Department of Geological Sciences, Faculty of Sciences
Masaryk University/Brno & Czech Geological Society

September 12-14, 2011

Short Course on Geological Hazards

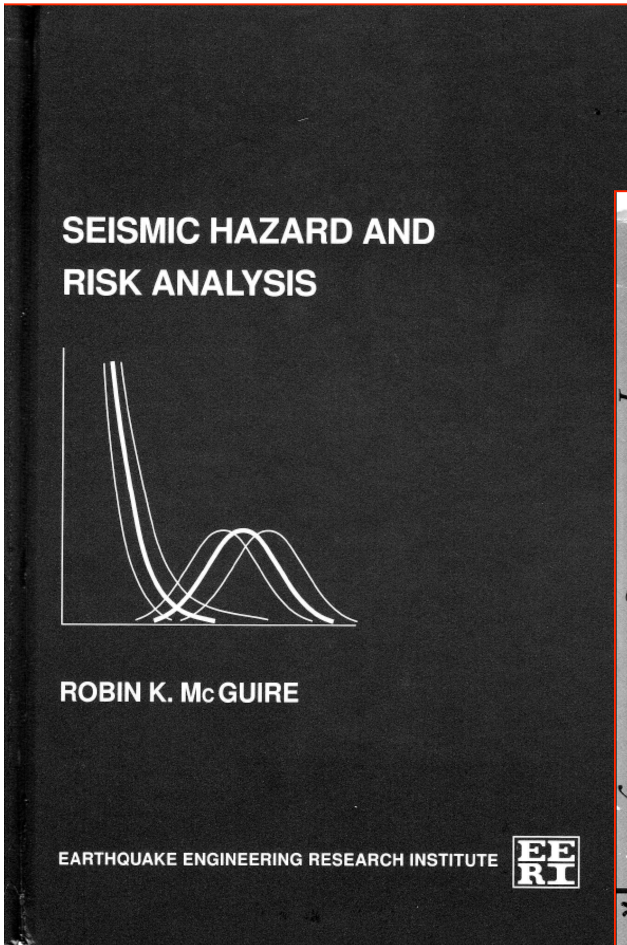
Day 2 (Tue AM), Lecture 3:

(Combines Topics 2 and 3 of Original Announcement)

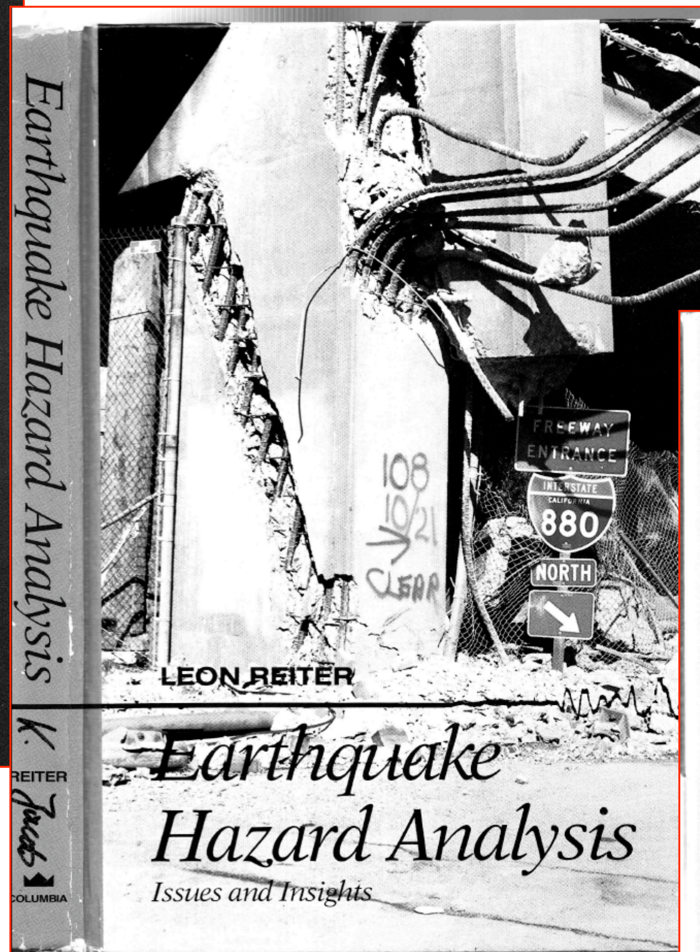
Basics of PSHA, with Examples for 2 US Bridges in Stable Continental Regions (SCR)

Klaus H. Jacob

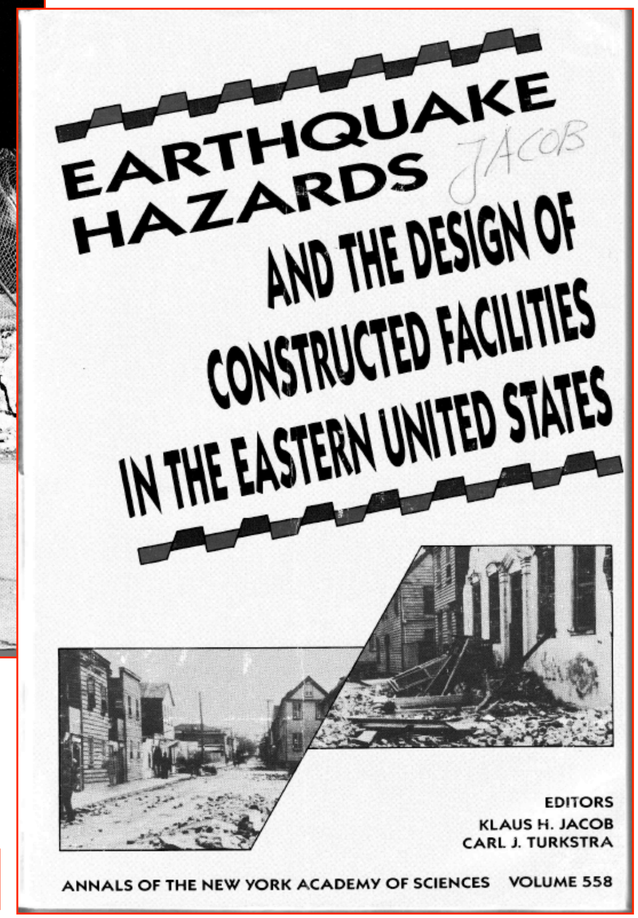
Lamont-Doherty Earth Observatory
of Columbia University, NY
jacob@ldeo.columbia.edu



2004



1990



1989

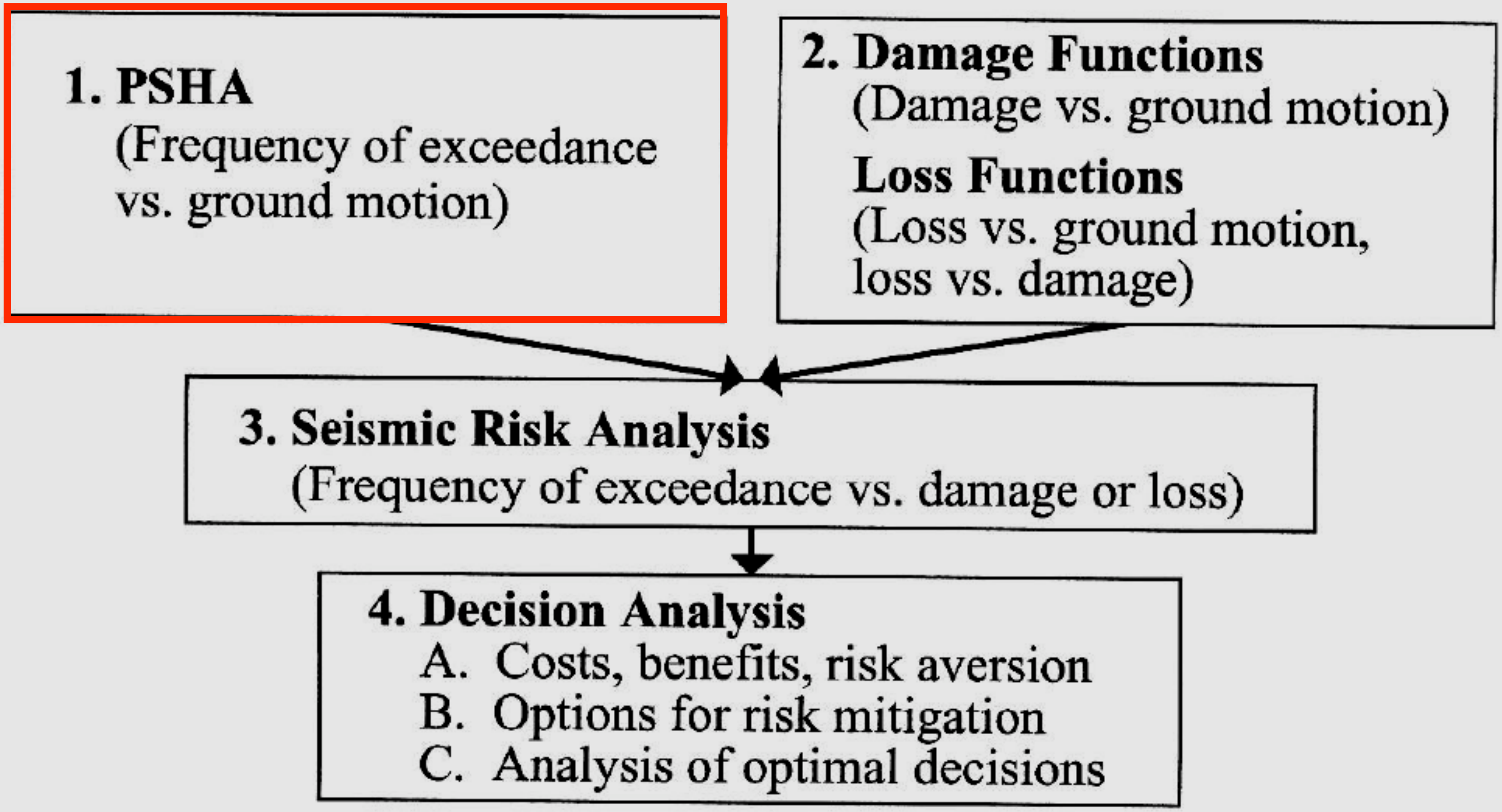


Figure 1. Steps in the mitigation of earthquake risk.

McGuire 2004

Table 1. Examples of uncertainties in seismic hazard analysis.

Aleatory Uncertainties U_a (Natural Randomness)

- Future earthquake locations
- Future earthquake source properties (e.g., magnitudes)
- Ground motion at a site given the median value of motion
- Details of the fault rupture process (e.g., direction of rupture)

Epistemic Uncertainties U_e (Modeling Uncertainties, Lack of Knowledge & Understanding)

- Geometry of seismotectonic and seismogenic zones
- Distributions describing source parameters (e.g., rate, *b* value, maximum magnitude)
- Median value of ground motion given the source properties
- Limits on ground shaking

McGuire 2004

PSHA applies Protocols (e.g. in US: "SSHAC") for Soliciting "Expert Opinions" that then are formally taken into account to quantify the combined effects of U_a and U_e

Science Tasks for Probabilistic Seismic Hazard Assessment (PSHA)

- **Create Cleaned-Up Earthquake Catalog**
  - Translate Intensity ==> Magnitude
  - Translate Various Magnitudes ==> Uniform Moment Magnitude, Mw Preferred
  - Completeness Checks, Remove Aftershocks, Other Checks: Doubles, Blasts, ...
- **Choose Seismic Source Zones**
  - Gridded Seismicity: Grid Size and Smoothing Parameter (==> a_{grid} , b)
  - Source Zone Geometry , Fit Rate Relation ==> $n(M_w)$, a, b, Max, h?
  - Faults, their Slip- or Moment-Rates; Characteristic Earthquakes M_{ch}?
- **Ground Motion Relations: Select from available (a,v,u, PSA,PSV,PGA)= f(M,d,h,ε)**

PSHA Procedural Steps:

- Choose "SSHAC" (or equivalent) Project Level/Protocol & Assemble Expert Team
- Choose PSHA Computer Algorithm
- Assign Multiple Model Choices and Logic Tree with Branch Weights
- Compute *n*(C≥c) per Site & for all Sources & for all Branches in Logic Tree
- Plot Results as Hazard Curves (n=n(c)) for Spectral Frequencies fi; Mean, Median
- Choose Probability Levels (Tr) and make respective Uniform Hazards Spectra
- Perform Deaggregation for (M*,d*,ε) at Given Ground Motion Values c*
- Obtain recorded or synthetic Ground Motions g(t) for M*,d* at given Tr
- Modify Ground Motion g(t) to be spectrally compatible with UHS at given Tr

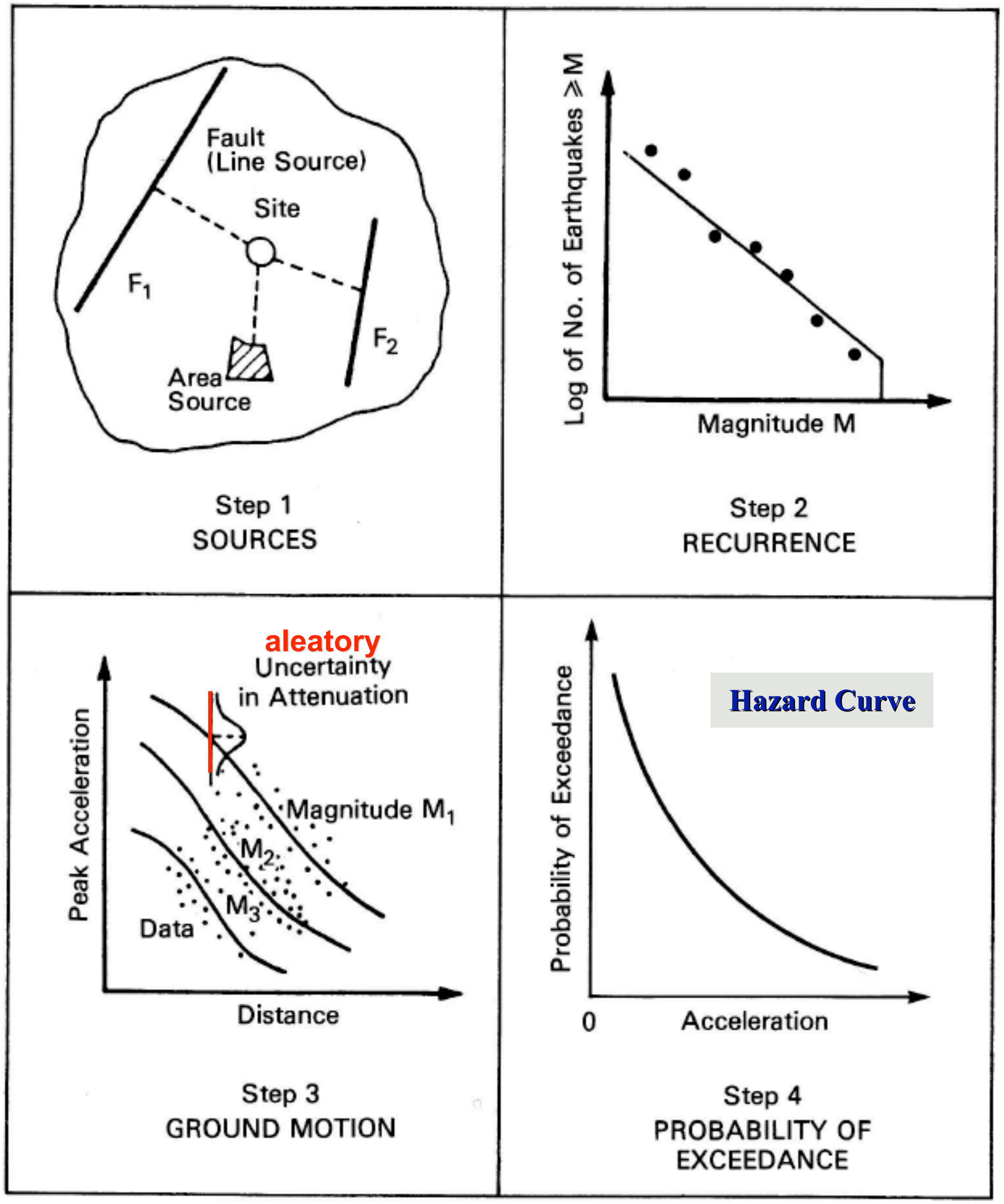


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

Basic Equation for Probabilistic Seismic Hazard Assessment, PSHA

before Consideration of Epistemic Uncertainties

$$E(z) = \sum_{i=1}^{N} \alpha_i \int_{m_o}^{m_u} \int_{r=0}^{r=\infty} f_i(m) f_i(r) P(Z > z | m, r)\, dr\, dm$$

E(z) Expected number of exceedances of ground motion levels **Z≥z** during period t

α_i is the mean rate of occurrence of earthquakes between lower and upper magnitudes (m_o and m_u) for source I during period t; (e.g. given by the (truncated) G-R relation).

N is the number of source zones considered

$f_i(m)$ is the probability density distribution of magnitude (recurrence relationship) for source i;

$f_i(r)$ is the probability density distribution of epicentral or source distances for between the various locations within source i and the site for which the hazard is being estimated;

P(z>z|m,r) is the probability that a given earthquake of magnitude **m** and epicentral distance **r** will exceed the ground motion level **z** (related to the used ground motion relation, **including its aleatory uncertainty).**

Reiter 1990

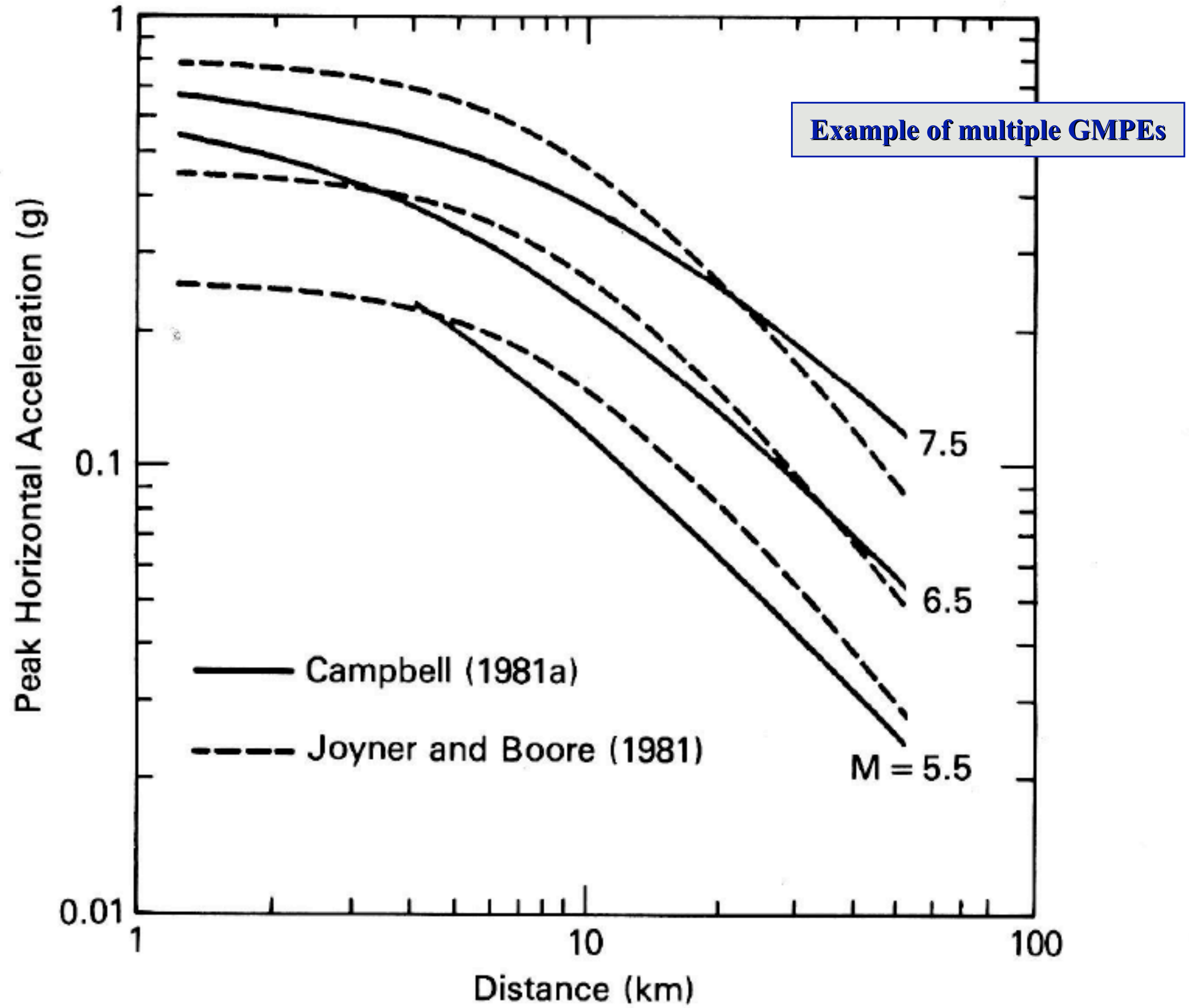


FIGURE 7.4 Median (50th percentile) estimates for peak horizontal acceleration from Campbell (1981a) and Joyner and Boore (1981). Joyner and Boore (1981) estimates of the maximum horizontal component have been reduced by 12% so that they may be compared with the (Campbell 1981a) estimates of the mean horizontal component (after Campbell 1981a).

How to treat epistemic (model) uncertainties U_e?

==> Logic Trees

Rules for Logic Trees:

Each Node has different Model Branches for the same topical Object (e.g. different Ground Motion Prediction Equations)

Each Branch emerging from a Node has a weight w assigned. The Sum of the Branch Weights at each Node must be 1 !

The end weights W at the ends of each branch sequence, i.e. at the local "top" of the tree, is the Product W of all branch weights w, running from the trunk to the last branch or "twig" at the top of the tree.

When you add up all the end weights W, located at the tops of the tree, the Sum must add up to 1 !

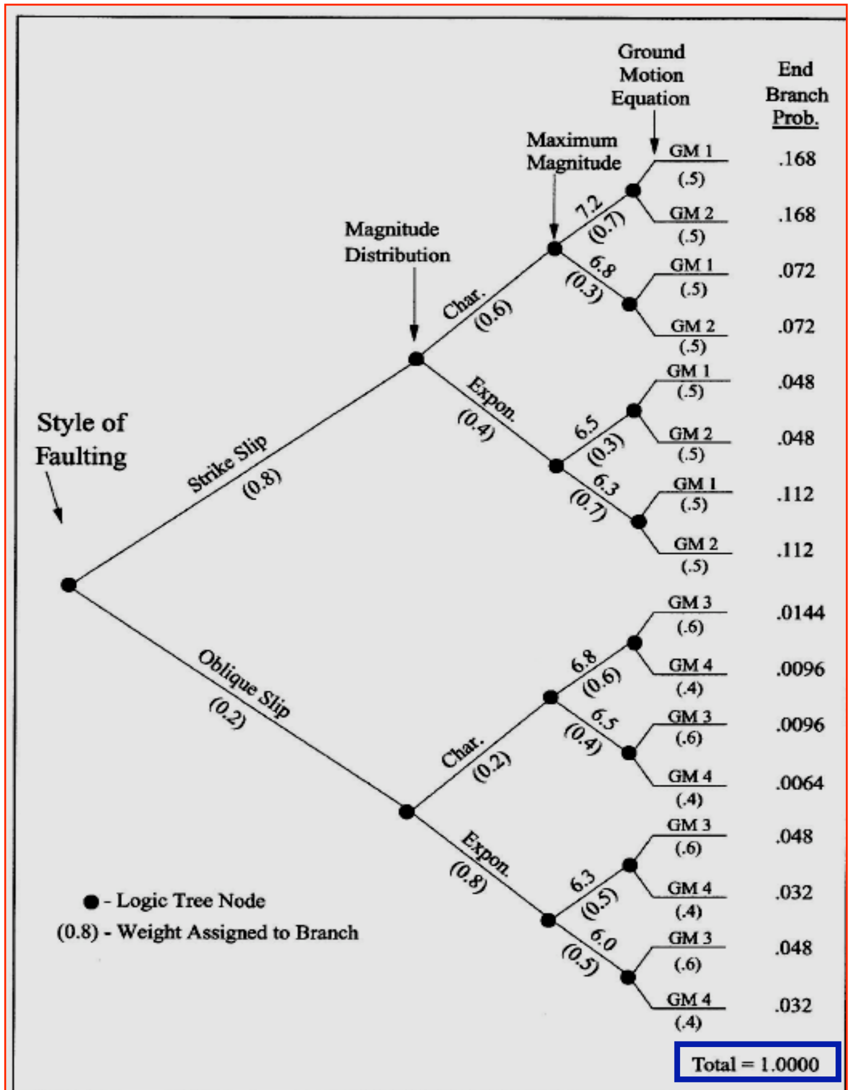
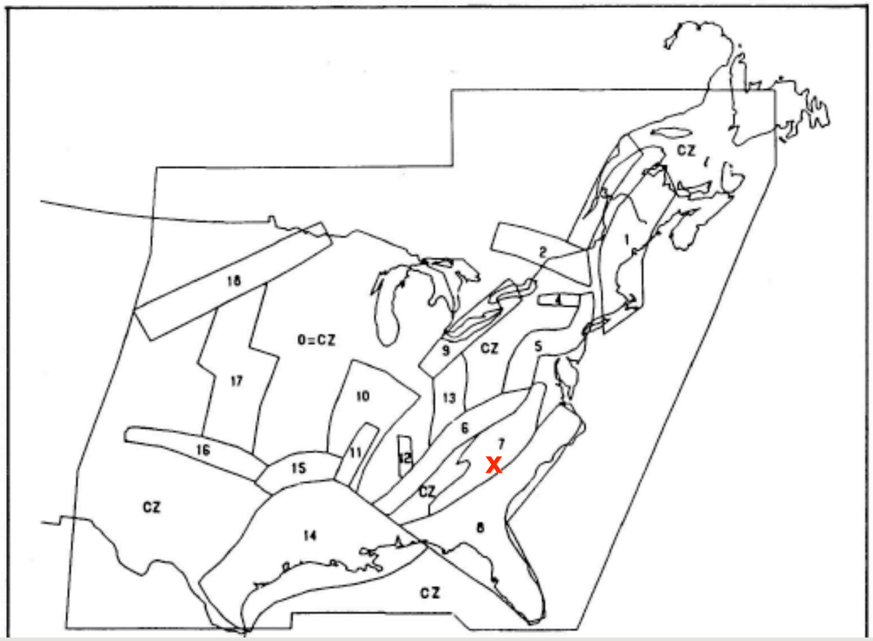
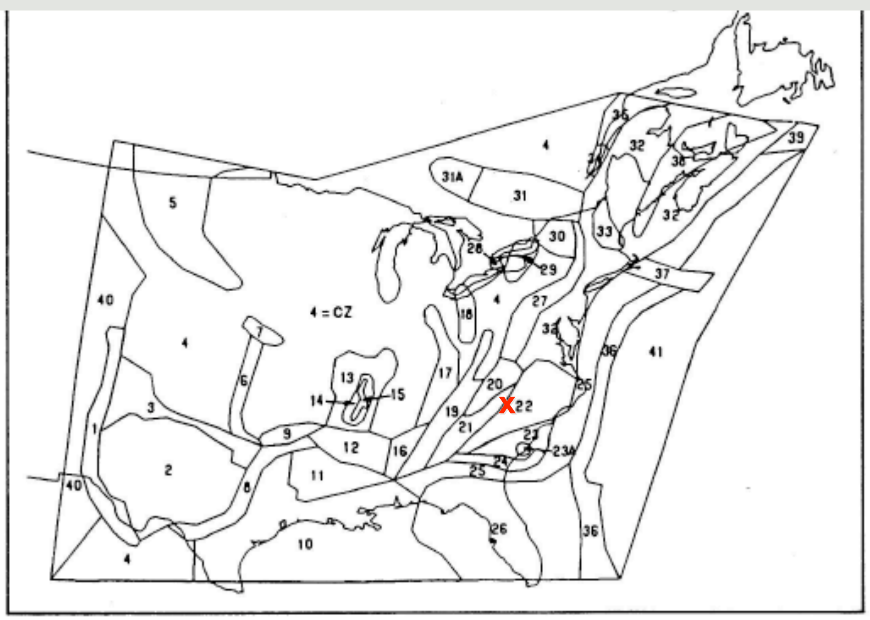


Figure 50. Sample logic tree for one fault.



Example of 2 different Expert Teams coming up with 2 different Seismic Source Zone models.



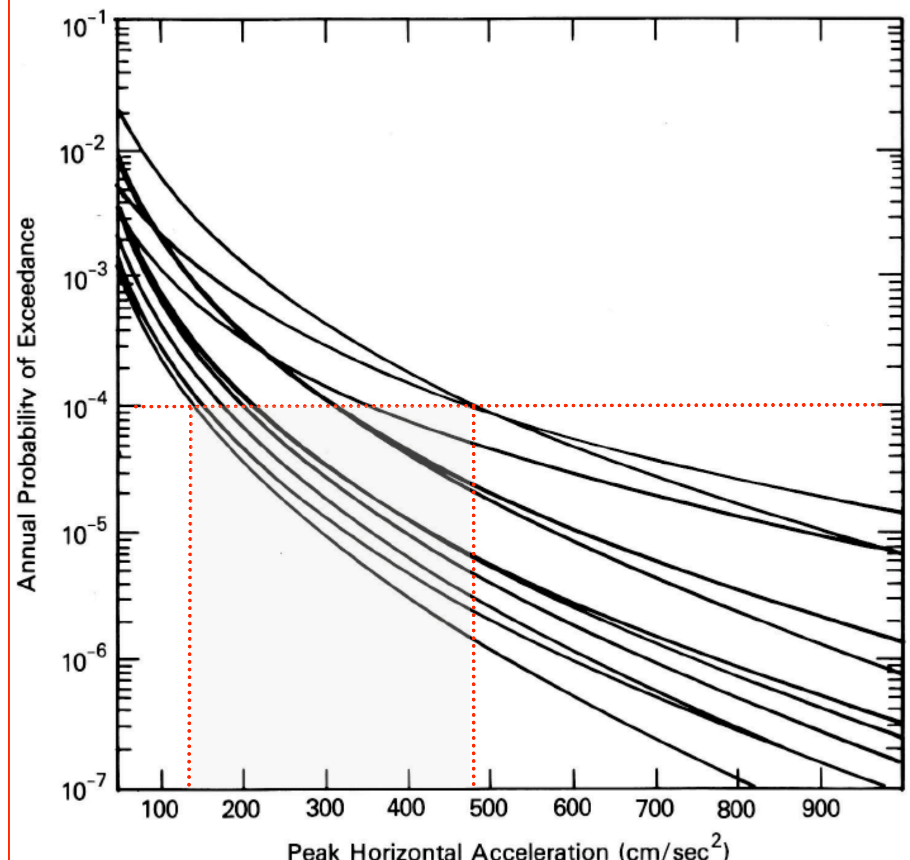


FIGURE 11.2 Hazard curves for the Vogtle Nuclear Power Plant site in Georgia based on best estimate source zone characteristics of eleven experts (after Bernreuter and others 1989).

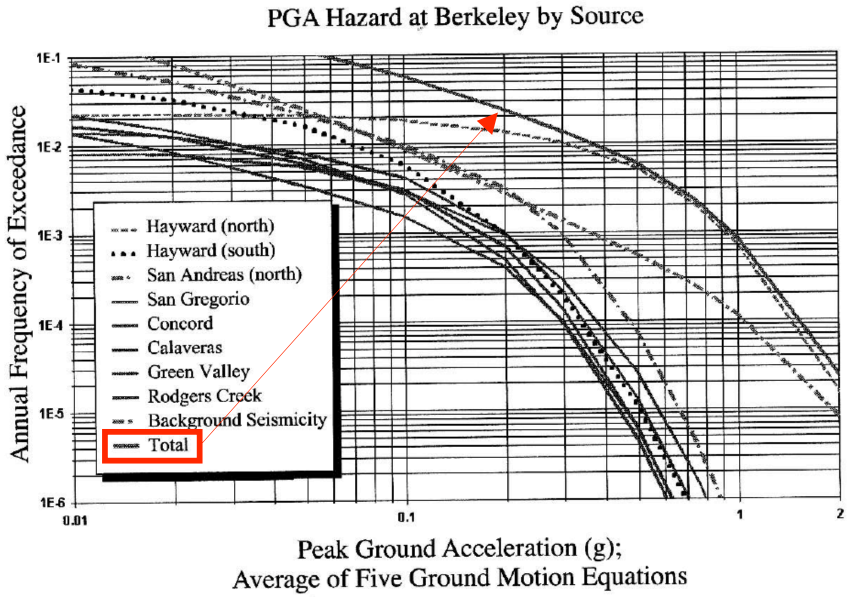


Figure 29. Contribution to the PGA hazard in Berkeley, for each fault and background seismicity.

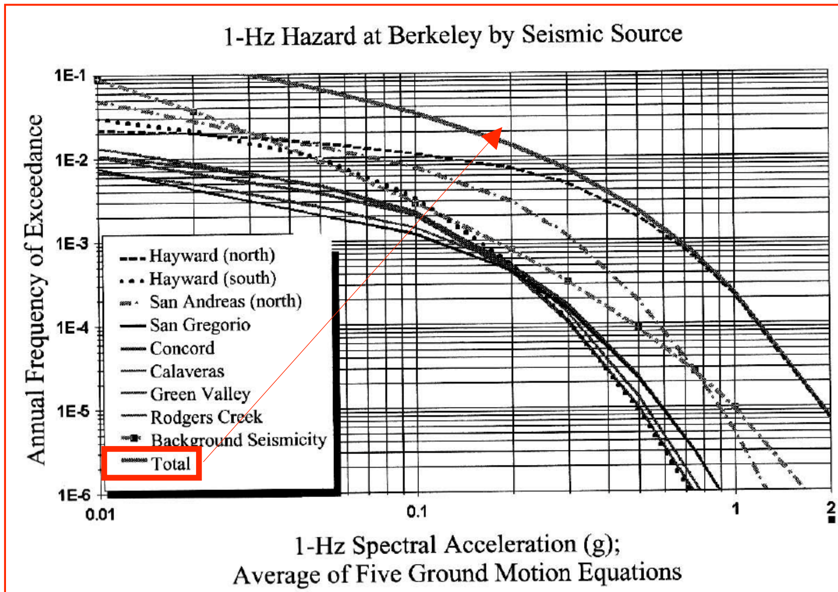


Figure 30. Contribution to the 1-Hz *SA* hazard in Berkeley, for each fault and background seismicity.

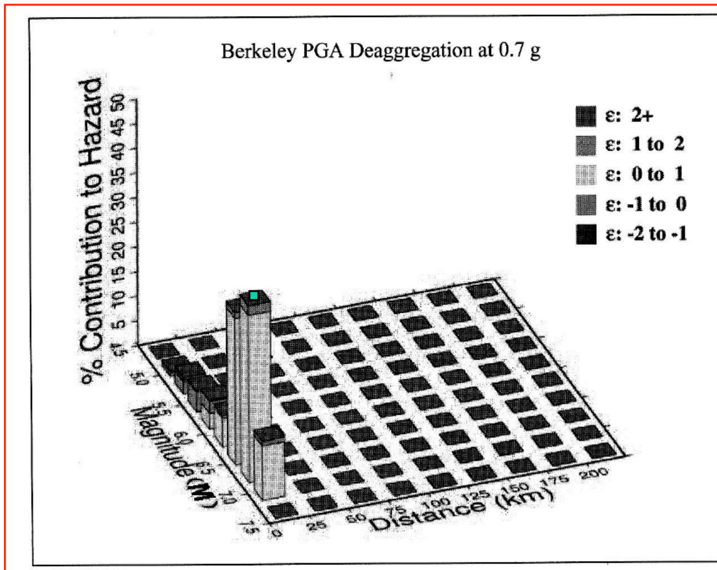


Figure 36. Deaggregation of the 0.7-g PGA hazard from the Hayward fault by **M**, *r*, and ε_C.

M* = 6.9
d* ≤ 12.5 km

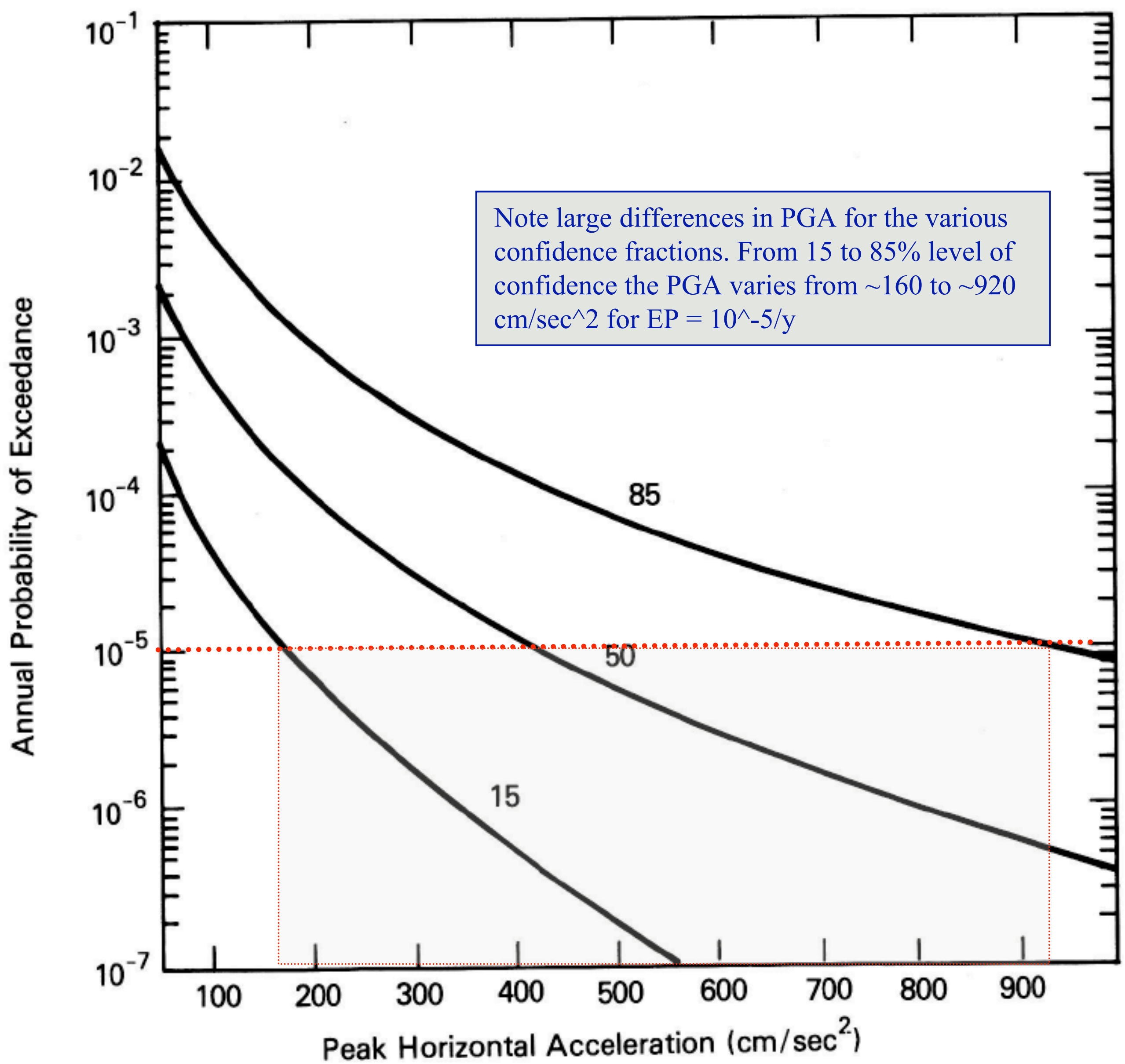


FIGURE 10.4 15th, 50th and 85th constant percentile hazard curves for the Vogtle Nuclear Power Plant site in Georgia (after Bernreuter and others 1989).

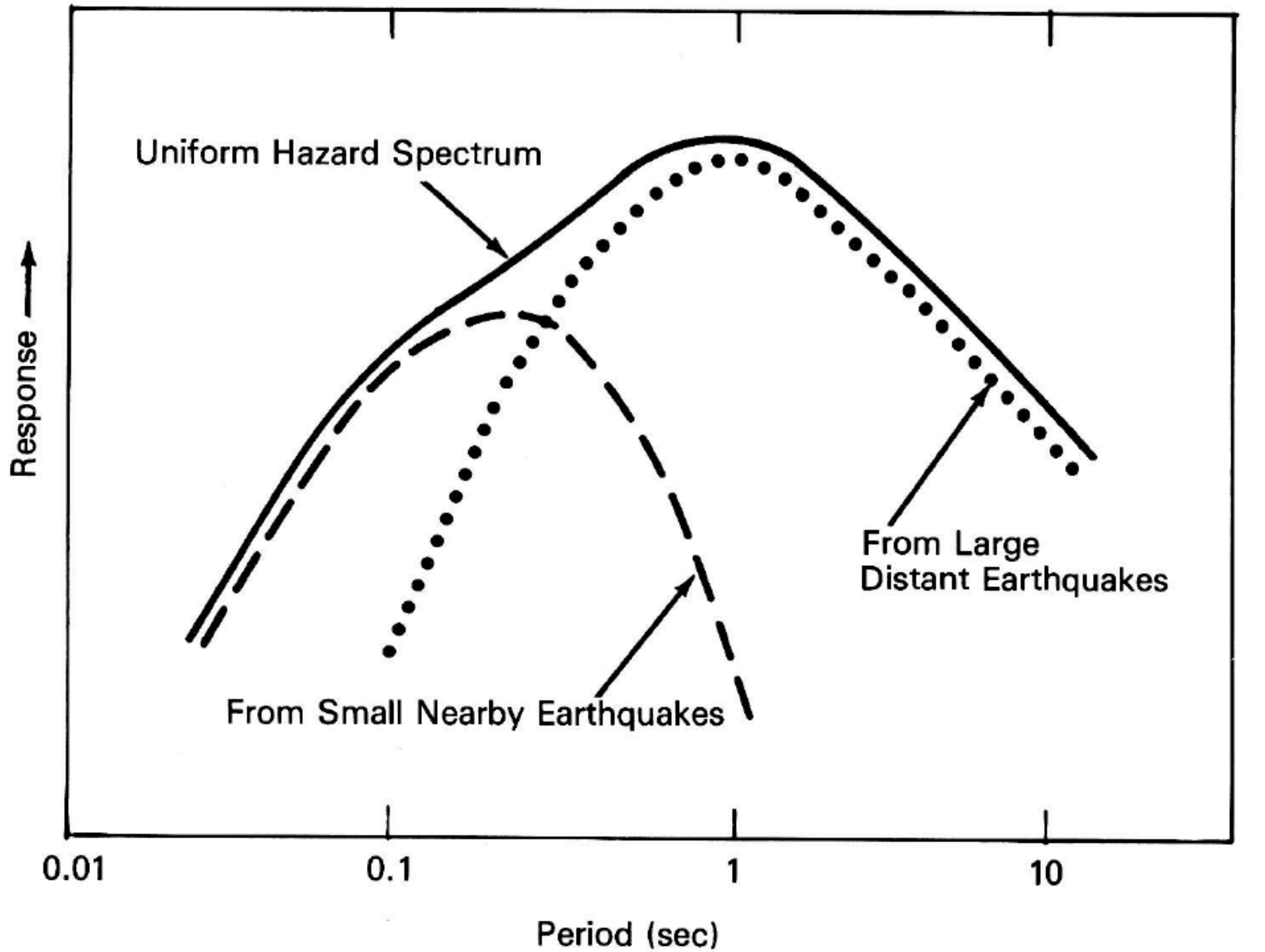
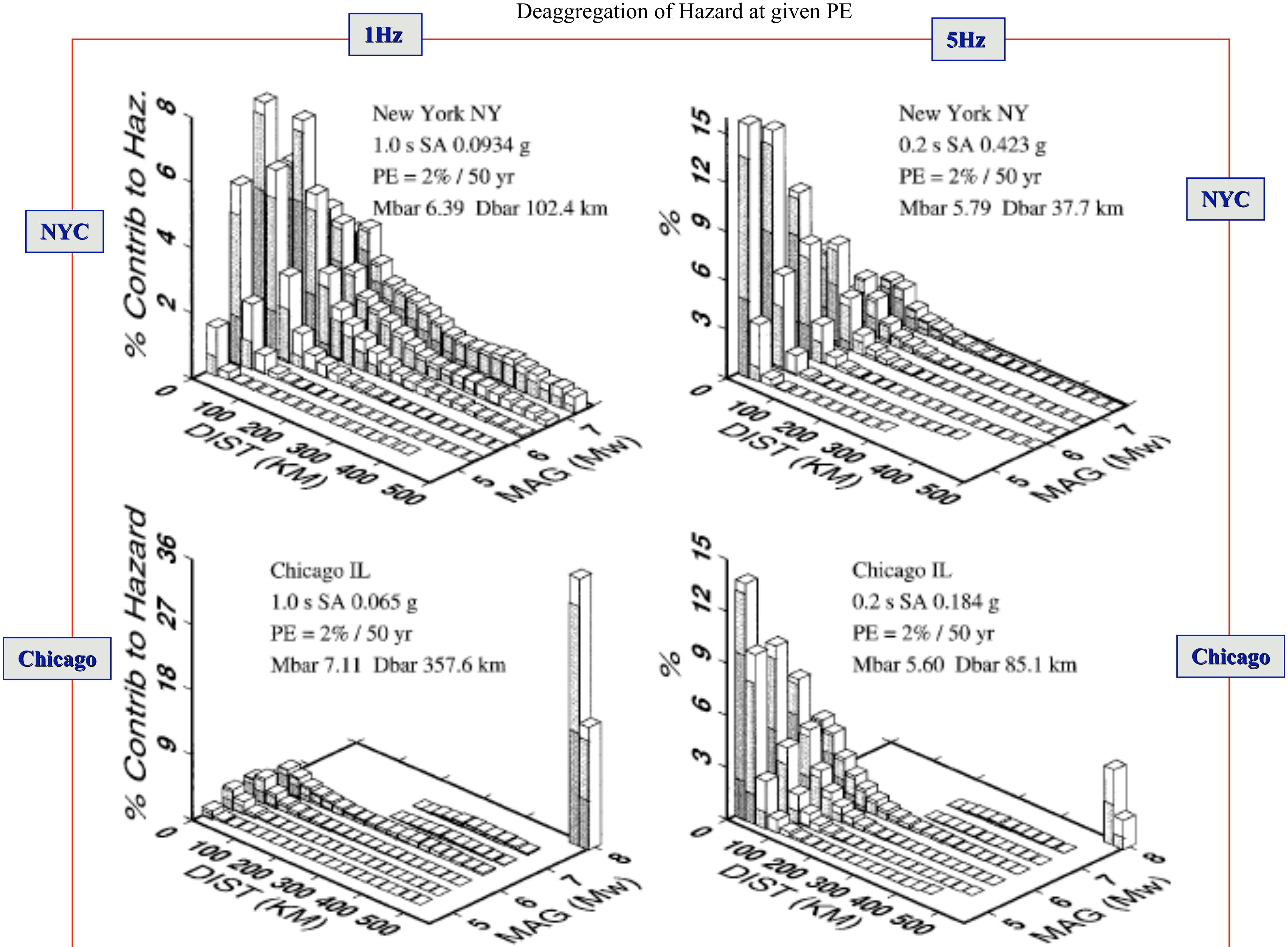


FIGURE 11.15 Schematic sketch of uniform hazard response spectrum (for example, 10^{-3} per year) in which the contributions to hazard at shorter and longer periods come from

Deaggregation of Hazard at given PE



S. Harmsen, D. Perkins, and A. Frankel

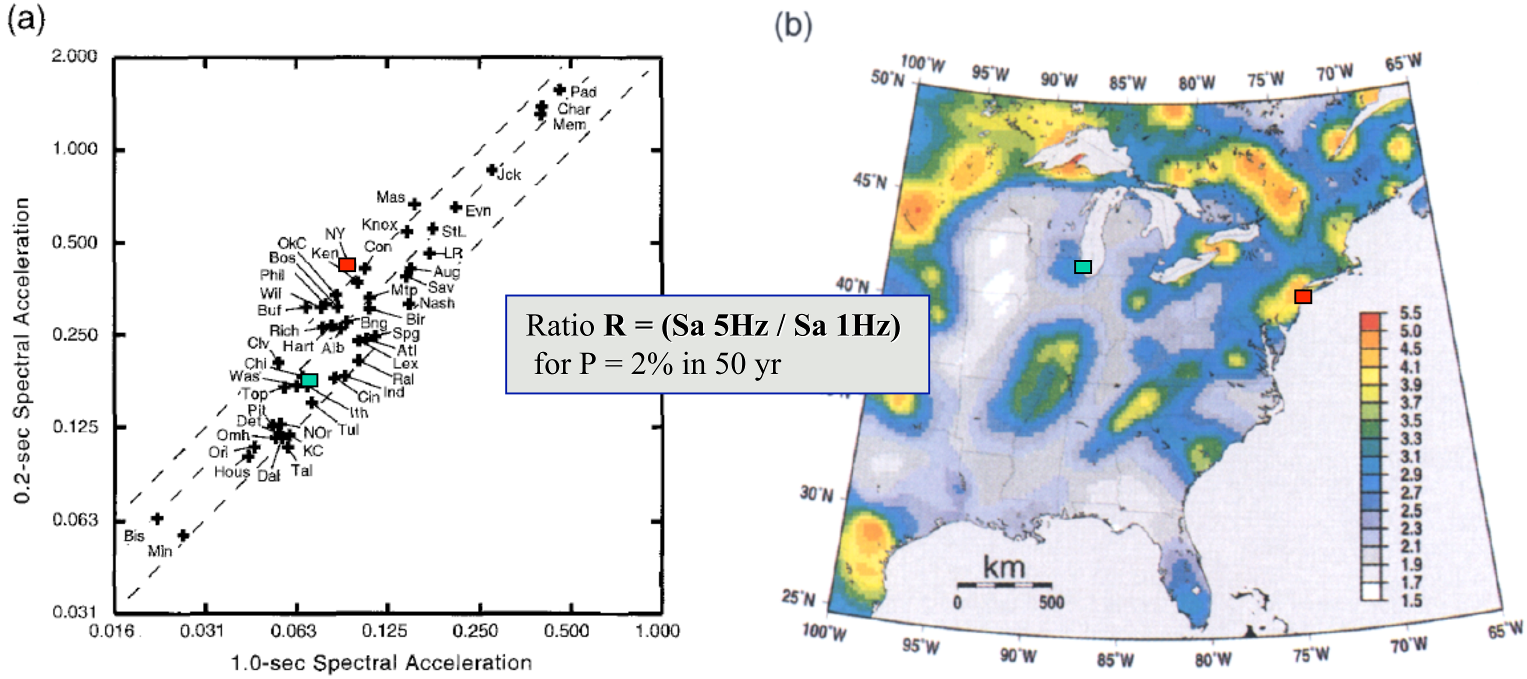
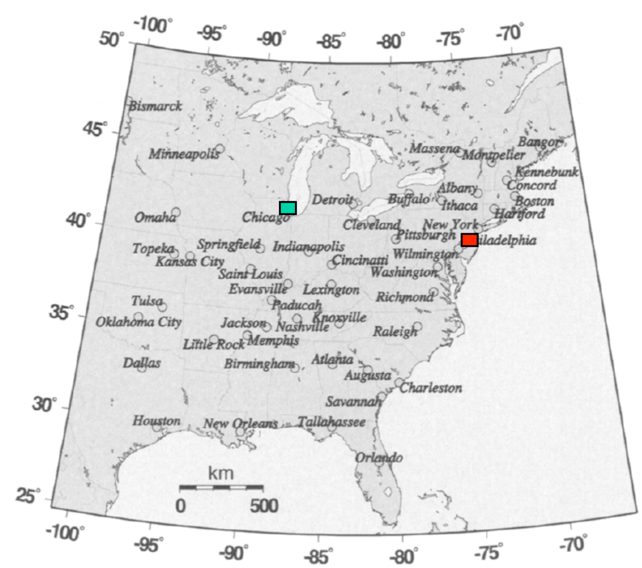


Figure 5. (a) 0.2-sec spectral acceleration vs. 1.0-sec spectral acceleration (1.0 sec) for ground motions having 2% probability of exceedance in 50 years. Dashed lines represent ratios, *R*, of 2 (lowest), 3, and 4. (b) Contour map of *R* in the CEUS.



Questions?

2d

Interim Report

PROBABILISTIC SEISMIC HAZARD ANALYSIS and ROCK GROUND MOTIONS

SEISMIC ANALYSIS AND RETROFIT DELAWARE MEMORIAL BRIDGE

Report Prepared for
HNTB Corporation
330 Passaic Avenue
Fairfield, NJ

Prepared by
J. Armbruster, N. Barstow, S. Horton, and K. Jacob

November, 1996

Lamont-Doherty Earth Observatory of Columbia University
Route 9W
Palisades, NY 10964

Table of Contents

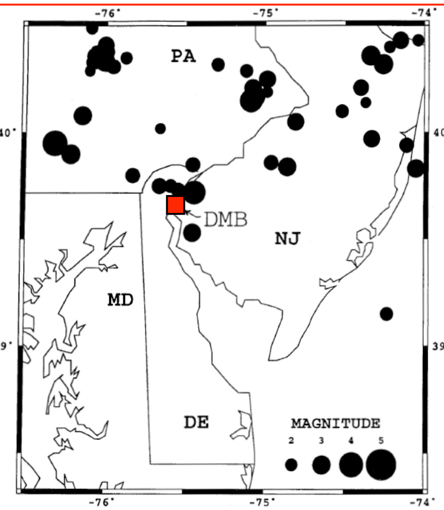
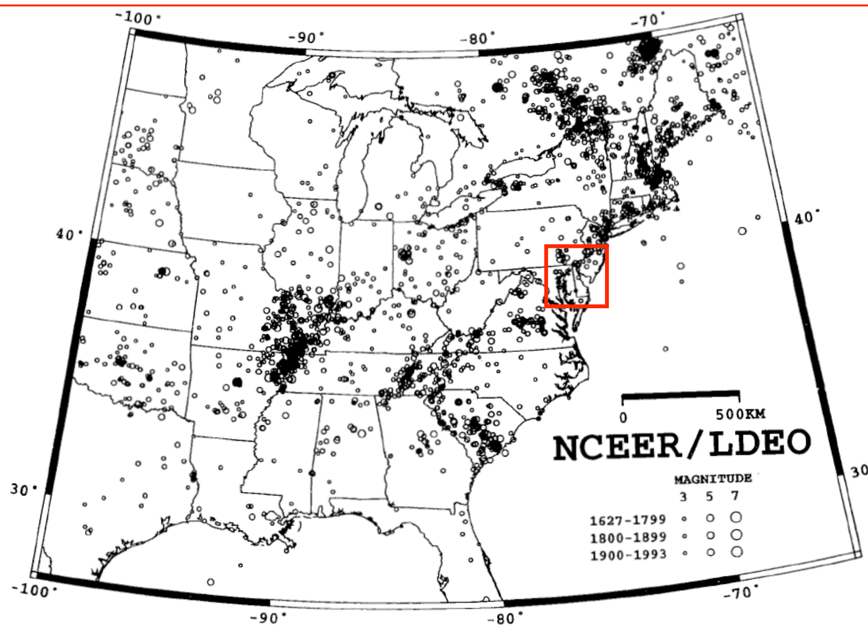


Figure 1b Historical and instrumentally determined earthquake epicenters in the region around the DMB site. The nearest earthquakes are in Wilmington, DE; there are several clusters in PA, and a more linear trend of epicenters in NJ.



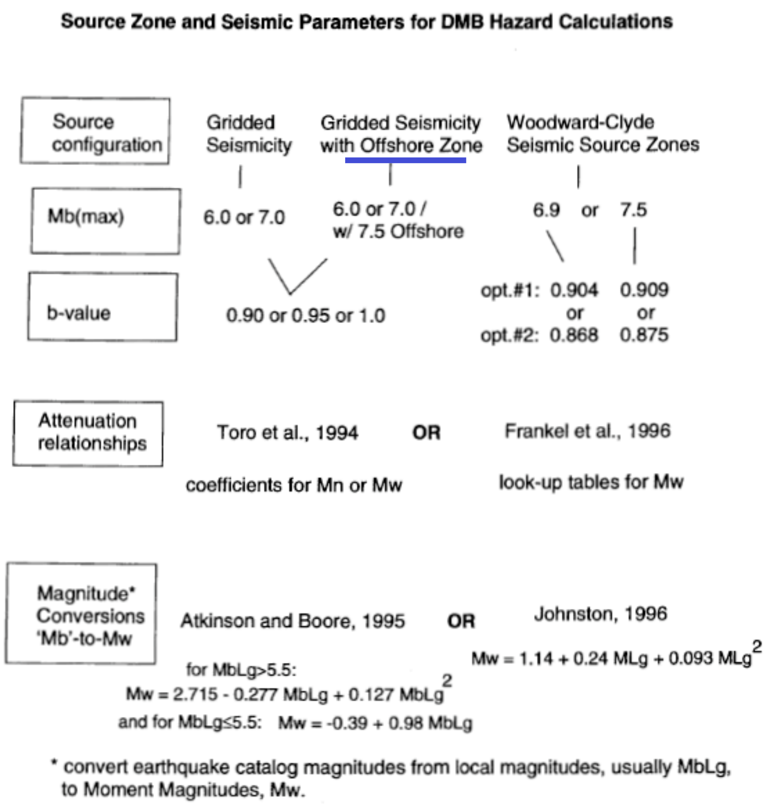


Figure 2 Variation in modeling parameters used as input to the PSHA calculations for the Delaware Memorial bridge site.

Figure 3a Seismic 'sources' (shaded areas) for the gridded seismicity model, centered on the DMB site. Grid-point spacing is 1/2 degree in latitude and longitude. Large areas of background, non-zero seismicity surround the grid.

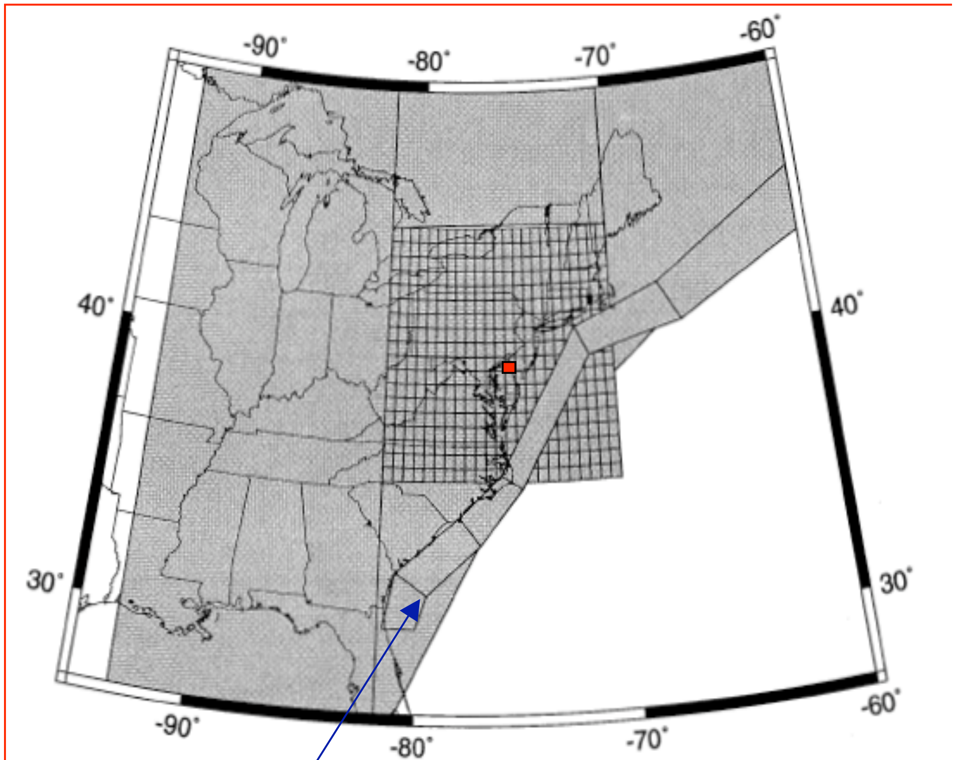


Figure 3b A second seismic source configuration differs from Figure 3a with the addition of an offshore seismic source zone which links three large historic earthquakes: Charleston, S.C., Grand Banks, Newfoundland, and Baffin Bay. Based on these earthquakes, the offshore zone produces M7 and greater earthquakes at a rate of 0.00025/100years/1km along its length.

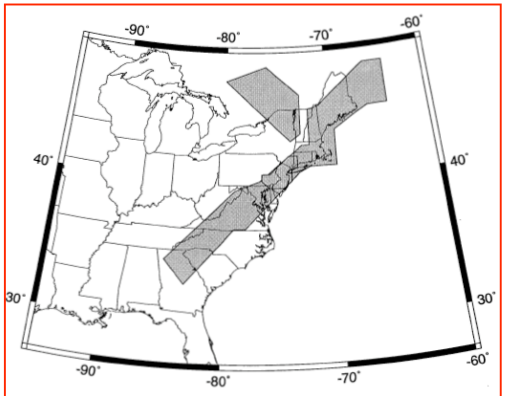


Figure 3c A third seismic source configuration with two source zones (shaded) from W-CC (1989). Seismicity is evenly smoothed within the two zones, one along the old Appalachian orogenic belt, the other extending from the PreCambrian of northern NY northwestward into Ontario and Quebec, Canada.

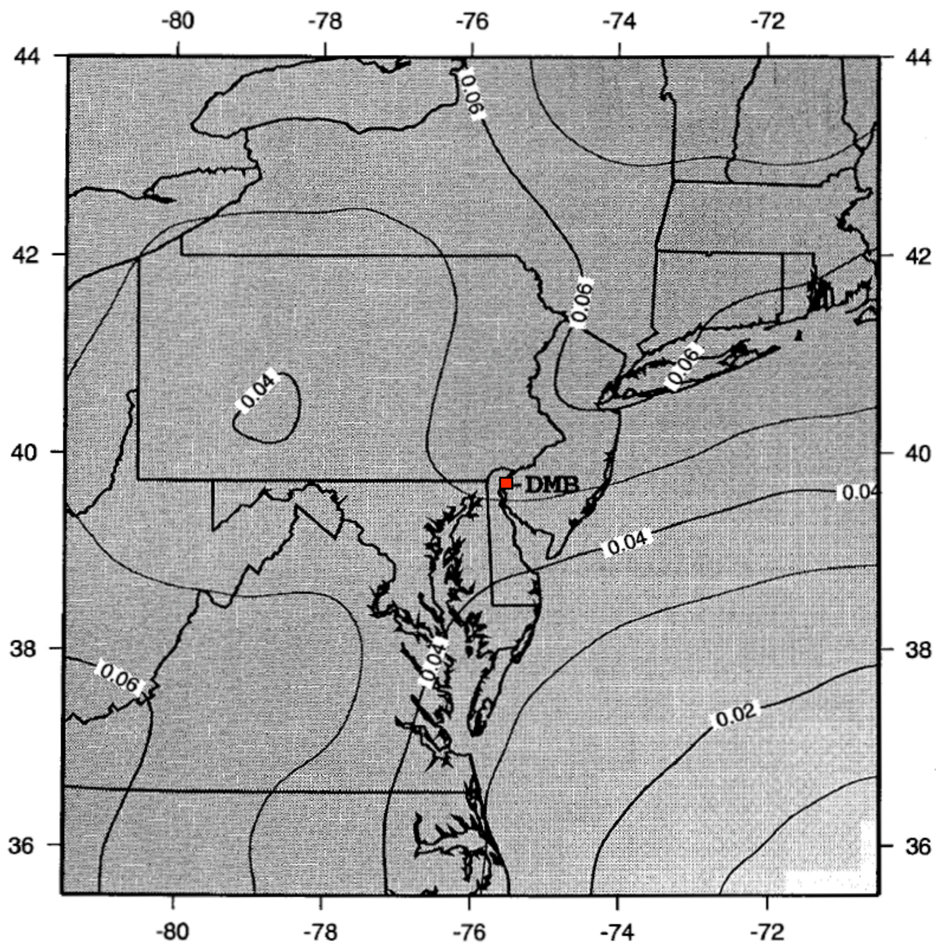


Figure 4a Seismic hazard map for 2% probability of exceedance in 50 years at 1.0 sec. period based on gridded seismic source model in Figure 3a. Mmax =7.0, *b* value = 0.9. The 0.05g contour is close to the DMB.

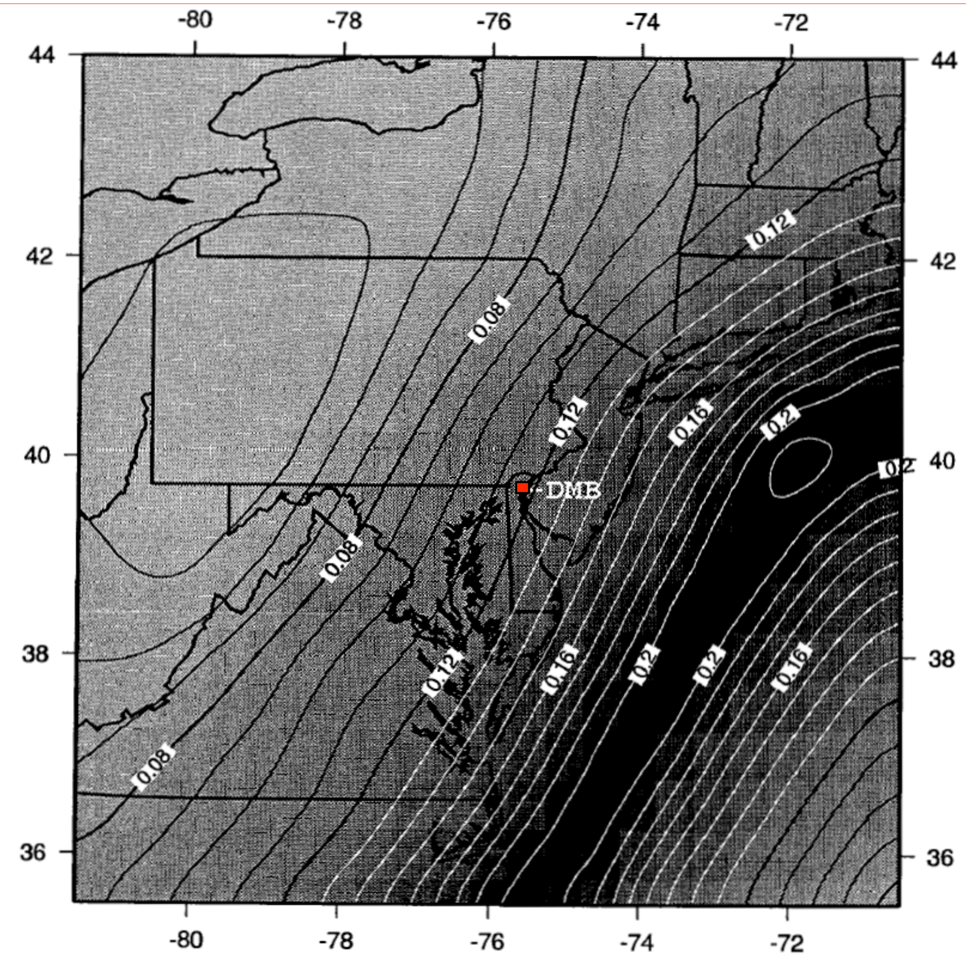


Figure 4b Seismic hazard map for 2% probability of exceedance in 50 years at 1.0 sec. period based on an offshore seismic zone added to the gridded seismic sources (Figure 3b). Mmax =7.0, *b* value = 0.9. The strongest accelerations are in the offshore zone which controls the hazard inland as well.

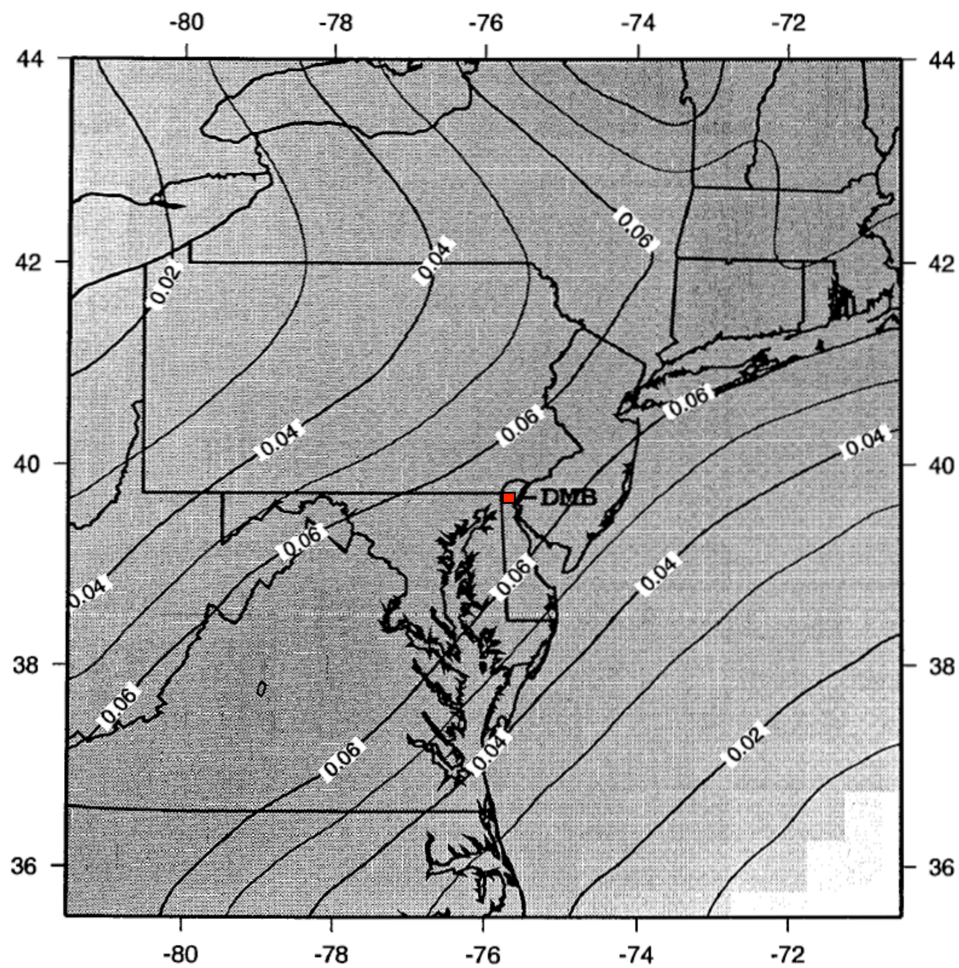


Figure 4c Seismic hazard map for 2% probability of exceedance in 50 years at 1.0 sec. period based on a W-CC seismic source zone model (Figure 3c). Mmax =6.9, *b* value = 0.904. Accelerations are similar in magnitude to the gridded model in 4a; the main difference is that the trend of contours parallel the Appalachian zone.

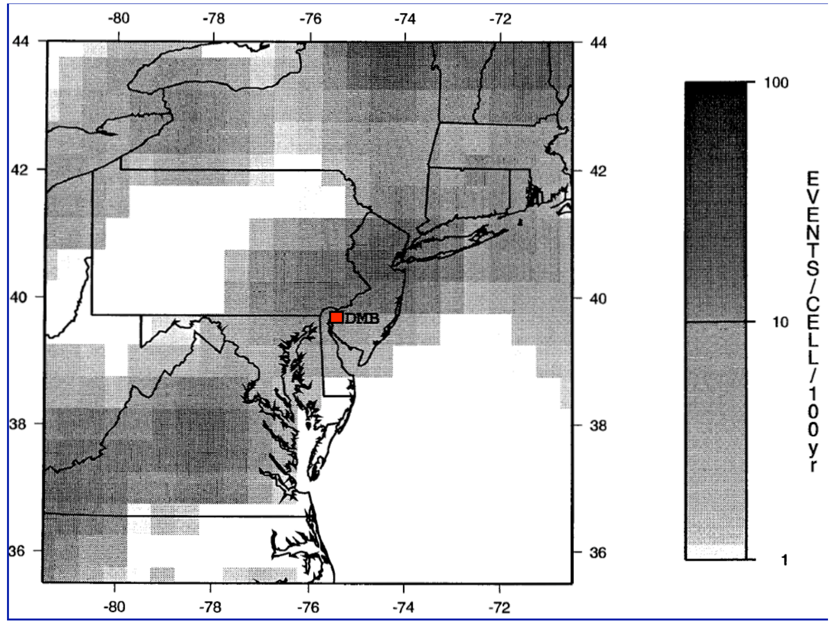


Figure 5 Seismicity rates smoothed over 1/2 cells of latitude and longitude normalized to M≥2 per 100 years per cell. Note shading is a *logarithmic scale*.

In the W-CC model (**Figure 3c**) two different a and b values are calculated based on two models of earthquake catalog completeness and two maximum magnitude options - M6.9 and M7.5 - available for each of the seismic source zones. Values are shown in **Table I** below.

Table I Recurrence Relation Estimates - W-CC Seismic Source Zone Model (1989)

Seismic Source Zone	Com-pleteness Option	Mmax= 6.9	Mmax=7.5
Appalachian	1	a = -2.311 b = 0.904	a = -2.293 b = 0.909
Appalachian	2	a = -2.427 b = 0.868	a = -2.293 b = 0.975
No.NY/Ontario	1	a = -1.464 b = 1.003	a = -1.451 b = 1.006
No.NY/Ontario	2	a = -1.331 b = 1.033	a = -1.314 b = 1.037

The minimum magnitude used to integrate over magnitude interval between Mmin and Mmax is Mb = 5.0 because this is the lowest magnitude for which we have Frankel et al. (1996)

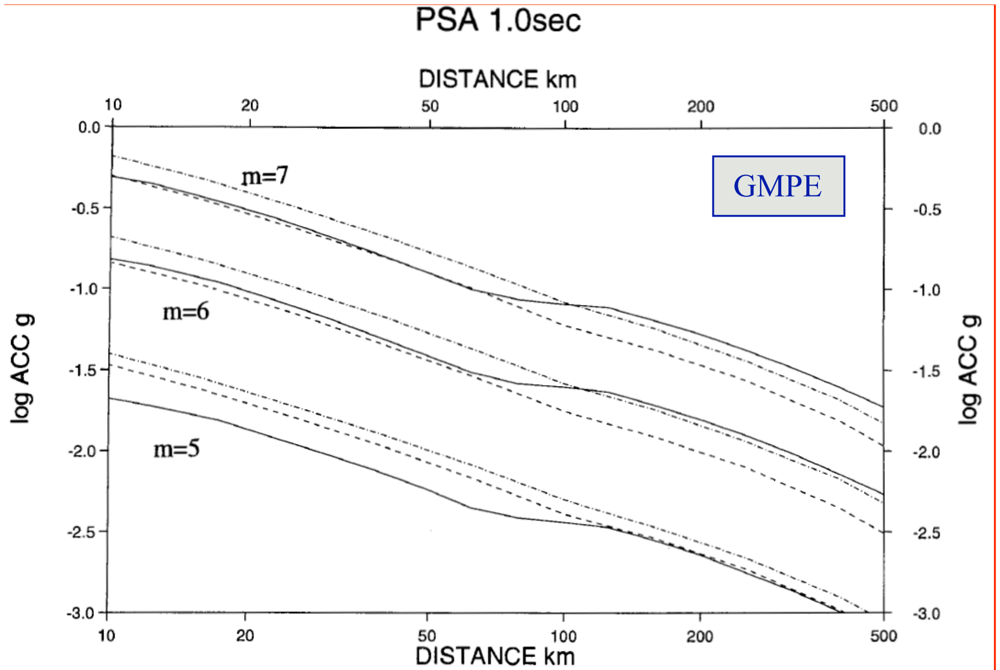


Figure 6 Attenuation curves for three magnitudes - m5, m6, and m7 - resulting from the three relations used in this study: Toro et al. (1996) for Mw (dashed line) and for Mn (dot-dashed line), and Frankel et al. (1996) (solid line). A change in slope in the Frankel curves reflects the contribution of post-critical reflected phases from the Moho discontinuity at distances around 100 km. Values are for the soft-rock reference site adopted by the USGS for National Hazard Maps.

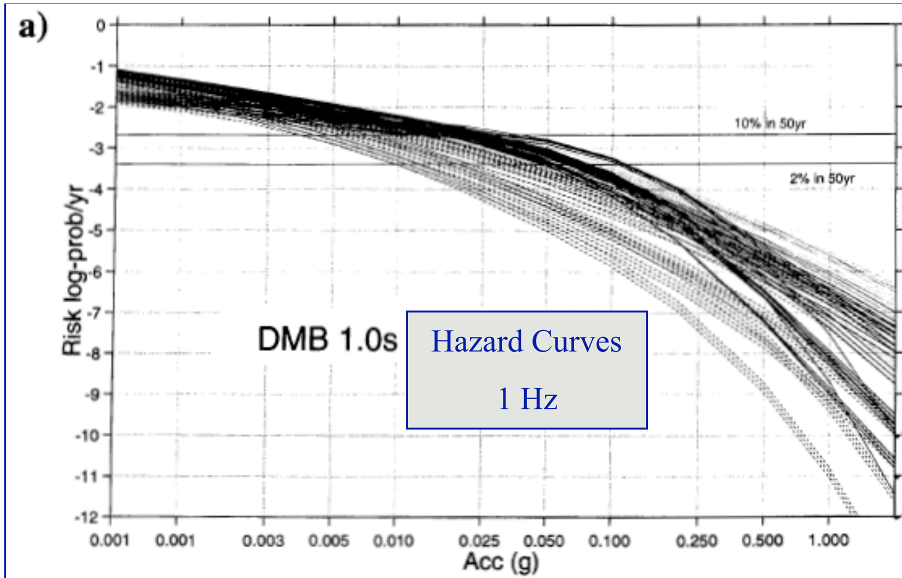
Table III Magnitude, Mw, converted from local Mb

Local 'Mb'	5.00	5.50	6.00	6.50	7.00
Mw Johnston 1996	4.67	5.28	5.94	6.64	7.39
Mw Atkinson & Boore 1995	4.51	5.00	5.63	6.28	7.00

hazard computations:

Sources * b values * Mmax * Attenuation * Magnitudes

2 sources * 3 bvals * 2 Mmax * 1 Attn (F) * 2 Mags
\+ 2 sources * 3 bvals * 2 Mmax * 1 Attn (T) * 3 Mags
\+ 1 sources * 2 bvals * 2 Mmax * 1 Attn (F) * 2 Mags
\+ 1 sources * 2 bvals * 2 Mmax * 1 Attn (T) * 3 Mags = 80



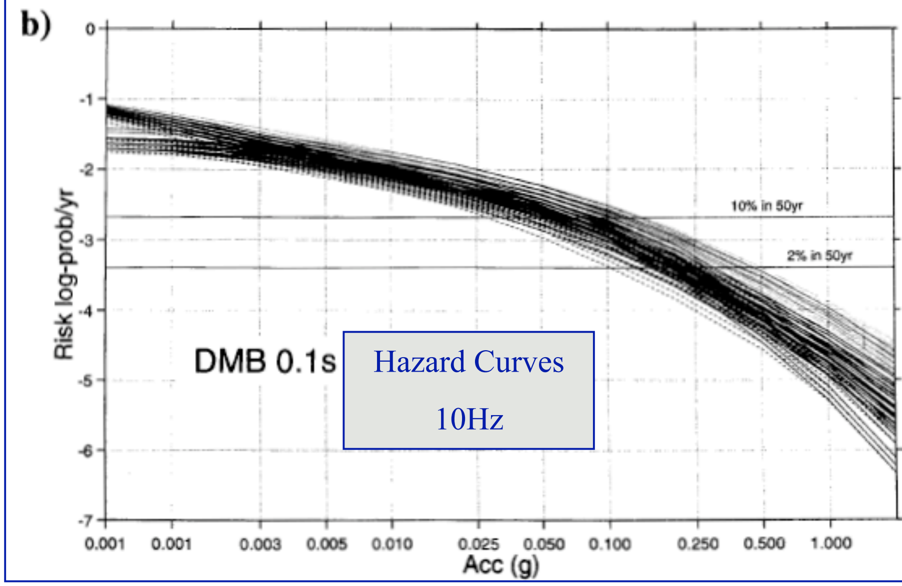


Figure 7 DMB hazard curves due to 80 different model parameters for 1.0 sec. and 0.1sec. periods. Three different line types indicate 3 source configurations: dashed=gridded seismicity; solid=offshore zone + gridded seismicity; and fine-dotted=W-CC source-zone model. Lines are drawn corresponding to annual probabilities associated with risk levels of 10% in 50 years and 2% in 50 years.

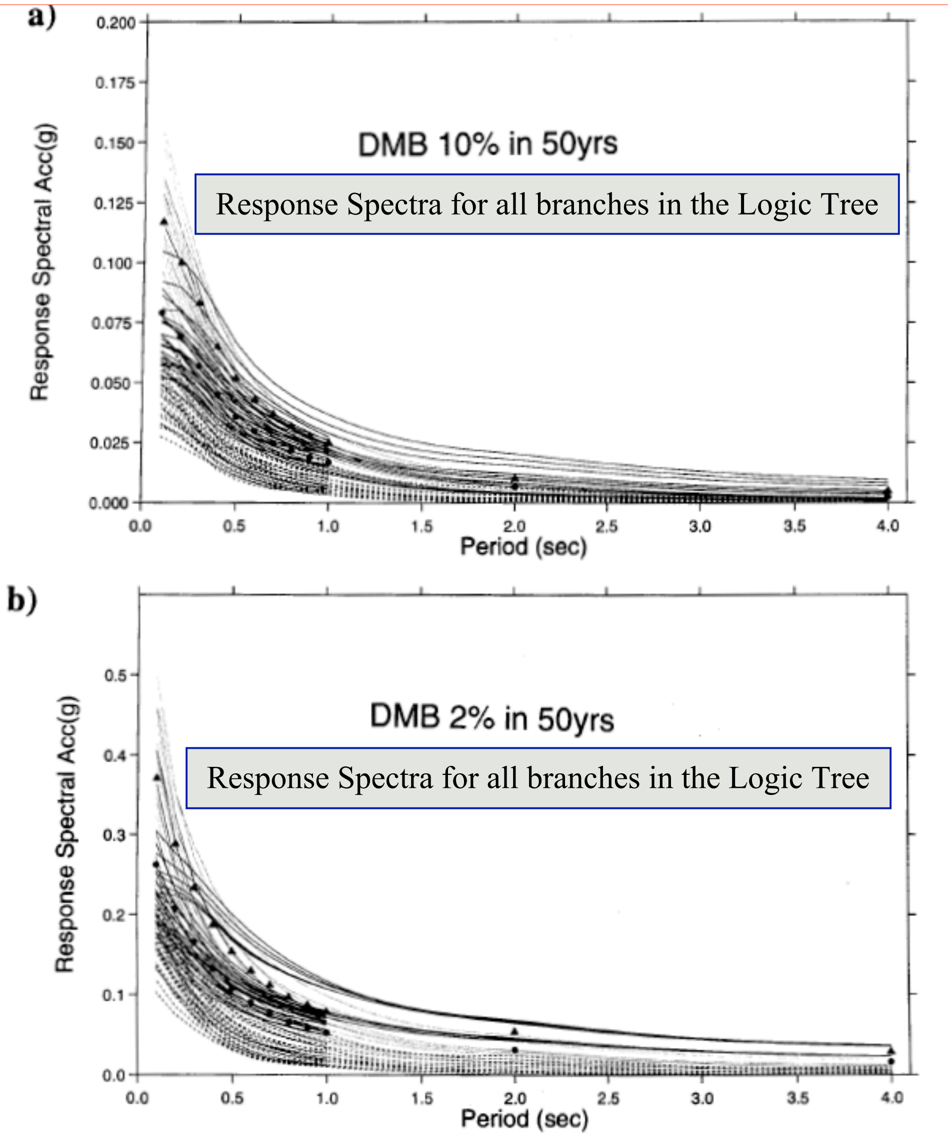


Figure 8 DMB hazard spectra due to 80 different model parameters for two risk levels. Response spectral acceleration is calculated for discreet periods given by the attenuation functions; values at remaining periods are interpolated with a spline-fitting function. The weighted mean (circles) and weighted mean plus one standard deviation (triangles) are shown.

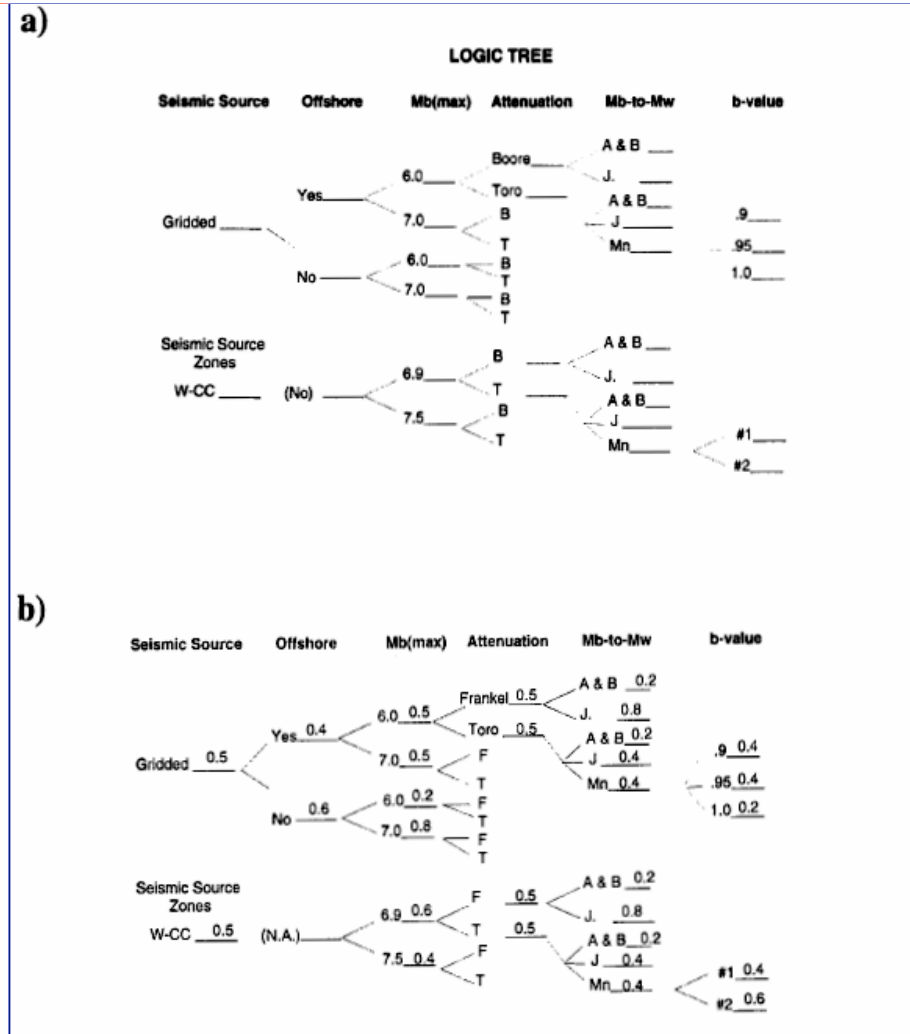


Figure 9 Logic tree constructed to assign weights to the different options used in this study to calculate the PSHA at the DMB. Each of the 4 authors filled in a blank logic tree (**9a**) so that values stemming from a single node add to 1.0 (example in **9b**). [Note the Offshore option does not apply to the W-CC option. The maximum magnitude option only affects the gridded portion of the Offshore option; in the offshore source zone, itself, the minimum magnitude is fixed at 7.0.]

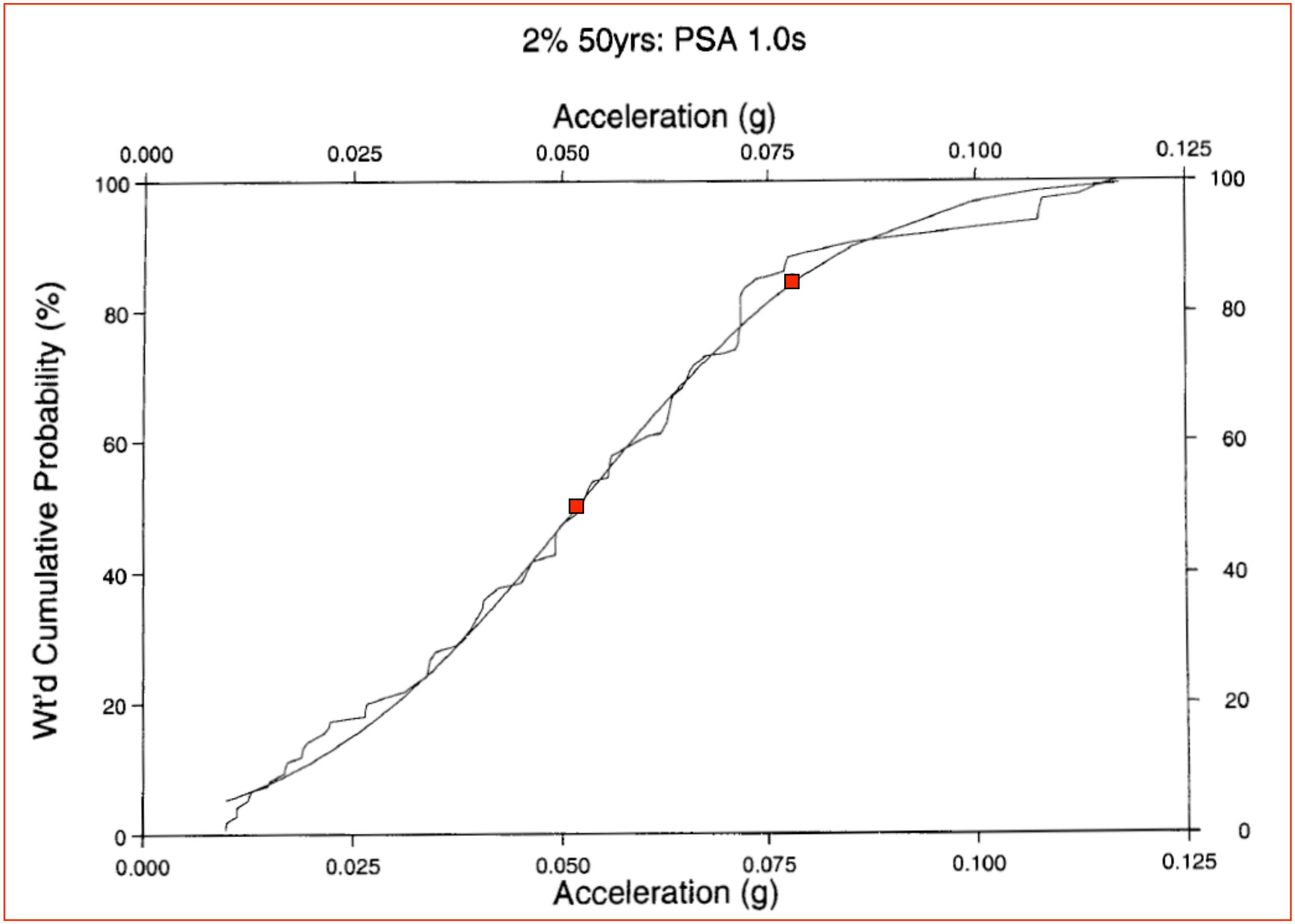


Figure 10 Cumulative probability (percent) of exceedance of response spectral acceleration (g) for a risk level of 2% probability in 50 years, 1.0 second period. Eighty weighted models are included (jagged curve). The smooth curve is a linear-normal fit to the data. Points on the fitted curve are the mean and mean plus one standard deviation.

Table IV Weighted Uniform Hazard Spectral Values

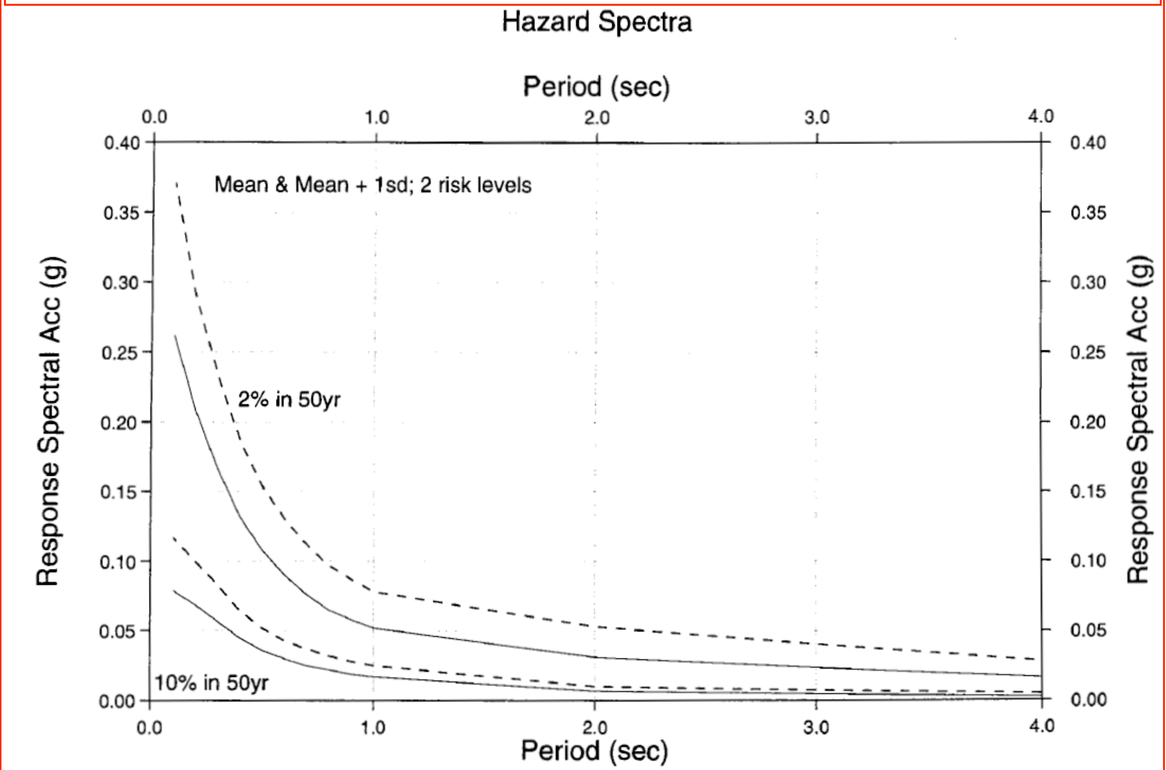
SPECTRAL ACC (G)

Period (s)	10% in 50 years Mean	10% in 50 years Mean + 1sd	2% in 50 years Mean	2% in 50 years Mean + 1sd
0.1	0.079	0.117	0.262	0.371
0.2	0.069	0.100	0.208	0.288
0.3	0.057	0.083	0.166	0.233
0.4	0.045	0.065	0.132	0.187
0.5	0.036	0.052	0.108	0.154
0.6	0.030	0.043	0.090	0.130
0.7	0.025	0.037	0.076	0.112
0.8	0.022	0.032	0.065	0.097
0.9	0.019	0.028	0.058	0.087
1.0	0.017	0.025	0.052	0.078
2.0	0.007	0.010	0.031	0.053
4.0	0.002	0.005	0.016	0.028

Table V Comparison of DMB Results (this study) with USGS National Hazard Maps

Period (s)	Mean	Mean + 1sd	**USGS Haz Map**	Risk Level
0.2	0.069	0.100	0.08	10% in 50yr
0.2	0.208	0.288	0.28	2% in 50yr
1.0	0.017	0.025	0.02 - 0.03	10% in 50yr
1.0	0.052	0.078	0.08 - 0.09	2% in 50yr

Figure 11 Uniform hazard spectra based on the mean (solid curves) or mean plus one standard deviation (dashed curves) of the normal distribution fit to weighted models. Both risk level are shown.



Steps for Translating Probabilistic Ground Motion Spectra into Hazard-Compatible Ground Motion Records in the Time Domain for Engineering Use:

1. **Deaggregate PSHA Results (for 2 given probabilities 5 and 2% in 50 years; and for 2 discrete frequencies 1Hz and 10Hz) into one or more discrete (M*, d*) pairs, depending on mode topography.**
2. **Obtain the seismic parameters for the model of the regional crust through which seismic waves propagate.**
3. **Choose regionally appropriate stress drop values (100 bar) and source depths *h* for the sources, and use focal mechanisms (reverse faulting or oblique SS with reverse components of slip).**
4. **Find a regionally appropriate "scattering function" that complements the viscoelastic (intrinsic) damping ($Q\alpha^*$ and $Q\beta^*$) for the layers of the seismic model of the regional crust.**
5. **Compute Synthetic Ground Motion Records (3 components: Z, R, T) with full wave theory.**
6. **Convolve the Synthetic Seismograms with the Scattering Function to obtain the appropriate ground motion duration and "coda-fall-off".**
7. **Optional: Make the records in the time domain spectrally compatible with UHS for the corresponding probabilities (2 and 10% in 50 years).**

M*, d*

Table VI Deaggregation Results: Magnitude/Distance Pairs at Three Periods

Risk Level	1.0sec period	0.2sec period	0.1sec period
10% in 50yr	mb5.85/35km mb7.05/295km	mb5.05/25km	mb5.05/25km
2% in 50yr	mb5.95/15km mb7.35/295km	mb5.05/15km	mb5.05/15km

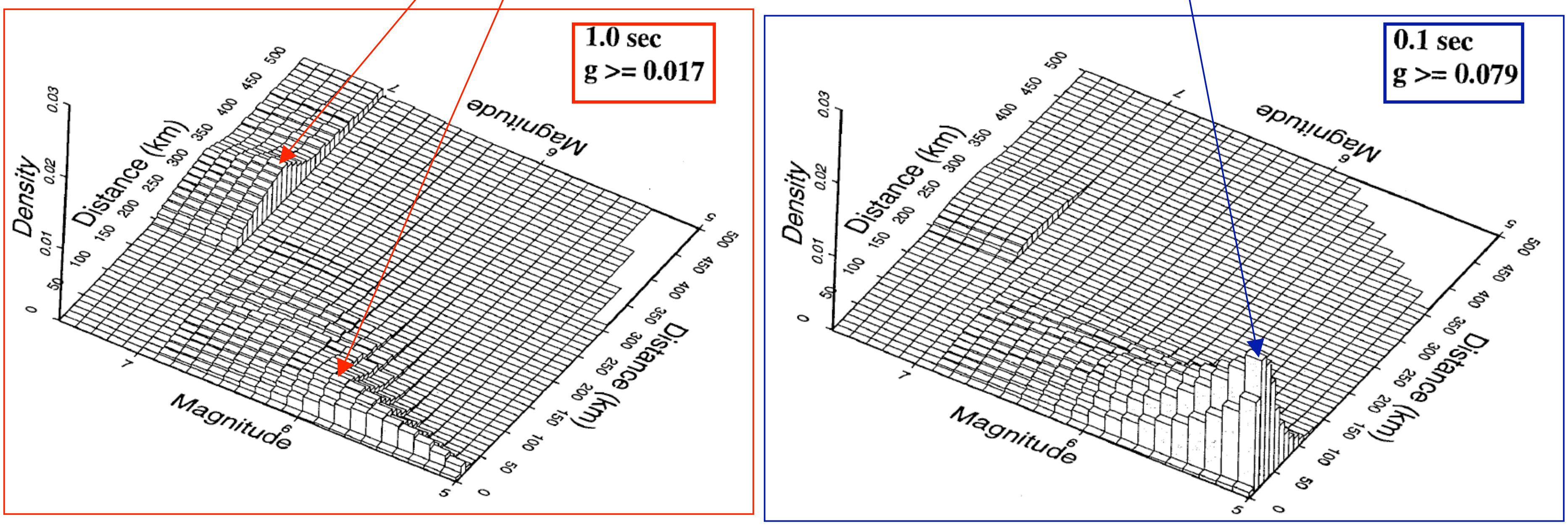
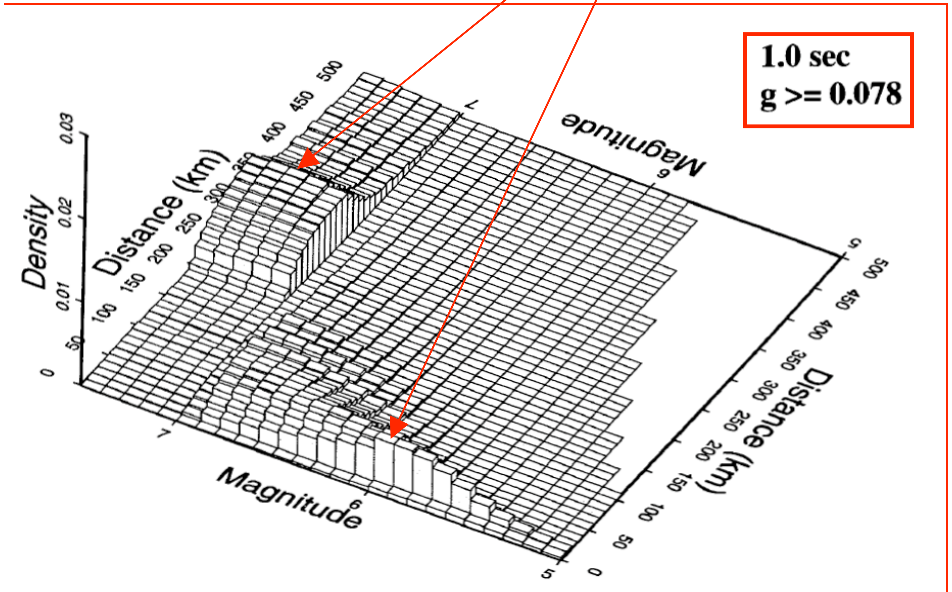


Figure 13 Deaggregation, 85-percentiles 10% in 50 years, 1.0 sec. and 0.1 sec. response spectral levels with target acceleration levels of 0.017g and 0.079g, respectively. Modal magnitude/distance pairs: 1.0 sec. is bi-modal with M5.85/35km and M7.05/295km; 0.1 sec. mode is 5.05/25km.

M*, d*

Table VI Deaggregation Results: Magnitude/Distance Pairs at Three Periods

Risk Level	1.0sec period	0.2sec period	0.1sec period
10% in 50yr	mb5.85/35km mb7.05/295km	mb5.05/25km	mb5.05/25km
2% in 50yr	mb5.95/15km mb7.35/295km	mb5.05/15km	mb5.05/15km



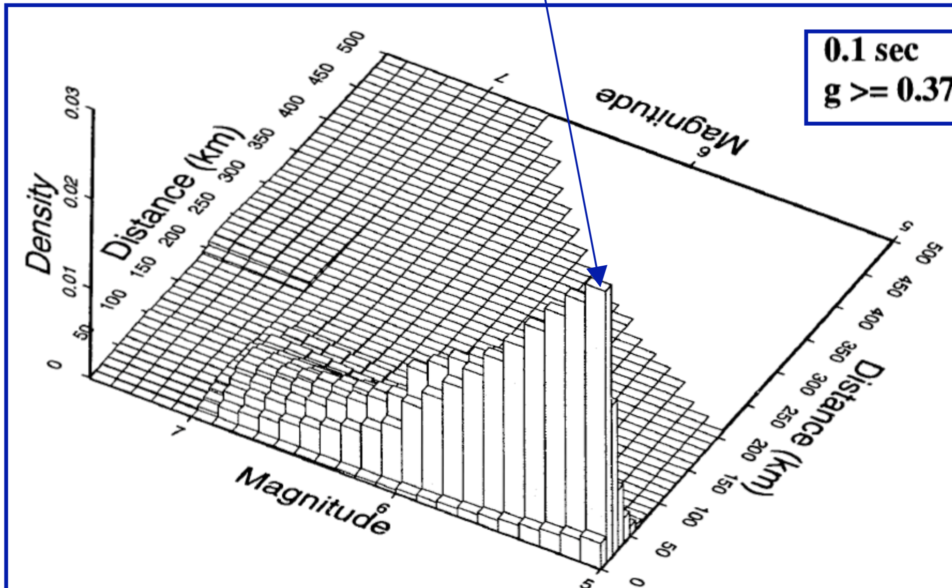


Figure 12 Deaggregation, 85-percentile of 2% in 50 years, 1.0 sec and 0.1 response spectral levels with target g-level exceedance 0.078 and 0.371, respectively. Modal magnitude/distance pairs: 1.0 sec is bi-modal with 5.95/15km and 7.35/295km; 0.1 sec is 5.05/15km.

Table VII Velocity/Q Model for Crust and lower Sediments

Depth to top - km	Thickness km	Vs km/s	Vp km/s	density g/cc	Qs *	Qp *
0						
.050	.050	0.61	1.07	2.0	120	240
.100	.050	0.97	1.69	2.1	200	400
.150	4.850	3.05	5.30	2.5	2000	2000
5.00	7.00	3.30	5.80	2.6	3000	3000
12.0	7.00	3.75	6.56	2.8	3000	3000
19.0	16.0	4.00	7.00	3.0	3000	3000
35.0		4.73	8.18	3.3	3000	3000

* Note: The Q values only account for viscoelastic (intrinsic) damping. The effective Q is lower than these values due to the scattering function described in the text.

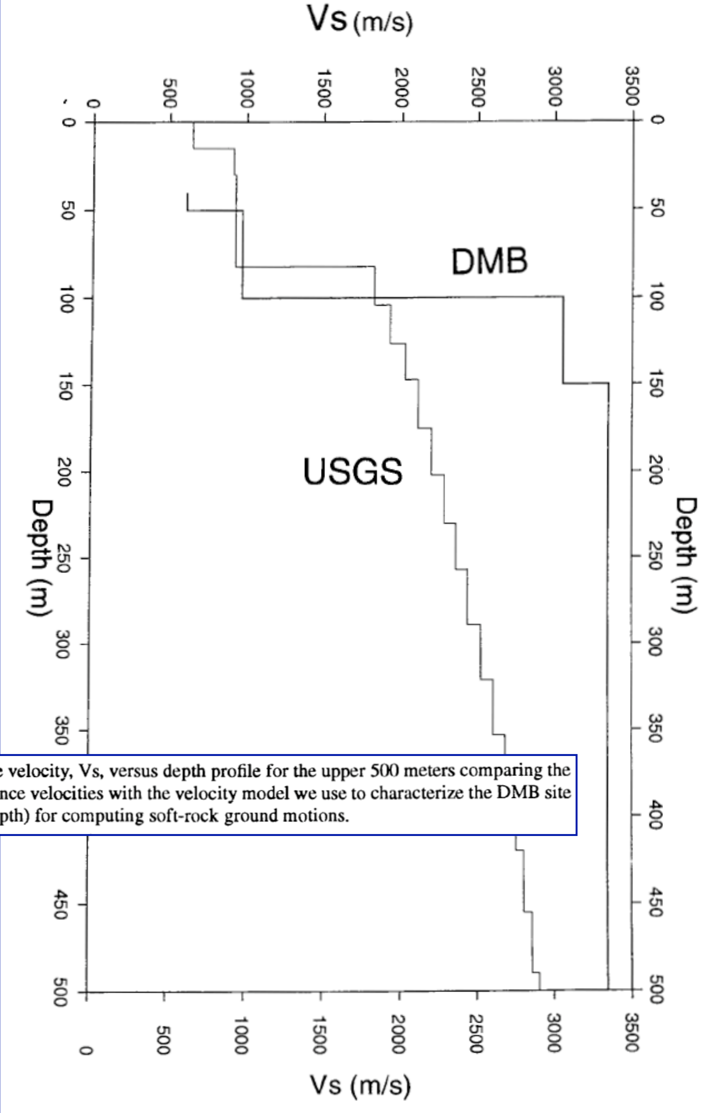


Figure 17 Shear-wave velocity, Vs, versus depth profile for the upper 500 meters comparing the USGS soft-rock-reference velocities with the velocity model we use to characterize the DMB site (from 46m to 500m depth) for computing soft-rock ground motions.

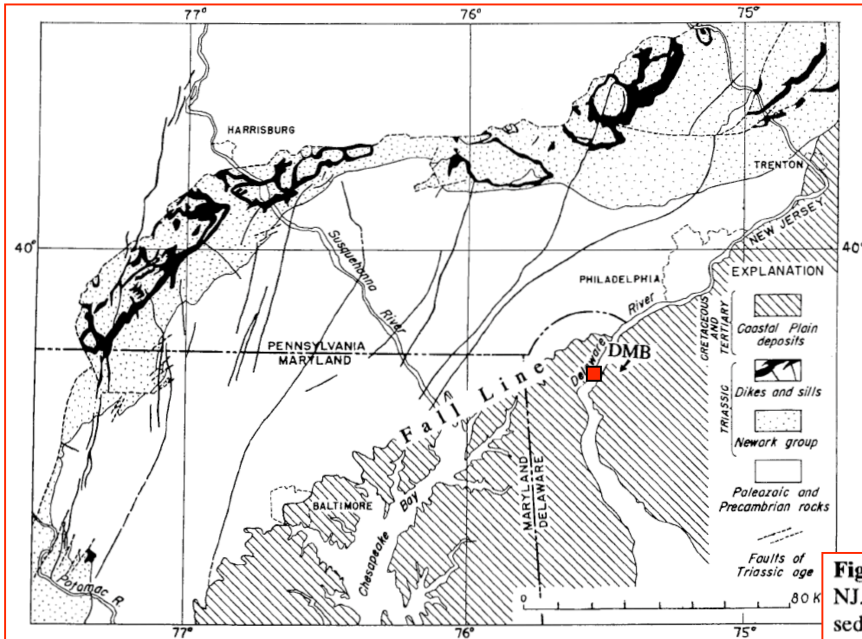


Figure 15 Generalized geologic map of southeastern PA, eastern MD, northern DE, and part of NJ. Young Coastal plain deposits onlap Paleozoic and Precambrian crystalline rocks, as well as sedimentary and igneous rocks of the Triassic (from King, 1977). The Fall Line is the surface line of intersection between young, onlapping Coastal plain sediments and the older rocks beneath them.

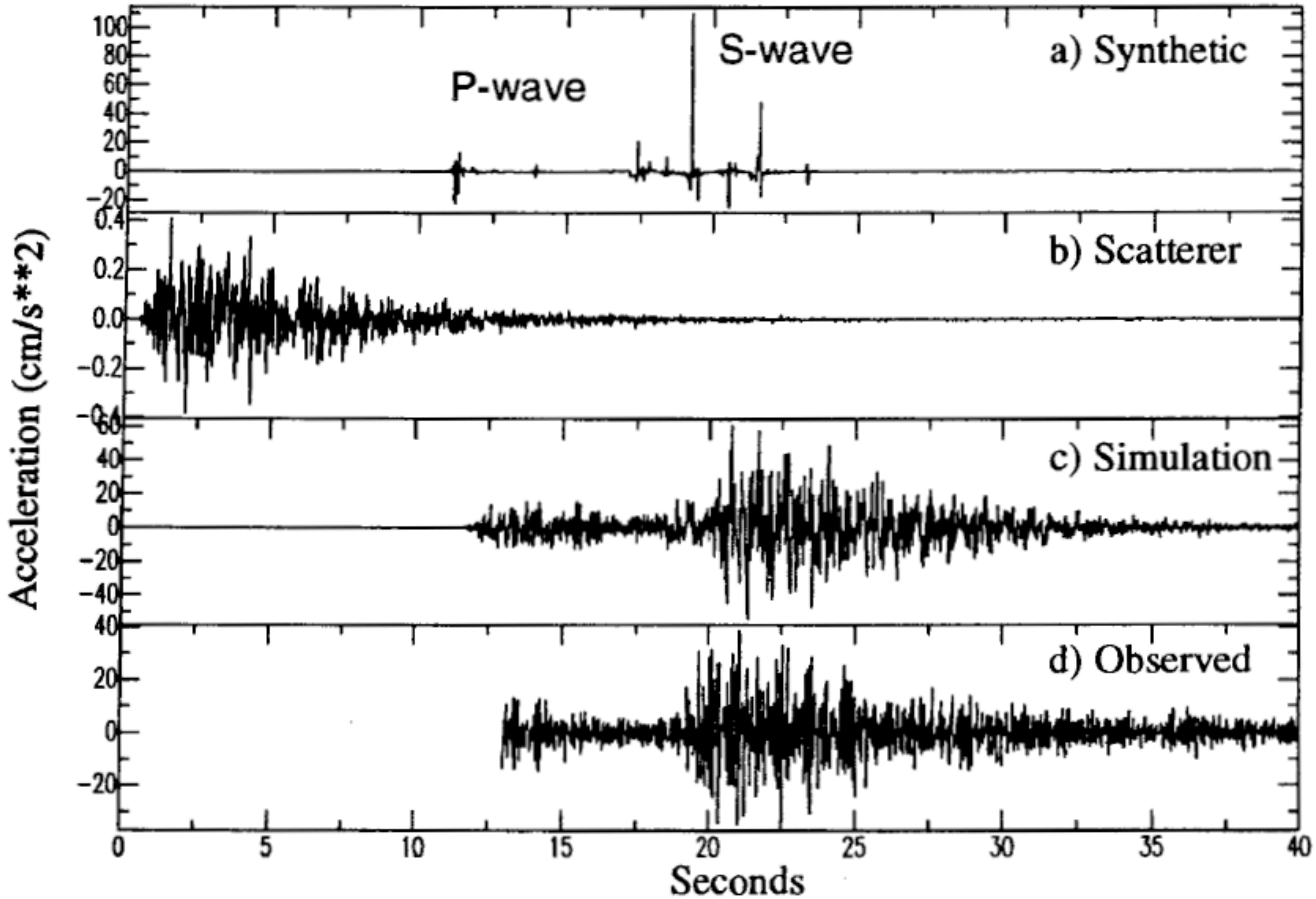


Figure 14 An example of the method for simulating earthquake ground motions compared to an observation at station S17, 64 km from the Saguenay, QUE earthquake Mw=5.8, 11/25/88. a) synthetic ground motion at station S17; b) scattering function; c) simulated ground motion; d) observed accelerogram.

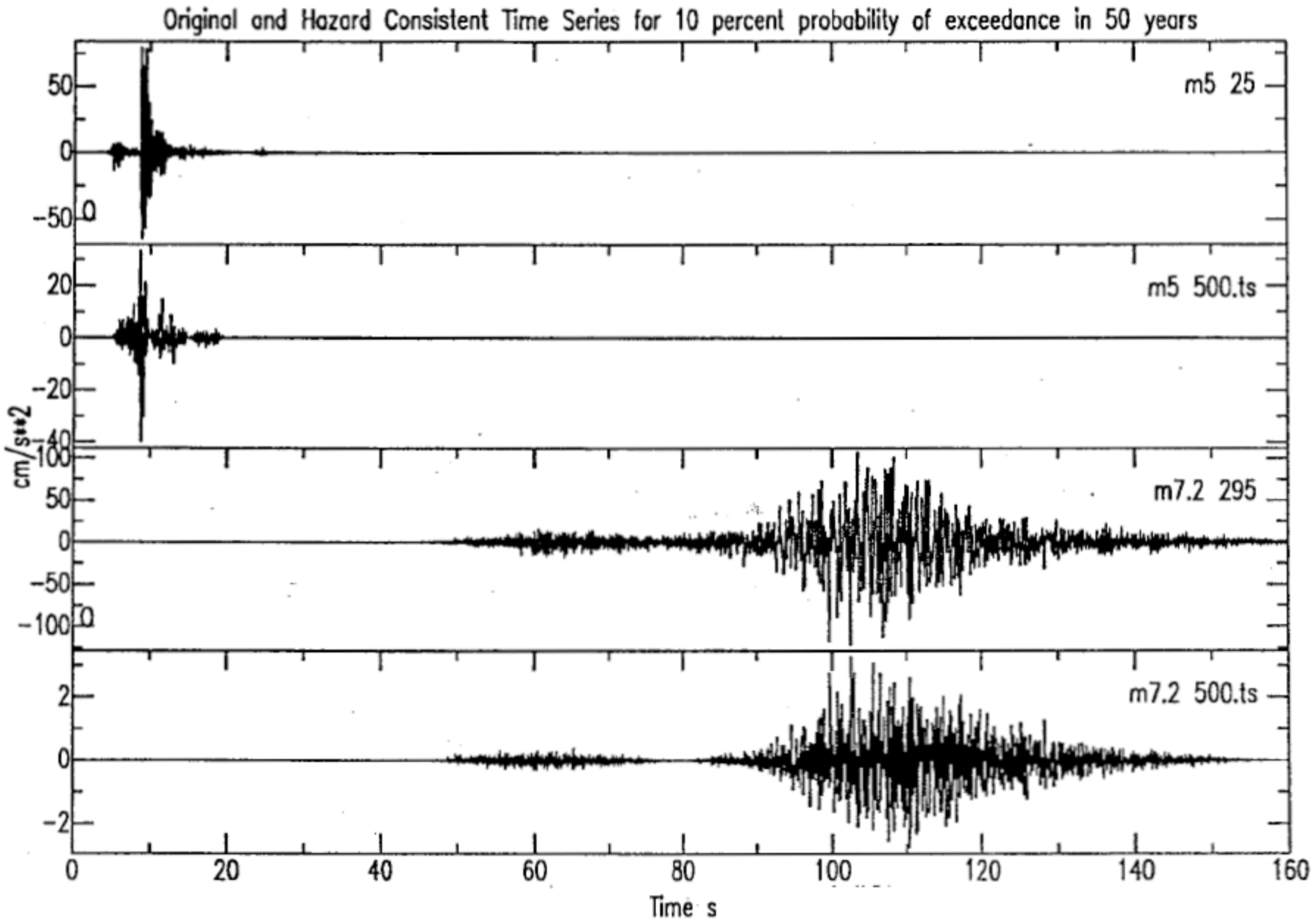


Figure 18a The original and hazard consistent time series for (mean plus 1 σ) 10% probability of exceedance in 50 years. A magnitude 5.05 at 25 km is the earthquake (mode) that contributes most to the expected level of hazard at 0.1 sec. period. The simulated time series for the M/D combination (m5 25) is plotted in the top box. The corresponding hazard consistent time series (m5 500.ts) is plotted just below. The time series have roughly similar duration although the spectral content differs drastically. A magnitude 7.25 at 295 km is the modal earthquake at 1 sec. period. The simulated time series for this M/D combination (m7.2 295) is plotted in the third box, and the corresponding hazard consistent time series (m7.2 500.ts) is plotted in the 4th box.

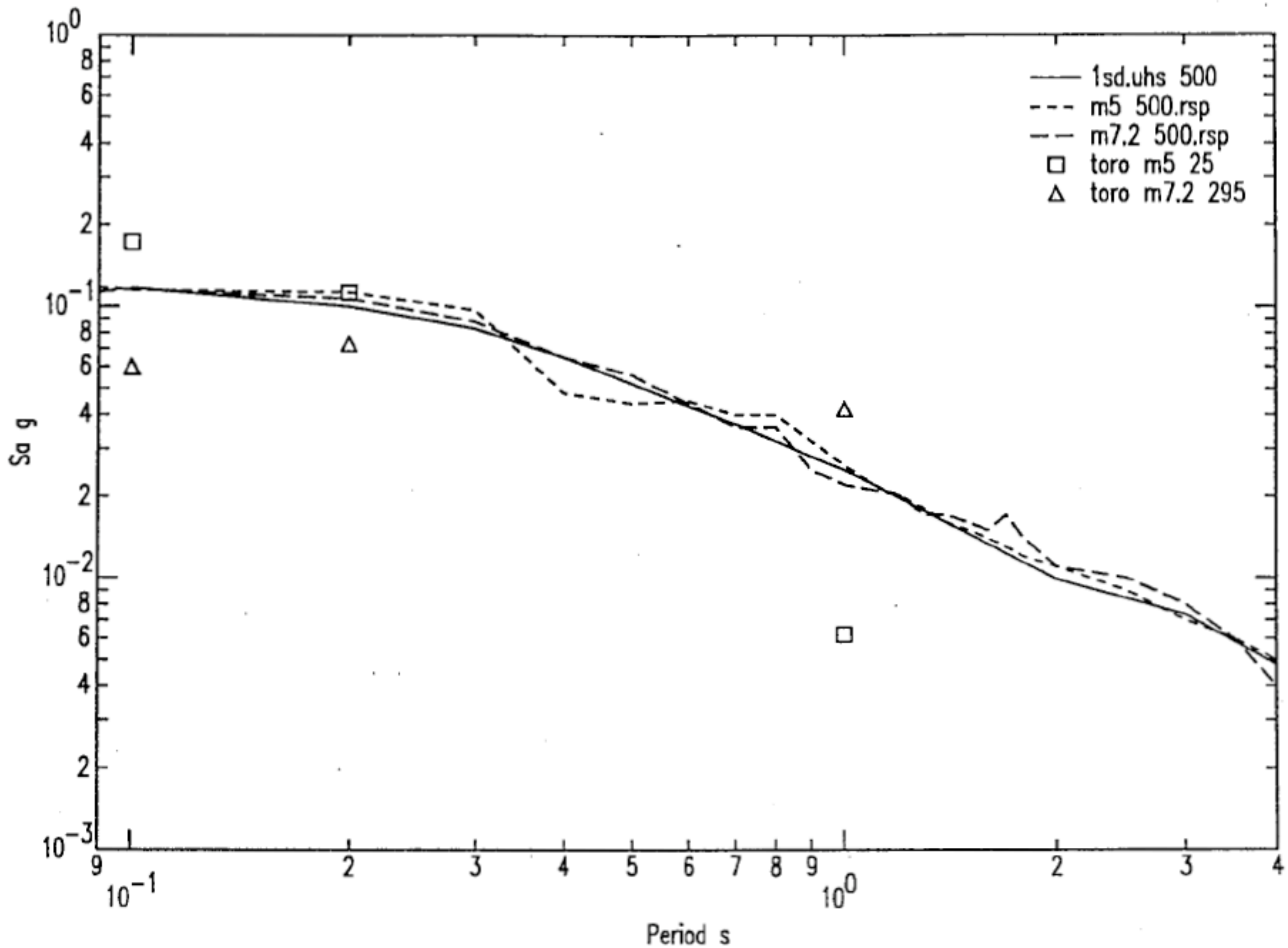


Figure 18b The (mean plus 1 σ) uniform hazard curve is plotted (solid line) for the 10% probability of exceedance in 50 years. The dotted line shows the 5% damped response spectrum of the m5 hazard consistent time series. The dashed line shows the 5% damped response spectrum of the m7.2 hazard consistent time series. Both spectra are within 5% difference of the target uniform hazard curve. Toro et al., (1994) predictions for the m5 event at 25 km (squares) and the m7.25 event at 295 km are plotted after applying soil correction factors (see Table II).

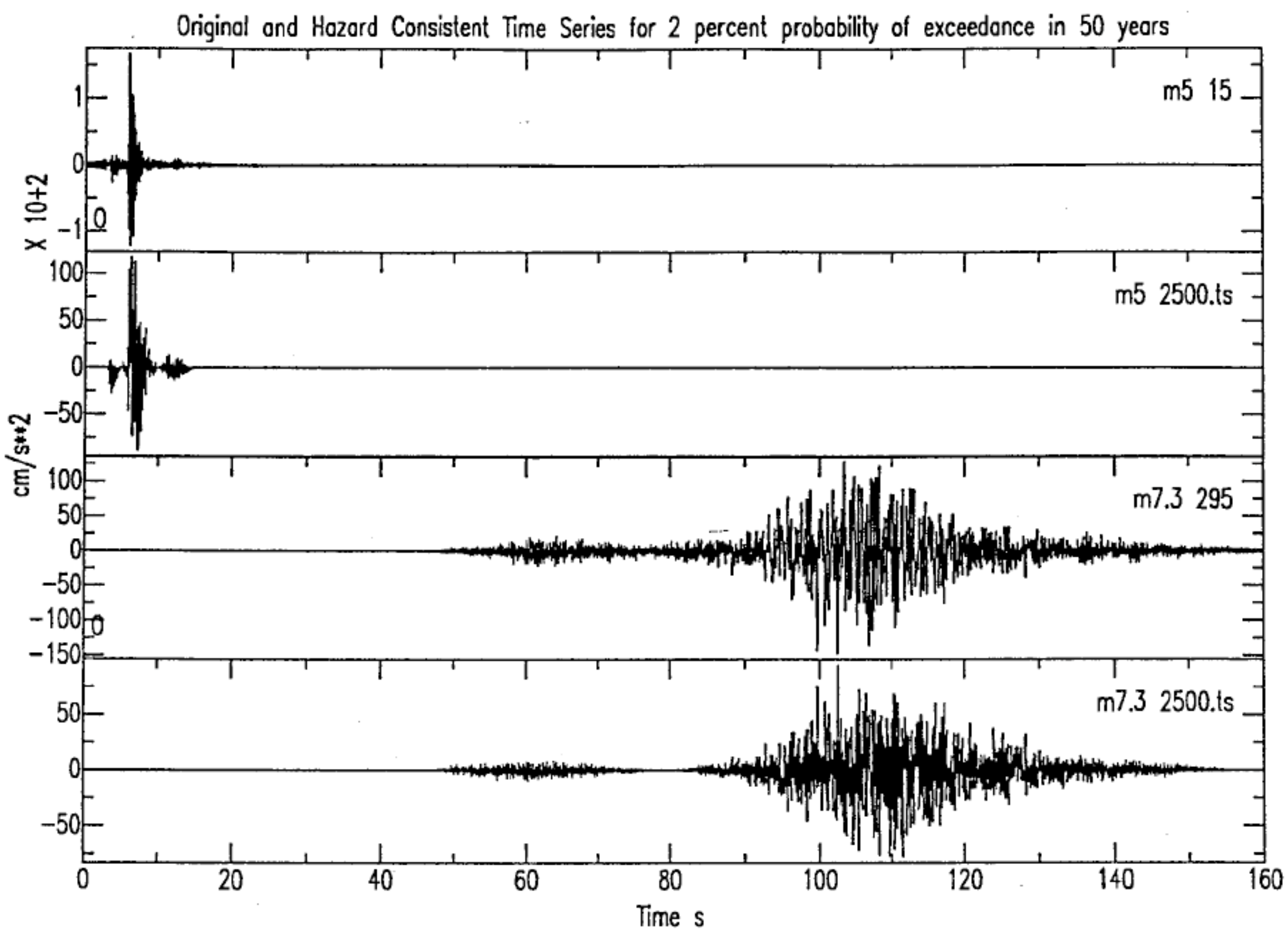


Figure 19a The (mean plus 1 σ) original and hazard consistent time series for 2% probability of exceedance in 50 years. A magnitude 5.05 at 15 km is the earthquake (mode) most likely to contribute to the expected level of hazard at 0.1 sec. period. The simulated time series for the M/D combination (m5 15) is plotted in the top box. The corresponding hazard consistent time series (m5 2500.ts) is plotted just below. The time series have roughly similar duration although the spectral content differs drastically. A magnitude 7.3 at 295 km is the modal earthquake contributing to the hazard at 1 sec. period. The simulated time series for this M/D combination (m7.3 295) is plotted in the third box, and the corresponding hazard consistent time series (m7.3 2500.ts) is plotted in the 4th box.

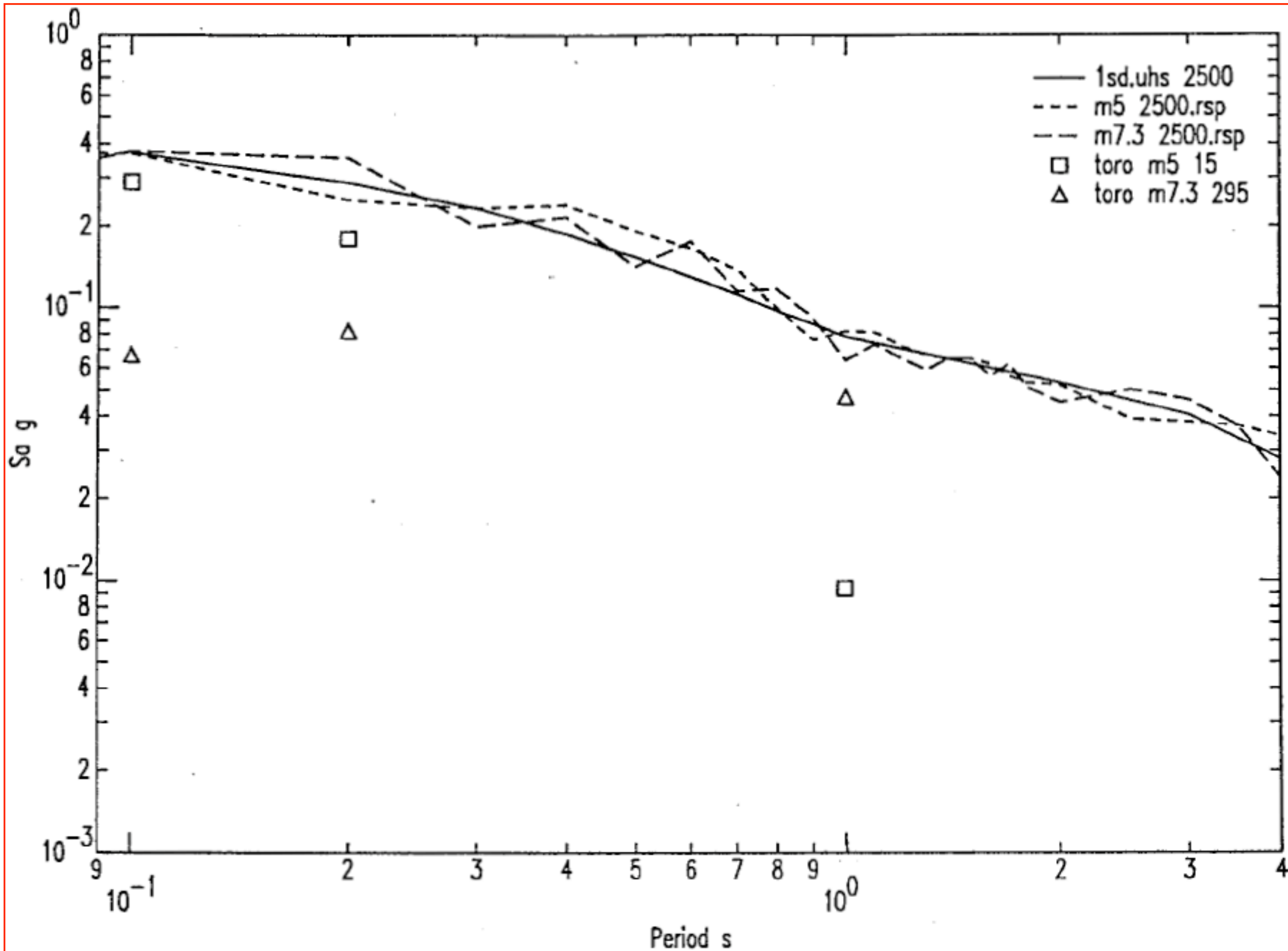


Figure 19b The (mean plus 1 σ) uniform hazard curve is plotted (solid line) for the 2% probability of exceedance in 50 years. The dotted line shows the 5% damped response spectrum of the m5 hazard consistent time series. The dashed line shows the 5% damped response spectrum of the m7.3 hazard consistent time series. Both spectra are within 5% difference of the target uniform hazard curve. Toro et al., (1994) predictions for the m5 event at 15 km (squares) and the m7.3 event at 295 km are plotted after applying soil correction factors (see Table II).

The Toro et al. (1994) predictions for the magnitude/distance combinations obtained from the deaggregation are all lower than the 85-percentile UHS, but especially low at long periods for the M5/15km event; and at short periods for the M7/295km event.

DISCUSSION

Clearly, the choice of input parameters to a probabilistic seismic hazard affects the result. For the PSHA at the site of the Delaware Memorial bridge, different source models, seismicity parameters, and attenuation relationships were applied. The difference in source models causes the greatest variability, more than a factor of 2 for 1 second period. The next most influential variable in the modeling is the magnitude conversion formula. Using the Johnston (1996) conversion from Mb to Mw yields response spectral accelerations 1.6 times greater, on average, than those calculated using the Atkinson and Boore (1995) conversion. Differences in maximum magnitude, *b* value, and attenuation relations result in smaller differences ranging from factors of 1.1 to 1.4. These factors are not necessarily multiplicative, but where they are, a large range of response spectral accelerations are possible. For example, a maximum ratio of 12 was found between results from extreme options for the 2%-in-50-year exceedance level at 1 second period.

It is important to keep in mind the high degree of variability, because it is easy to lose sight of during subsequent derivation and synthesis of time series. The 85-percentile uniform hazard spectra were deaggregated to determine the earthquakes, defined by magnitude and distance, that contributed most strongly to the selected hazard level. Rock-ground motions of these dominant earthquakes were then simulated to account for average source properties, crustal wave propagation effects, and duration of ground shaking. In turn, these source, path, and site effects are all associated with uncertainties, though not quantified for time series simulations. Finally, the ground-motion simulations were modified to be compatible with the 85-percentile uniform hazard spectra, while still maintaining some of the "original" character of the simulations, such as duration of shaking and phase arrival times. In the next phase of the project the hazard-spectrum-compatible time series will be further modified by simulated propagation through soft sediments specific to the DMB site. Methods used in this study are fairly standard.

Questions?

2d

Example for Hybrid, Constant Recurrence Period (CRP) Method.
This isn't a PSHA and does not account for uncertainties Ua and Ue,
but allows to model hazard-consistent ground motions for specified Tr.

TAPPAN ZEE BRIDGE SEISMIC STUDY

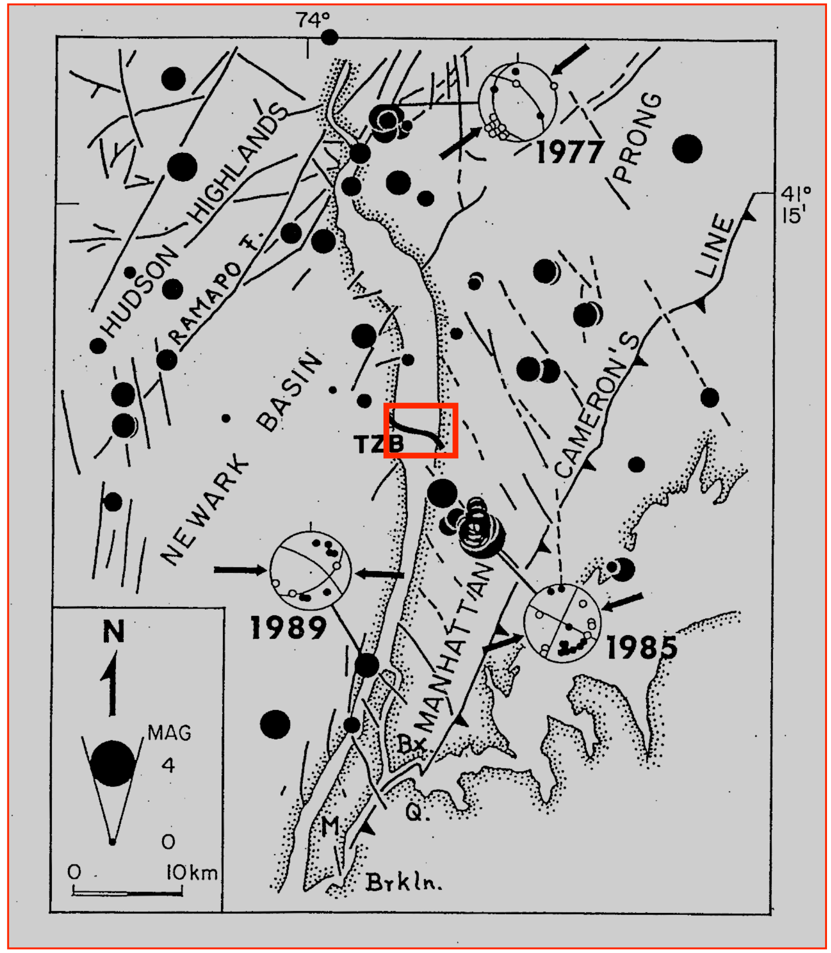
Final Report, Part 1:

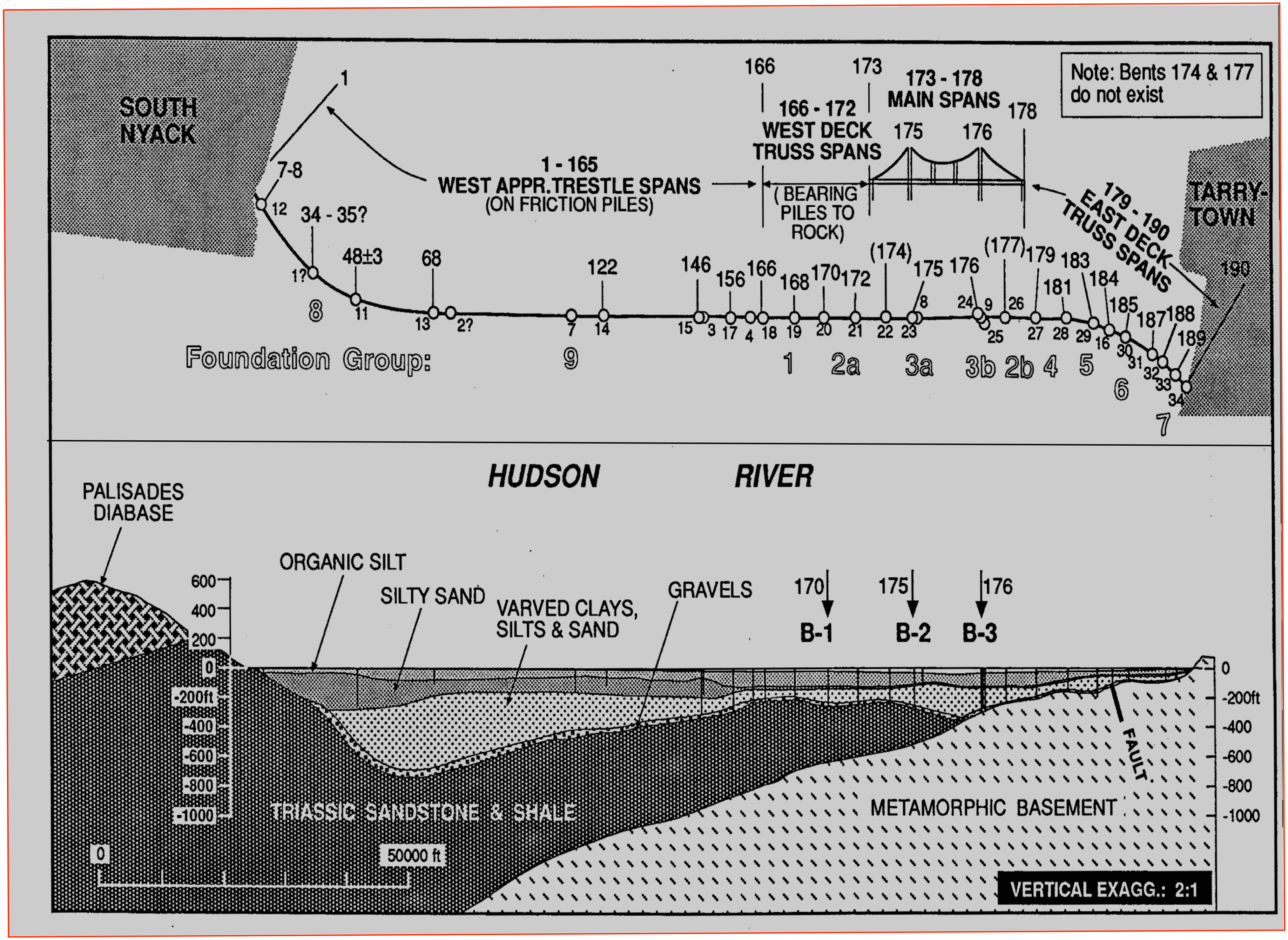
Seismic Hazard Assessment, Design Ground Motions and Comments on Liquefaction Potential for the Site of the Tappan Zee Bridge, New York.

Prepared by

K. Jacob, S. Horton, N. Barstow, and J. Armbruster

Lamont-Doherty Earth Observatory of Columbia University
Route 9W, Palisades, N.Y. 10964
Phone: (914) 365 8440
Fax: (914) 365 8150





SOUTH NYACK
TARRY-TOWN
Note: Bents 174 & 177 do not exist
1 - 165
WEST APPR.TRESTLE SPANS
(ON FRICTION PILES)
166 - 172
WEST DECK TRUSS SPANS
(BEARING PILES TO ROCK)
173 - 178
MAIN SPANS
179 - 190
EAST DECK TRUSS SPANS
Foundation Group:
HUDSON RIVER
PALISADES DIABASE
ORGANIC SILT
SILTY SAND
VARVED CLAYS, SILTS & SAND
GRAVELS
B-1
B-2
B-3
FAULT
TRIASSIC SANDSTONE & SHALE
METAMORPHIC BASEMENT
50000 ft
VERTICAL EXAGG.: 2:1

$$\log n = (-2.305 \pm 0.642) - (0.775 \pm 0.153)\, M \quad (1b)$$

$$\log N = \log n + \log S + \log T \quad (2a)$$

$$\log N = a - bM + \log S + \log T \quad (2b)$$

$$\log 1 = 0 = a - bM + \log S + \log T \quad (3)$$

$$\log S = \log (2\pi d^2) = bM - a - \log T \quad (4a)$$

$$\log d = (bM - a - \log T - \log 2\pi)/2 \quad (4b)$$

$$\log d = (0.775\, M + 2.305 - \log T - \log 2\pi)/2 \quad (7)$$

Table 2: *Median distances **d (km)** expected for earthquakes with magnitudes M and recurrence periods T (years) for an unconfined seismic source with uniform cumulative rate log n (y^{-1} km^{-2}) = -2.305 -.775 M.*

Magnitude M	Average Recurrence Period T (years) 500	1000	2500	5000
5	22	16	10	7
6	54	38	24	17
7	131	92	58	42

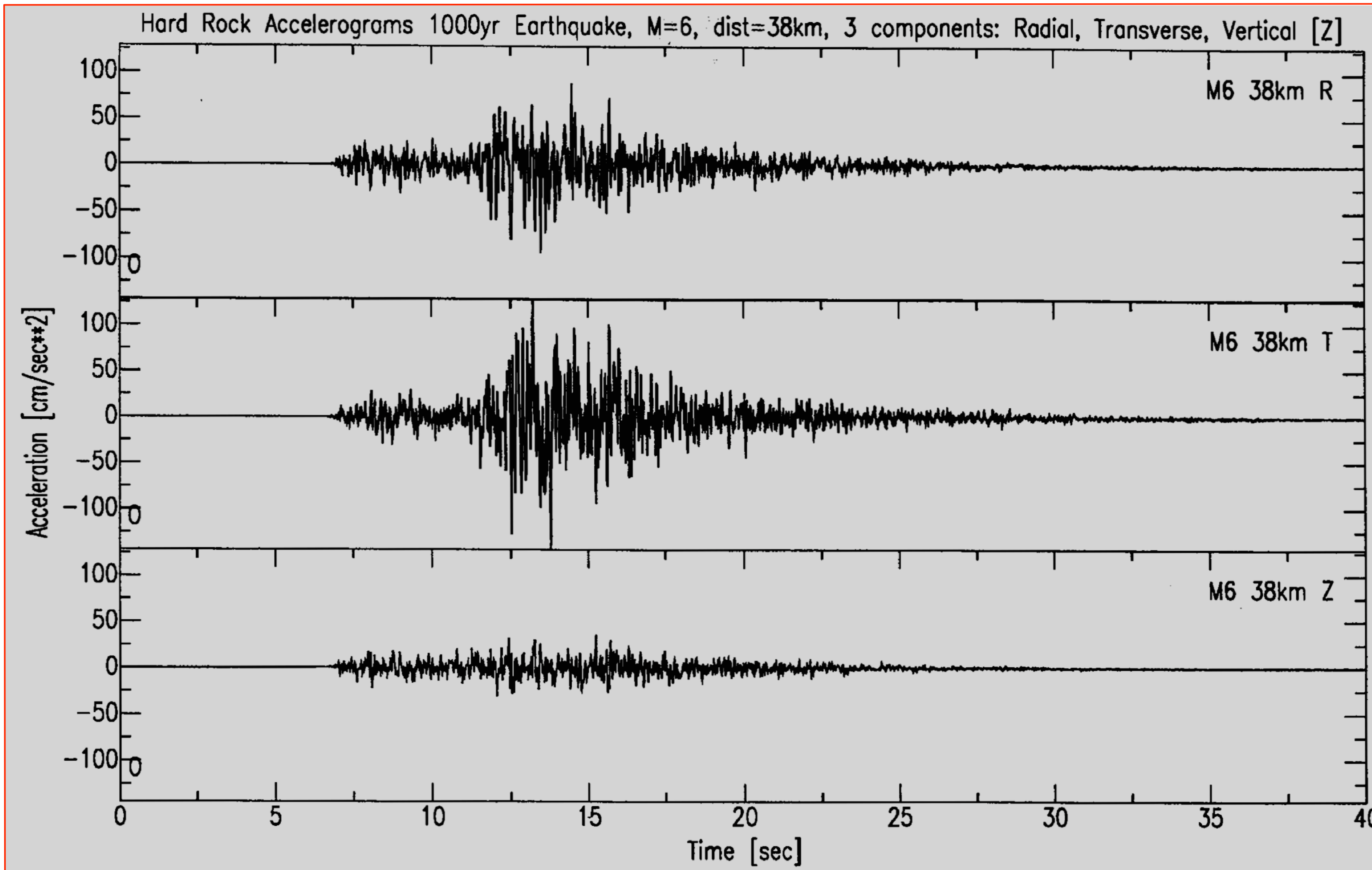


Figure 6. Three components of computed hard-rock accelerations for an earthquake with a recurrence period of 1,000 years, and related magnitude-distance (M-d) combination of M=6 at d=38km. The three components are from top to bottom: R, radial; T, transverse; and Z, vertical component.

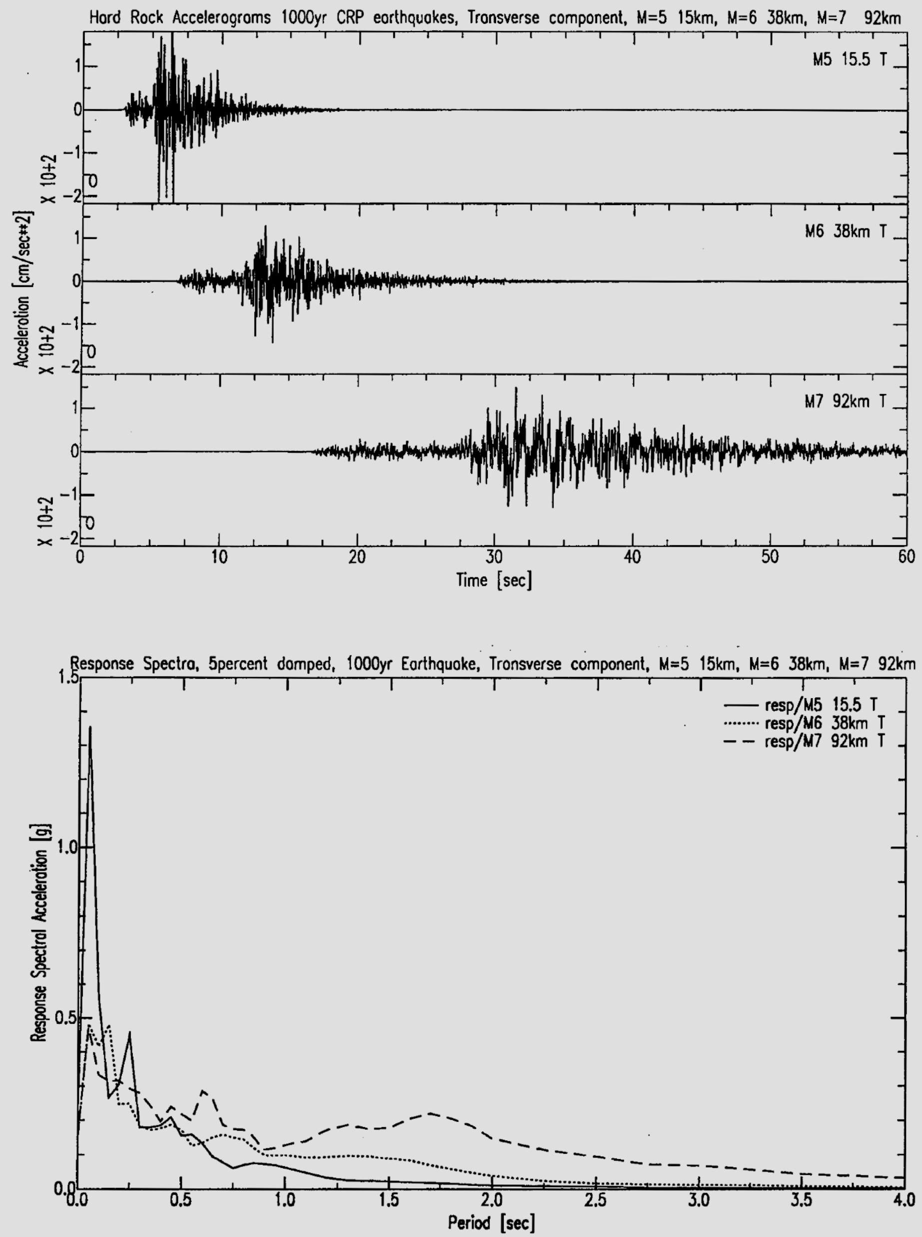


Figure 7. (Top): Transverse components of computed hard-rock accelerations for three equally probable earthquakes with a constant recurrence period (CRP) of 1,000 years, but different magnitude-distance (M-d) combinations M=5 at d=15.5 km; M=6 at d=38km; and M=7 at d=92 km. (Bottom): 5% damped response spectra for the same 1000-year accelerations shown above. Note the small earthquake at short distance dominates the short periods, the large earthquake at large distance the long periods. The envelope to the three spectra is called a CRP envelope response spectrum.

Table 3: *"New England" Crustal Structure Used in the TZB Ground Motion Simulations.*

Layer	Thickness (km)	Depth to Top (km)	P-velocity (km/s)	S-velocity (km/s)	Density (g/cm³)	Q_p (intrinsic*)	Q_s
1	2.0	0.0	6.00	3.50	2.50	3000	1500
2	13.0	2.0	6.10	3.60	2.60	6000	3000
3	25.0	15.0	7.00	4.10	2.90	6000	3000
4	∞	40.0	8.10	4.70	3.20	6000	3000

* These Q factors represent only the intrinsic anelastic absorption (attenuation) of crustal materials. The additional attenuation from scattering is separately accounted for by the procedure of Horton (1994).

Table 4: *Source Parameters Used for the TZB Ground Motion Simulations*

Magn. M	Moment M_o ($Nm \times 10^{16}$)	Stress Drop (bar)	Corner Frequ. (Hz)	Focal Depth (km)	Strike ----------(degr)--------	Dip	Rake
5	3.98	100	1.10	7	0	80	20
6	126.00	100	0.35	7	observed at 22.5 degrees		
7	3980.00	100	0.11	7	from strike		

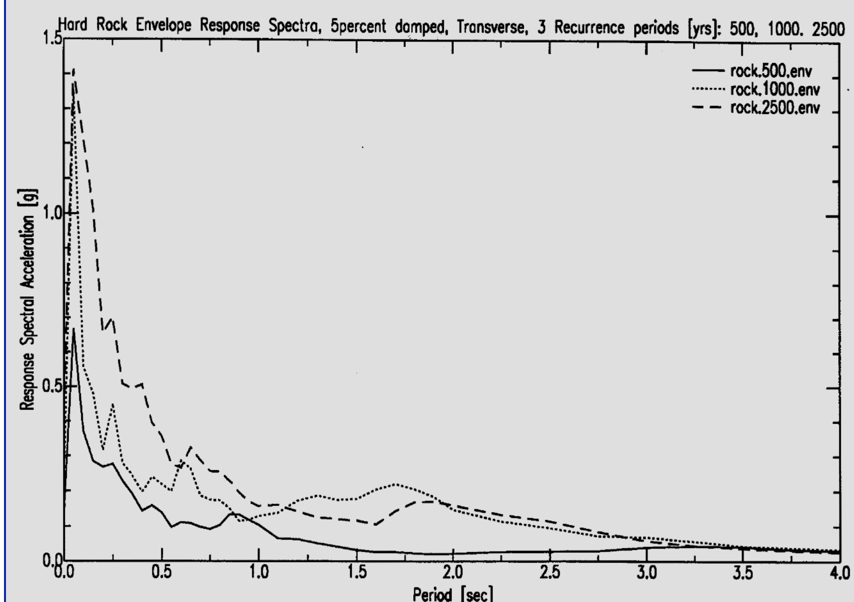


Figure 8. Constant recurrence period (CRP) envelope response spectra for three different constant recurrence periods of CRP = 500, 1,000 and 2,500 years. Note that the 1,000-year spectrum exceeds the 2,500-year spectrum at periods between about 1 and 2 seconds because of contributions from super-critical Moho reflections for the constituent 1,000-year event of M=7 being located at d=92 km.

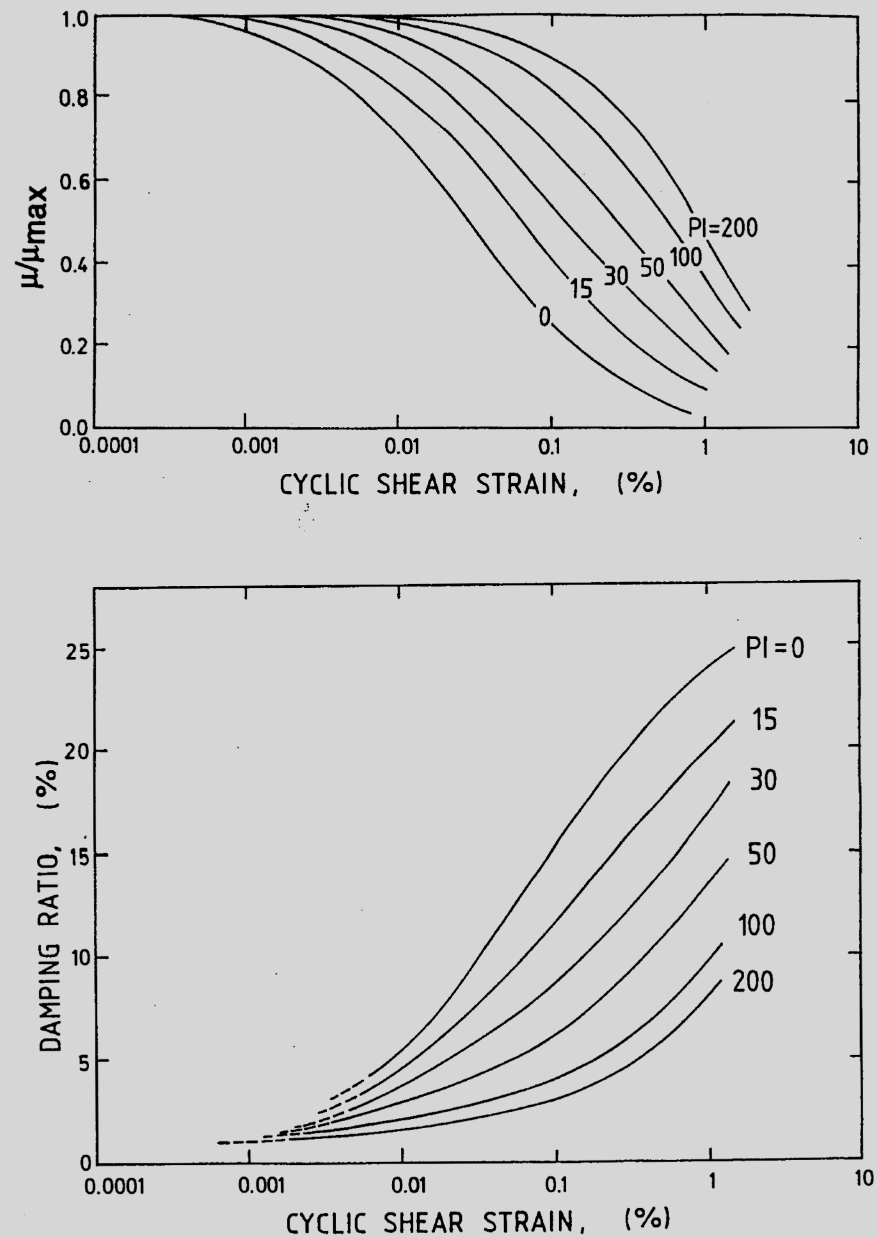
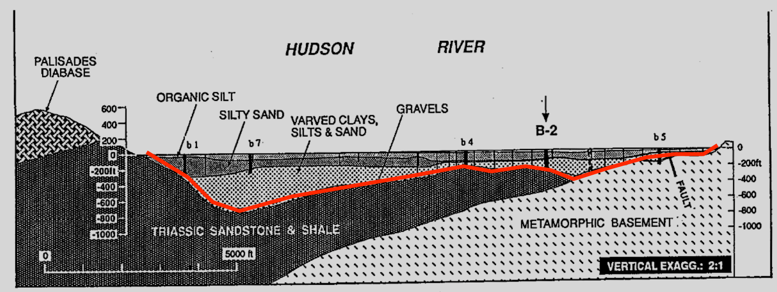


Figure 12. *(Top):* Shear modulus degradation G/G_{max} (labeled here μ/μ_{max}) as a function of cyclic shear strain (in %) for soils with different plasticity index, PI. *(Bottom):* Damping ratio ß as a function of cyclic shear strain for soils with different PI. Both curves are taken from Vucetic and Dobry (1991) and apply to normally consolidated or only slightly overconsolidated soils.

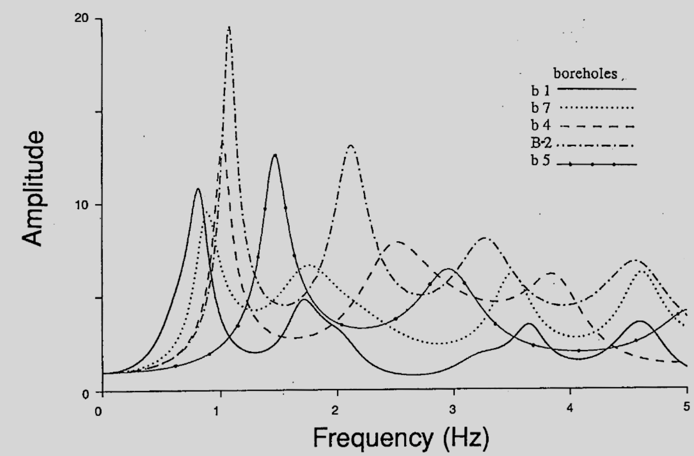
Table 5: Plasticity Index (PI) Assigned to the Soils at TZB Site.

Rock or Soil	PI
Organic Silts	30
Silty Clays	15
Silty Clays with some Sand	10
Sand	3
Varved Clays (interbedded clays and sands)	3
Gravel	0
Triassic Red Sandstone	∞ *
Serpentinite	∞ *

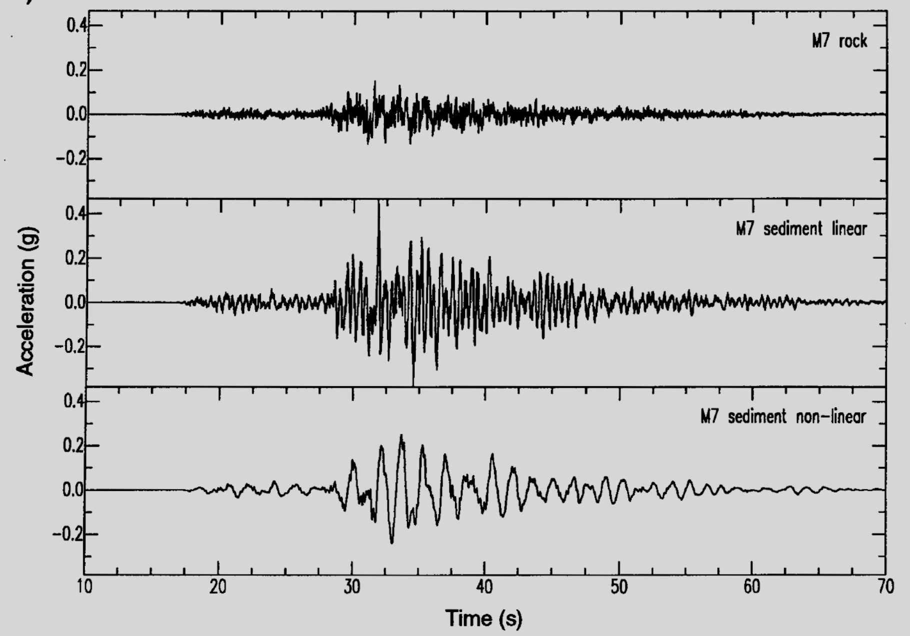
* The concept of plasticity is not applicable to rocks.



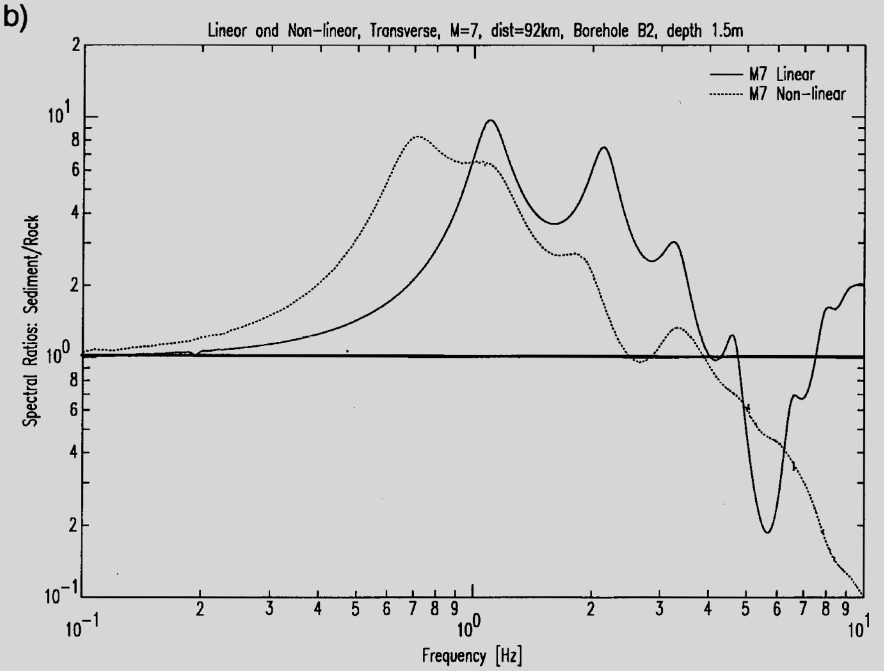
SEDIMENT TRANSFER FUNCTIONS

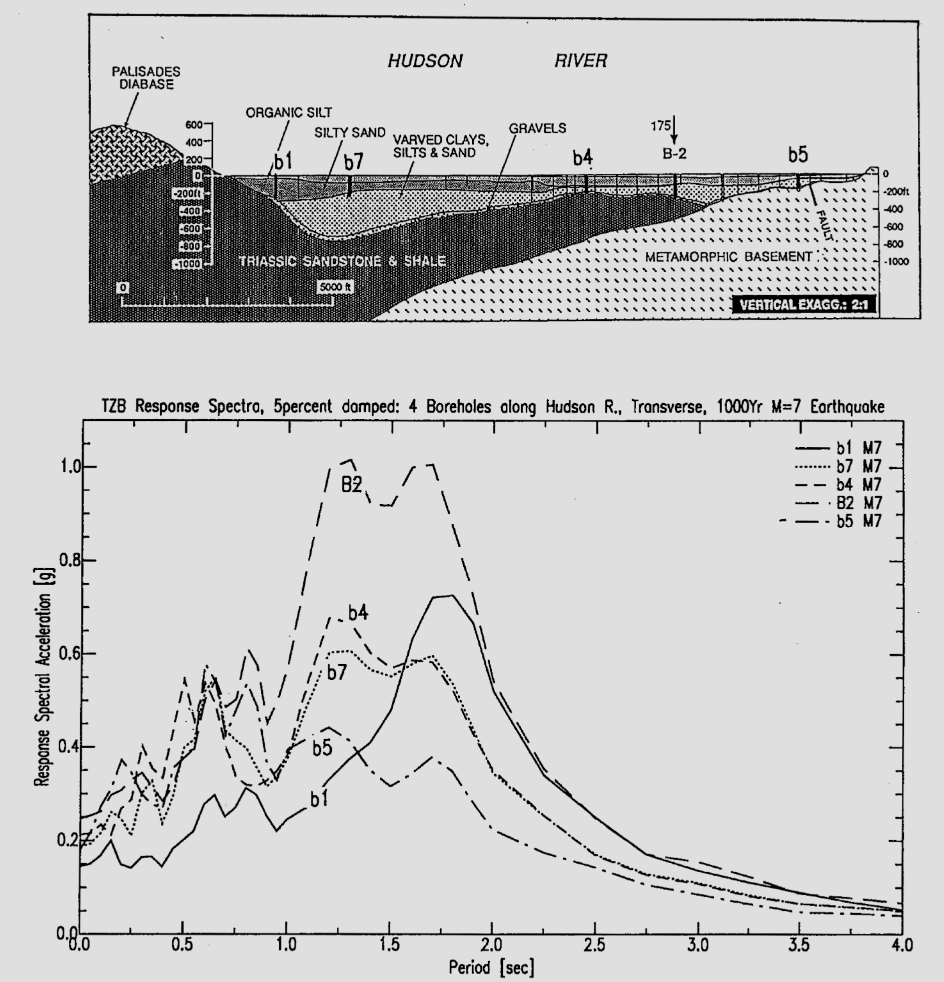


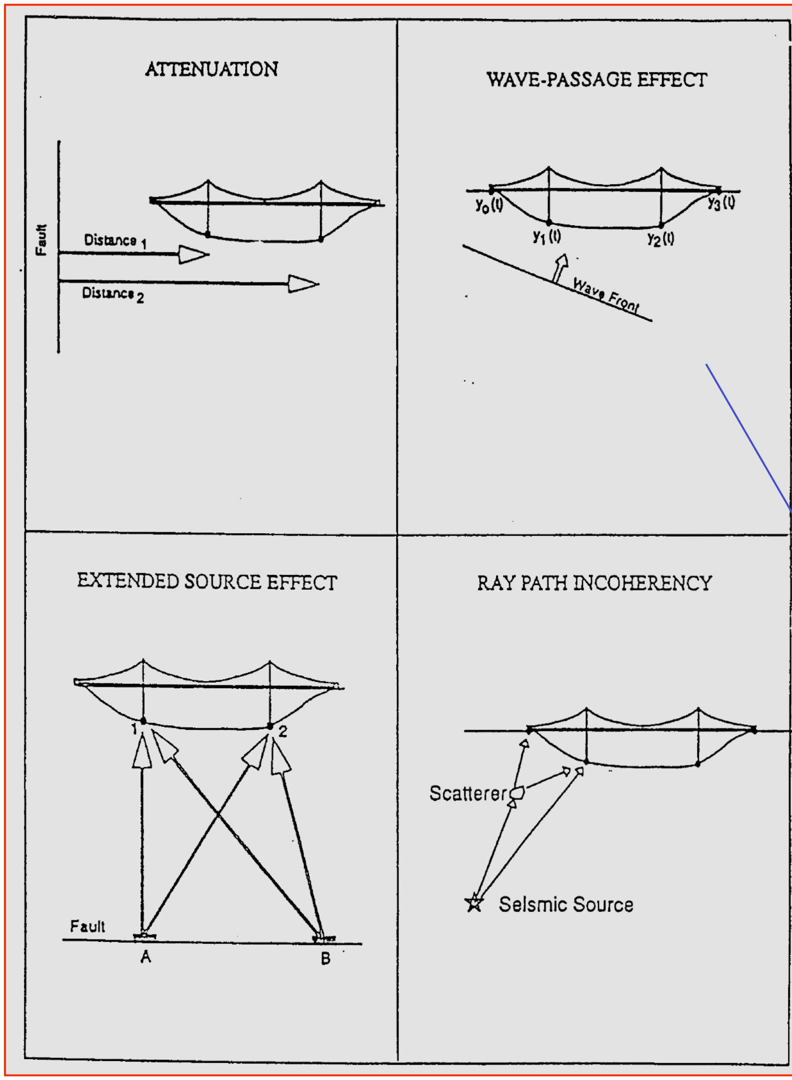
a)

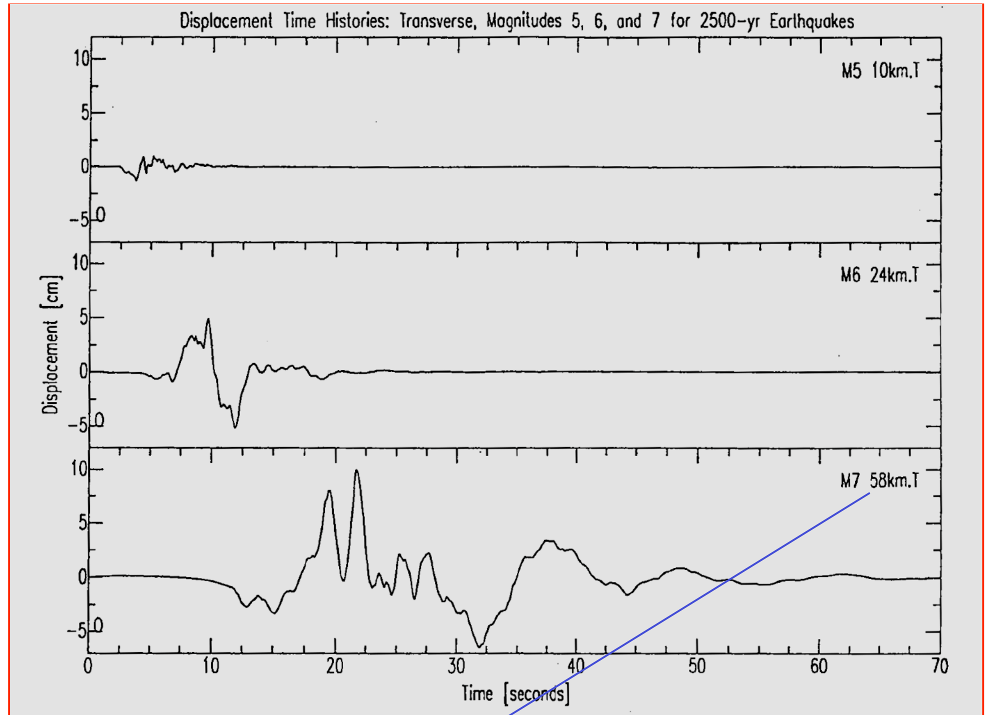

M7 rock
M7 sediment linear
M7 sediment non-linear
Acceleration (g)
Time (s)

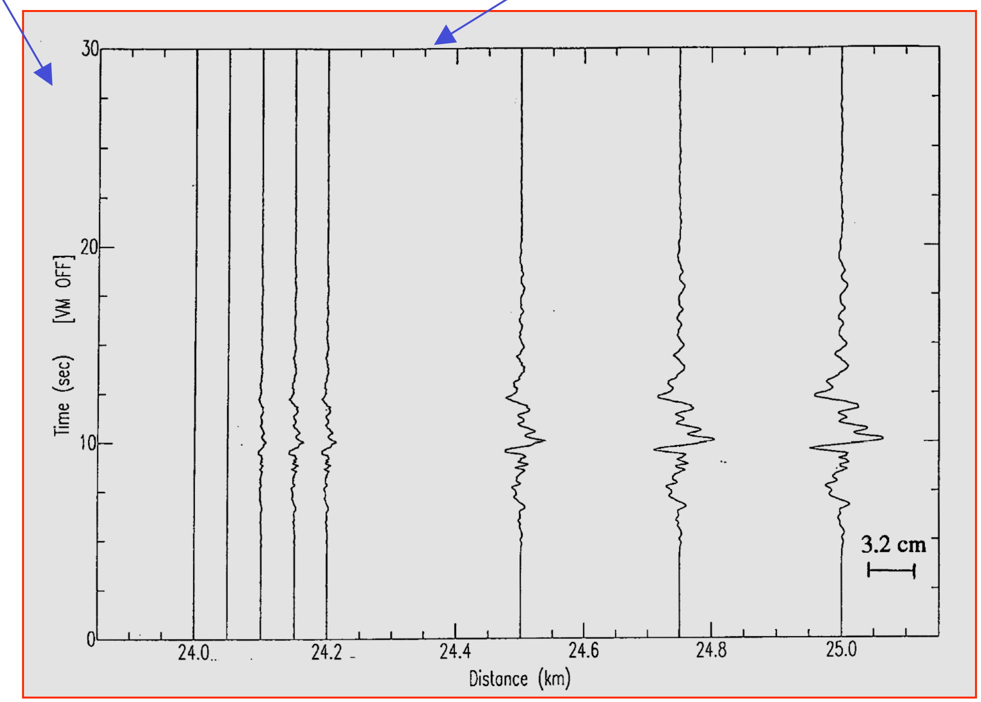
b)


Linear and Non-linear, Transverse, M=7, dist=92km, Borehole B2, depth 1.5m
M7 Linear
M7 Non-linear
Spectral Ratios: Sediment/Rock
Frequency [Hz]


HUDSON
RIVER
PALISADES DIABASE
ORGANIC SILT
SILTY SAND
VARVED CLAYS, SILTS & SAND
GRAVELS
175
B-2
b1
b7
b4
b5
TRIASSIC SANDSTONE & SHALE
METAMORPHIC BASEMENT
FAULT
5000 ft
VERTICAL EXAGG.: 2:1
TZB Response Spectra, 5percent damped: 4 Boreholes along Hudson R., Transverse, 1000Yr M=7 Earthquake
b1 M7
b7 M7
b4 M7
B2 M7
b5 M7
B2
Response Spectral Acceleration [g]
Period [sec]


ATTENUATION
Fault
Distance 1
Distance 2
WAVE-PASSAGE EFFECT
Wave Front
EXTENDED SOURCE EFFECT
Fault
A
B
RAY PATH INCOHERENCY
Scatterer
Seismic Source


Displacement Time Histories: Transverse, Magnitudes 5, 6, and 7 for 2500-yr Earthquakes
M5 10km.T
M6 24km.T
M7 58km.T
Displacement [cm]
Time [seconds]


Time (sec) [VM OFF]
Distance (km)
3.2 cm

Questions?

2d