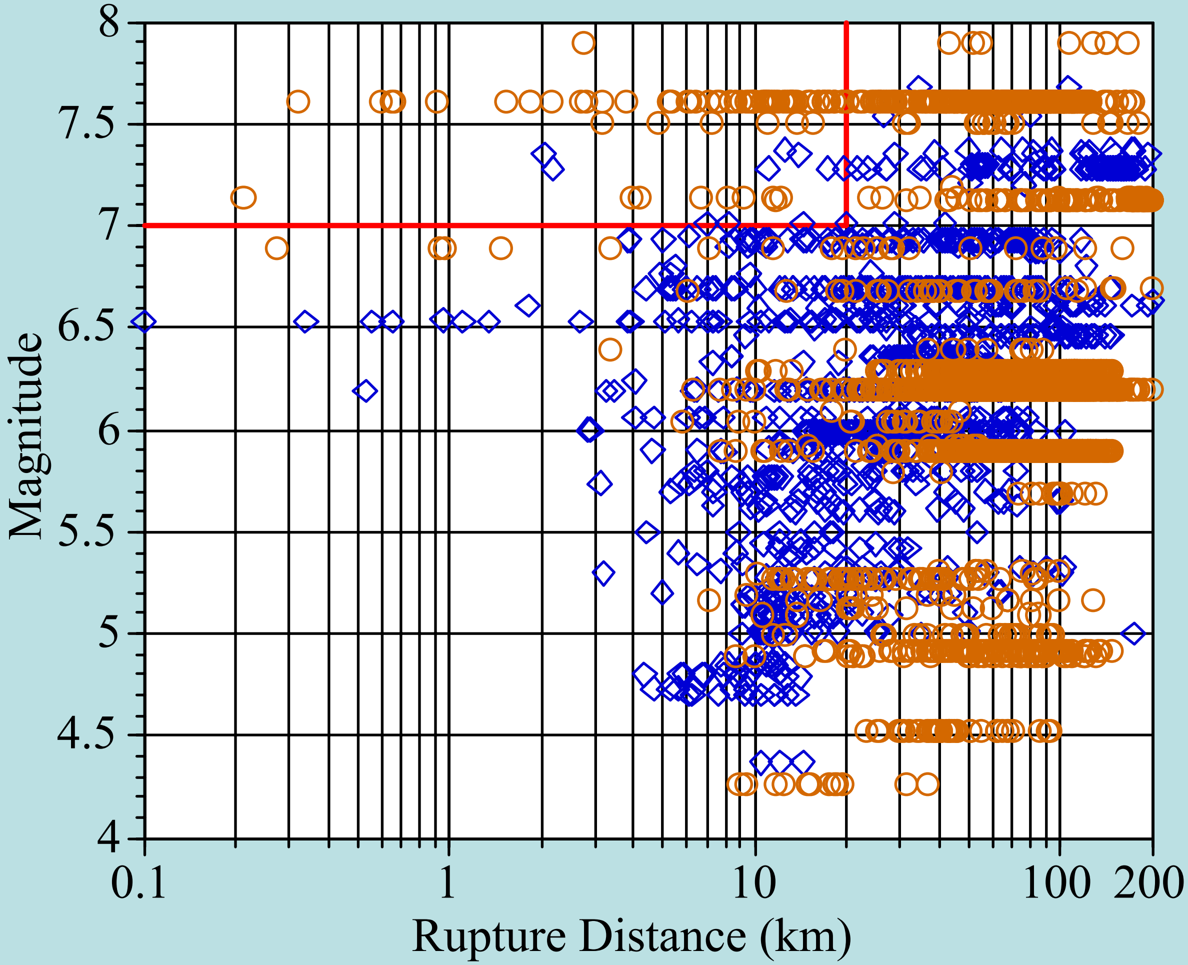
- Main basis for current models
- Few data from M>7, Dist<20 km
- Extrapolation of scaling for M6-7 up to M8

Recent Large Magnitude Earthquakes with Ground Motion Data

- 1999 Kocaeli, Turkey (M7.5)
- 1999 Chi-Chi, Taiwan (M7.6)
- 1999 Duzce, Turkey (M7.1)
- 1999 Hector Mine, CA (M7.1)
- 2002 Denali, Alaska (M7.9)

Empirical Models, Pre-1995

Shallow Crustal Earthquakes in Active Regions

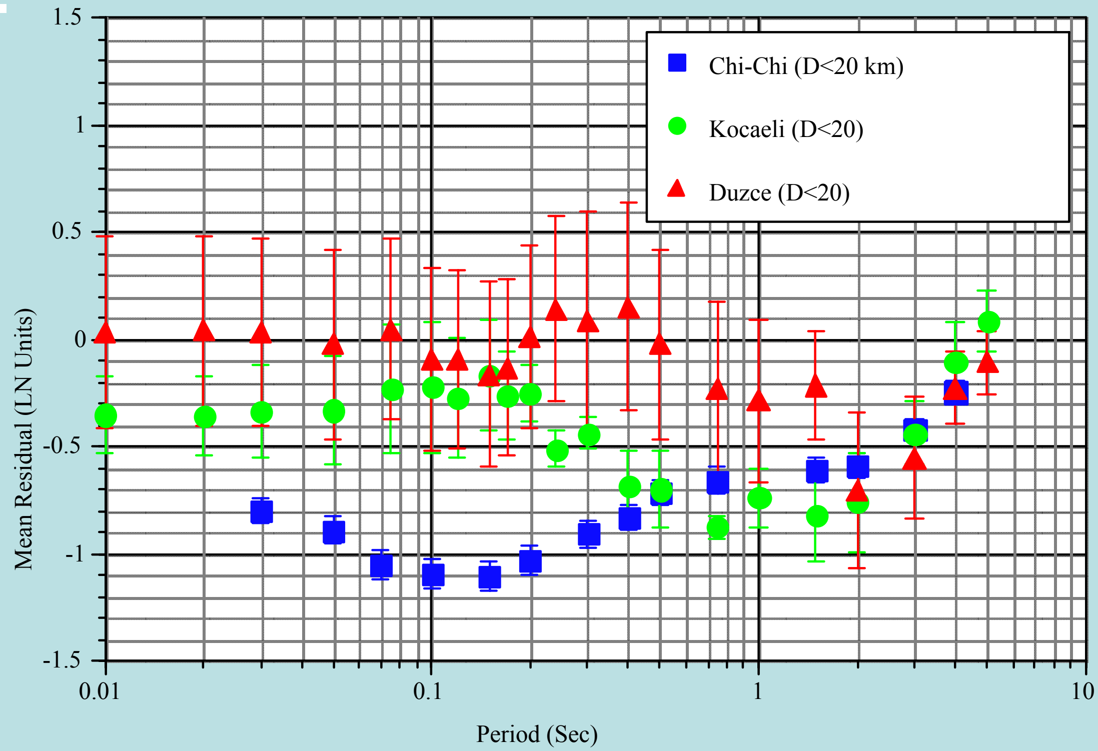


- Basis for new models
- Additional data for M>7, Dist<20 km mainly foreign

Recordings Close to Large Earthquakes

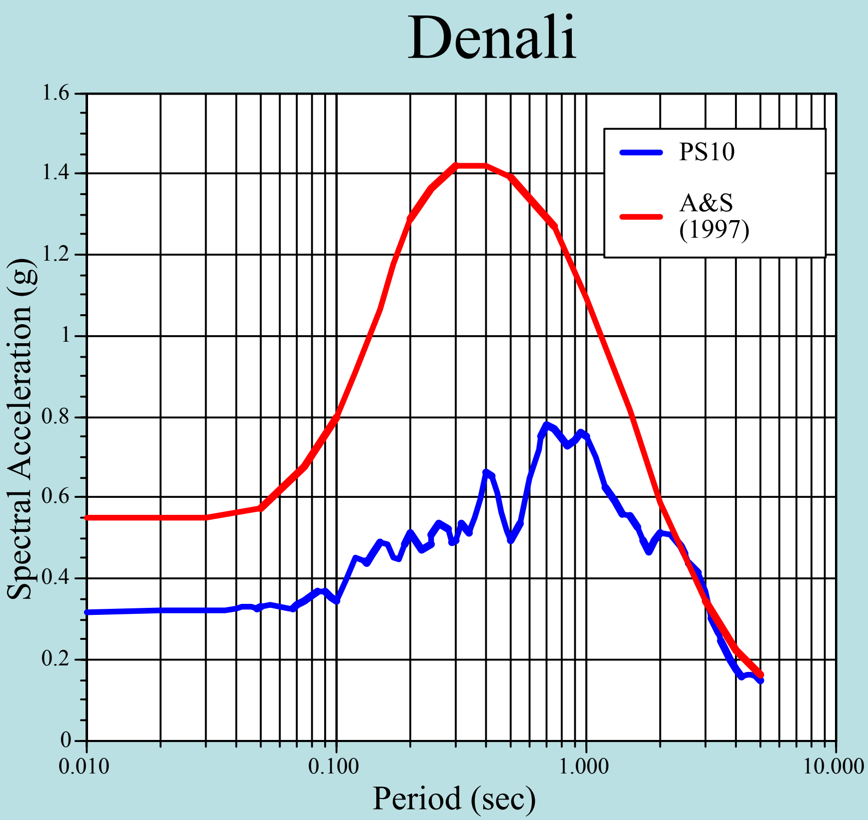
	M≥7.0 D ≤ 20 km	M≥7.0 D ≤ 10 km	M≥7.0 D ≤ 5 km
Prior to 1999	11	4	2
1999 Kocaeli	6	3	2
1999 Chi-Chi	63	32	14
1999 Duzce	6	2	1
1999 Hector Mine	1	0	0
2002 Denali	1	1	1

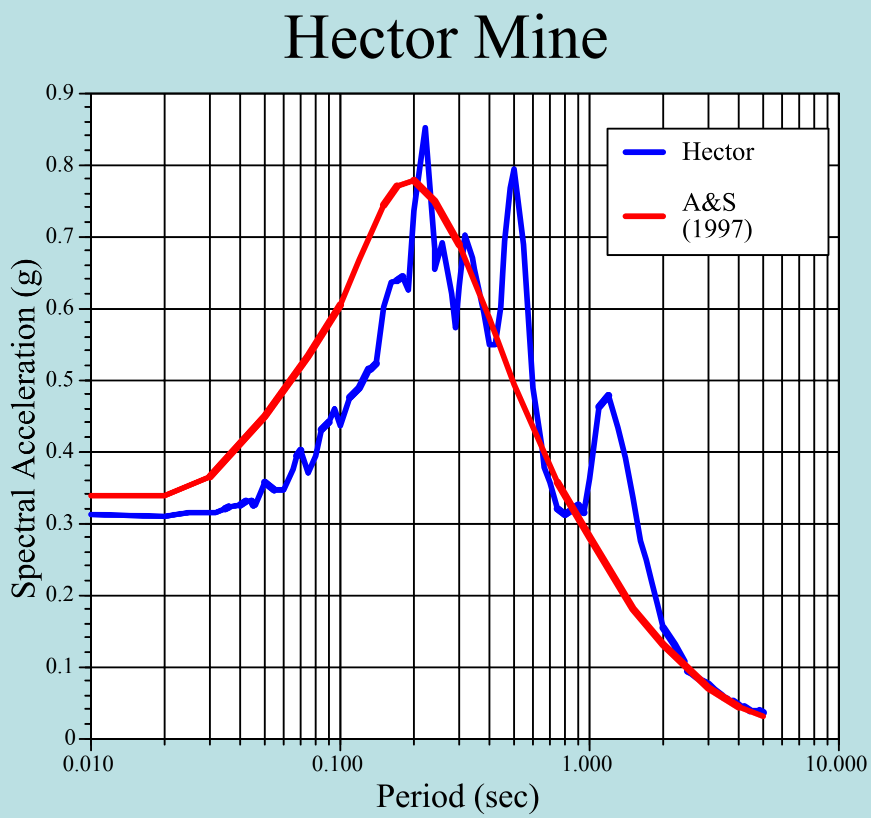
Comparison of New Data with Current Ground Motion Models



- Close-in data are over-predicted by current models
- Denali & Hector Mine have just one recordings < 20 km

Comparison of New Data with Current Ground Motion Models





Issues for Ground Motion Data from Recent Large Earthquakes

- Are the data from these non-California earthquakes applicable to California?
  - Regional differences in stress-drop, crustal structure?
- Were these earthquakes just randomly weaker?
  - With large variability, will future earthquakes have higher ground motions?
- Are the recorded data representative of the overall shaking?
  - Were the locations of ground motion recorders biased to lower than average ground motions?

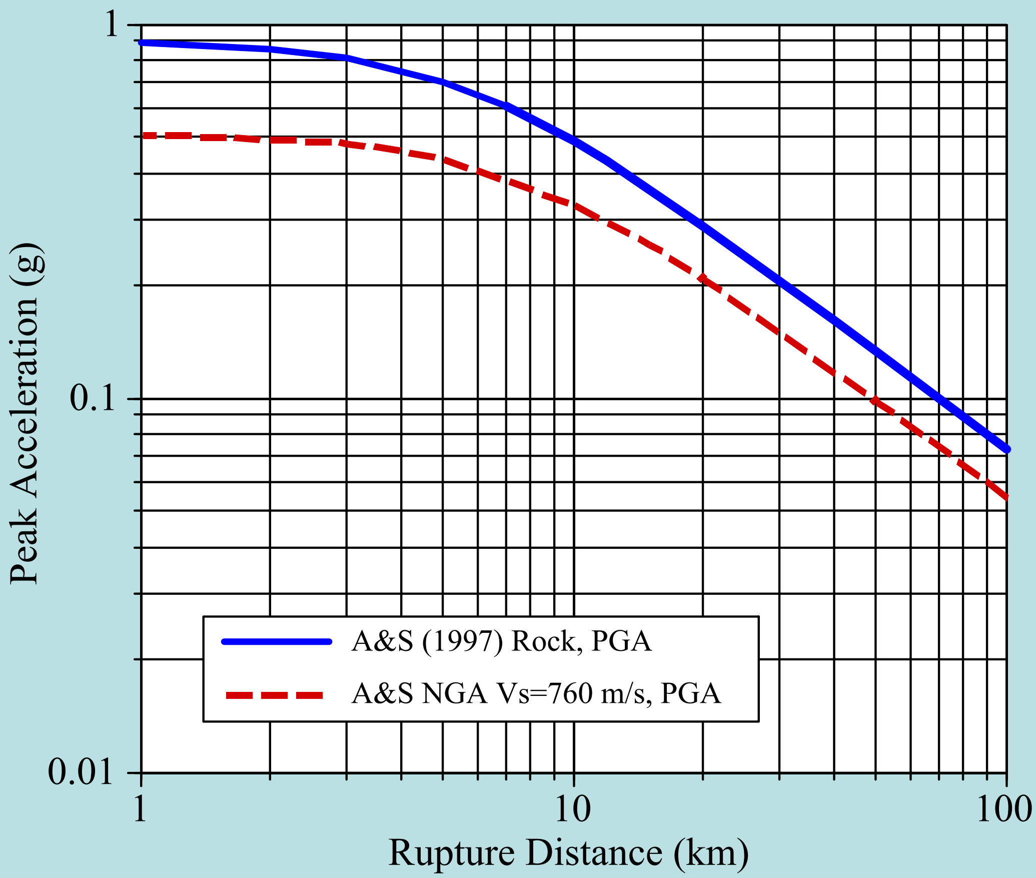
NGA Project

- Develop new ground motion attenuation relations for shallow crustal earthquakes in active regions
  - Sponsors
    - PEER, Caltrans, PG&E, Calif Energy Commission
  - Partners
    - SCEC, USGS, CGS
  - Multiple ground motion model developer teams
    - Abrahamson & Silva
    - Boore and Atkinson
    - Campbell and Bozorgnia
    - Chiou and Youngs
    - Idriss

Site Classification for NGA Project

- Major effort to estimate V_{S30} for strong motion sites
  - Studies to measure V_{S30}
  - Correlation of V_{S30} with surface geology
- Allows the NGA models to use V_{S30} rather than generic soil categories

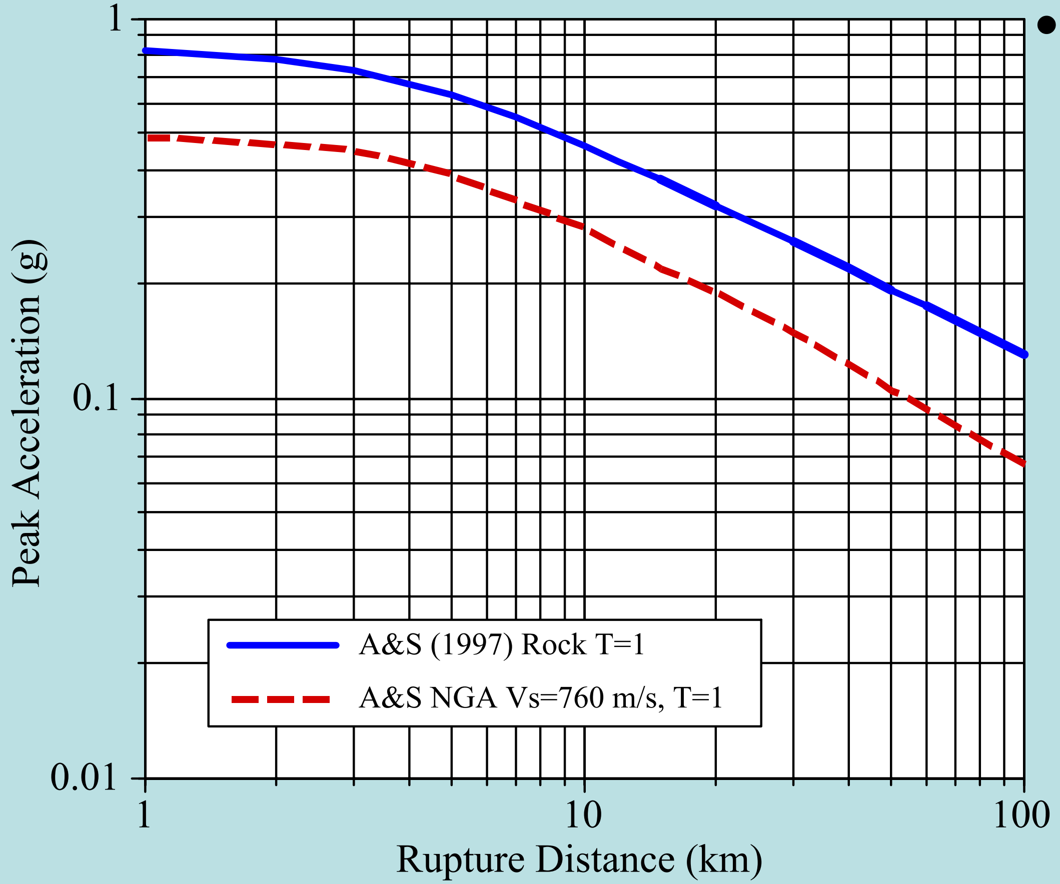
Example NGA Result
M8, PGA, SS, rock



- 12% reduction due to Vs30 differences

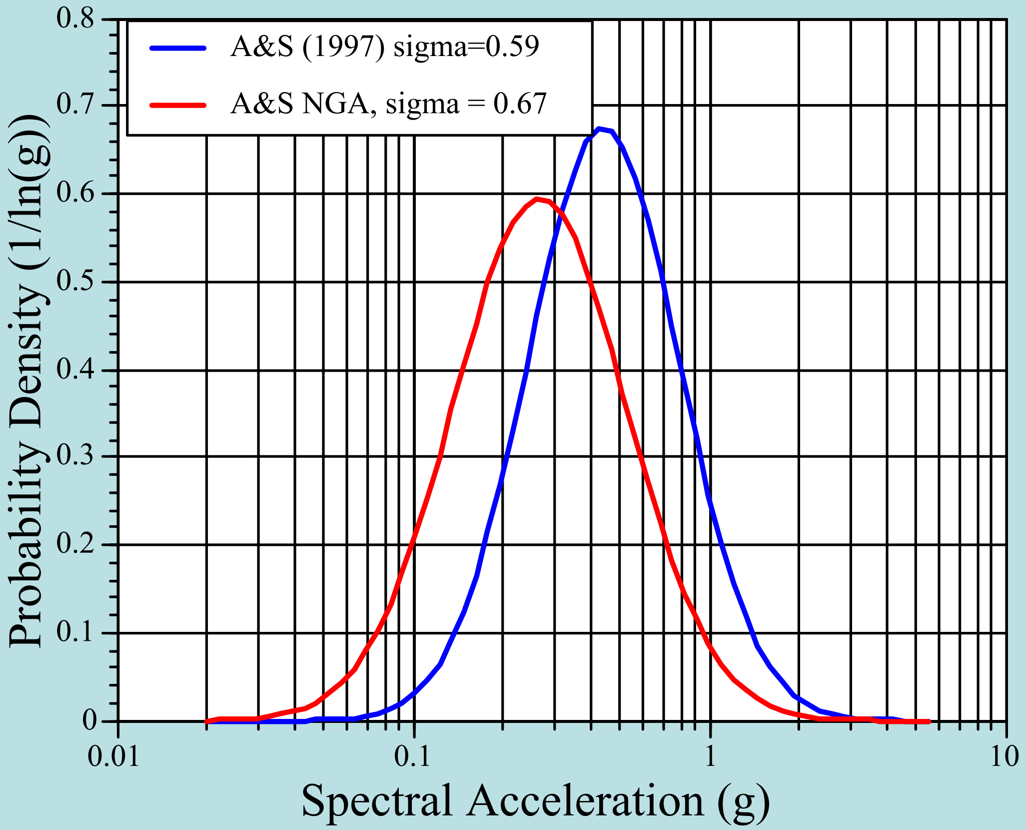
  (760 m/s vs generic rock)

Example NGA Result
M8, T=1 sec, SS, rock



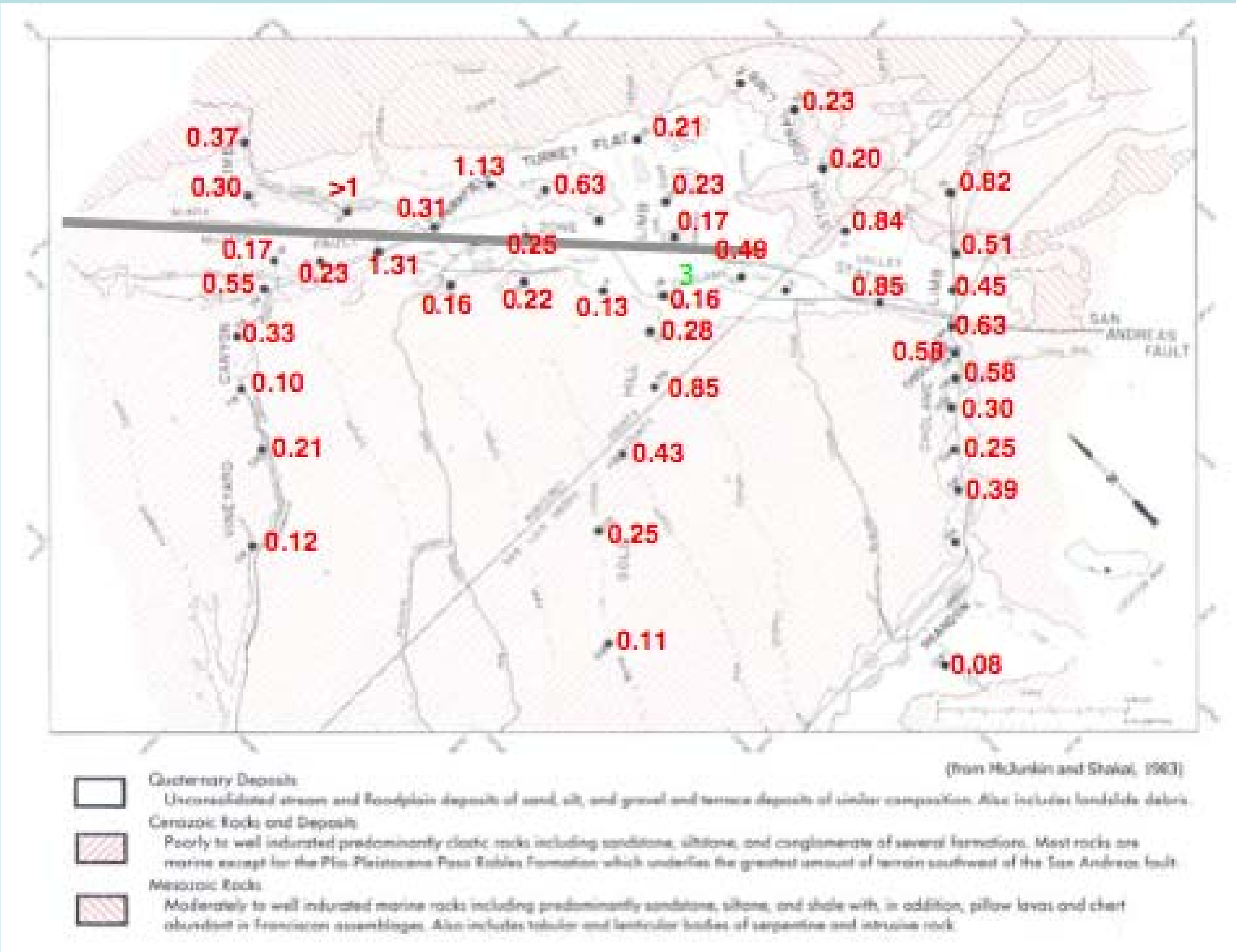
- 25% reduction due to Vs30 differences
  (760 m/s vs generic rock)

Example NGA Variability M8, R10, SS, Rock, T=1 sec



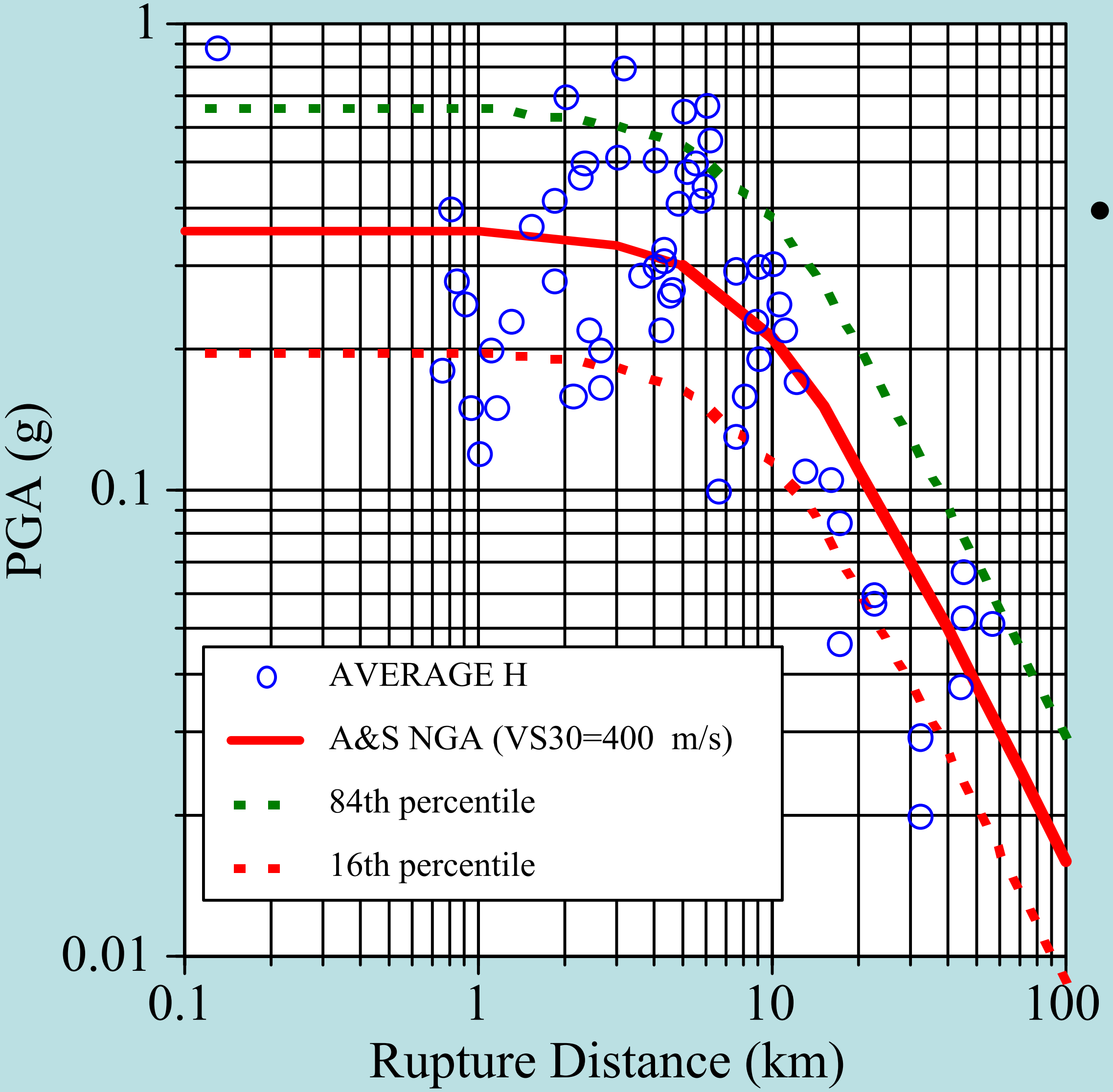
- NGA models have larger variability for M8
- This offsets some of the effect of reduction in median

What about 2004 Parkfield (M6)?



- Very high ground motions observed
- Several PGA>1g
- Most are much smaller

Parkfield PGA



- Parkfield PGA values are consistent with NGA models
  - Median
  - Standard deviation

Characteristics of Rock Motions Including Near-Fault Effects

Near Fault Effects

- Directivity
  - Related to the direction of the rupture front
    - Forward directivity: rupture toward the site
      (site away from the epicenter)
    - Backward directivity: rupture away from the site (site near the epicenter)
- Fling
  - Related to the permanent tectonic deformation at the site

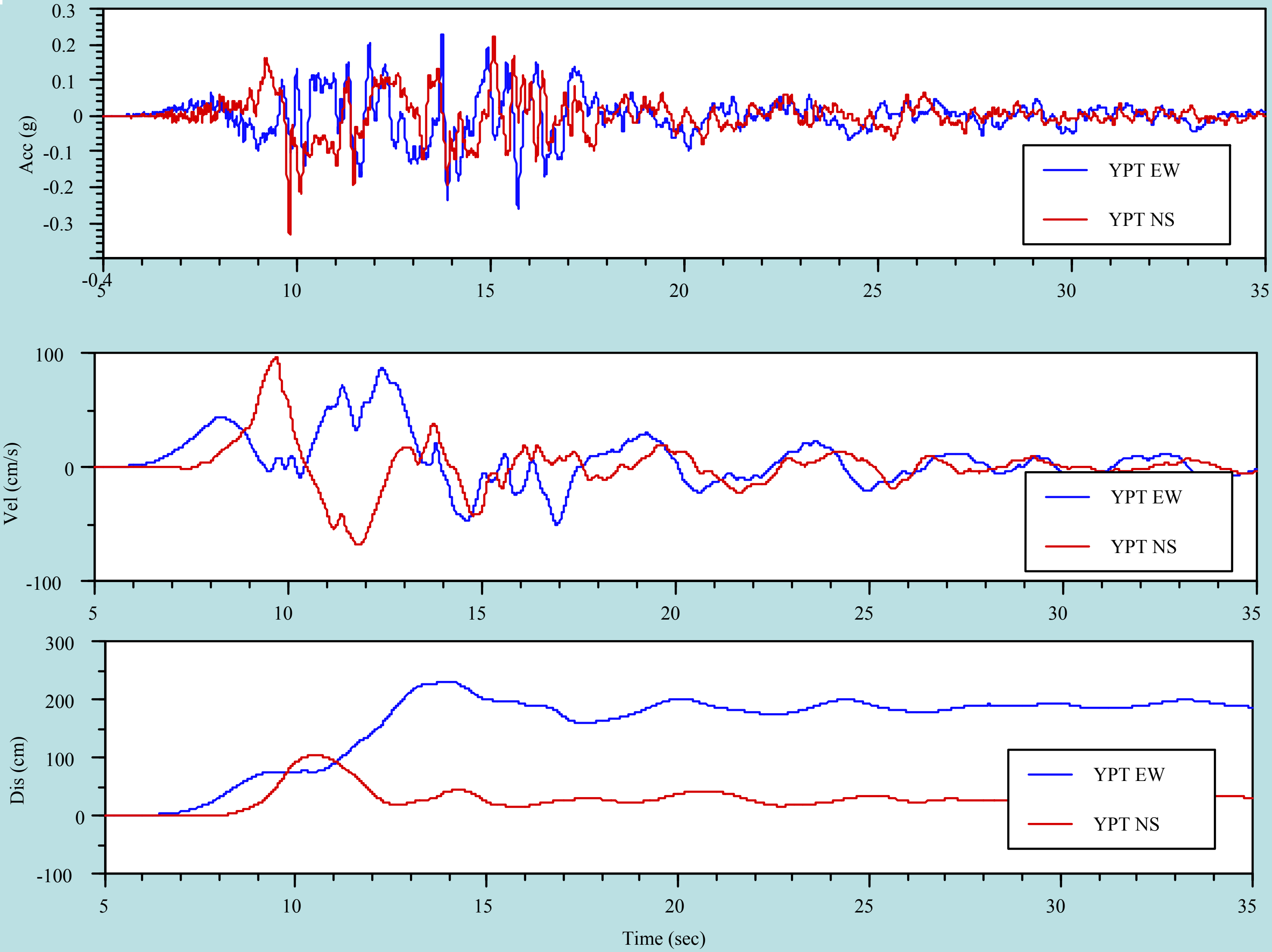
Velocity Pulses

- Forward Directivity
  - Two-sided velocity pulse due to constructive interference of SH waves from generated from parts of the rupture located between the site and epicenter
    - Constructive interference occurs if slip direction is aligned with the rupture direction
    - Occurs at sites located close to the fault but away from the epicenter for strike-slip
- Fling
  - One-sided velocity pulse due to tectonic deformation
  - Occurs at sites located near the fault rupture independent of the epicenter location

Observations of Directivity and Fling

Sense of Slip	**Directivity**	**Fling**
Strike-Slip	Fault Normal	Fault Parallel
Dip-Slip	Fault Normal	Fault Normal

Example of Near-Fault Effects
(Kocaeli Earthquake)

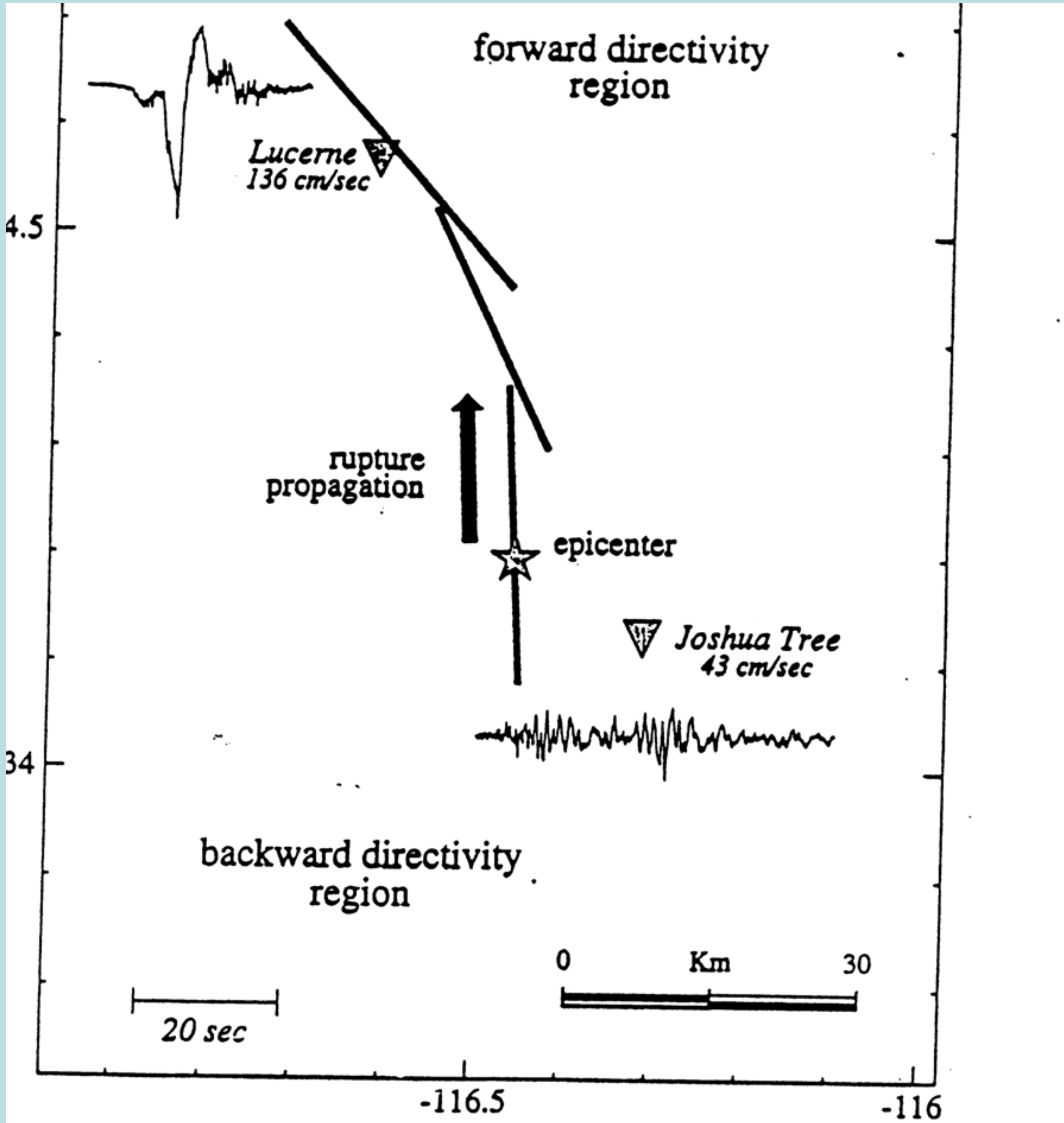


Directivity Effects

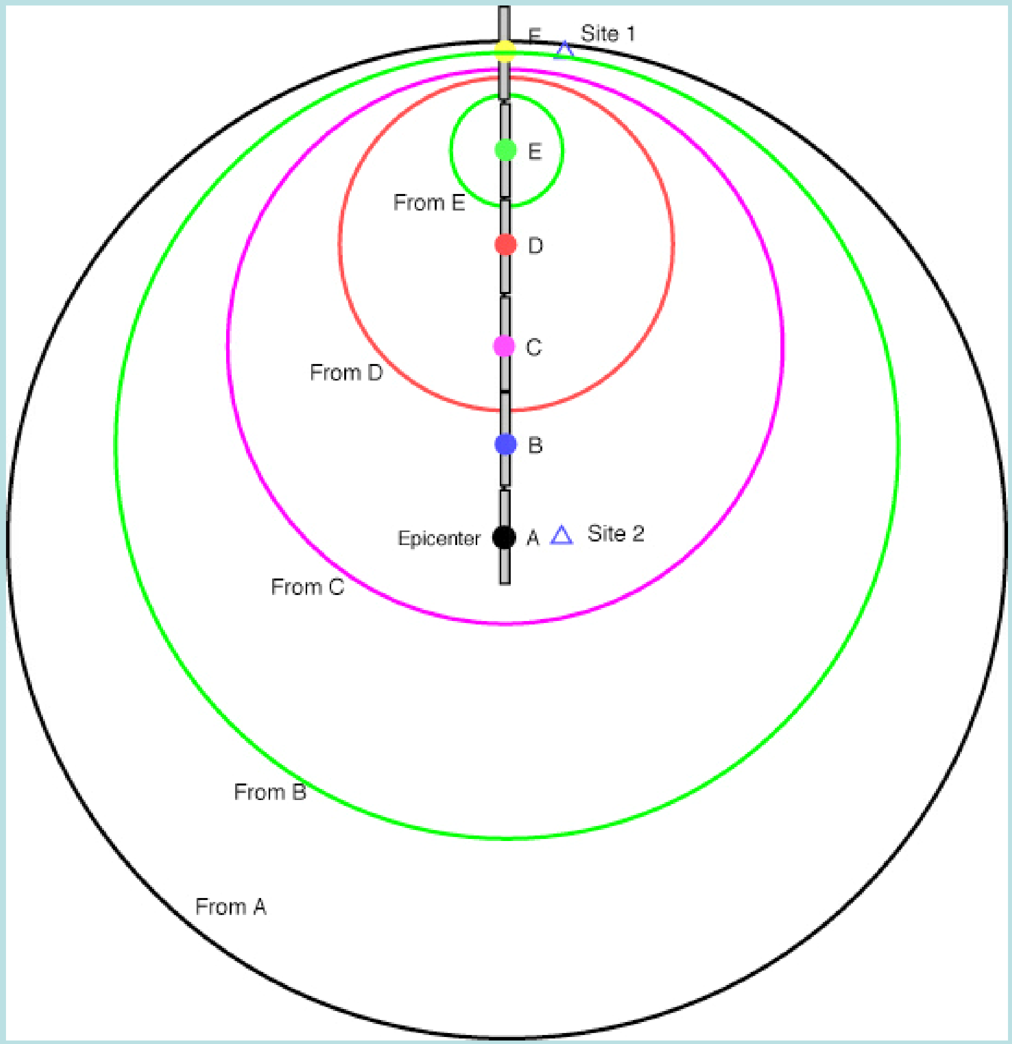
(Somerville et al, 1997)

Two Effects on Ground Motion Amplitudes

- Changes in the average horizontal component as compared to standard attenuation relations
  - Increase in the amplitude of long period ground motion for rupture toward the site
  - Decrease in the amplitude of long period ground motion for rupture away from the site
- Systematic differences in the ground motions on the two horizontal components
  - Fault normal component is larger than the fault parallel component at long periods


forward directivity region
Lucerne
136 cm/sec
4.5
rupture propagation
epicenter
Joshua Tree
43 cm/sec
34
backward directivity region
0
Km
30
20 sec
-116.5
-116

Directivity



Model for Directivity Effects

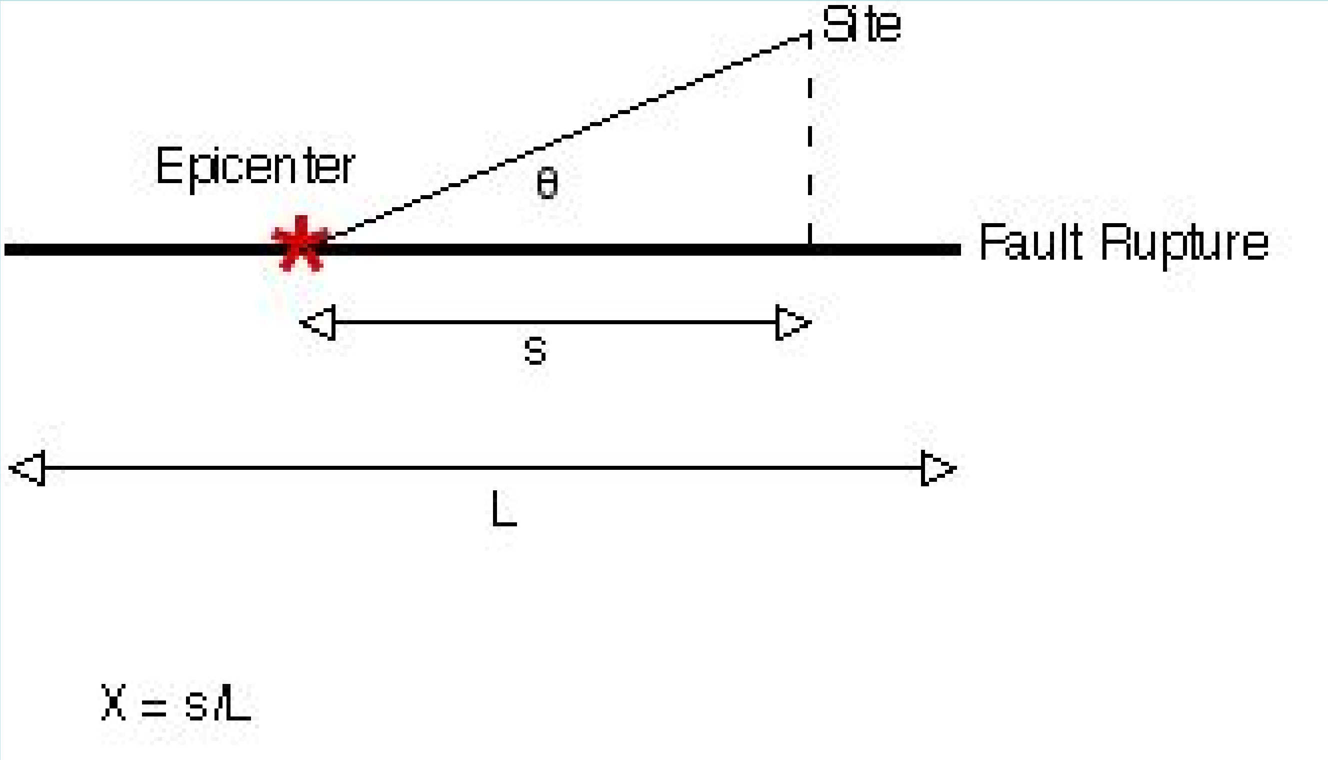
Additional Parameters Required

- Strike-Slip Fault

  X = fraction of fault rupture between the epicenter and the site

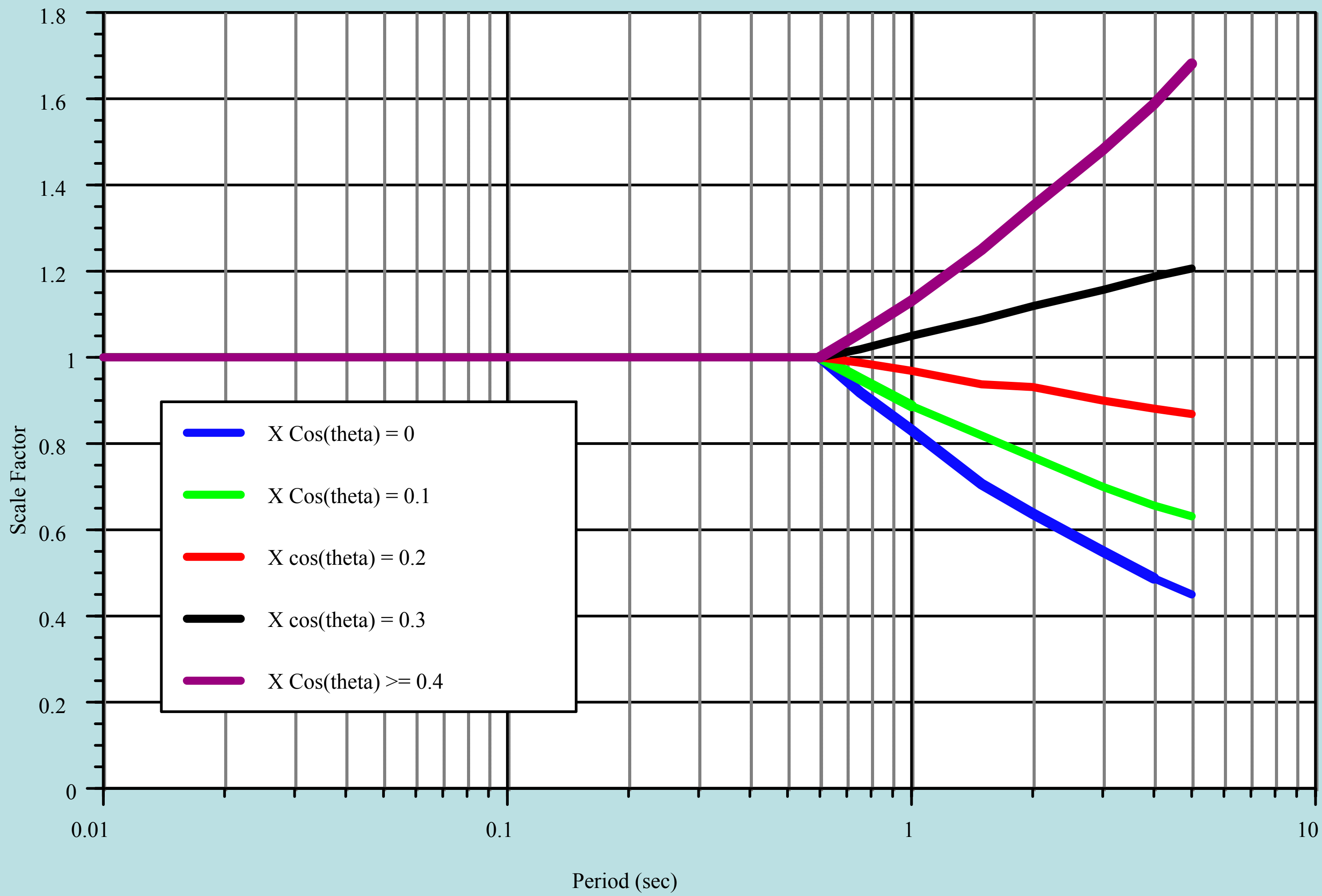
  θ = angle between the fault strike and the epicentral direction from the site

Directivity Parameters for Strike-Slip Faults



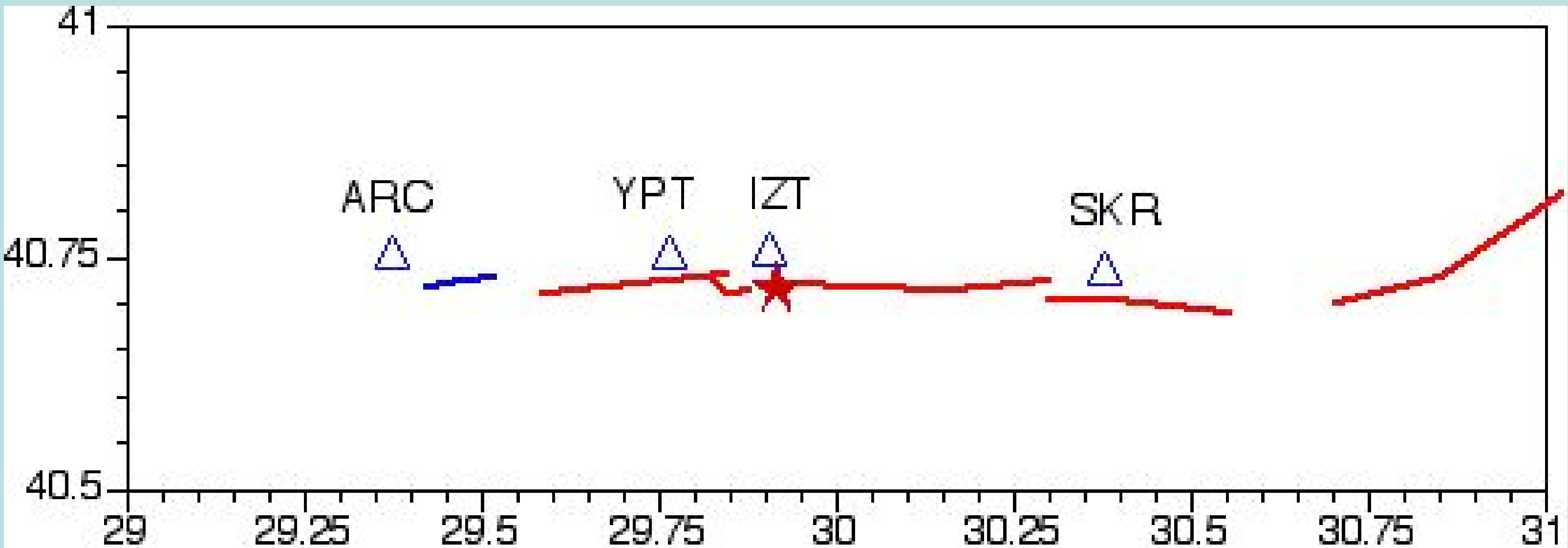
Abrahamson (2000) Directivity Factors

5% damping, Ave Horiz, Strike-Slip

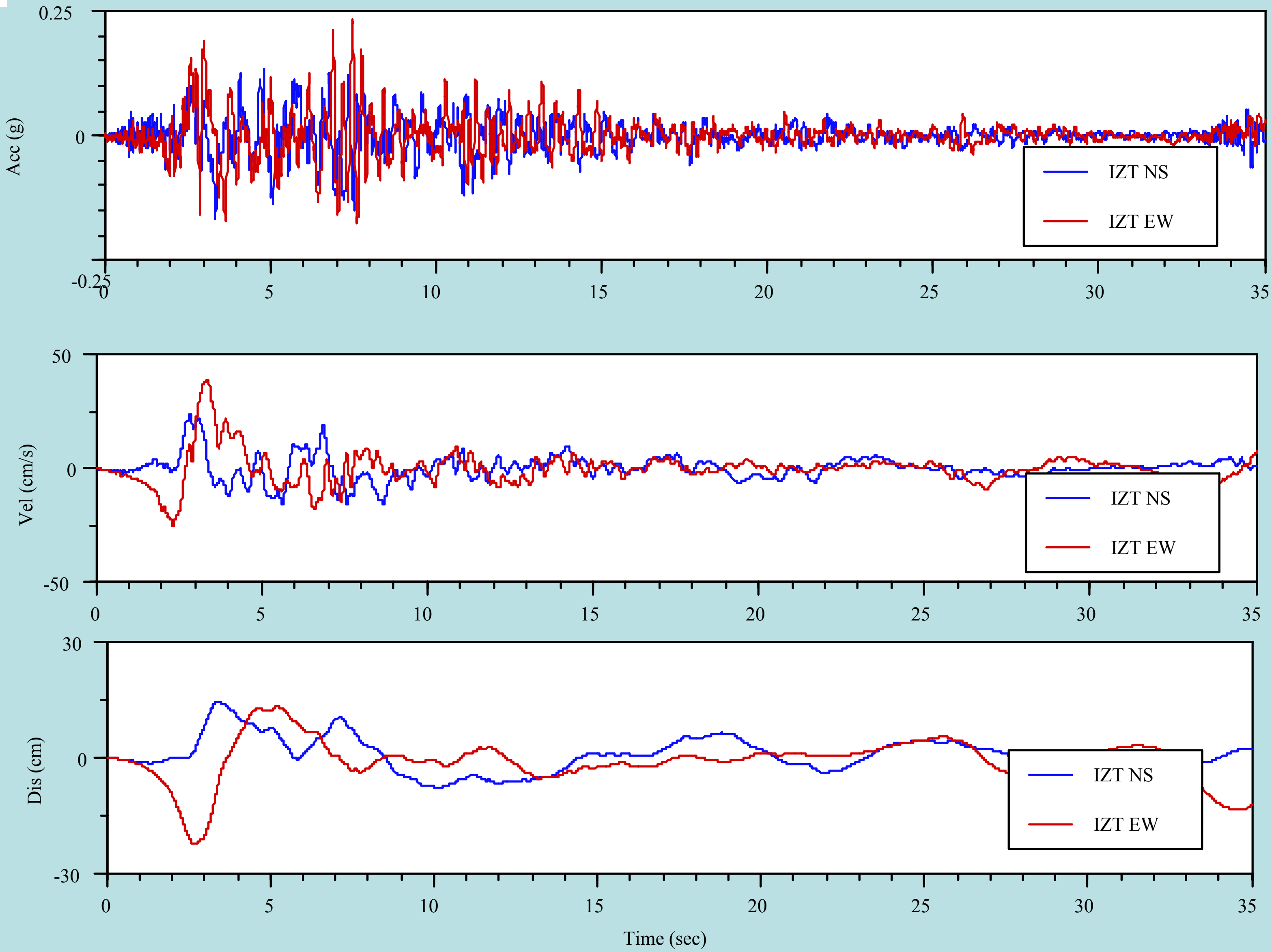


Somerville et al (1997) Scale Factors for FN/Ave Horiz

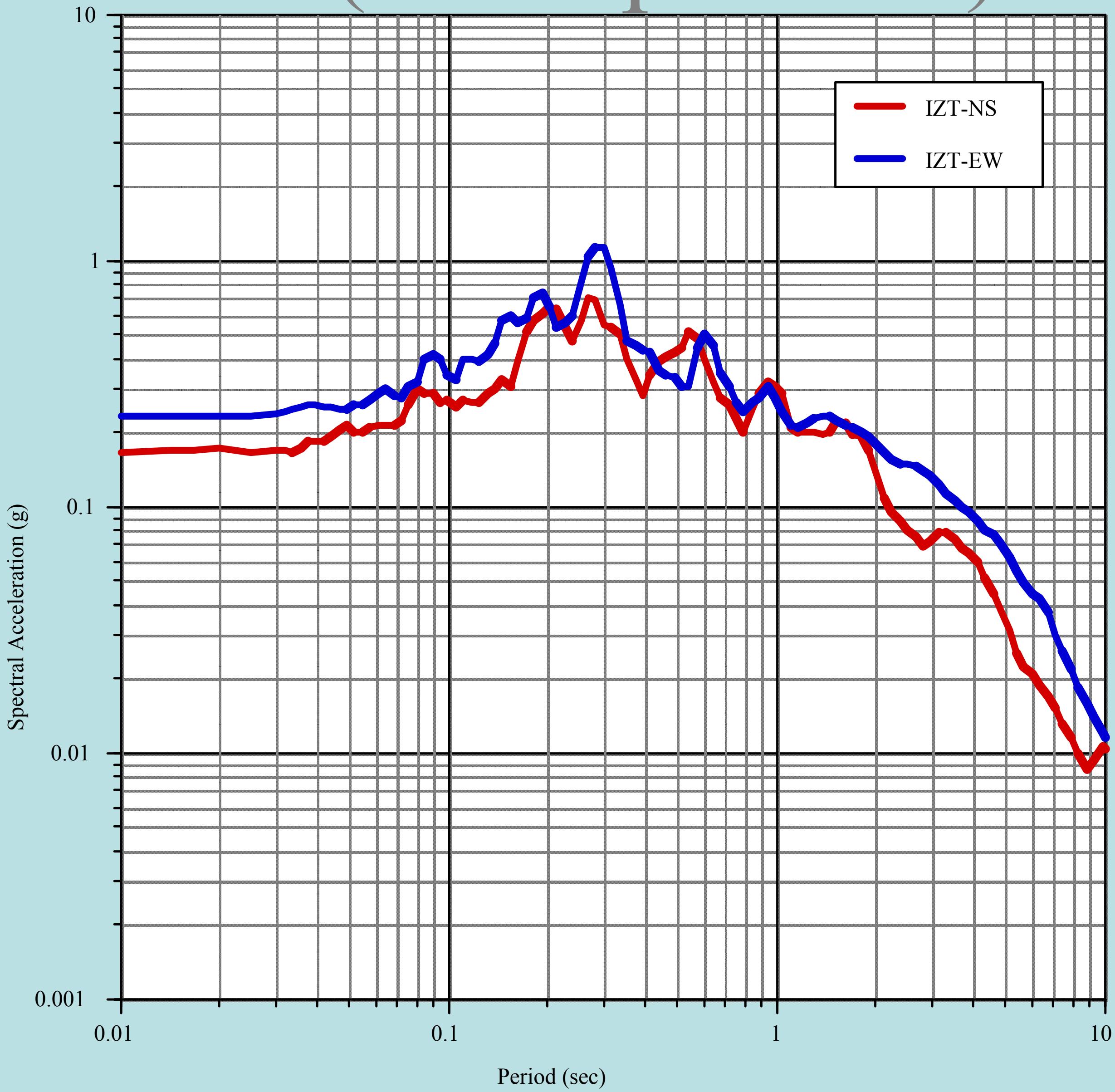
Kocaeli Rupture and Strong Motion Stations



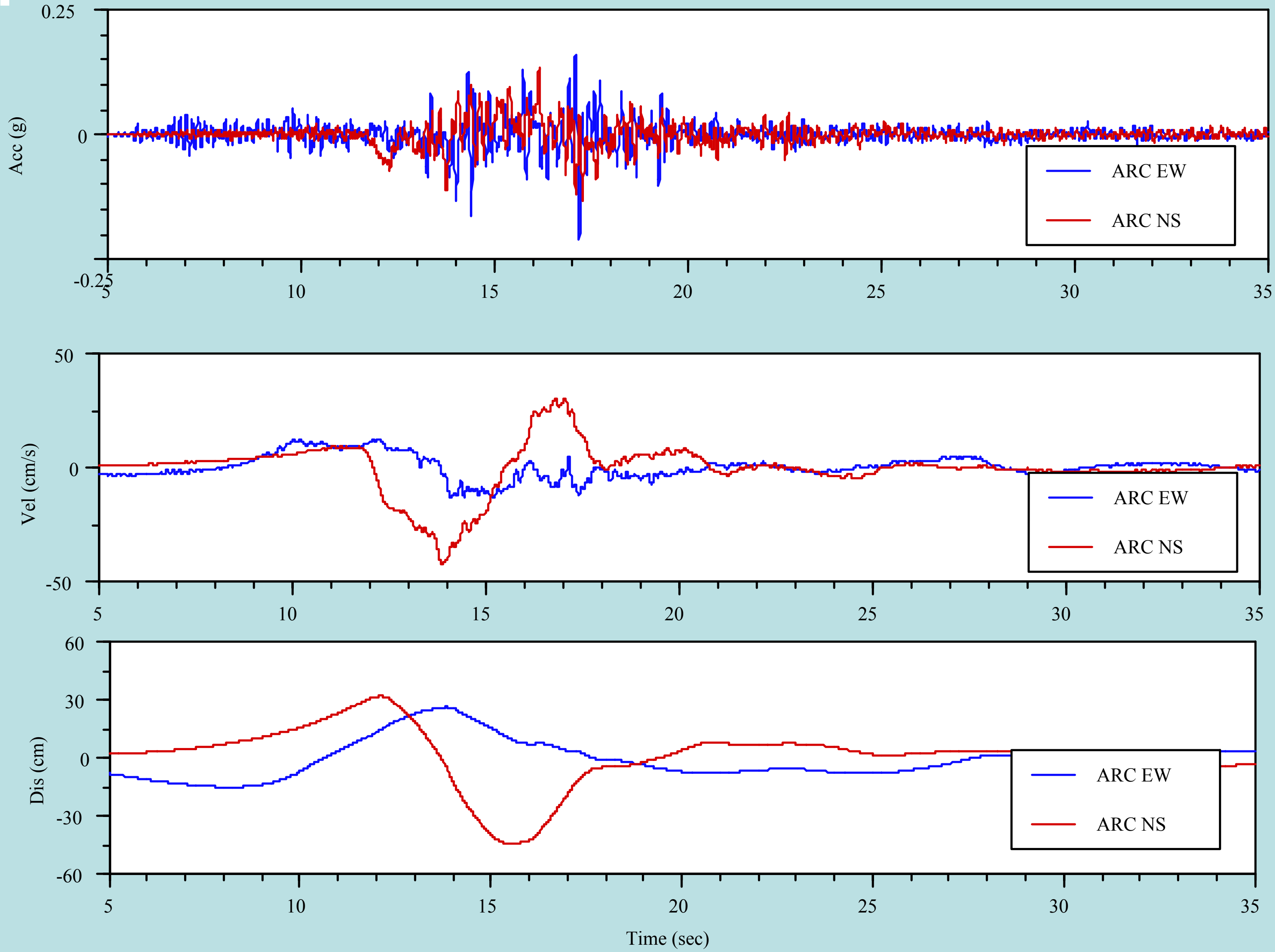
IZT (near epicenter)



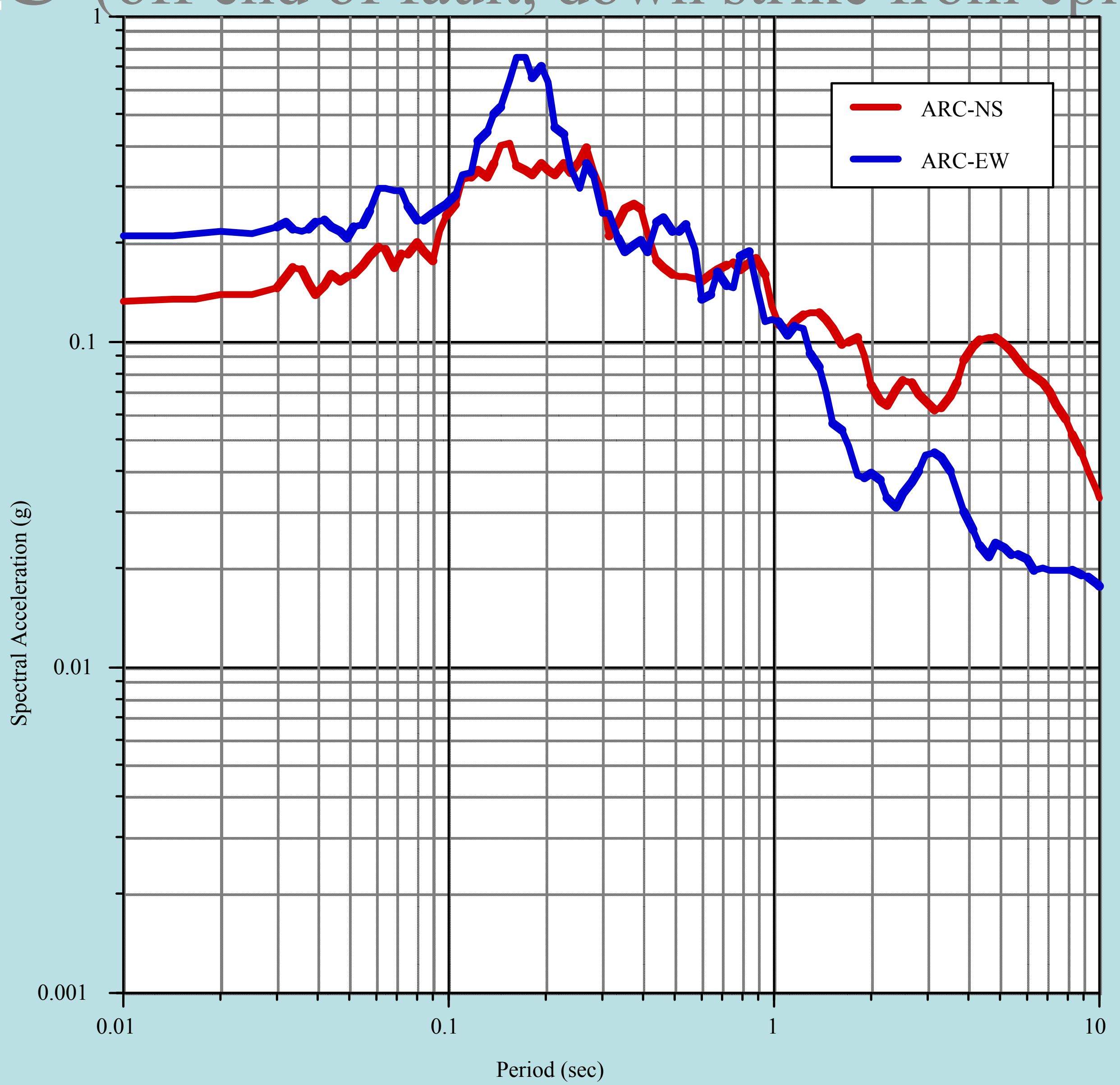
IZT (near epicenter)



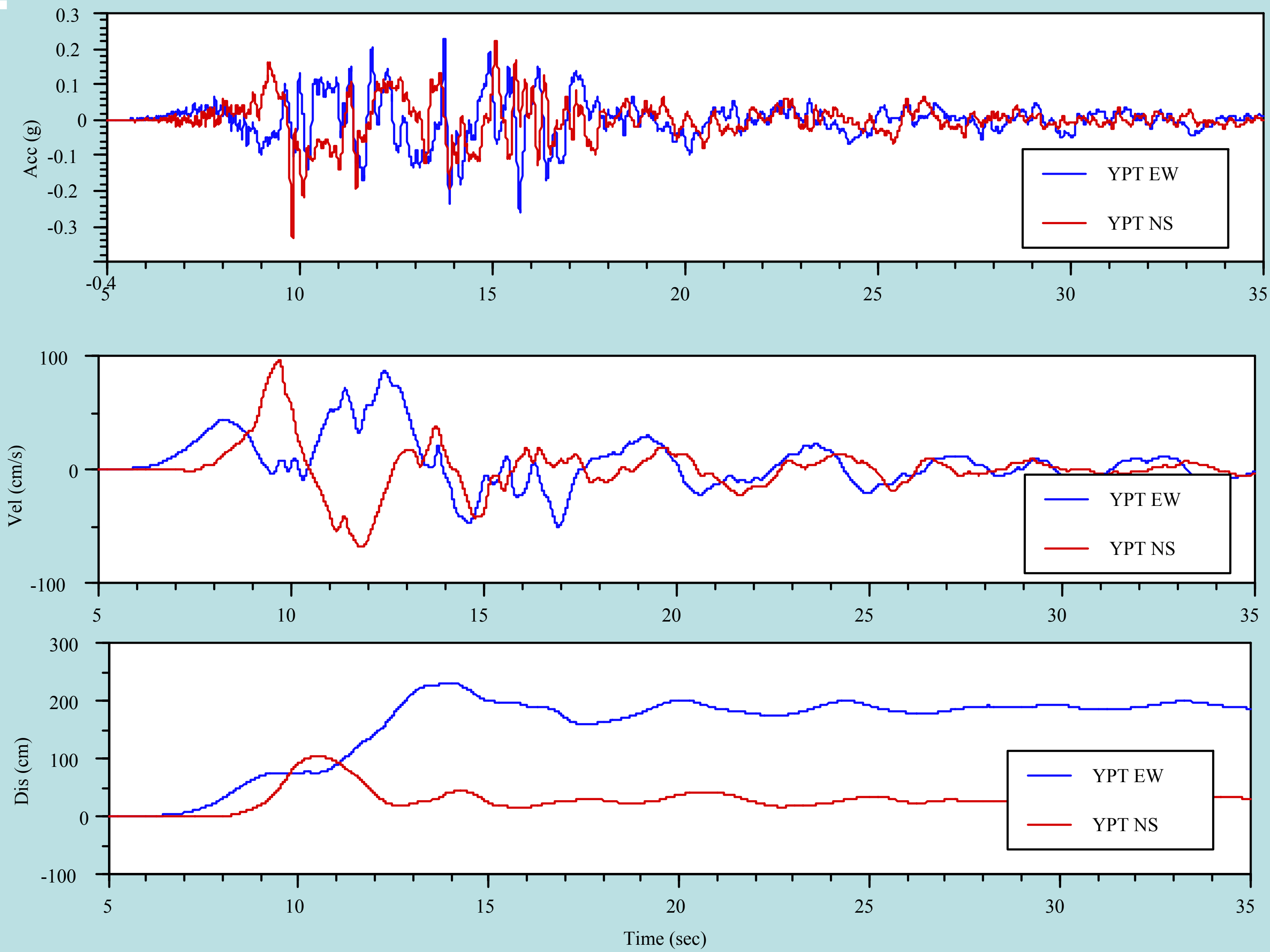
ARC (off end of fault, down strike from epicenter)



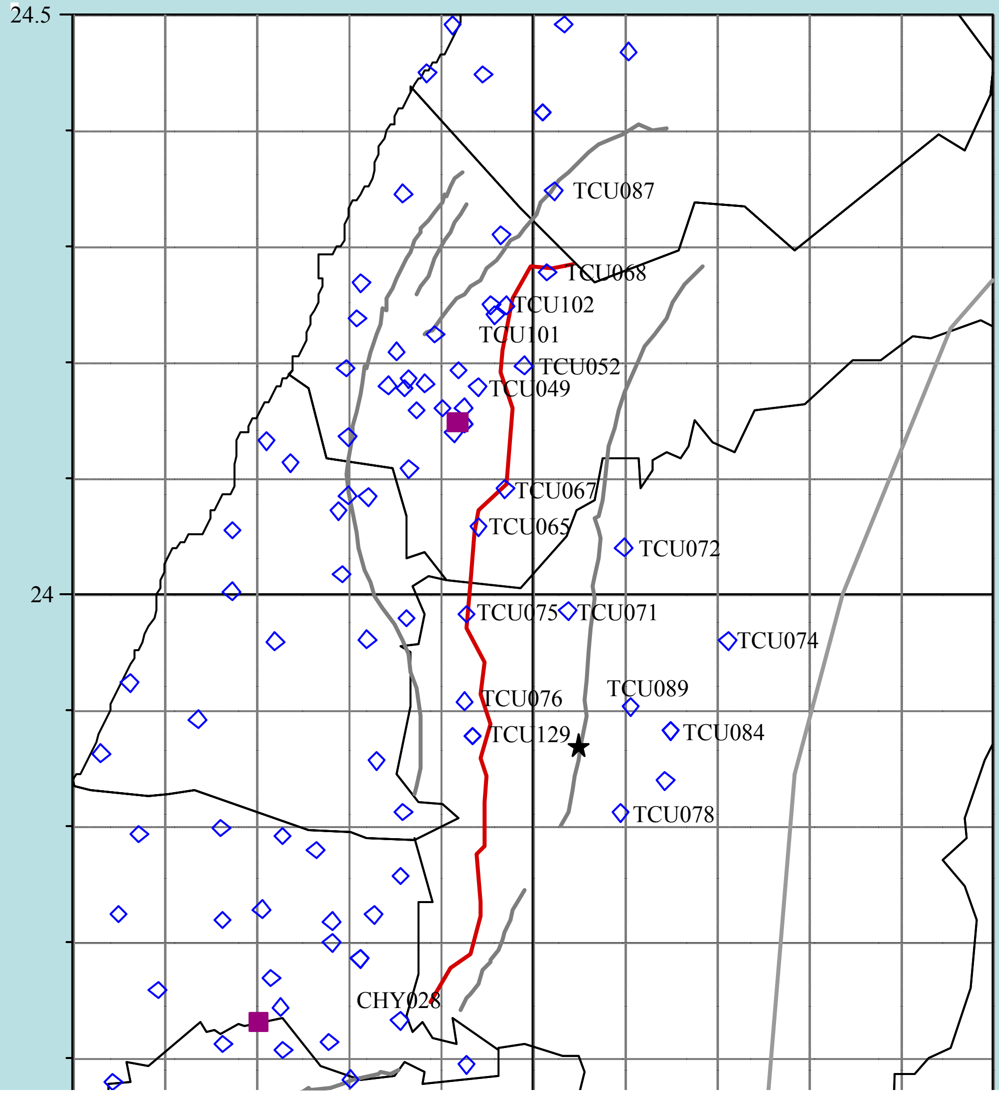
ARC (off end of fault, down strike from epicenter)



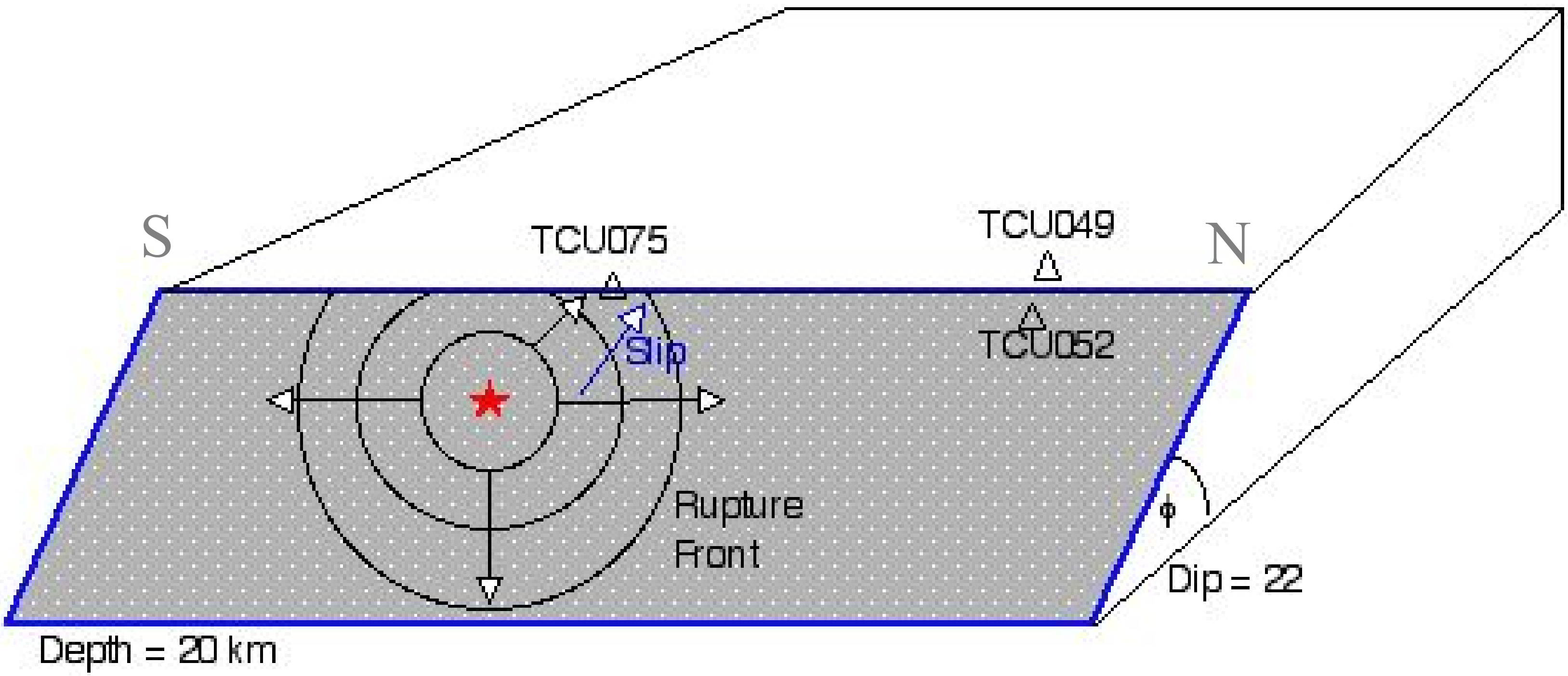
YPT (near fault, down strike from epicenter)



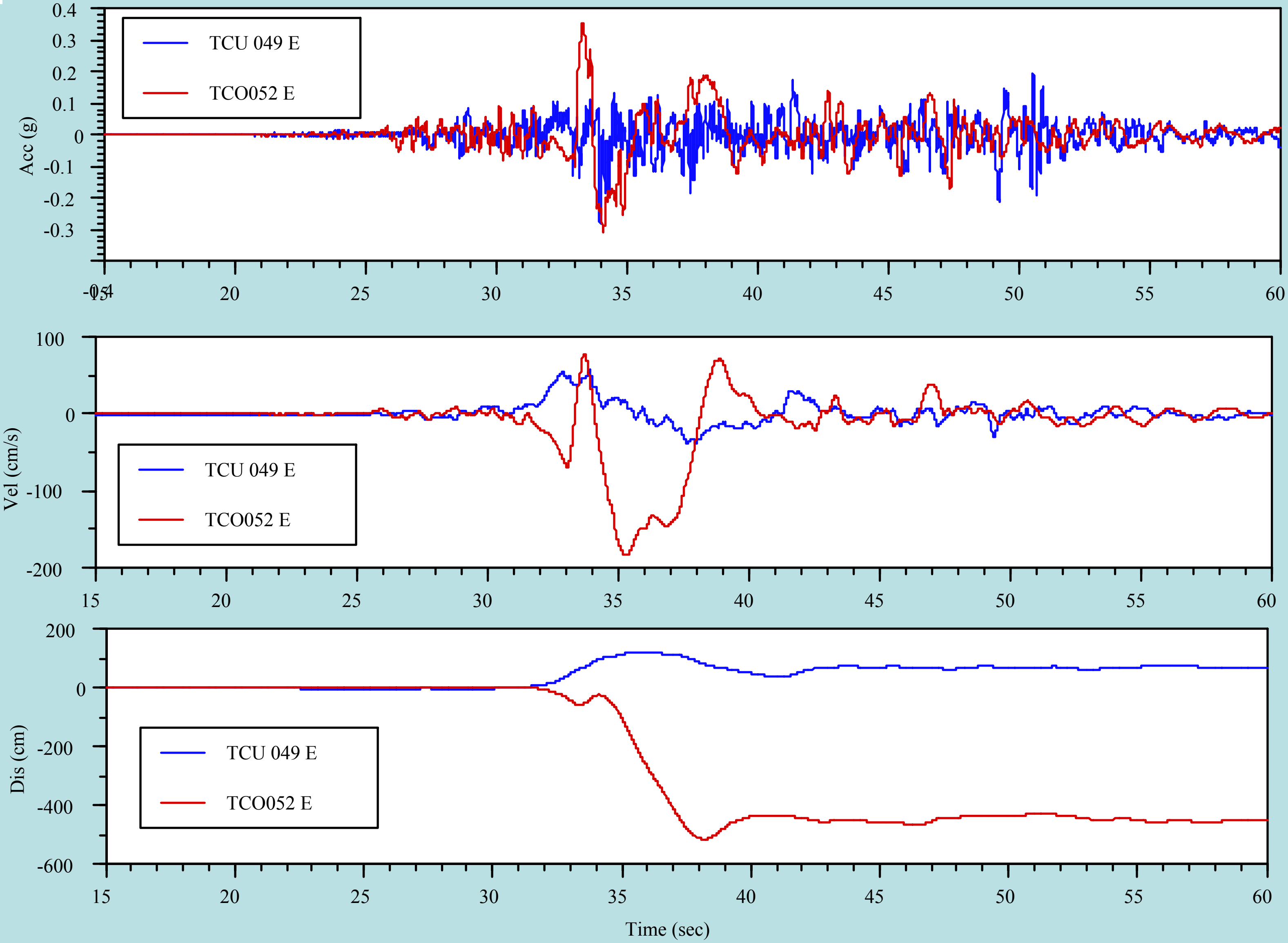
Strong Motion Stations from the Chi-Chi Earthquake



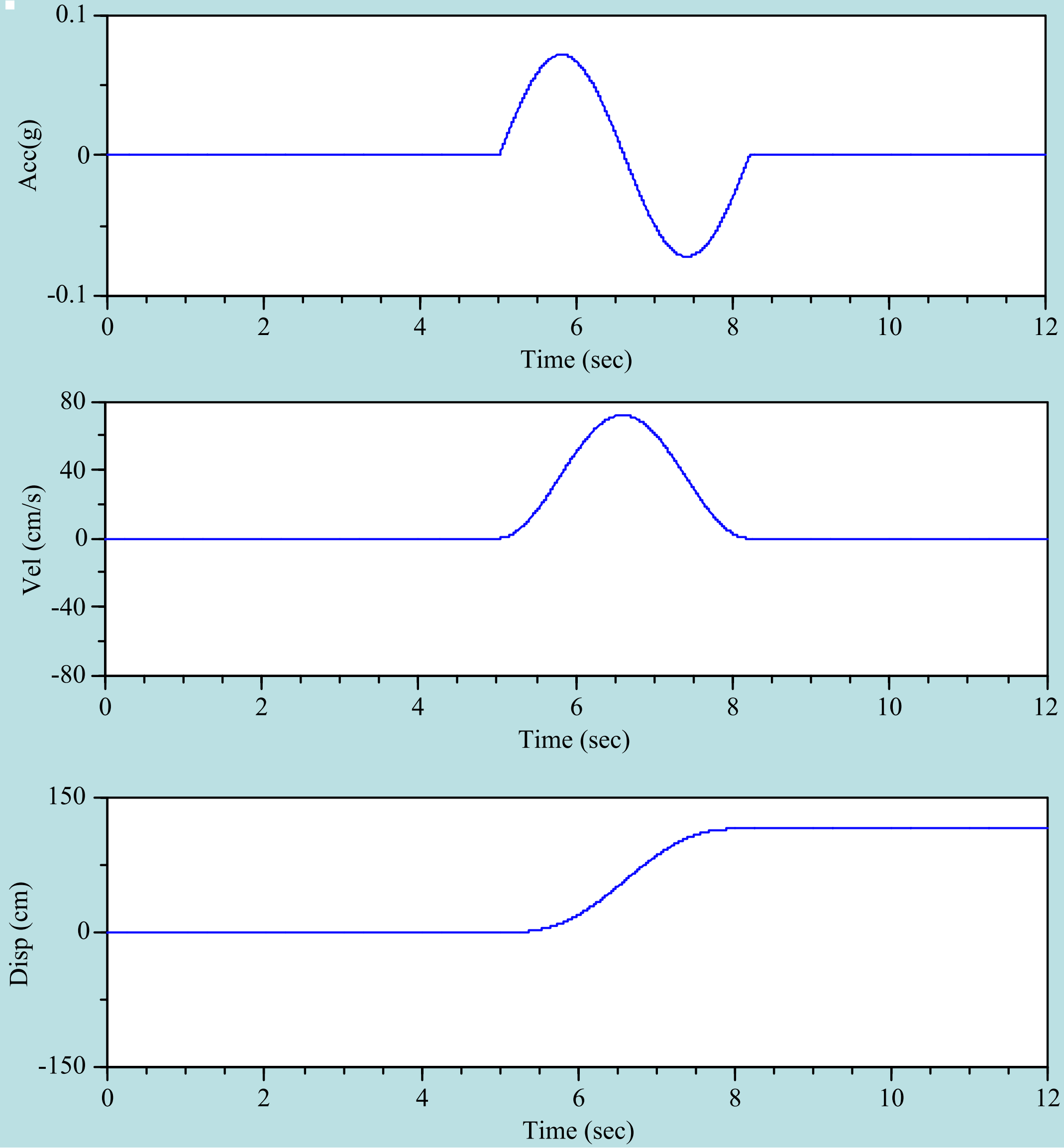
Chi-Chi Earthquake



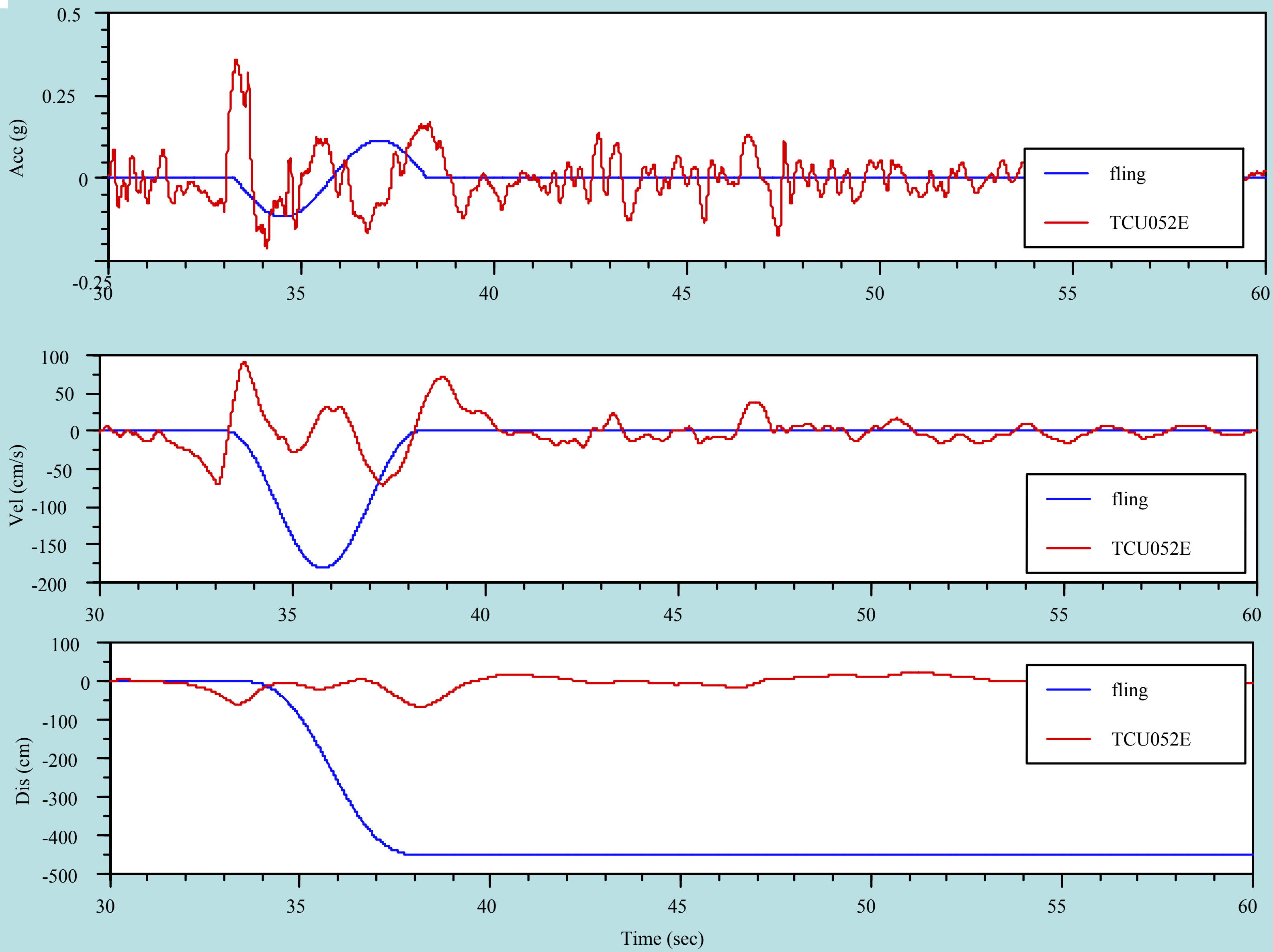
Fling Effects



Time Domain Fling Model



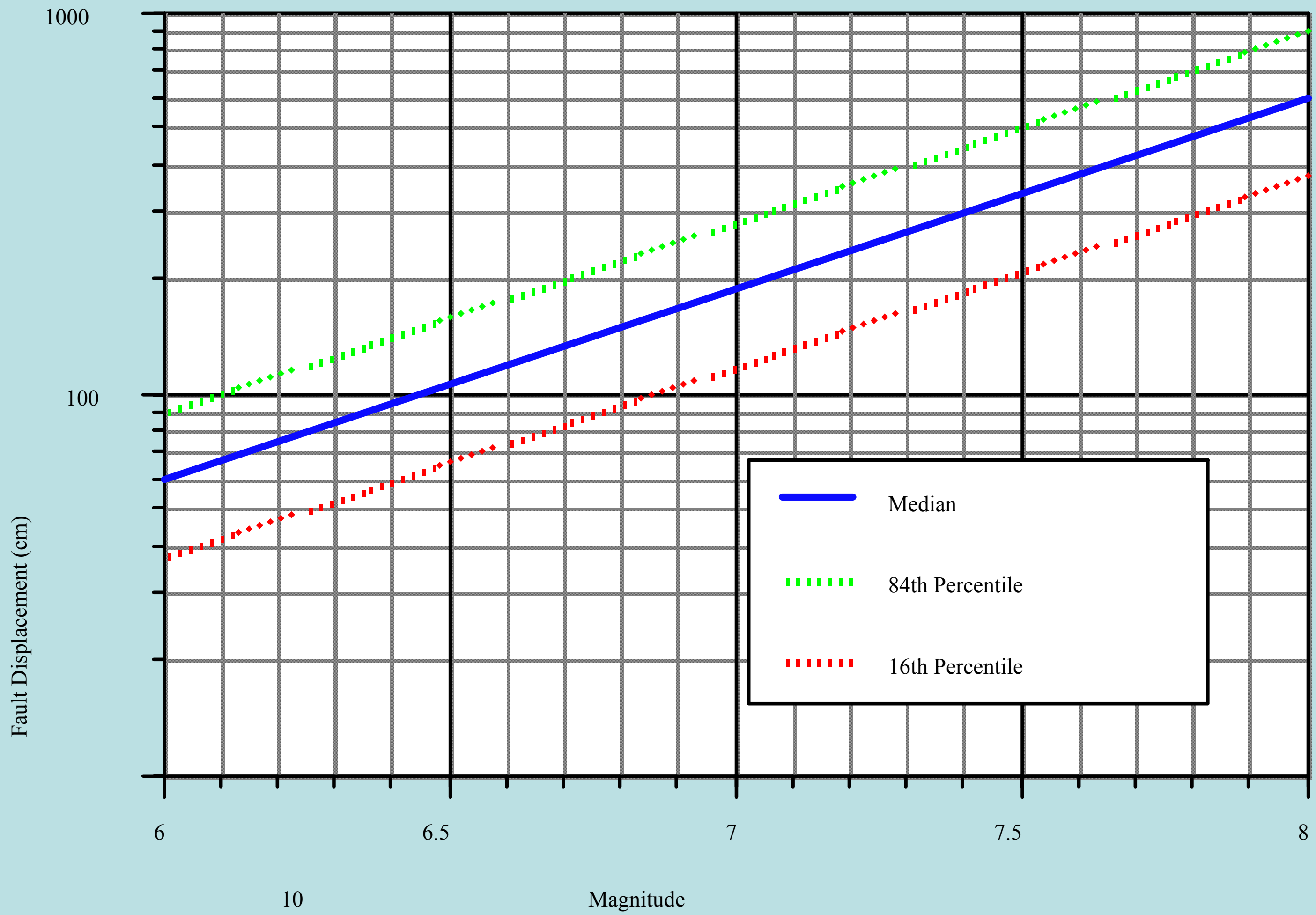
Separation of Fling and Wave Propagation Effects



Parameters Required for Fling

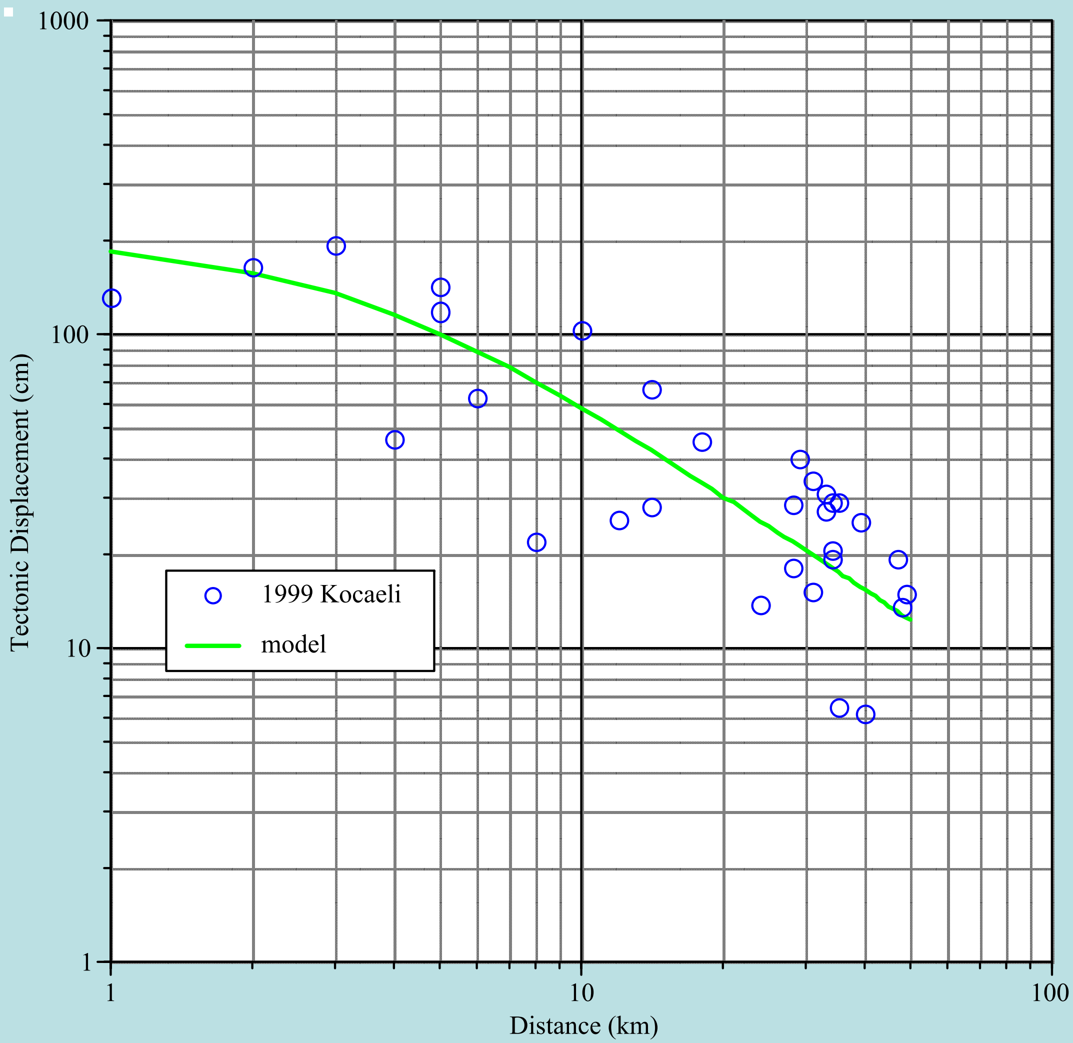
- Amplitude of Fling
  - From fault slip and geodetic data
- Duration (period) of Fling
  - From strong motion data
- Arrival Time of Fling
  - From numerical modeling
  - Relative timing of fling and S-waves

Fault Displacement

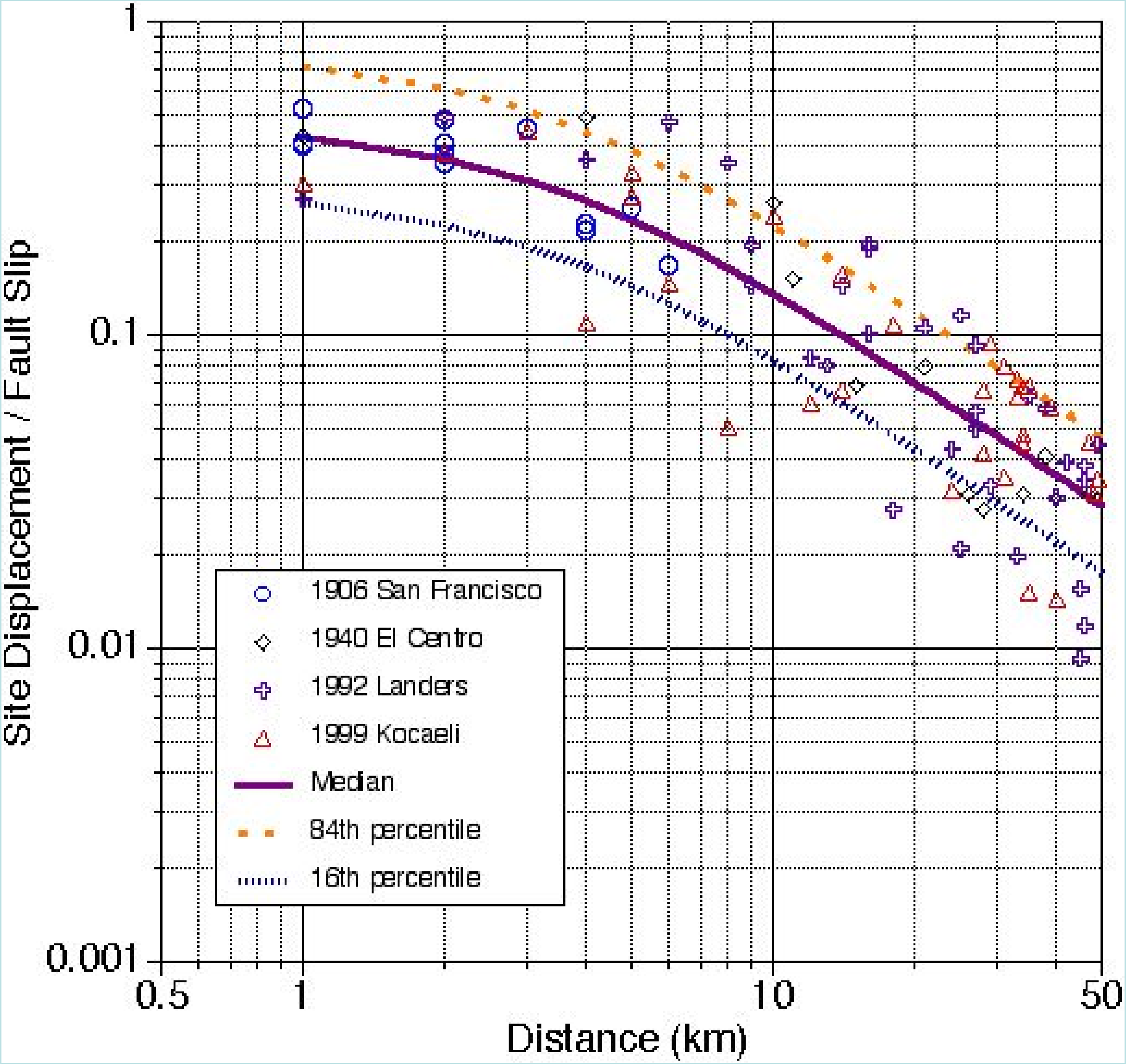


Attenuation of Fling Amplitude

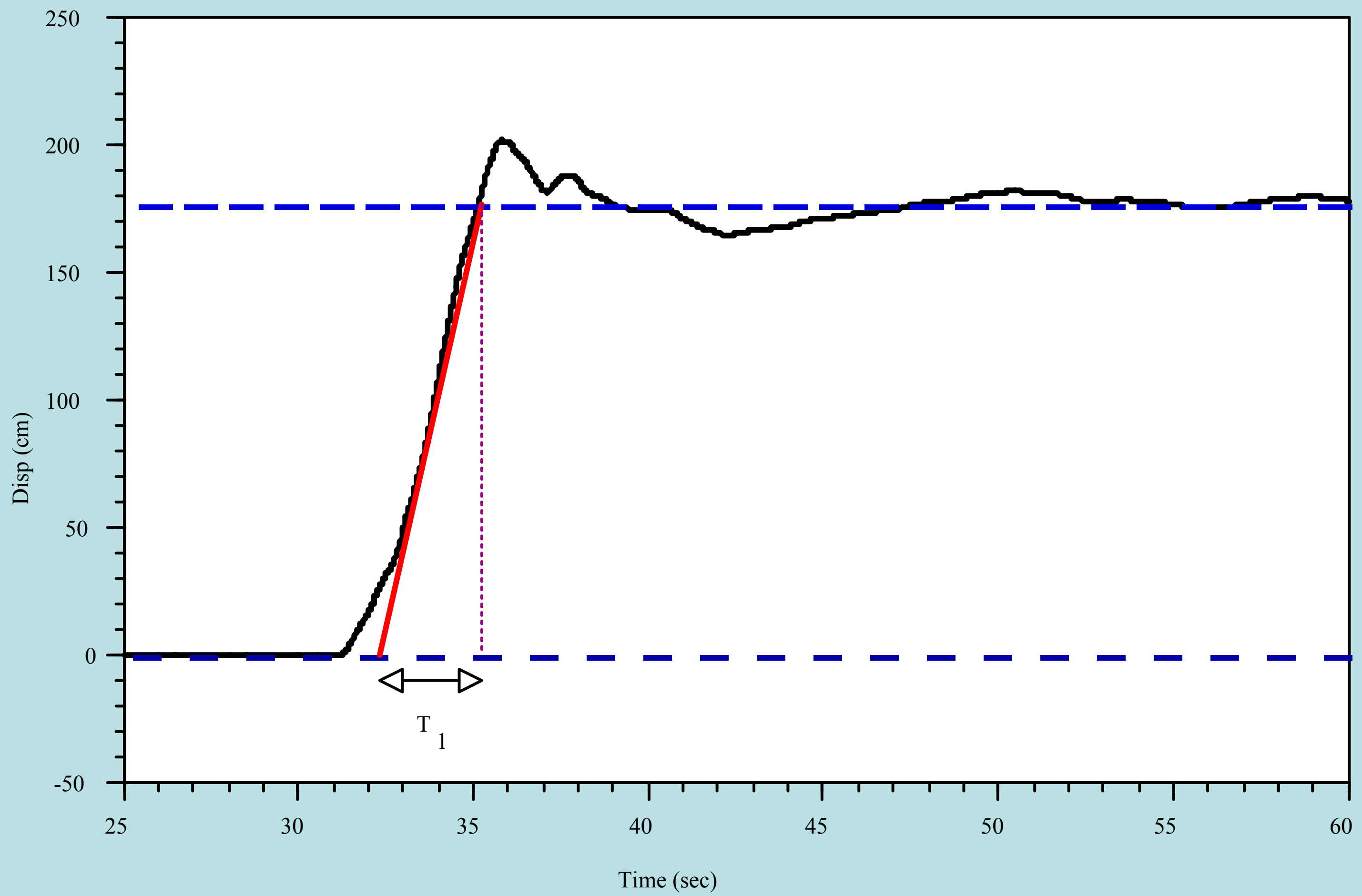
Example from Kocaeli Geodetic Data



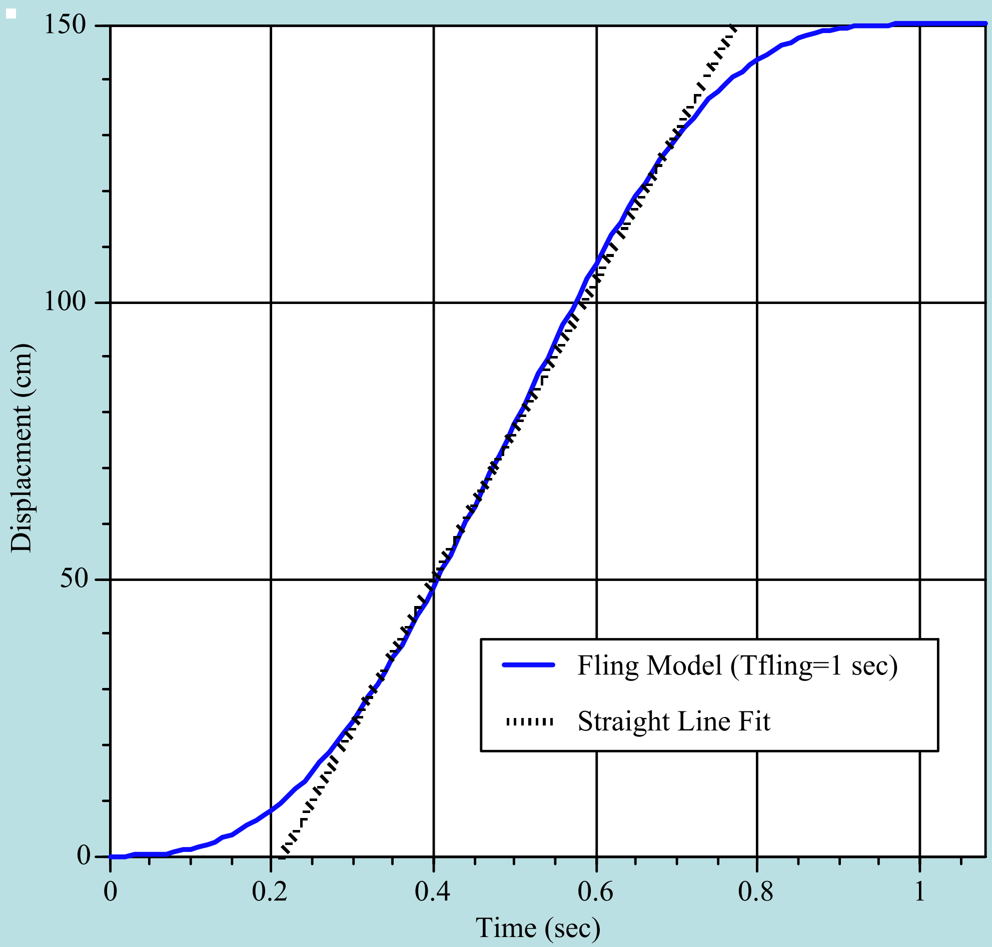
Attenuation of Fling Amplitude



Duration of Fling
Measured from Strong Motion Recordings
(SKR from Kocaeli)

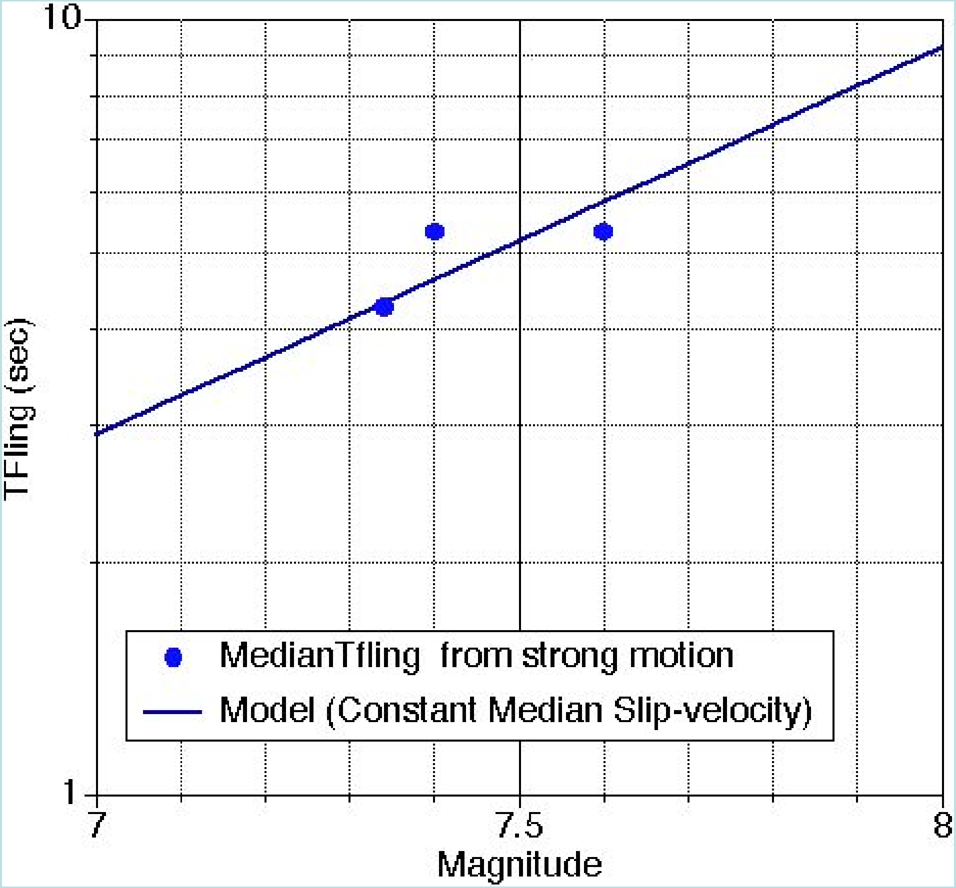


Fling Period



Model for Duration of Fling

(slope fixed by assuming median slip-velocity is independent of magnitude)



Summary of Near Fault Effects from Recent Earthquakes

- Near fault ground motions can have large velocity pulses caused by directivity and/or fling
- Forward Directivity Effects
  - Observed in Kocaeli and Denali earthquakes
    - Consistent with previously derived models
  - Not observed in Chi-Chi earthquake due to shallow depth of hypocenter
- Fling
  - Observed in Kocaeli, Chi-Chi, and Denali

Near Fault Effects

- Current scaling relations for directivity effects are consistent with data from new earthquakes
- Current attenuation relations do not include fling
  - Fling effects scale differently with magnitude and distance than ground motion due to wave propagation
- A separate ground motion model is needed for the fling, which then needed to be combined with the ground motion due to wave propagation

Example Application: DCPP

- Design Earthquake
  - M=7.25
  - Distance = 4.5 km
  - Strike-Slip Mechanism

Directivity Parameters

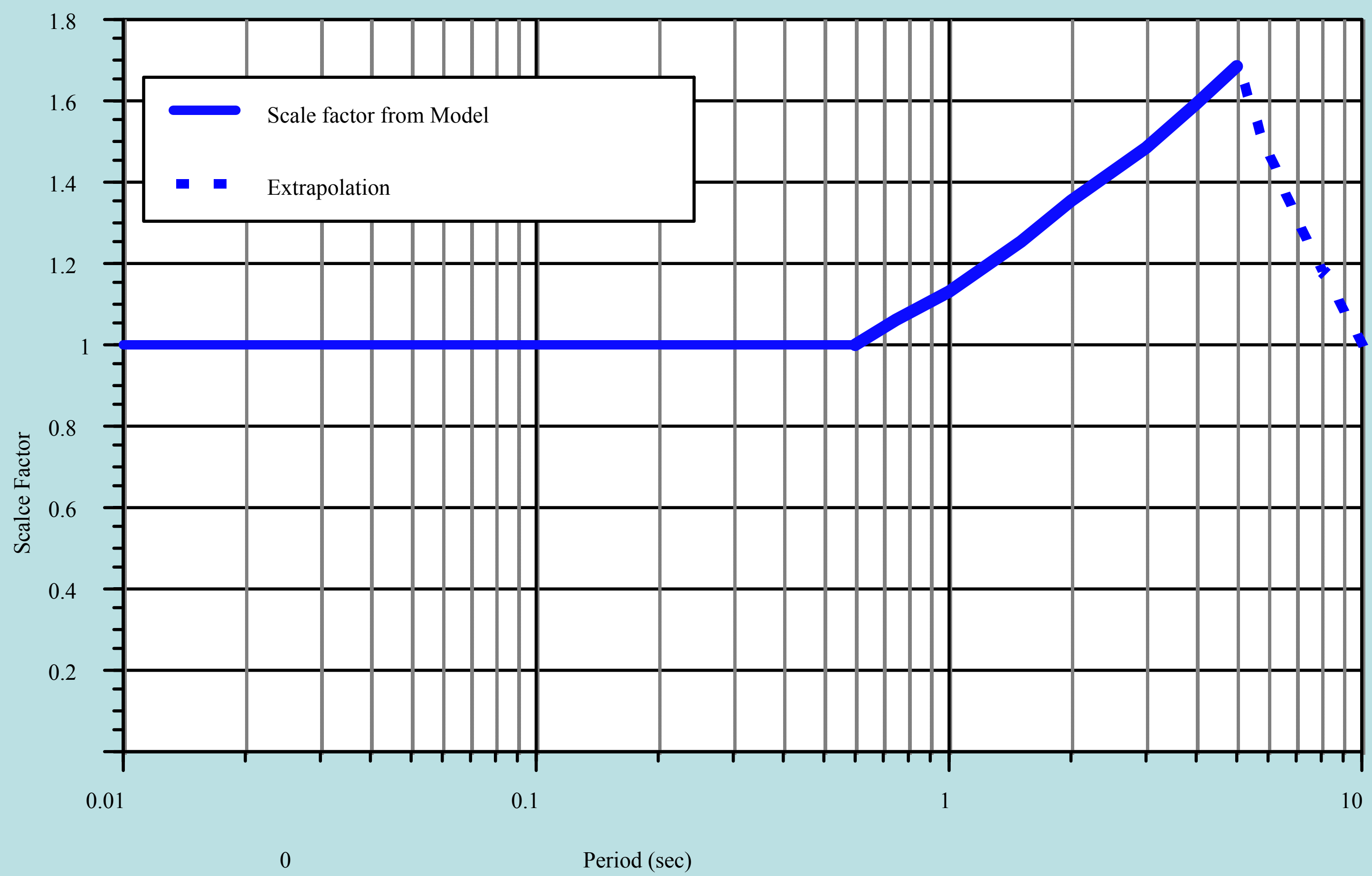
- Epicenter assumed to be located at end of Hosgri fault (maximum directivity effect)

X = 70 km / 110 km = 0.64

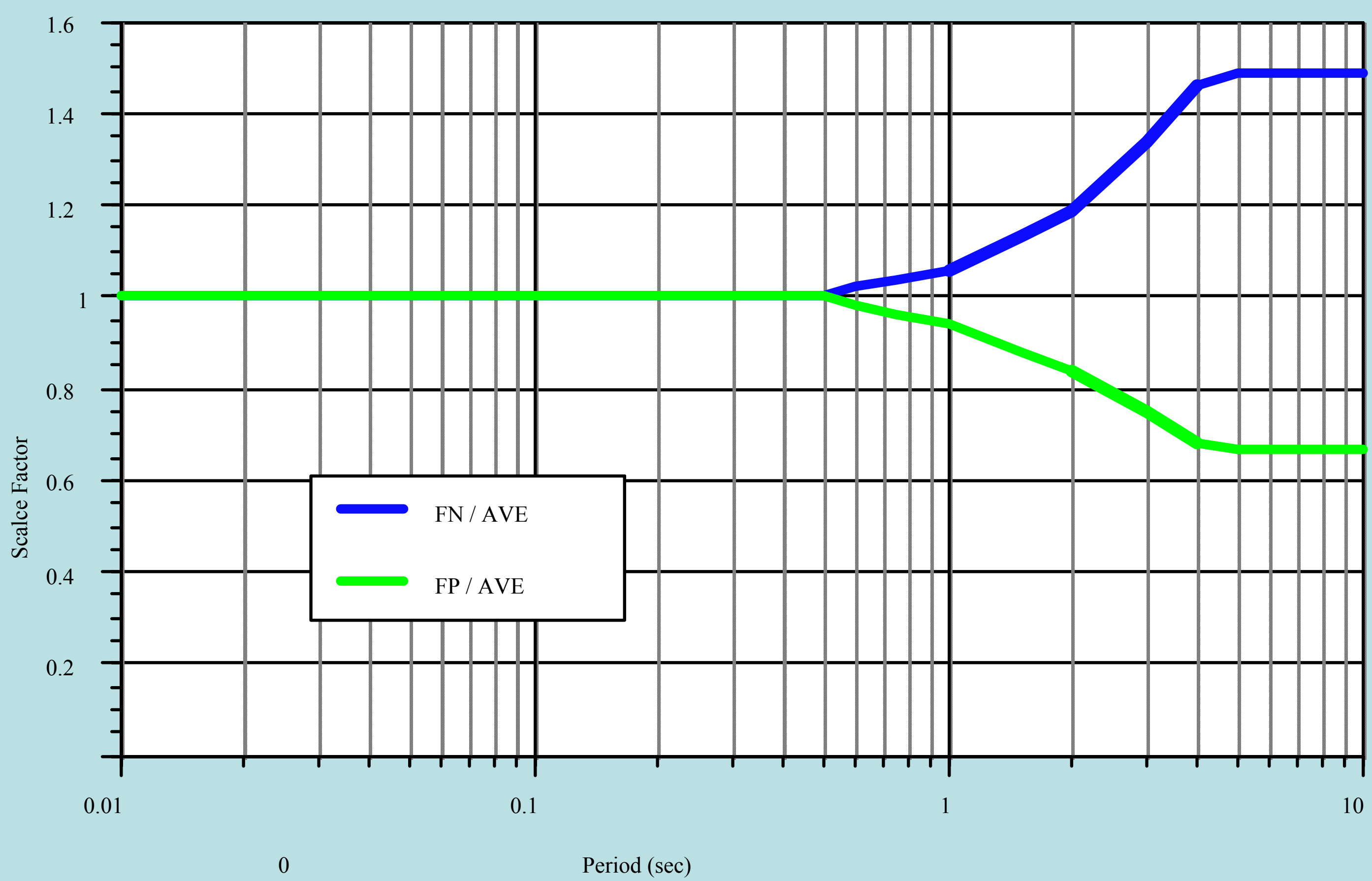
θ = 3 degrees

X cos(θ) = 0.64

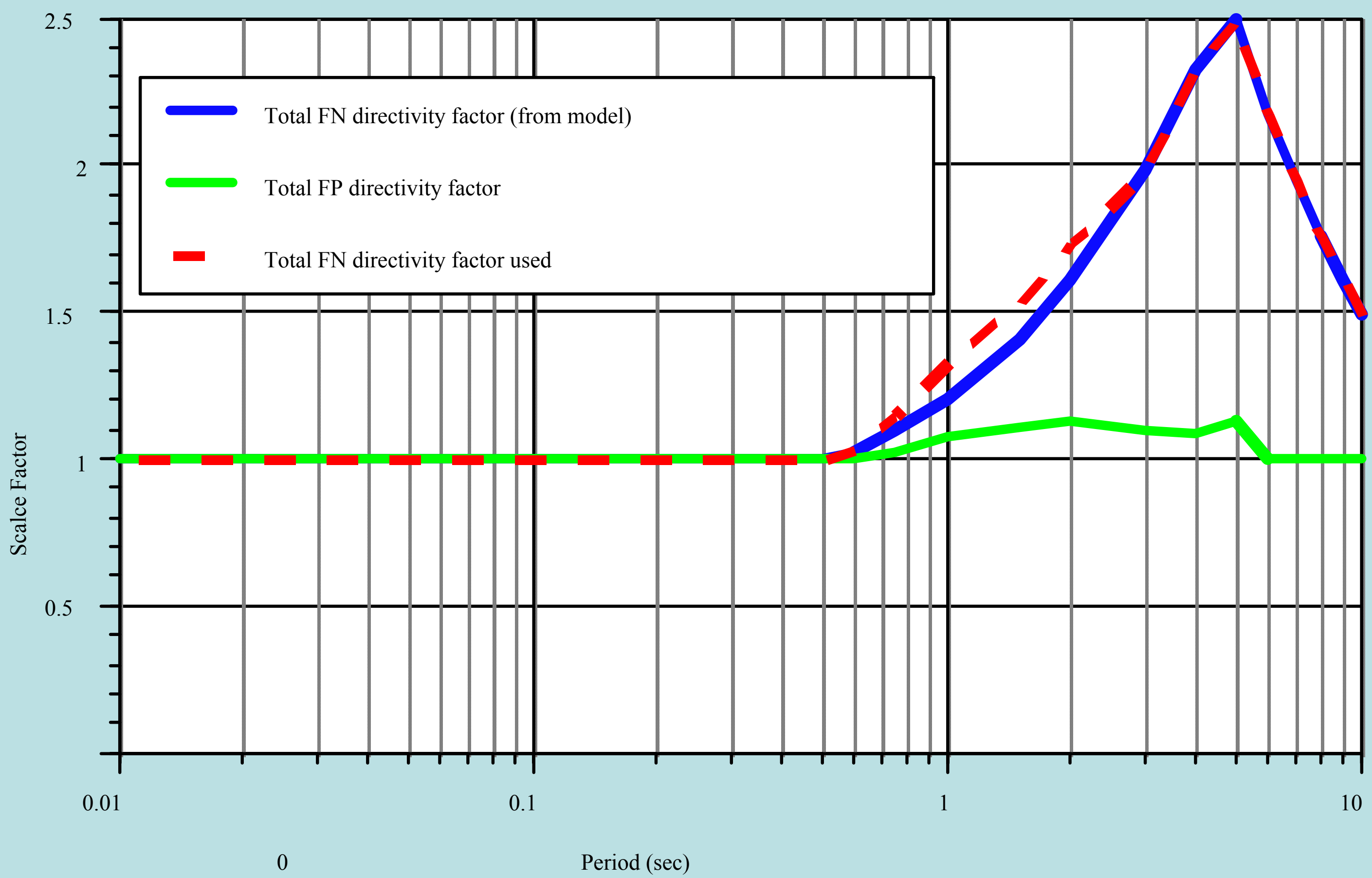
Directivity Effects on the Average Horizontal Component



Directivity Effects on FN/Ave and FP/Ave



Combined Directivity Effects



Fling

- Use 84th Percentile
  - Two parameters: Displacement at site, Fling period
    - Use 84th percentile displacement,
    - Use fling period to give 84th percentile acceleration

Fling Displacement

Median slip on fault = 233 cm

Median disp at site = 59 cm

84th percentile disp at site = 115 cm

Fling Period

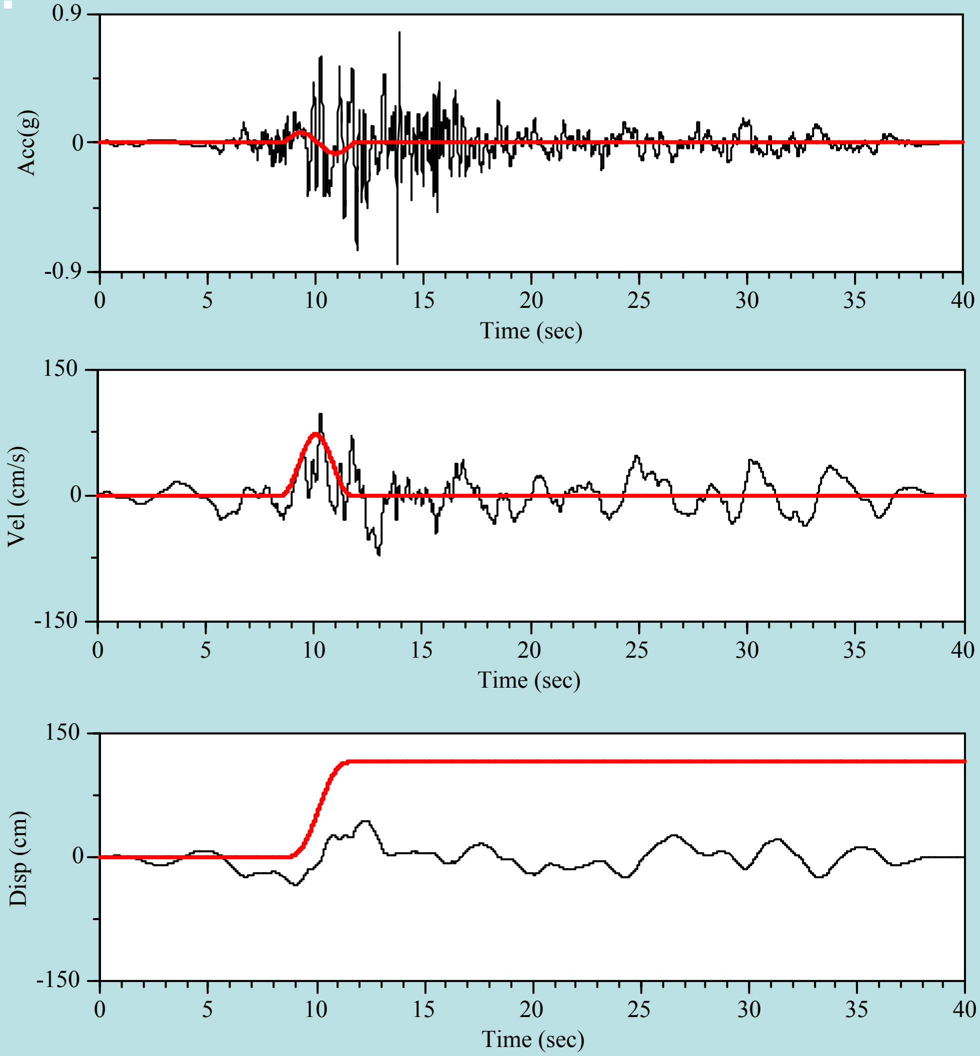
3.2 sec

(84th percentile acc = 0.072g)

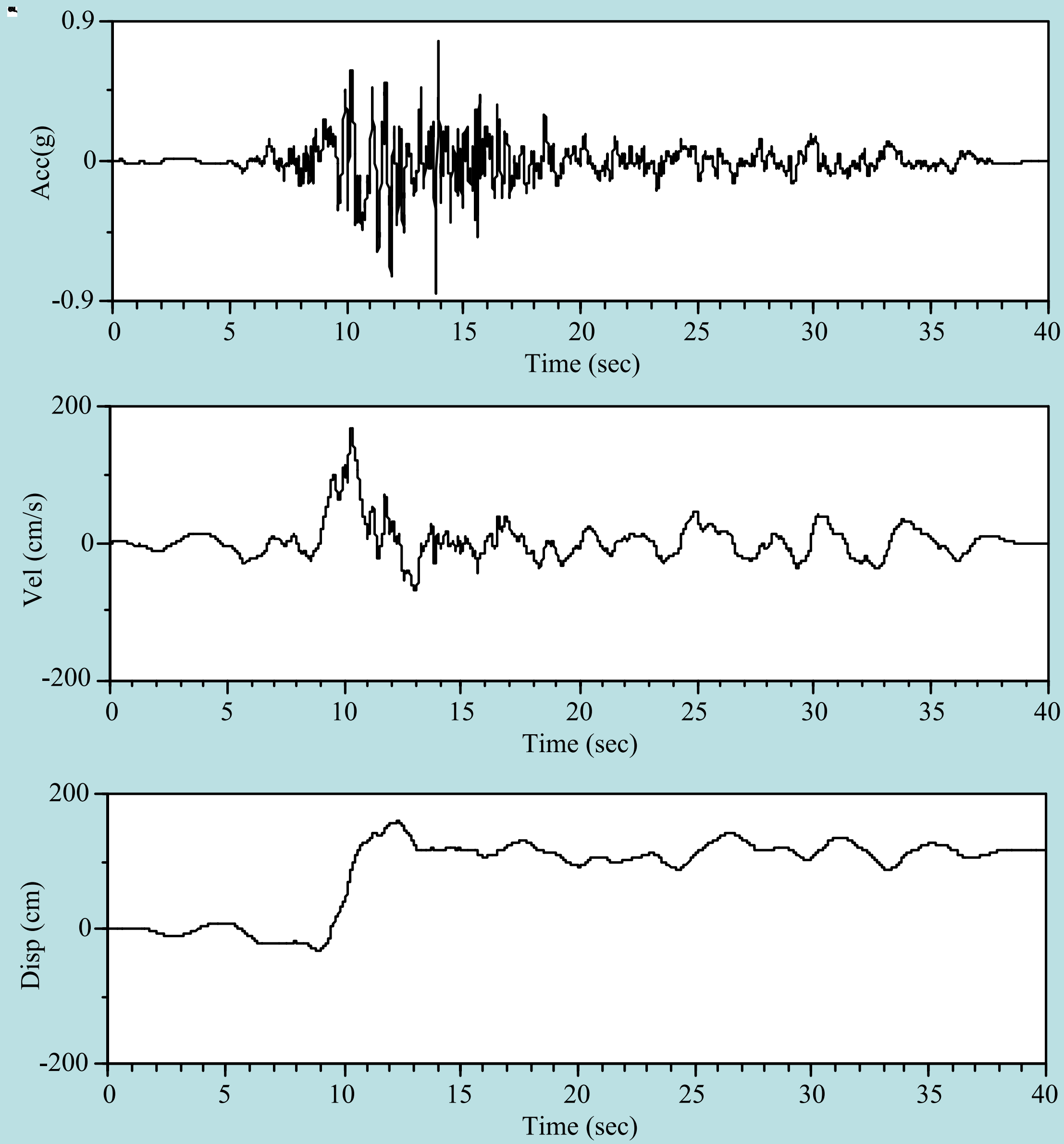
Issues for Combining Fling and Vibratory Ground Motion

- What is the timing between fling and S-waves?
  - For sites close to the fault, fling arrives near the S-wave
- Polarity of fling and S-waves?
  - For design ground motions, require constructive interference of velocity

Example Timing of Fling



Ground Motion with Fling



Average Spectrum Including Fling