# Ground Motions for Performance-Based Seismic Design

*Indian Institute of Science (IISc) Department of Civil Engineering Seminar*


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*U.S. Geological Survey*

*Golden, Colorado*


FEMA

USGS
science for a changing world

Building Seismic Safety Council

# Outline of Presentation

**Tomorrow:**

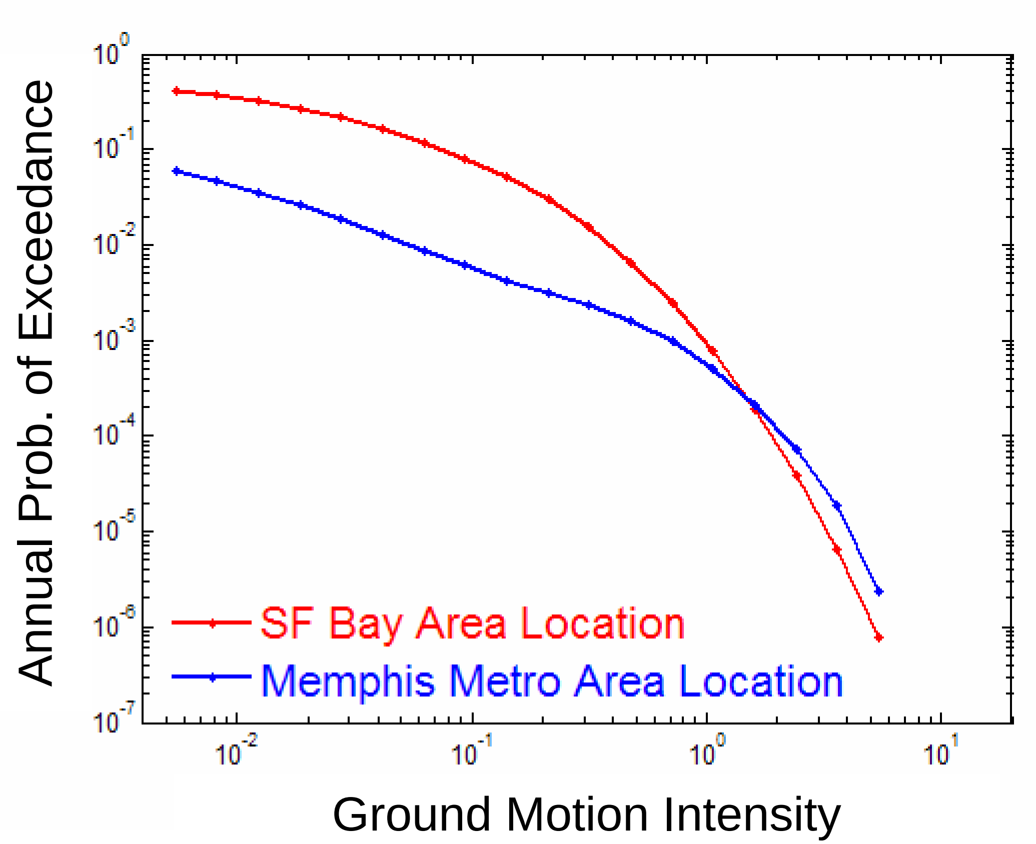
- New “Risk-Targeted” Seismic Maps Introduced into USA Building Codes

**Today:**

- Probabilistic Seismic Hazard Analysis (PSHA)
- Previous “uniform-hazard” maps in USA building codes
- Ground motions for Next Generation Performance-Based Seismic Design Procedures for New and Existing Buildings (“ATC-58 Project”, funded by FEMA)

# Probabilistic Seismic Hazard *Curves*

Results of Probabilistic Seismic Hazard Analysis (PSHA), pioneered by the late Prof. C. Allin Cornell in 1968.



# Probabilistic Seismic Hazard *Analysis*

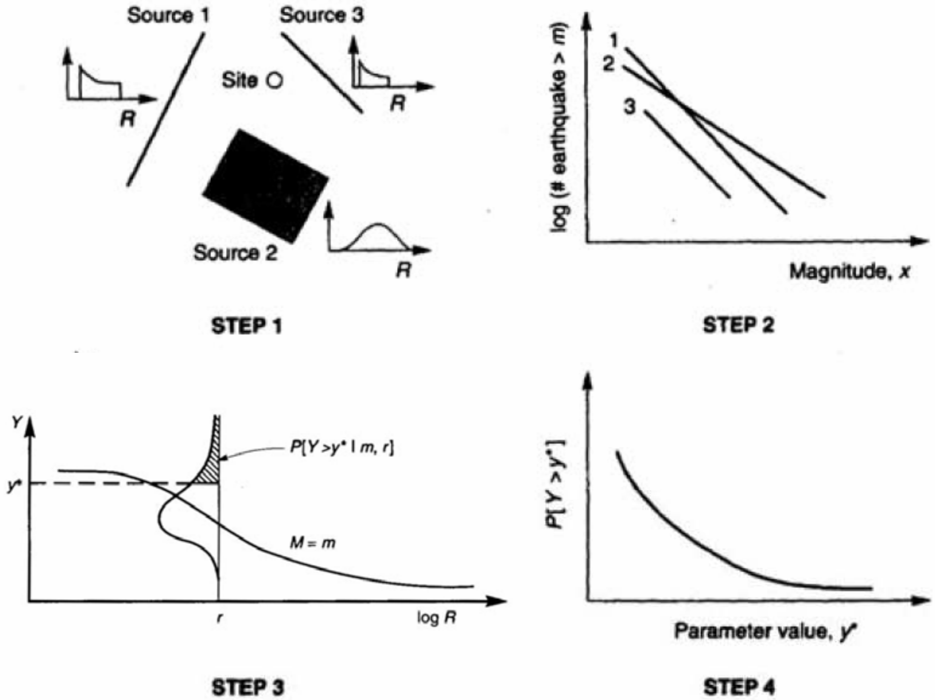



Figure B-3 Steps in probabilistic seismic hazard assessment (Kramer, 1996)

**Steps**:

1) Identify earthquake sources & develop PDF's for source-to-site distances, $f_{Ri}(r)$.

2) Develop frequencies of earthquakes, $\nu_i$, & PDF's for magnitudes, $f_{Mi}(m)$.

3) Determine CDF for ground motion intensity *y* given *m* & *r*.

4) For each source …

$$\lambda_{y} = \nu_i \cdot P_i[Y > y] = \nu_i \cdot \iint P[Y > y \mid m, r] \, f_{M_i}(m) \, f_{R_i}(r) \, dm \, dr$$

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# Probabilistic Seismic Hazard *Analysis*

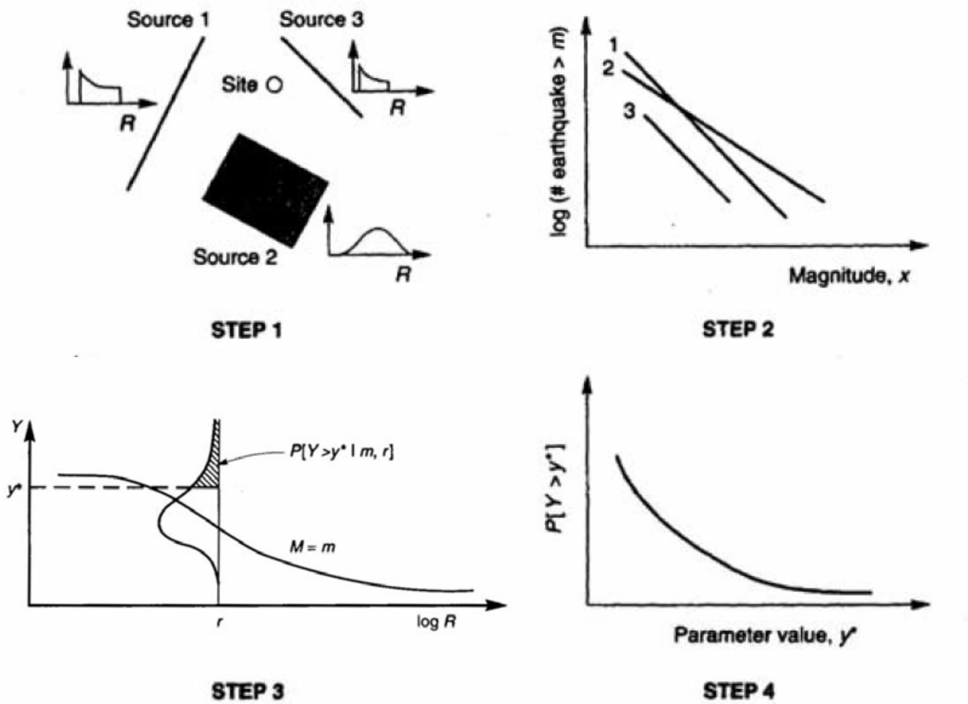



Figure B-3 Steps in probabilistic seismic hazard assessment (Kramer, 1996)

**Notes:**

1)Frequencies can be summed across earthquake sources:

$$\lambda = \sum_i \lambda_i$$

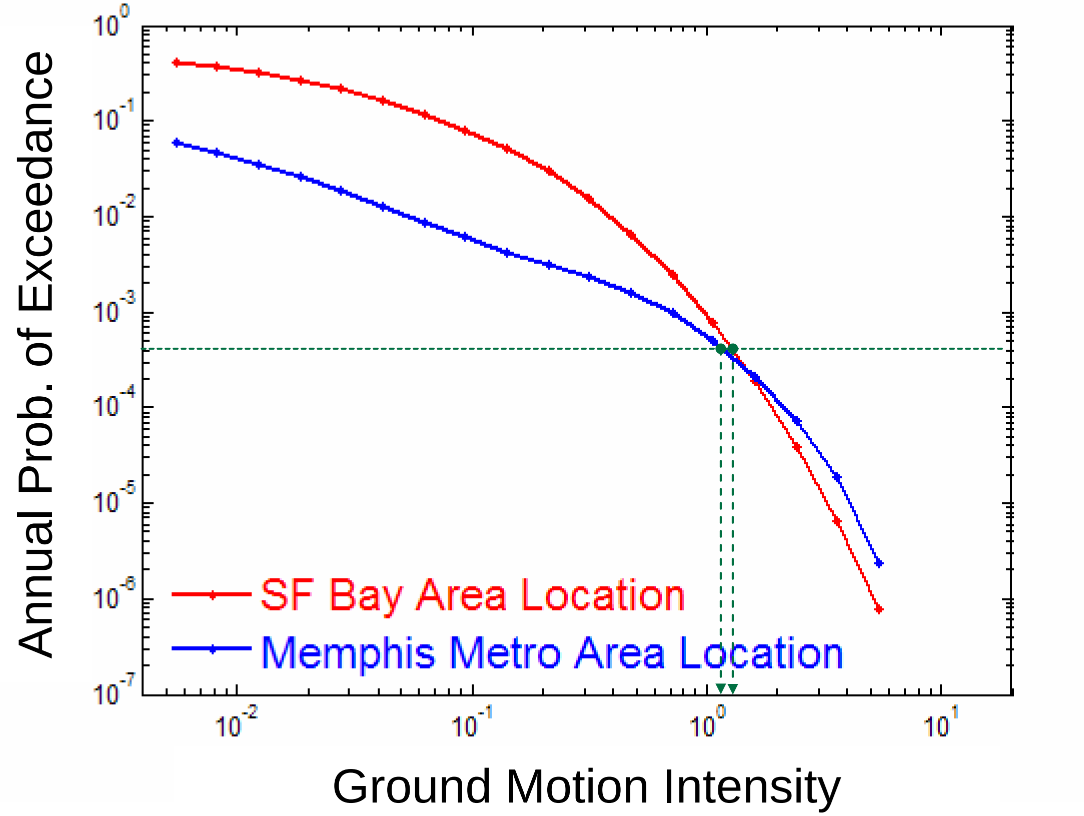
2)Assuming Poisson probability distribution in time …

$$P[Y > y] = 1 - \exp(-\lambda t)$$

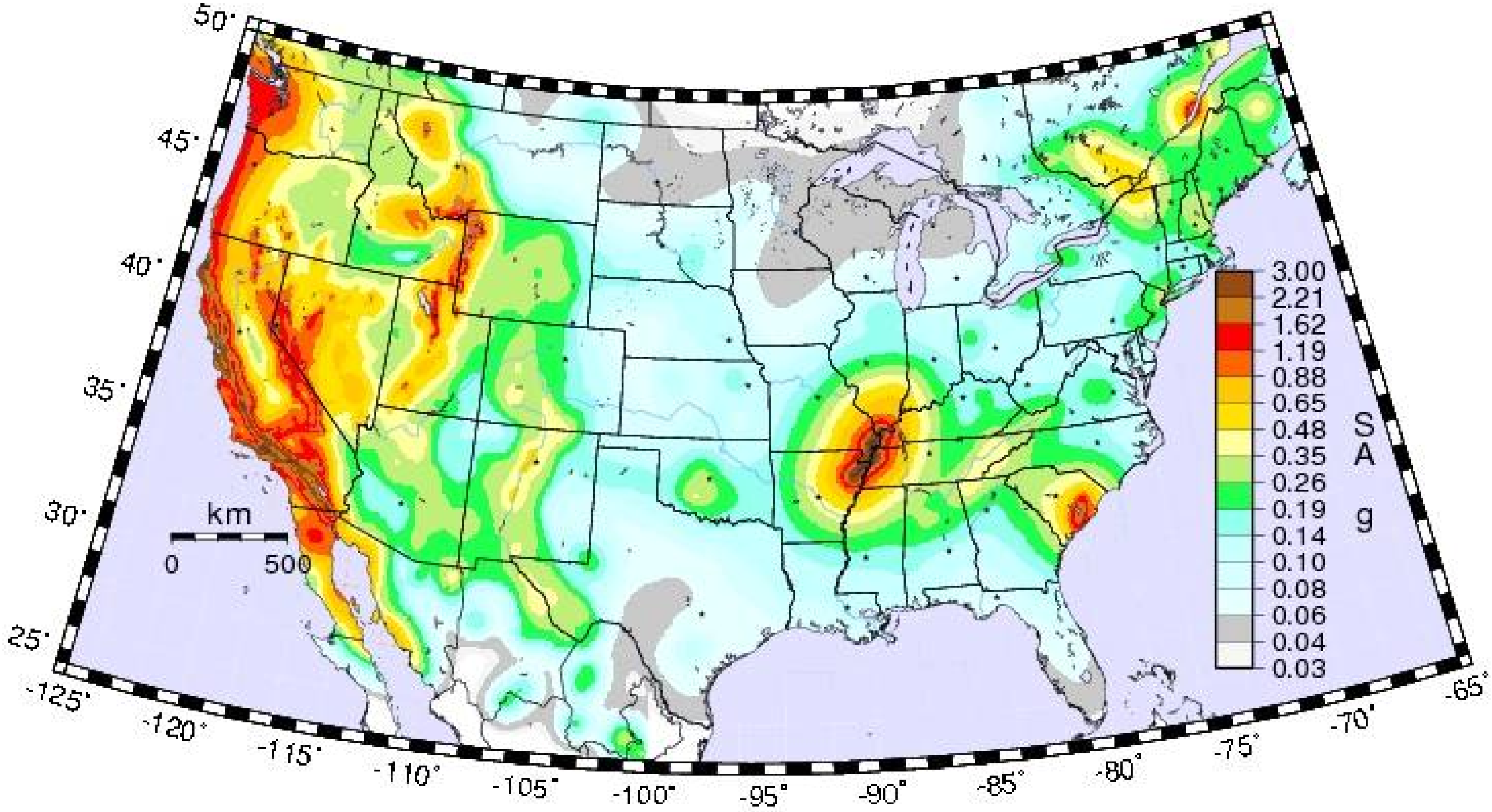
$$\lambda_i = \nu_i \cdot P_i[Y > y] = \nu_i \cdot \iint P[Y > y \mid m, r] \, f_{M_i}(m) \, f_{R_i}(r) \, dm \, dr$$

# Probabilistic Seismic Hazard *Curves*

Results of Probabilistic Seismic Hazard Analysis (PSHA), pioneered by the late Prof. C. Allin Cornell in 1968.



# e.g., ground motion intensity with a uniform 1/2500 annual probability of being exceeded



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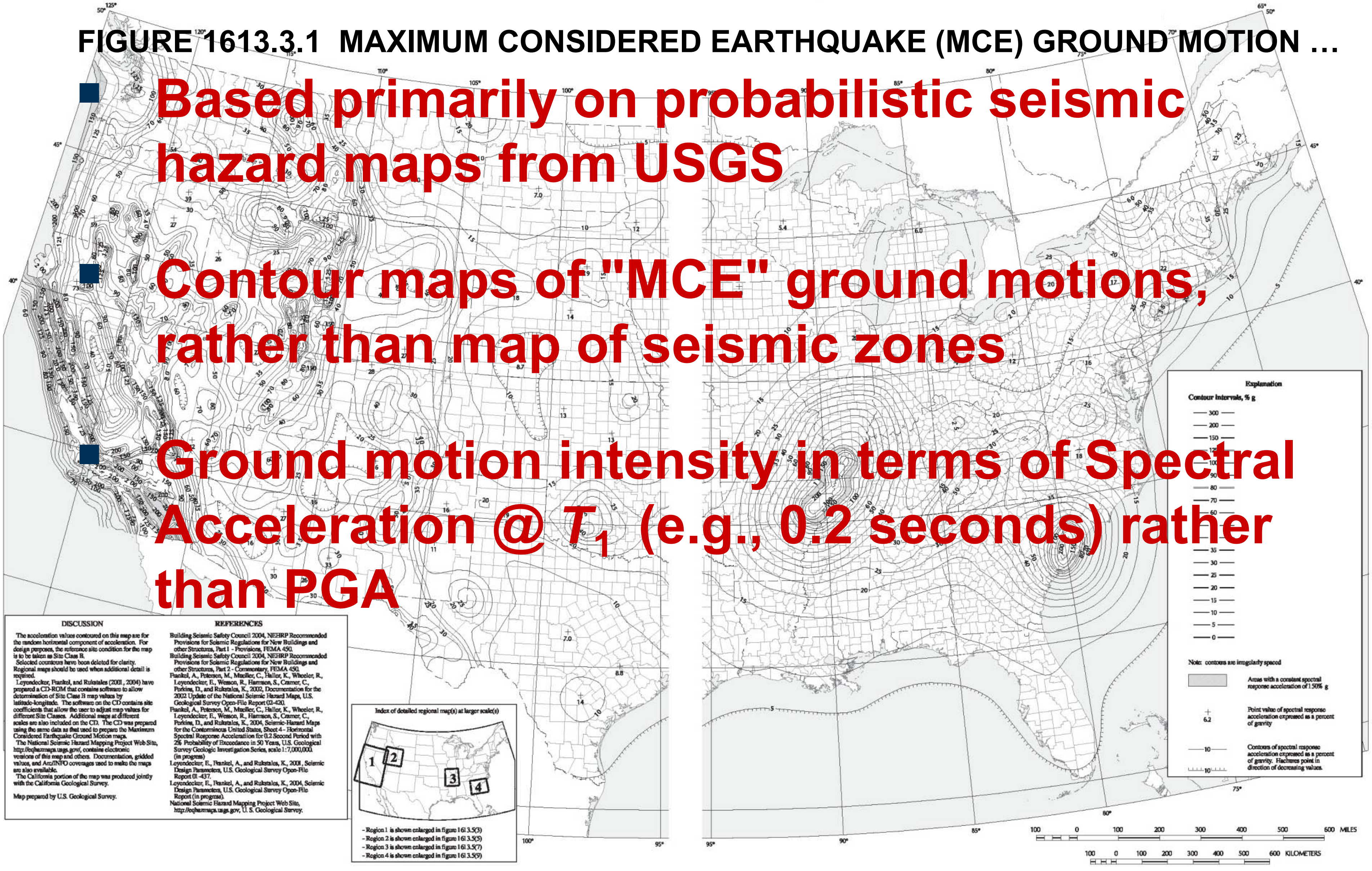
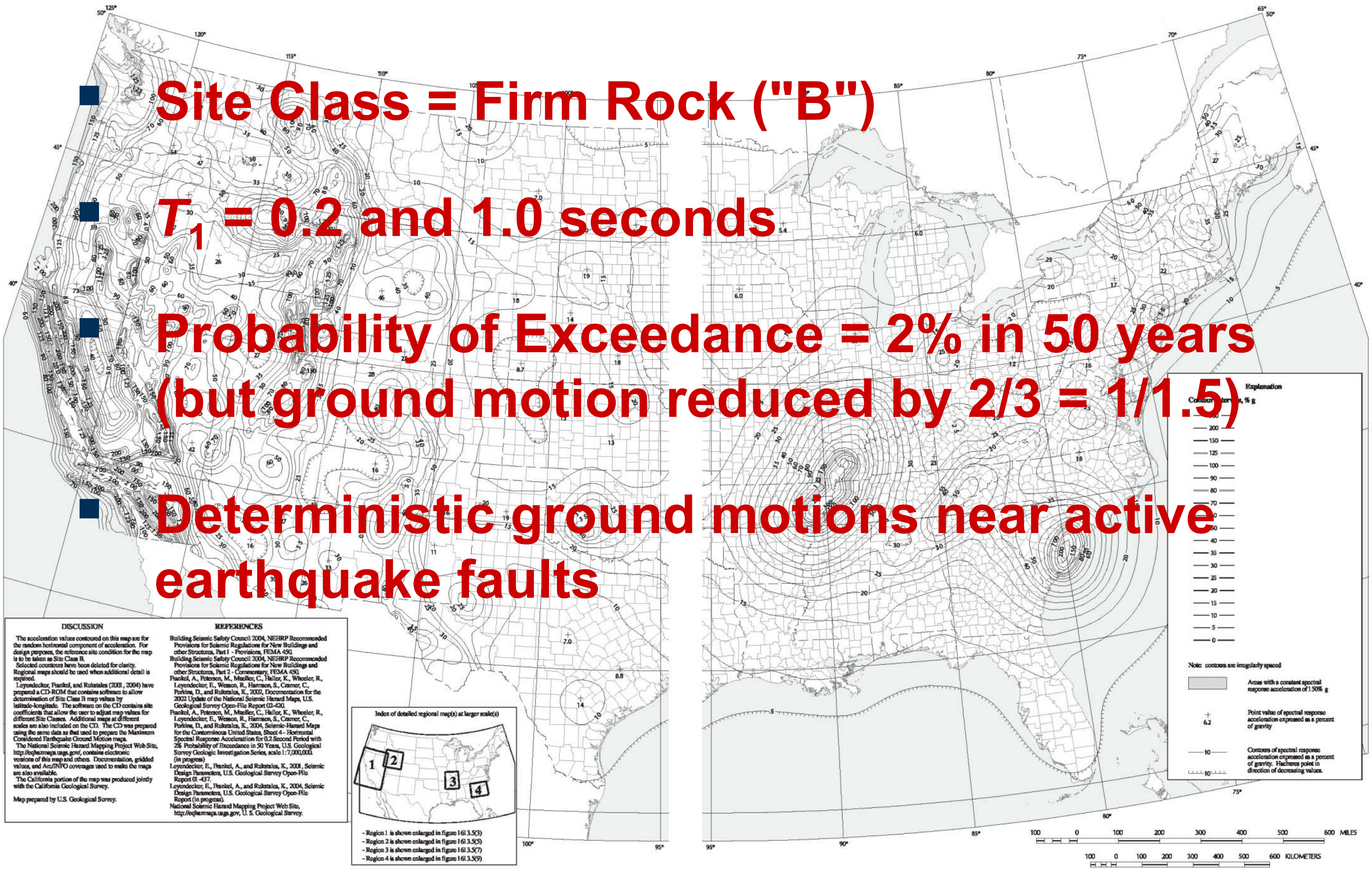
# Pre-2012 “International” Building Code

**FIGURE 1613.3.1 MAXIMUM CONSIDERED EARTHQUAKE (MCE) GROUND MOTION …**




- Based primarily on probabilistic seismic hazard maps from USGS
- Contour maps of "MCE" ground motions, rather than map of seismic zones
- Ground motion intensity in terms of Spectral Acceleration @ $T_1$ (e.g., 0.2 seconds) rather than PGA

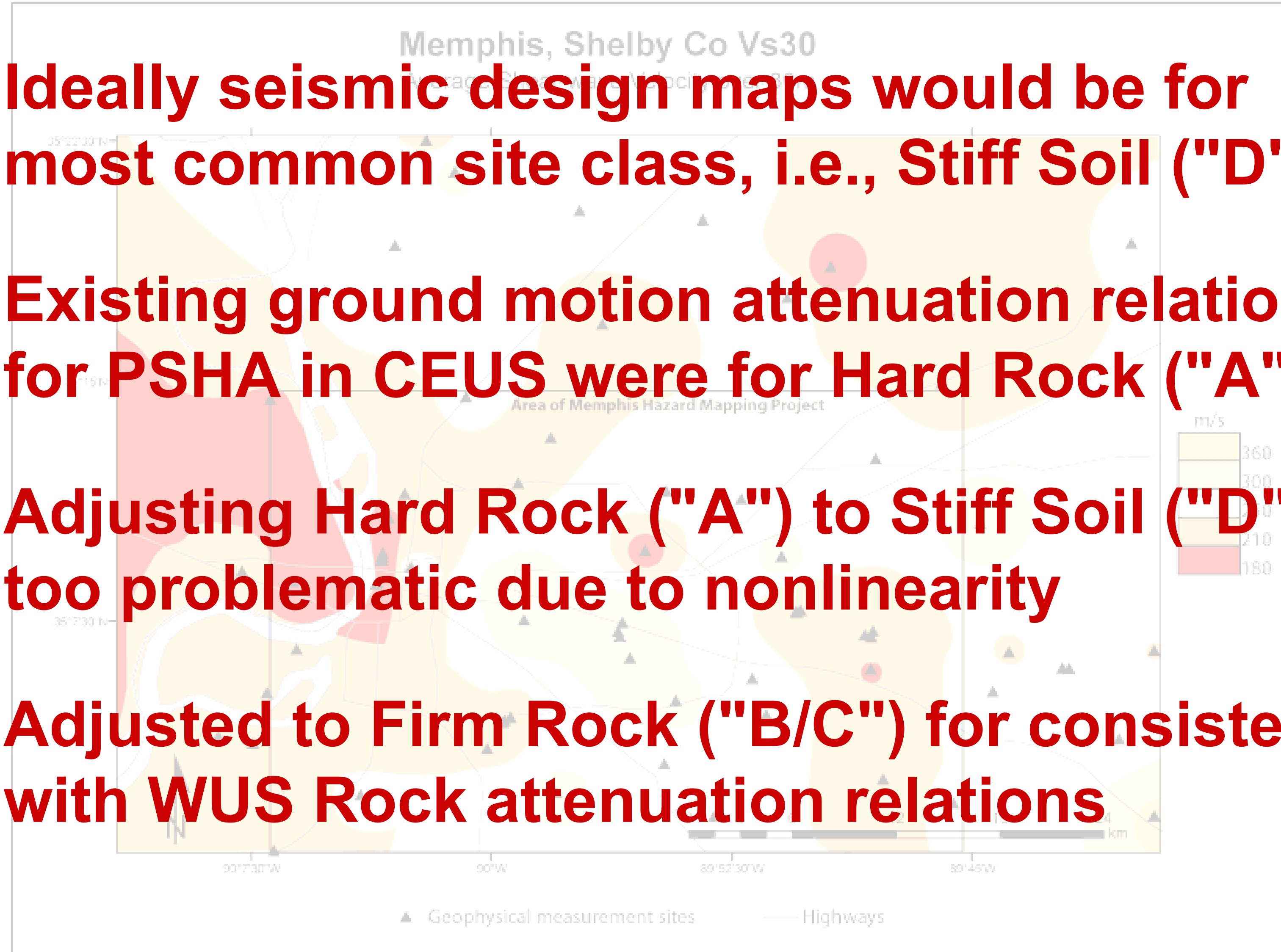
# Decisions Behind Pre-2012 IBC Maps




- Site Class = Firm Rock ("B")
- $T_1$ = 0.2 and 1.0 seconds
- Probability of Exceedance = 2% in 50 years (but ground motion reduced by 2/3 = 1/1.5)
- Deterministic ground motions near active earthquake faults

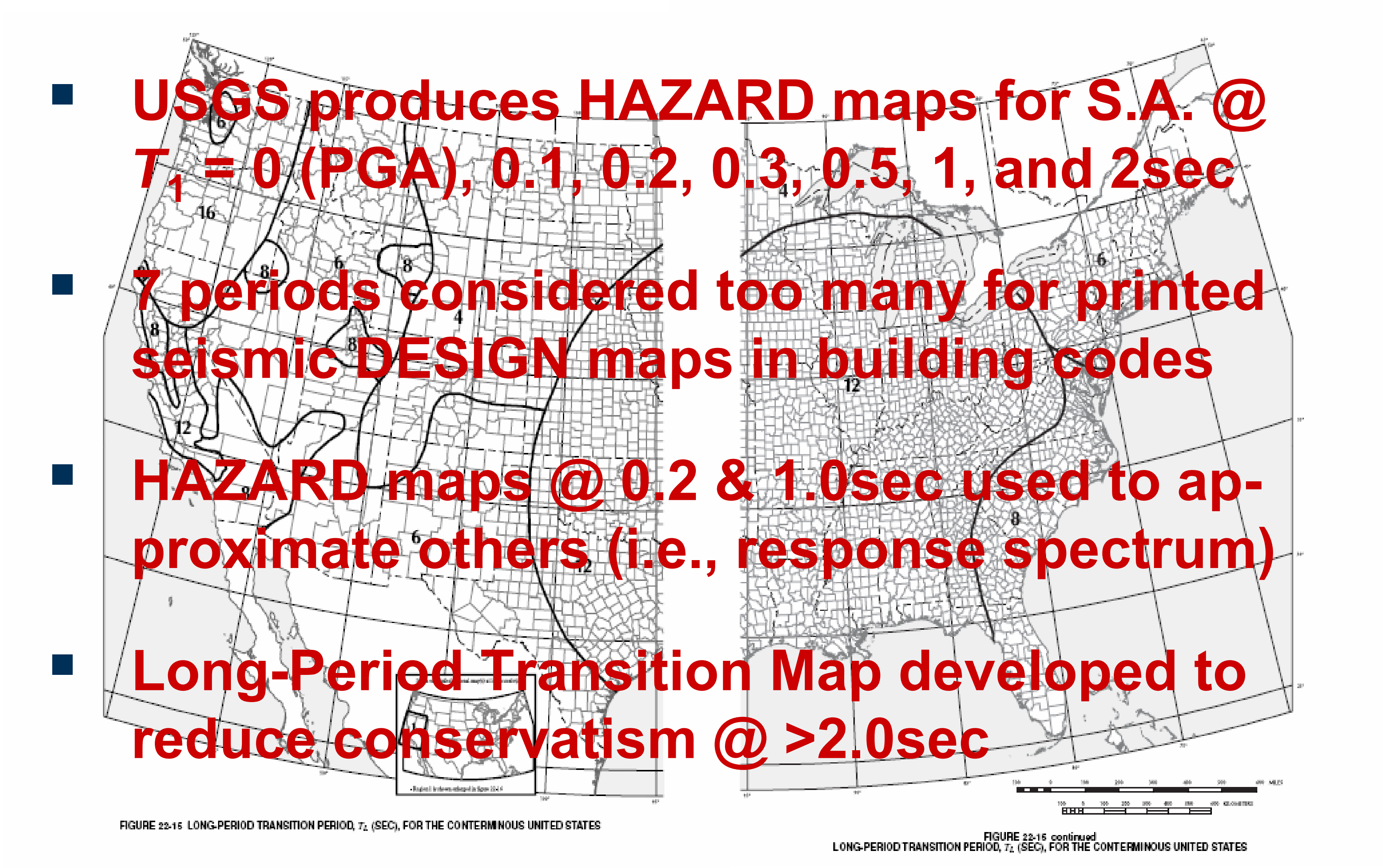
# Reference Site Class Decision

- Ideally seismic design maps would be for most common site class, i.e., Stiff Soil ("D")
- Existing ground motion attenuation relations for PSHA in CEUS were for Hard Rock ("A")
- Adjusting Hard Rock ("A") to Stiff Soil ("D") too problematic due to nonlinearity
- Adjusted to Firm Rock ("B/C") for consistency with WUS Rock attenuation relations



# Periods of Vibration Decision

- USGS produces HAZARD maps for S.A. @ $T_1$ = 0 (PGA), 0.1, 0.2, 0.3, 0.5, 1, and 2sec
- 7 periods considered too many for printed seismic DESIGN maps in building codes
- HAZARD maps @ 0.2 & 1.0sec used to approximate others (i.e., response spectrum)
- Long-Period Transition Map developed to reduce conservatism @ >2.0sec



# Periods of Vibration Decision

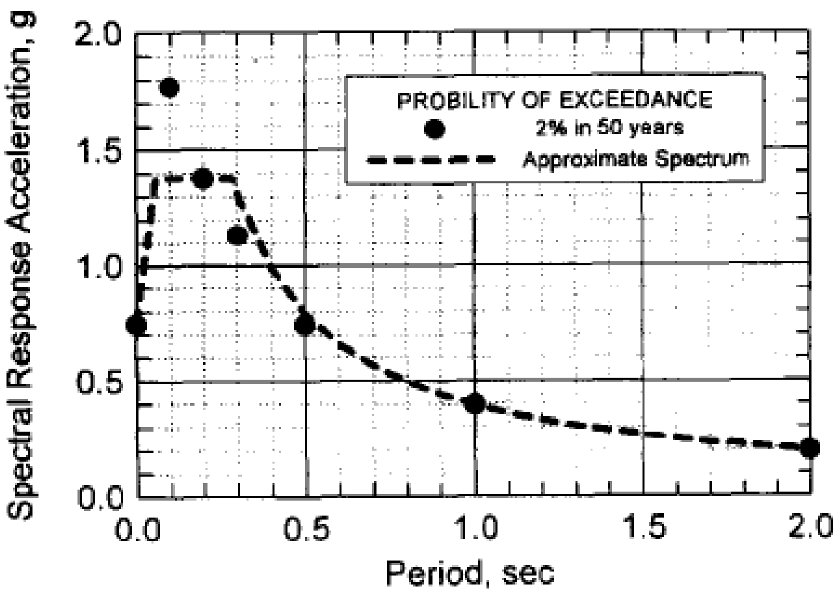



**Figure 8.** Charleston uniform hazard response spectrum data for 2% probability of exceedance in 50 years and approximate spectrum.

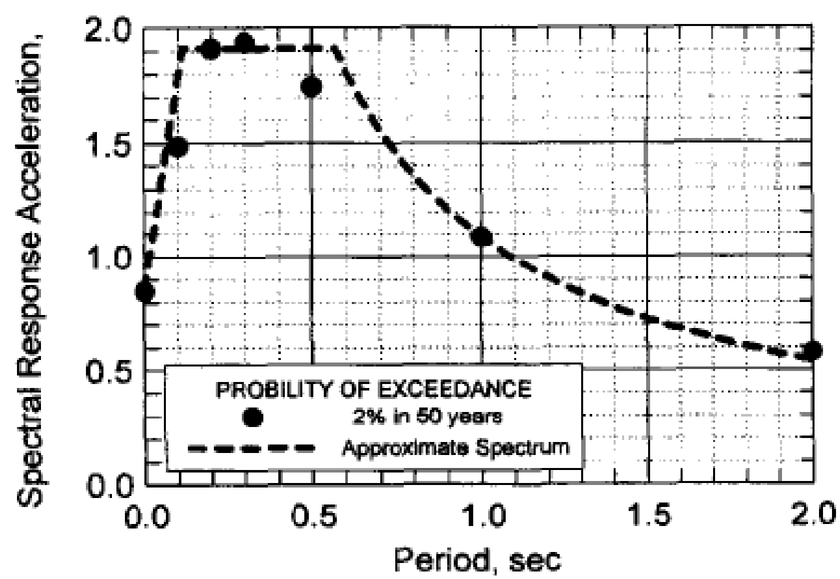
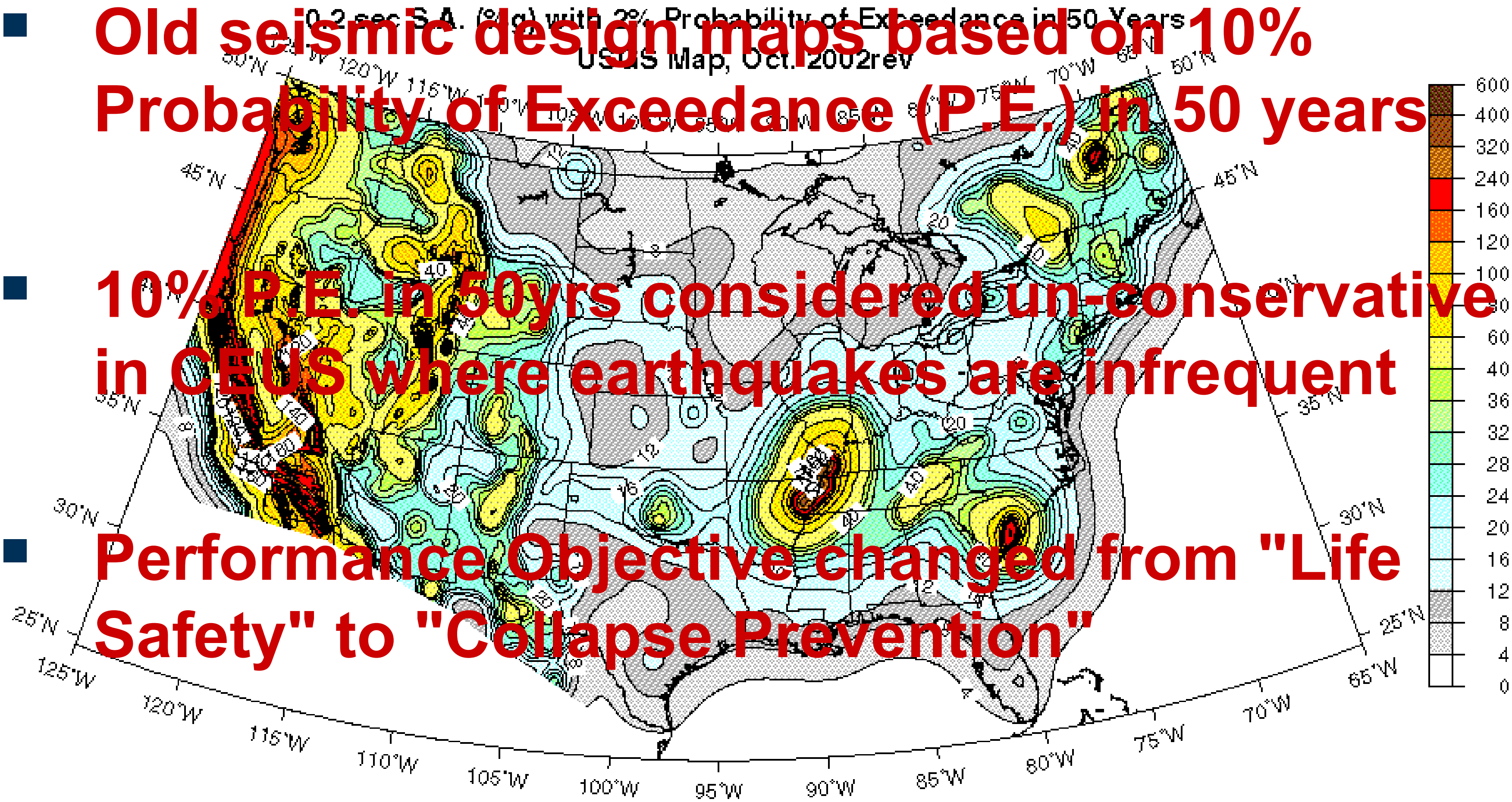



**Figure 7.** San Francisco uniform hazard response spectrum data for 2% probability of exceedance in 50 years and approximate spectrum.

**From "Development of MCE Ground Motion Maps" by E.V. Leyendecker et al. (*Earthquake Spectra*, 2001)**

# Probability of Exceedance Decision

- Old seismic design maps based on 10% Probability of Exceedance (P.E.) in 50 years
- 10% P.E. in 50yrs considered un-conservative in CEUS where earthquakes are infrequent
- Performance Objective changed from "Life Safety" to "Collapse Prevention"



# Probability of Exceedance Decision

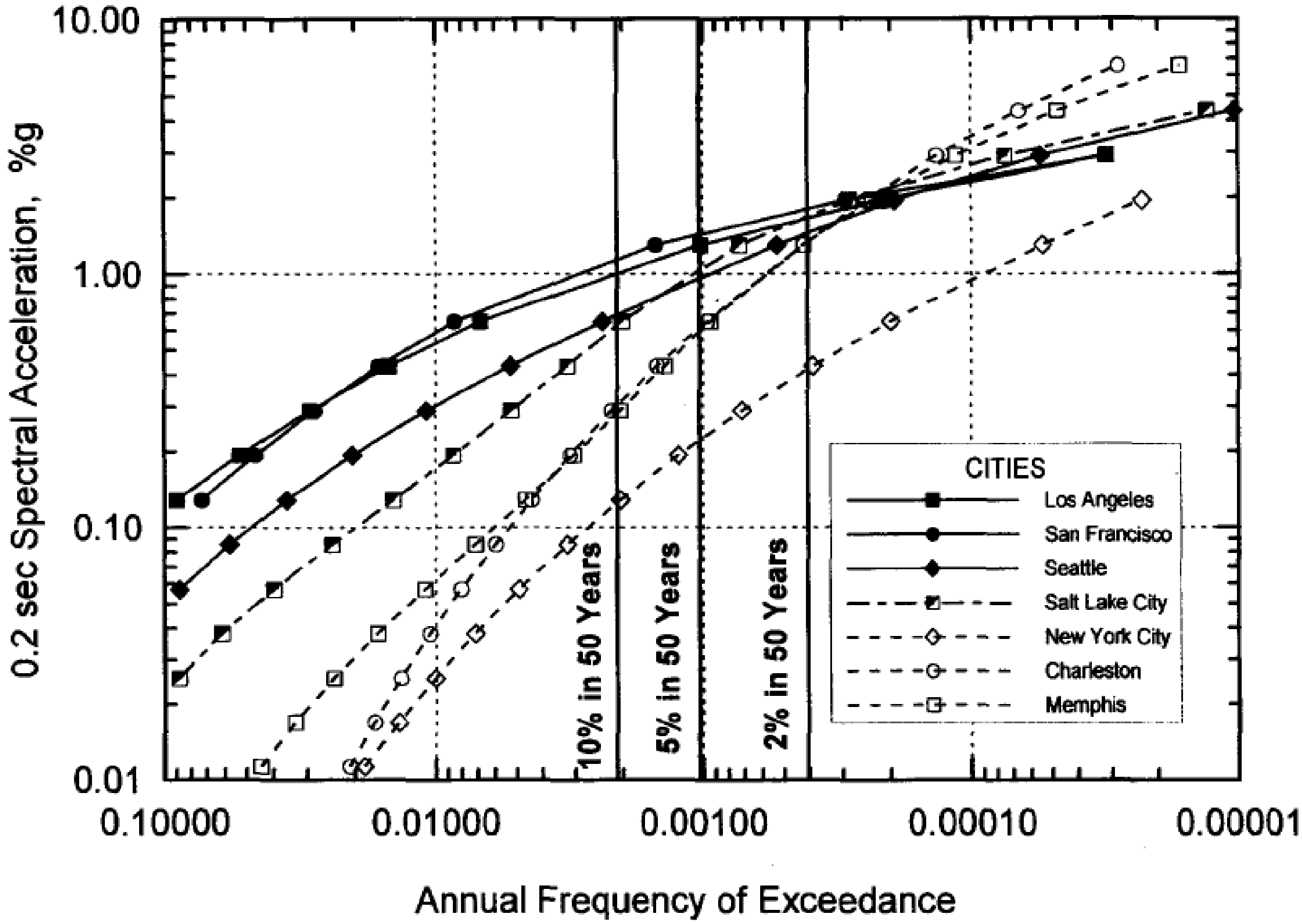
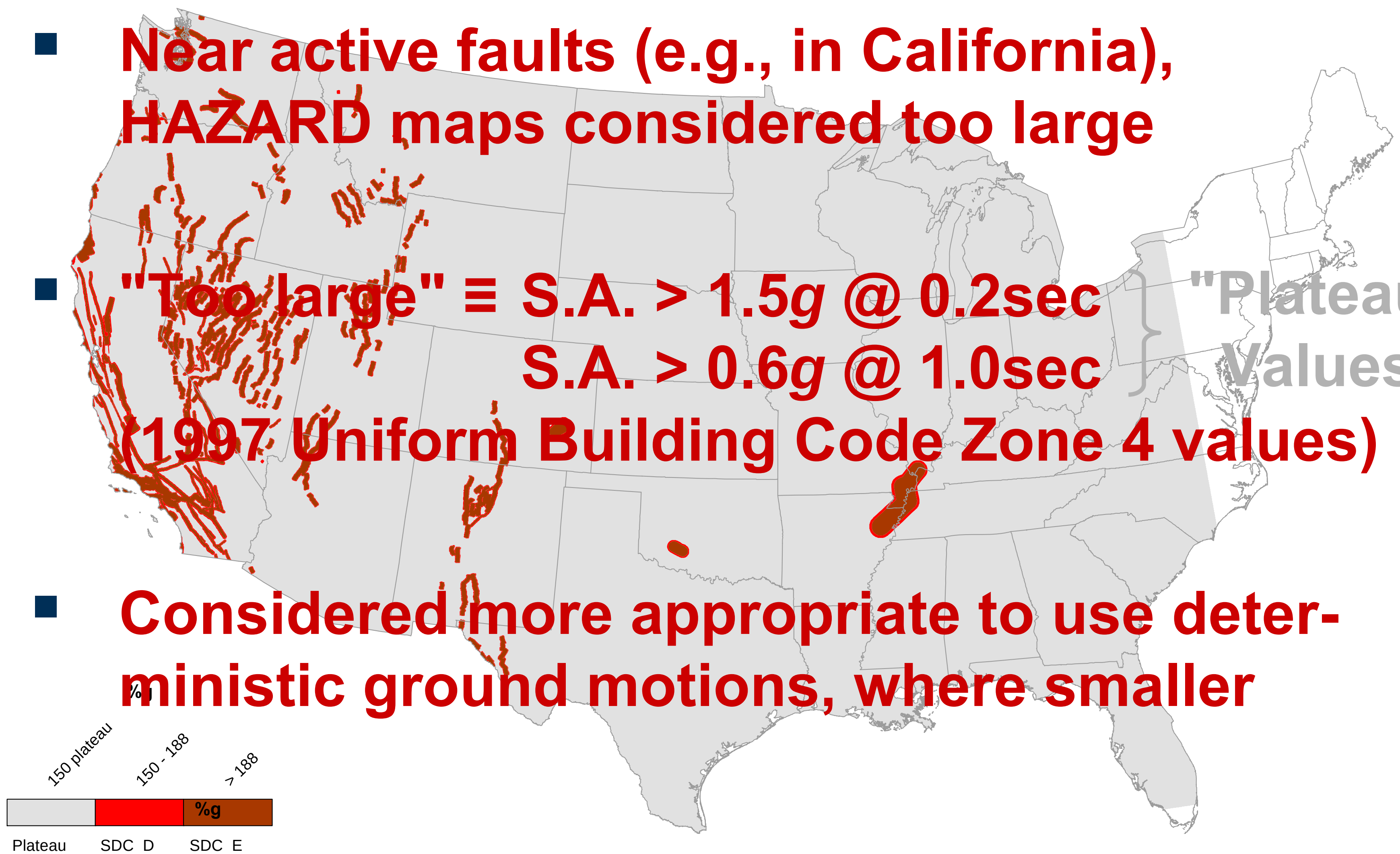



**Figure 1.** Hazard curves for selected cities.

**(Leyendecker et al., 2000)**

# Deterministic Ground Motion Decision

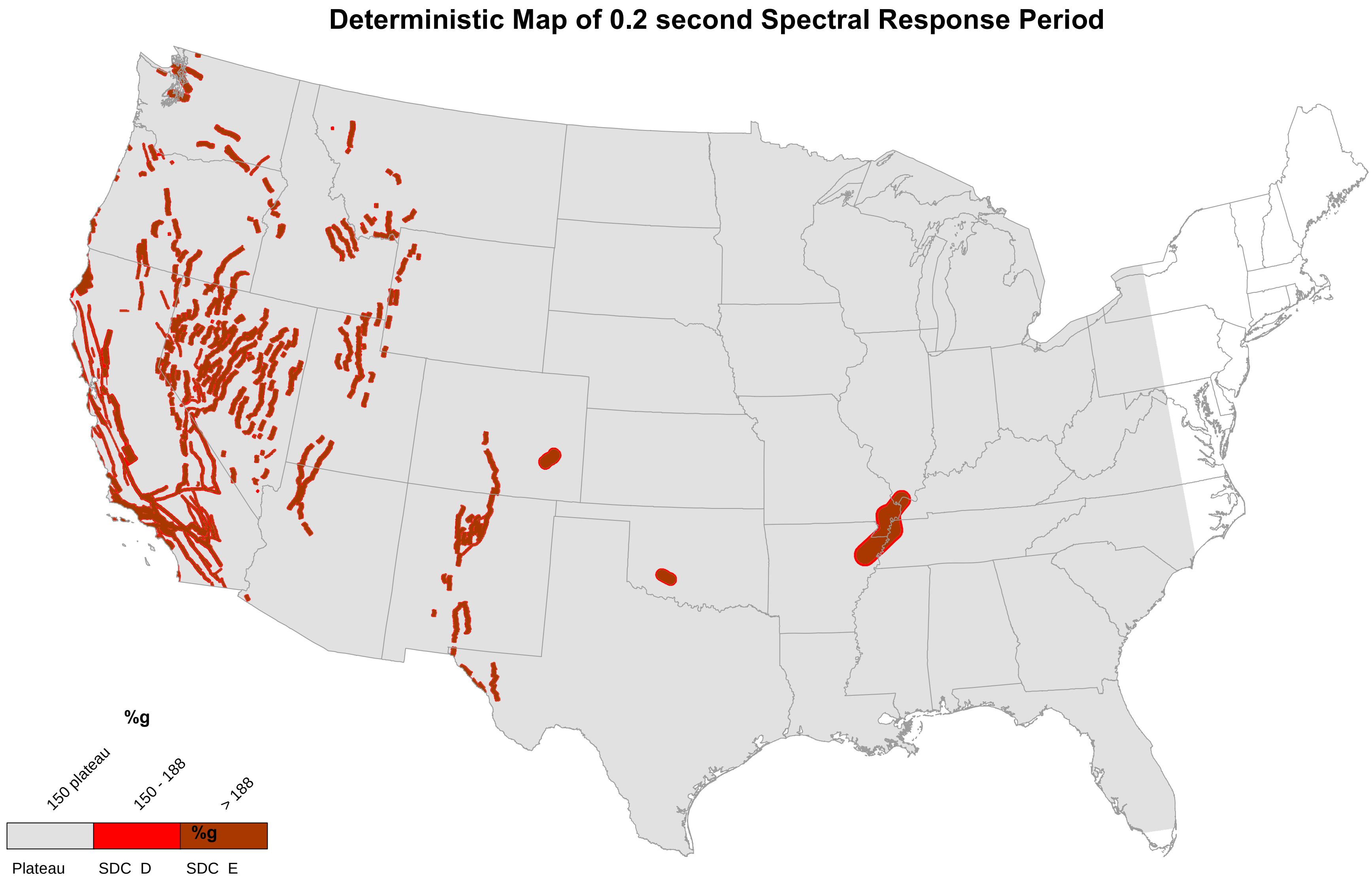
**Deterministic Map of 0.2 second Spectral Response Period**




- Near active faults (e.g., in California), HAZARD maps considered too large
- "Too large" ≡ S.A. > 1.5*g* @ 0.2sec
  S.A. > 0.6*g* @ 1.0sec
  (1997 Uniform Building Code Zone 4 values)

  "Plateau Values"
- Considered more appropriate to use deterministic ground motions, where smaller

# Deterministic Ground Motion Maps



# *Deterministic* Seismic Hazard Analysis

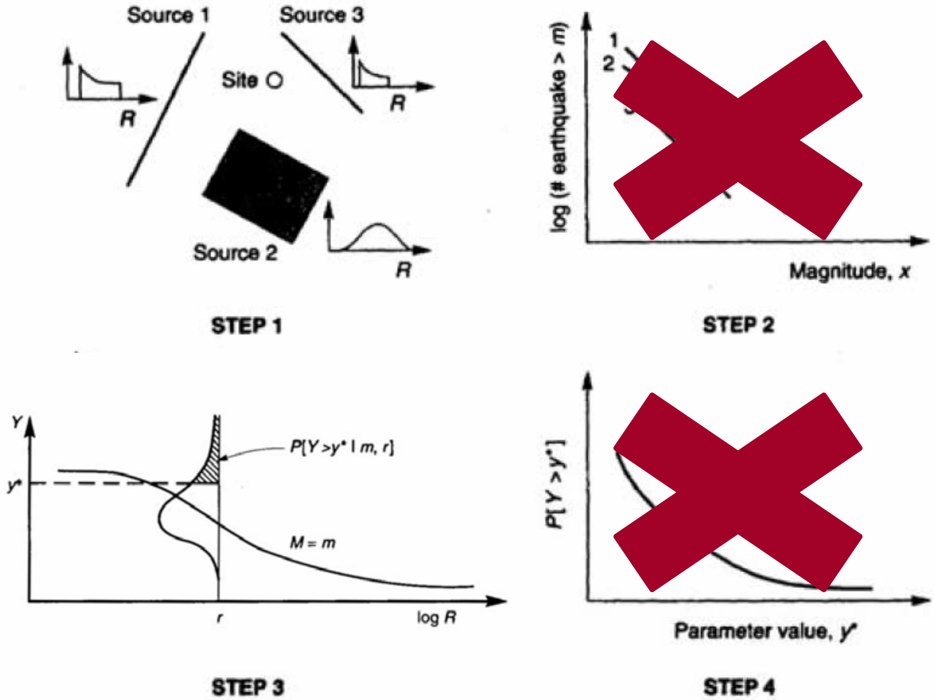



Figure B-3 Steps in probabilistic seismic hazard assessment (Kramer, 1996)

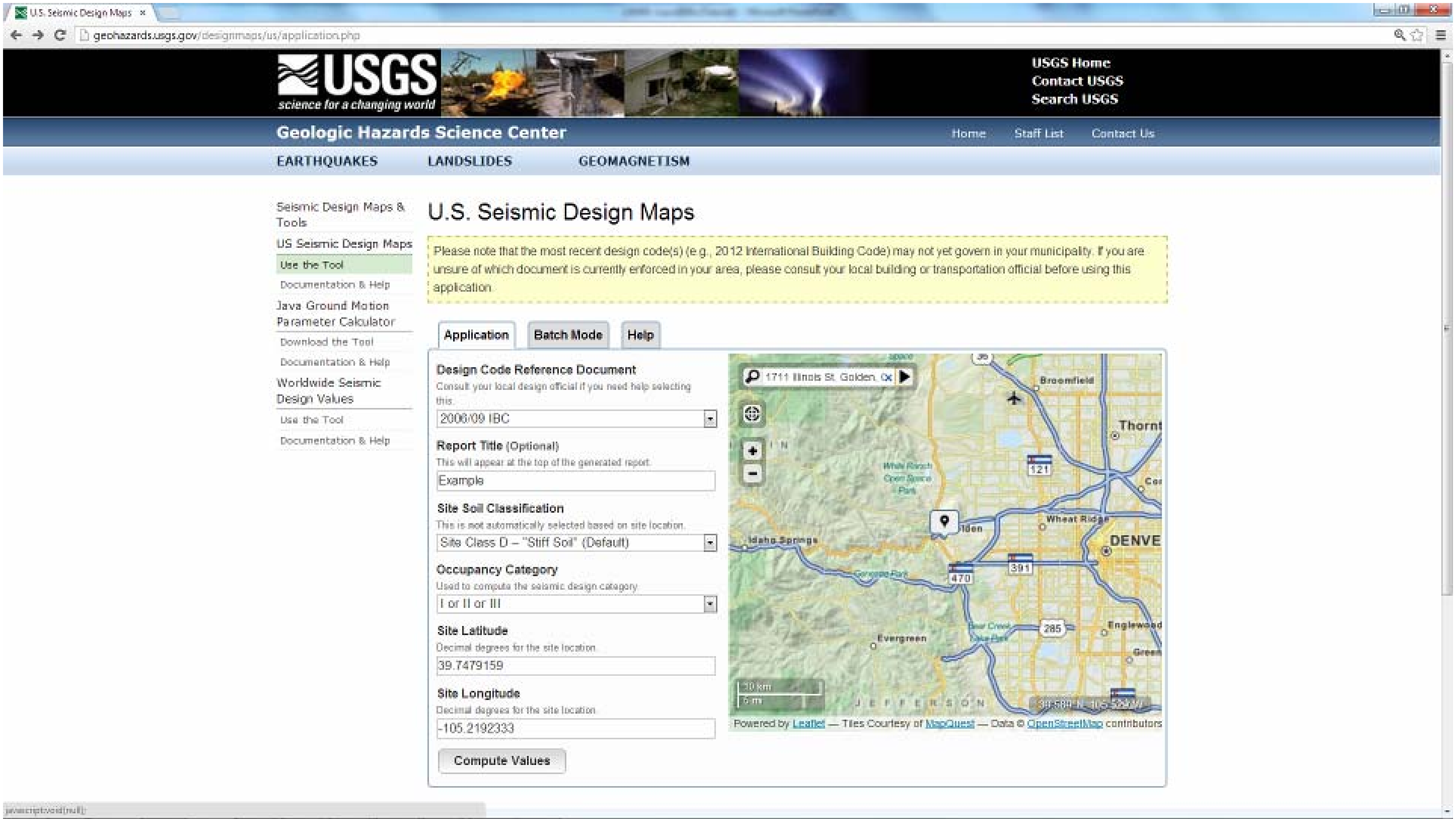
ATC-58-1 – Vol. 1 B: Ground Shaking Hazards B-5

**Steps:**

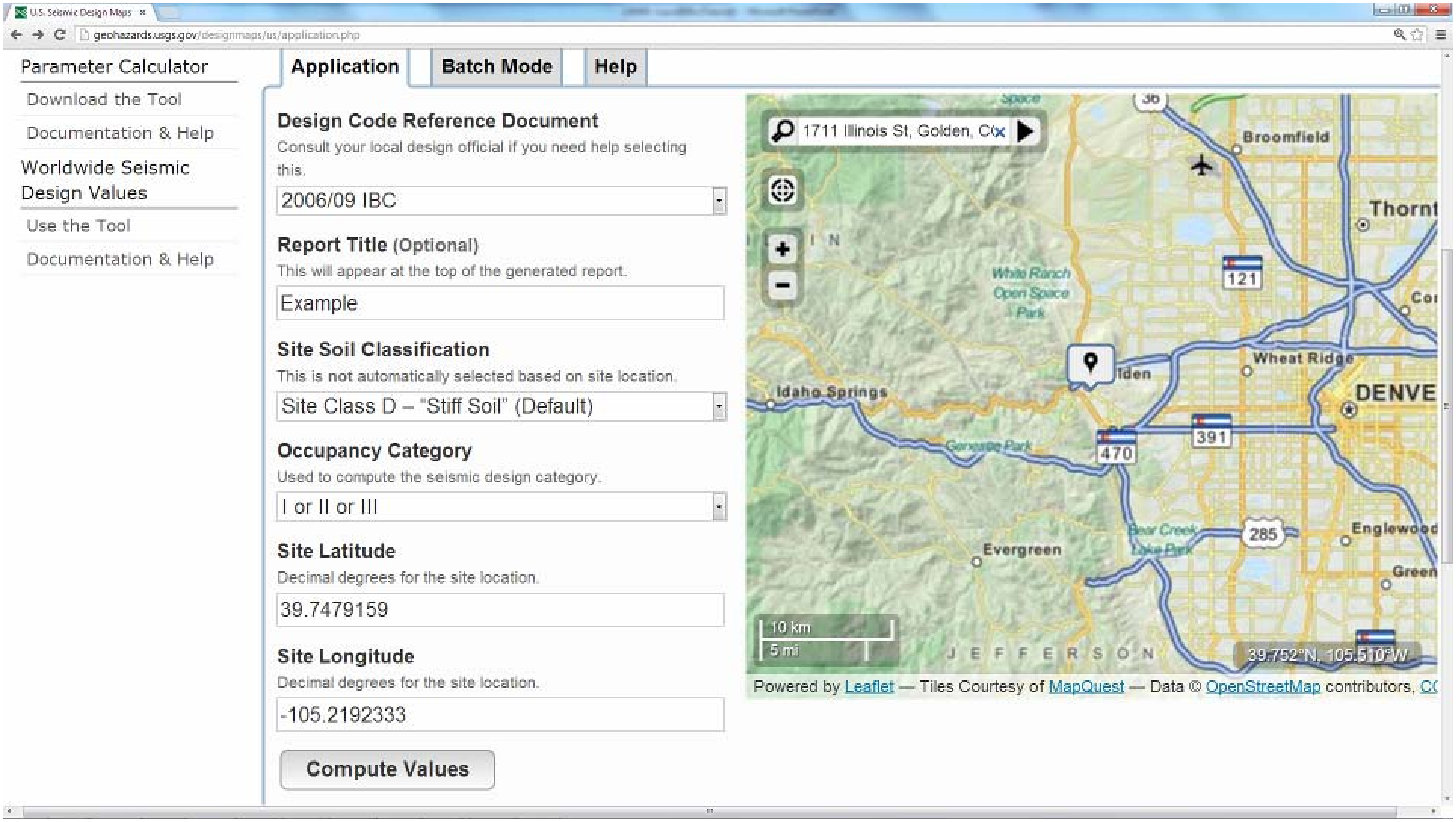
1) Identify earthquake sources & develop ~~PDF's for~~ source-to-site distances~~, $f_{Ri}(r)$~~.
2) Develop ~~frequencies of earthquakes, $\nu_i$, & PDF's for~~ magnitudes~~, $f_{Mi}(m)$~~.
3) Determine ~~CDF for~~ ground motion intensity *y* given *m* & *r*.
4) ~~For each~~Choose source …

# Development of MCE GM Maps

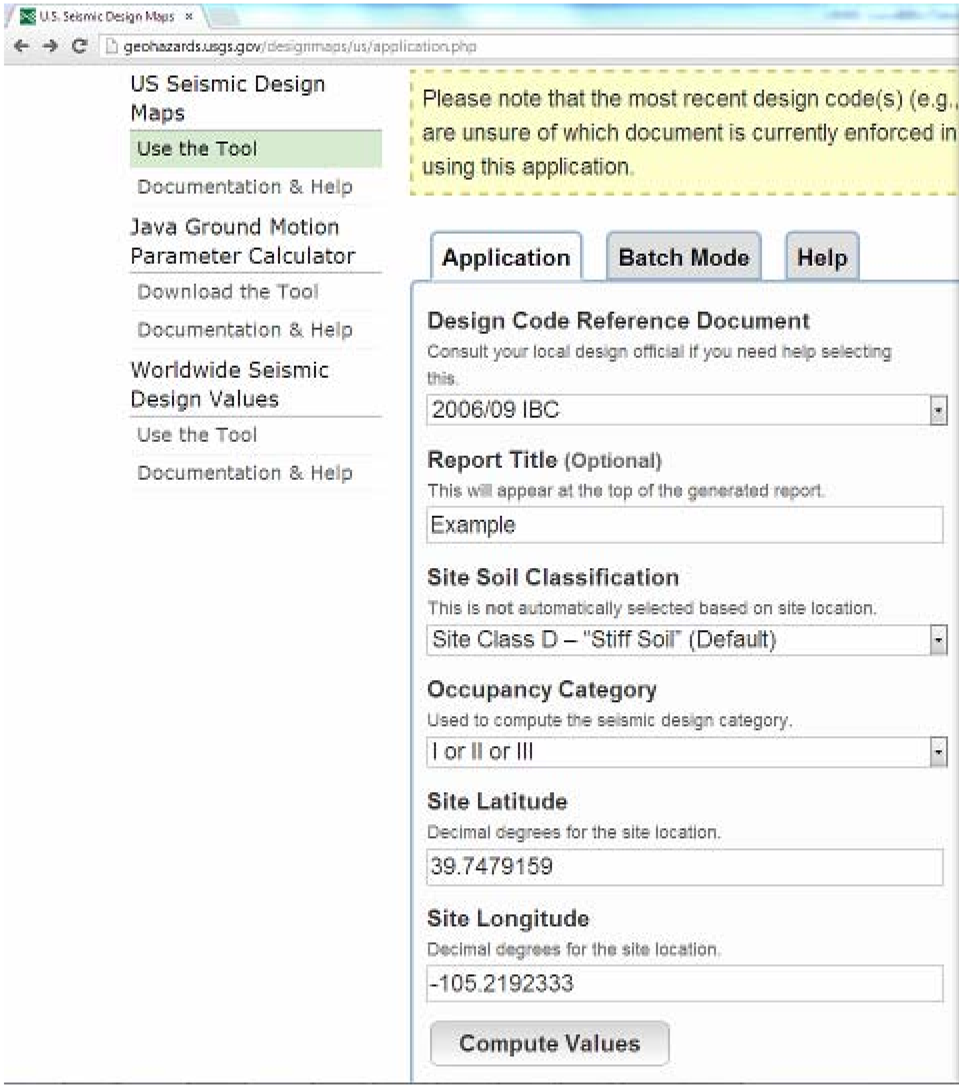
# Use of MCE Ground Motion Maps

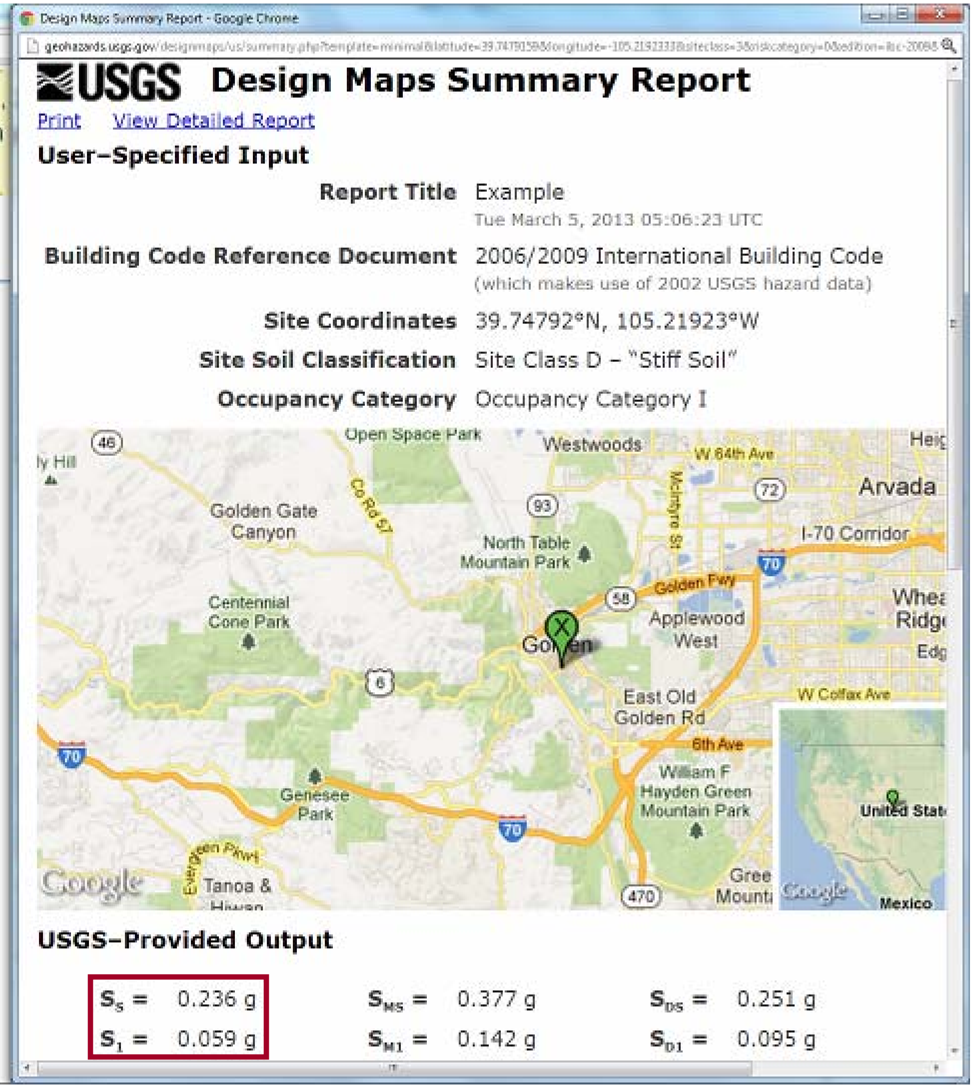


# Use of MCE Ground Motion Maps

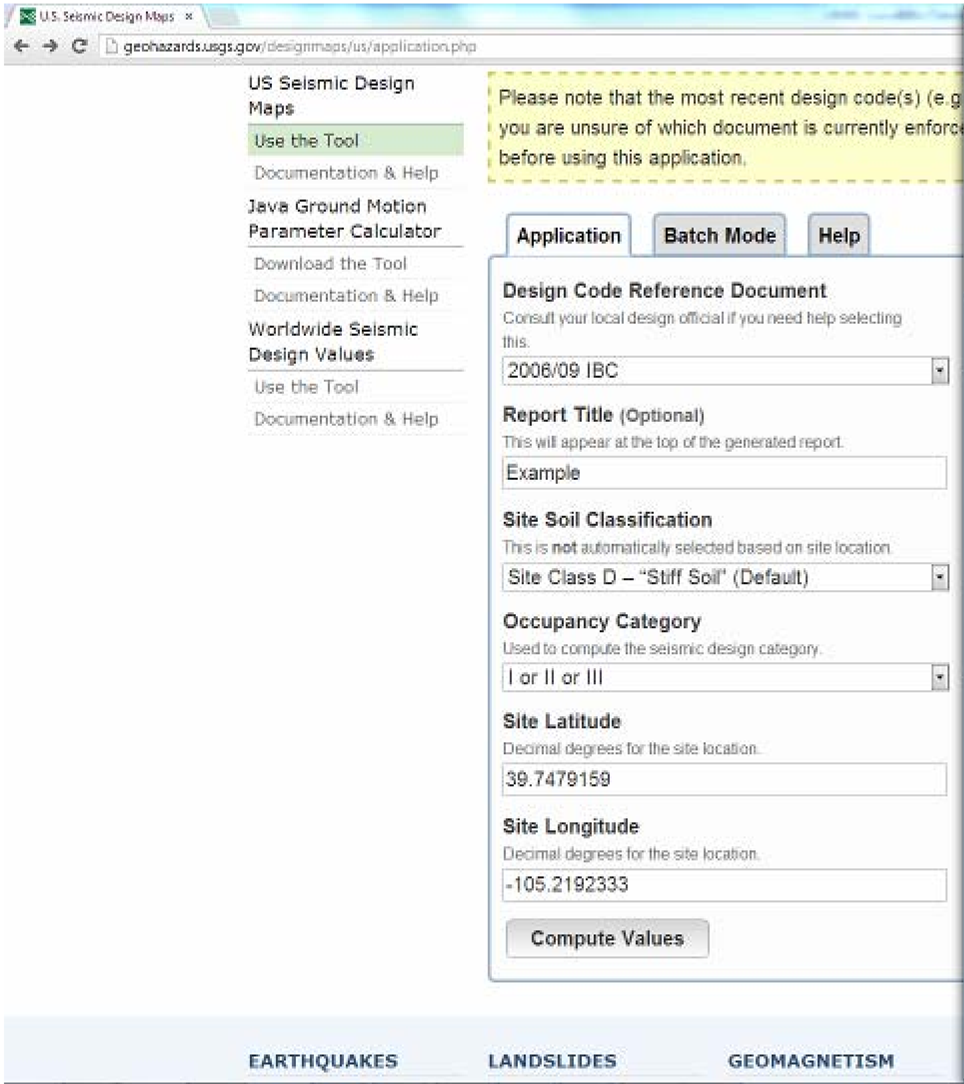


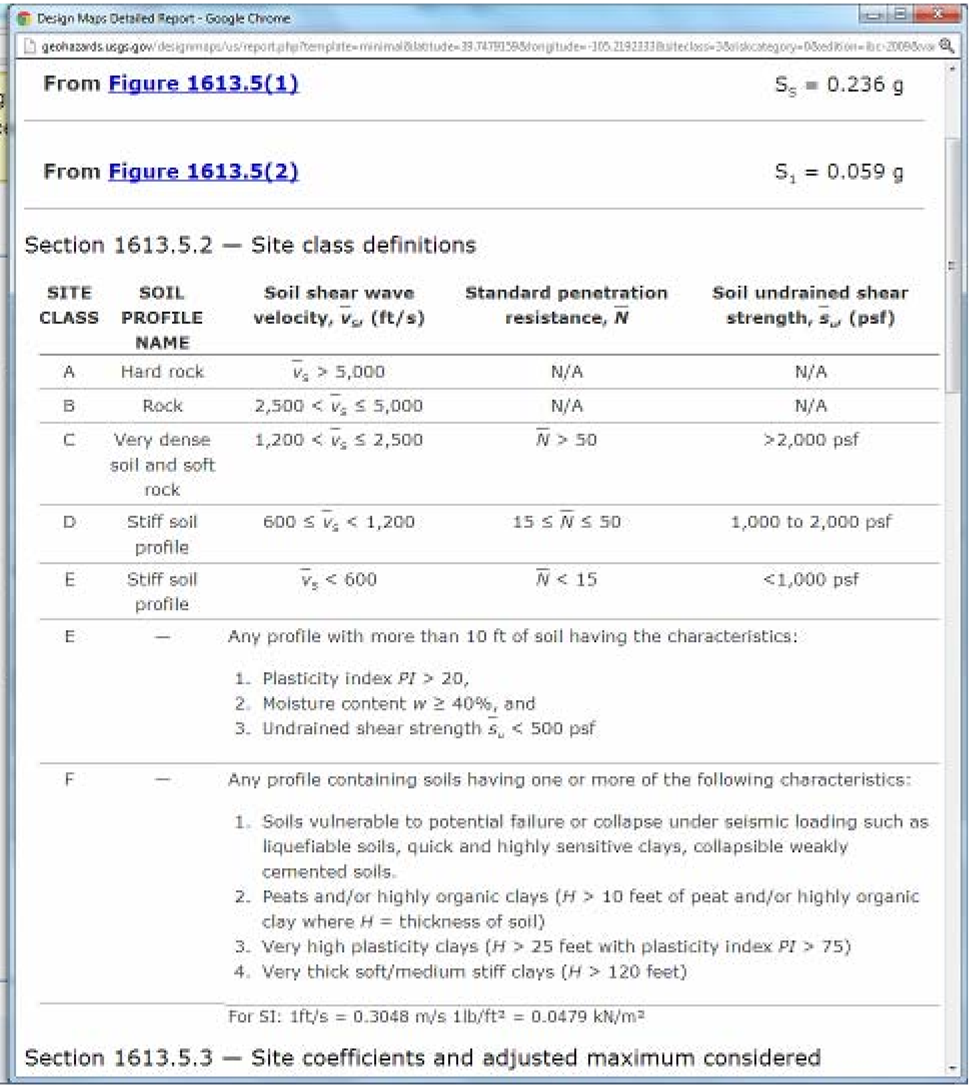
# Use of MCE Ground Motion Maps



# Soil Adjustments





Design Maps Detailed Report - Google Chrome

From Figure 1613.5(1) $S_S = 0.236$ g

From Figure 1613.5(2) $S_1 = 0.059$ g

Section 1613.5.2 — Site class definitions

| SITE CLASS | SOIL PROFILE NAME | Soil shear wave velocity, $\bar{v}_s$, (ft/s) | Standard penetration resistance, $\bar{N}$ | Soil undrained shear strength, $\bar{s}_u$, (psf) |
|---|---|---|---|---|
| A | Hard rock | $\bar{v}_s > 5{,}000$ | N/A | N/A |
| B | Rock | $2{,}500 < \bar{v}_s \le 5{,}000$ | N/A | N/A |
| C | Very dense soil and soft rock | $1{,}200 < \bar{v}_s \le 2{,}500$ | $\bar{N} > 50$ | >2,000 psf |
| D | Stiff soil profile | $600 \le \bar{v}_s < 1{,}200$ | $15 \le \bar{N} \le 50$ | 1,000 to 2,000 psf |
| E | Stiff soil profile | $\bar{v}_s < 600$ | $\bar{N} < 15$ | <1,000 psf |
| E | — | Any profile with more than 10 ft of soil having the characteristics: 1. Plasticity index $PI > 20$, 2. Moisture content $w \ge 40\%$, and 3. Undrained shear strength $\bar{s}_u < 500$ psf | | |
| F | — | Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays ($H > 10$ feet of peat and/or highly organic clay where $H$ = thickness of soil) 3. Very high plasticity clays ($H > 25$ feet with plasticity index $PI > 75$) 4. Very thick soft/medium stiff clays ($H > 120$ feet) | | |

For SI: 1ft/s = 0.3048 m/s 1lb/ft² = 0.0479 kN/m²

Section 1613.5.3 — Site coefficients and adjusted maximum considered

# Soil Adjustments

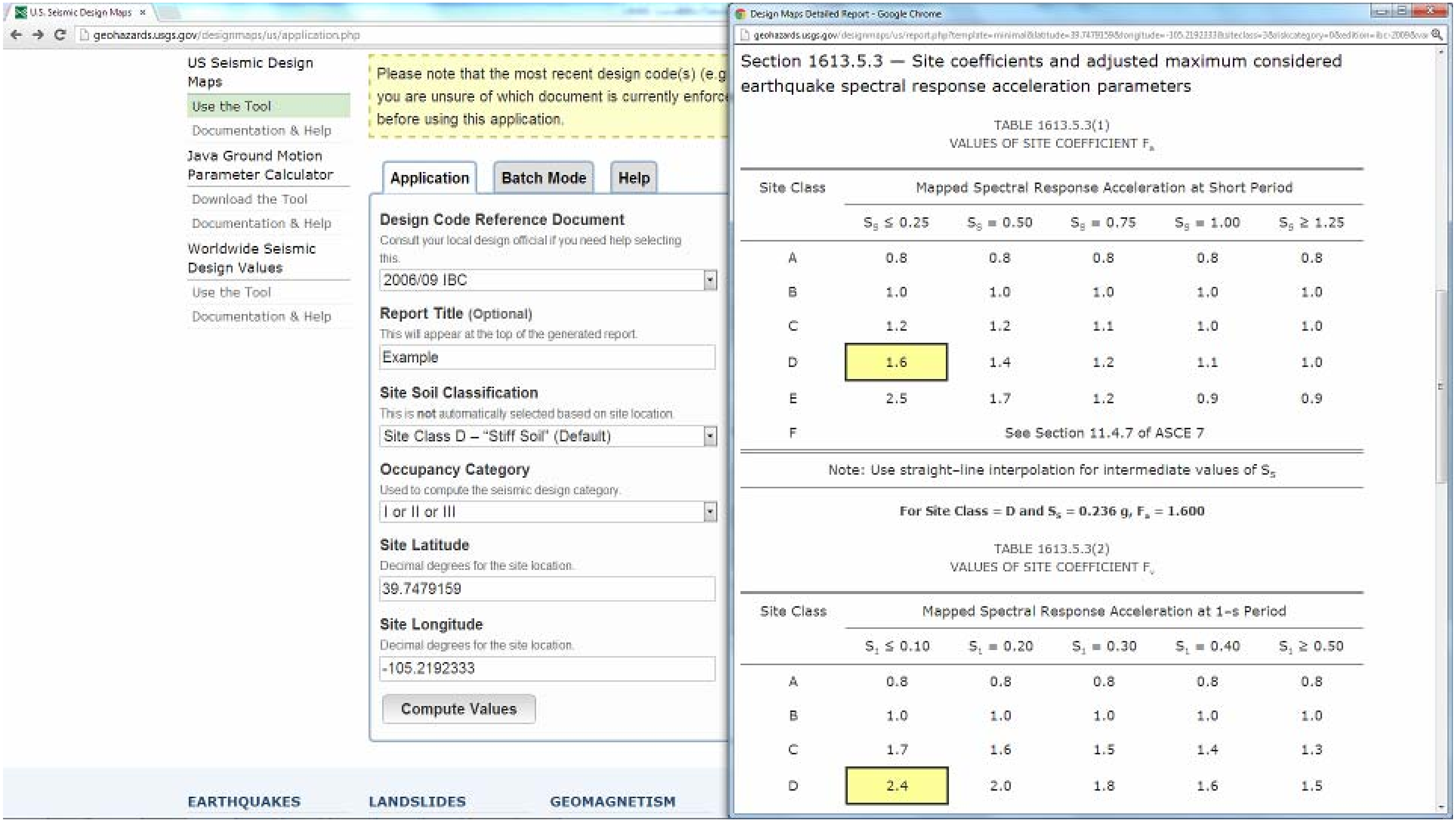



TABLE 1613.5.3(1)
VALUES OF SITE COEFFICIENT $F_a$

| Site Class | Mapped Spectral Response Acceleration at Short Period | | | | |
|---|---|---|---|---|---|
| | $S_S \le 0.25$ | $S_S = 0.50$ | $S_S = 0.75$ | $S_S = 1.00$ | $S_S \ge 1.25$ |
| A | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| B | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| C | 1.2 | 1.2 | 1.1 | 1.0 | 1.0 |
| D | 1.6 | 1.4 | 1.2 | 1.1 | 1.0 |
| E | 2.5 | 1.7 | 1.2 | 0.9 | 0.9 |
| F | See Section 11.4.7 of ASCE 7 | | | | |

Note: Use straight-line interpolation for intermediate values of $S_S$

**For Site Class = D and $S_S$ = 0.236 g, $F_a$ = 1.600**

TABLE 1613.5.3(2)
VALUES OF SITE COEFFICIENT $F_v$

| Site Class | Mapped Spectral Response Acceleration at 1-s Period | | | | |
|---|---|---|---|---|---|
| | $S_1 \le 0.10$ | $S_1 = 0.20$ | $S_1 = 0.30$ | $S_1 = 0.40$ | $S_1 \ge 0.50$ |
| A | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| B | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| C | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 |
| D | 2.4 | 2.0 | 1.8 | 1.6 | 1.5 |

# Soil Adjustments

U.S. Seismic Design Maps

geohazards.usgs.gov/designmaps/us/application.php

US Seismic Design Maps
- Use the Tool
- Documentation & Help

Java Ground Motion Parameter Calculator
- Download the Tool
- Documentation & Help

Worldwide Seismic Design Values
- Use the Tool
- Documentation & Help

Please note that the most recent design code(s) (e.g
you are unsure of which document is currently enforc
before using this application.

Application | Batch Mode | Help

**Design Code Reference Document**
Consult your local design official if you need help selecting this.
2006/09 IBC

**Report Title** (Optional)
This will appear at the top of the generated report.
Example

**Site Soil Classification**
This is **not** automatically selected based on site location.
Site Class D – "Stiff Soil" (Default)

**Occupancy Category**
Used to compute the seismic design category.
I or II or III

**Site Latitude**
Decimal degrees for the site location.
39.7479159

**Site Longitude**
Decimal degrees for the site location.
-105.2192333

Compute Values

EARTHQUAKES LANDSLIDES GEOMAGNETISM

Design Maps Detailed Report - Google Chrome

geohazards.usgs.gov/designmaps/us/report.php?template=minimal&latitude=39.7479159&longitude=-105.2192333&siteclass=3&riskcategory=0&edition=ibc-2009&vari

| | | | | | |
|---|---|---|---|---|---|
| D | 1.6 | 1.4 | 1.2 | 1.1 | 1.0 |
| E | 2.5 | 1.7 | 1.2 | 0.9 | 0.9 |
| F | See Section 11.4.7 of ASCE 7 | | | | |

Note: Use straight-line interpolation for intermediate values of $S_S$

**For Site Class = D and $S_S$ = 0.236 g, $F_a$ = 1.600**

TABLE 1613.5.3(2)
VALUES OF SITE COEFFICIENT $F_v$

| Site Class | Mapped Spectral Response Acceleration at 1-s Period | | | | |
|---|---|---|---|---|---|
| | $S_1 \le 0.10$ | $S_1 = 0.20$ | $S_1 = 0.30$ | $S_1 = 0.40$ | $S_1 \ge 0.50$ |
| A | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| B | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| C | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 |
| D | 2.4 | 2.0 | 1.8 | 1.6 | 1.5 |
| E | 3.5 | 3.2 | 2.8 | 2.4 | 2.4 |
| F | See Section 11.4.7 of ASCE 7 | | | | |

Note: Use straight-line interpolation for intermediate values of $S_1$

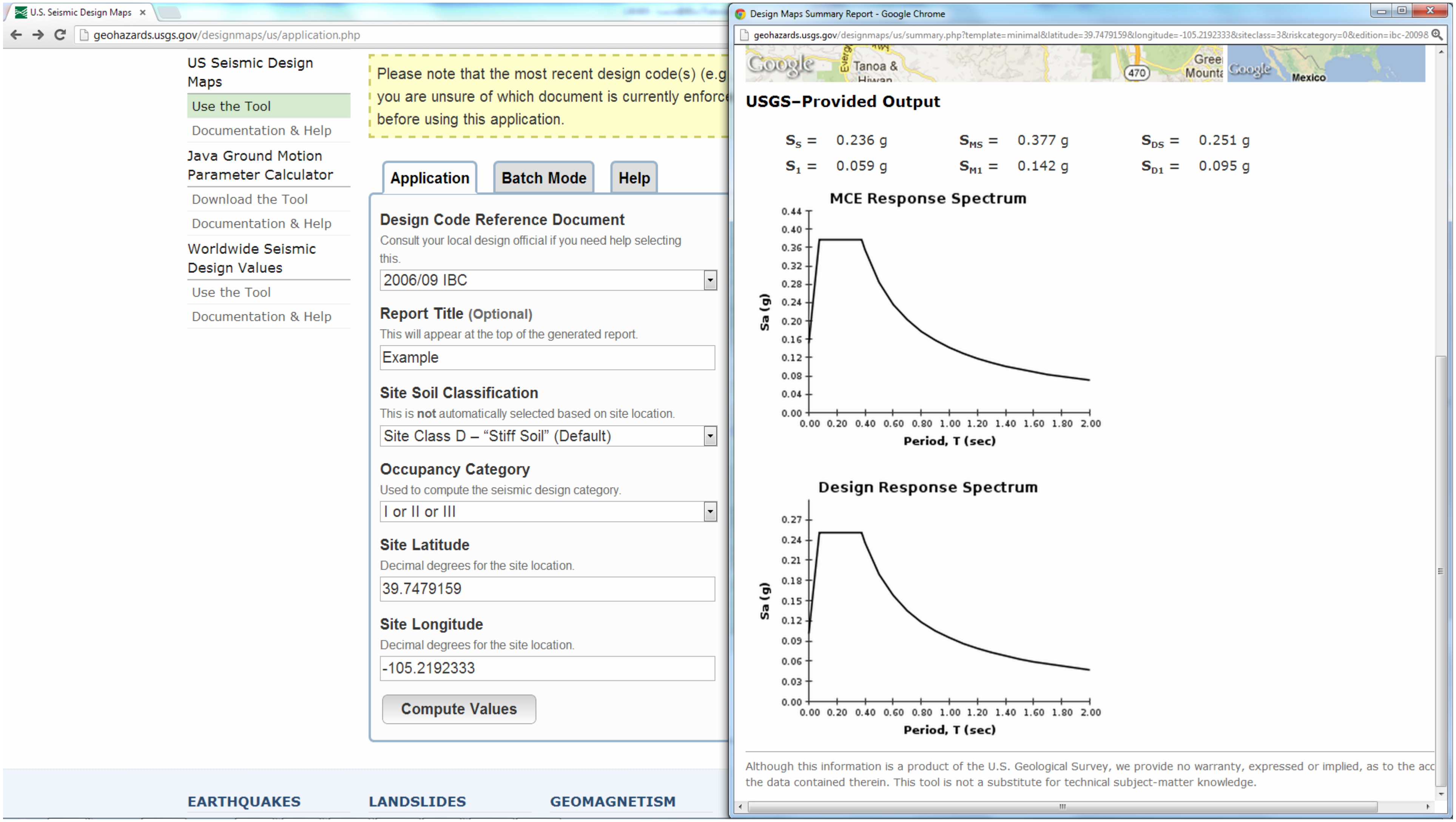
**For Site Class = D and $S_1$ = 0.059 g, $F_v$ = 2.400**

In the equations below, the equation number corresponding to the 2006 edition is listed first, and that corresponding to the 2009 edition is listed second.

**Equation (16-37; 16-36):** $S_{MS} = F_aS_S = 1.600 \times 0.236 = 0.377$ g

**Equation (16-38; 16-37):** $S_{M1} = F_vS_1 = 2.400 \times 0.059 = 0.142$ g

# Design Response Spectrum



# Indian Building Code

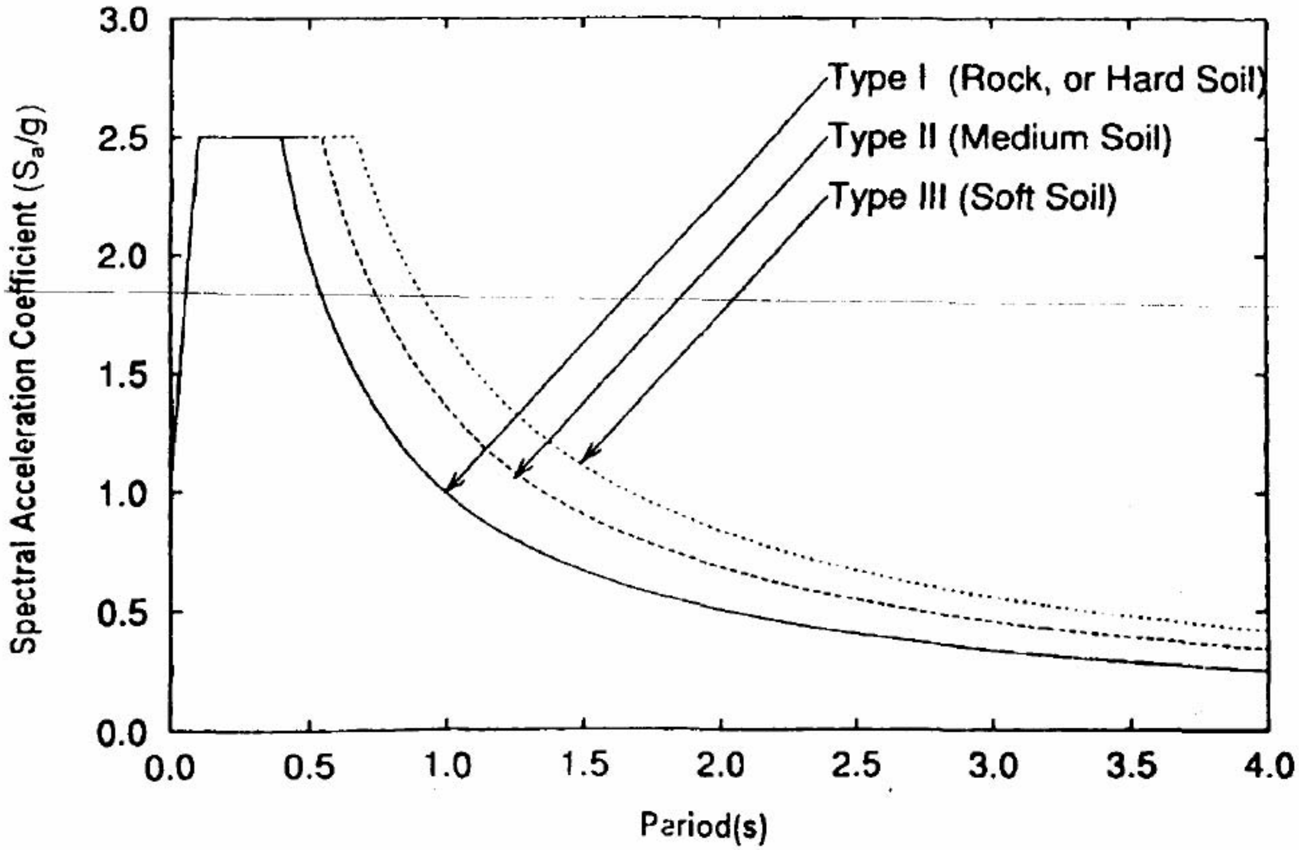



**Fig. 2 Response Spectra For Rock and Soil Sites For 5 Percent Damping**

# Indian Building Code

**ANNEX E**

(Foreword)

**ZONE FACTORS FOR SOME IMPORTANT TOWNS**

| *Town* | *Zone* | *Zone Factor, Z* | *Town* | *Zone* | *Zone Factor, Z* |
|---|---|---|---|---|---|
| Agra | III | 0.16 | Chitradurga | II | 0.10 |
| Ahmedabad | III | 0.16 | Coimbatore | III | 0.16 |
| Ajmer | II | 0.10 | Cuddalore | III | 0.16 |
| Allahabad | II | 0.10 | Cuttack | III | 0.16 |
| Almora | IV | 0.24 | Darbhanga | V | 0.36 |
| Ambala | IV | 0.24 | Darjeeling | IV | 0.24 |
| Amritsar | IV | 0.24 | Dharwad | III | 0.16 |
| Asansol | III | 0.16 | Dehra Dun | IV | 0.24 |
| Aurangabad | II | 0.10 | Dharampuri | III | 0.16 |
| Bahraich | IV | 0.24 | Delhi | IV | 0.24 |
| Bangalore | II | 0.10 | Durgapur | III | 0.16 |
| Barauni | IV | 0.24 | Gangtok | IV | 0.24 |
| Bareilly | III | 0.16 | Goa | III | 0.16 |
| Bhatinda | III | 0.16 | Gulbarga | II | 0.10 |
| Bhilai | II | 0.10 | Gaya | III | 0.16 |
| Bhopal | II | 0.10 | Gorakhpur | IV | 0.24 |
| Bhubaneswar | III | 0.16 | Hyderabad | II | 0.10 |

# Previous Generation PBSD

BUILDING SEISMIC SAFETY COUNCIL

A council of the National Institute of Building Sciences

BSSC
Seismic
Rehabilitation
Project

**NEHRP GUIDELINES FOR THE SEISMIC REHABILITATION OF BUILDINGS (FEMA Publication 273)**

Prepared for the
BUILDING SEISMIC SAFETY COUNCIL
Washington, D.C.

By the
APPLIED TECHNOLOGY COUNCIL (ATC-33 Project)
Redwood City, California

With funding by
FEDERAL EMERGENCY MANAGEMENT AGENCY
Washington, D.C.

October 1997
Washington, D.C.

**Basis for previous (pre-2012 IBC) uniform-hazard maps in building codes**

***Table 2-2 Rehabilitation Objectives***

| Earthquake Hazard Level | Building Performance Levels: Operational Performance Level (1-A) | Immediate Occupancy Performance Level (1-B) | Life Safety Performance Level (3-C) | Collapse Prevention Performance Level (5-E) |
|---|---|---|---|---|
| 50%/50 year | a | b | c | d |
| 20%/50 year | e | f | g | h |
| BSE-1 (~10%/50 year) | i | j | k | l |
| BSE-2 (~2%/50 year) | m | n | o | p |

k + p = BSO
k + p + any of a, e, i, m; or b, f, j, or n = Enhanced Objectives
o = Enhanced Objective
k alone or p alone = Limited Objectives
c, g, d, h = Limited Objectives

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**Today:**

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# ATC-58 "Next Generation" PBSD

- Instead of satisfying a performance objective through prescriptive requirements (like in building codes), quantify/assess performance explicitly.

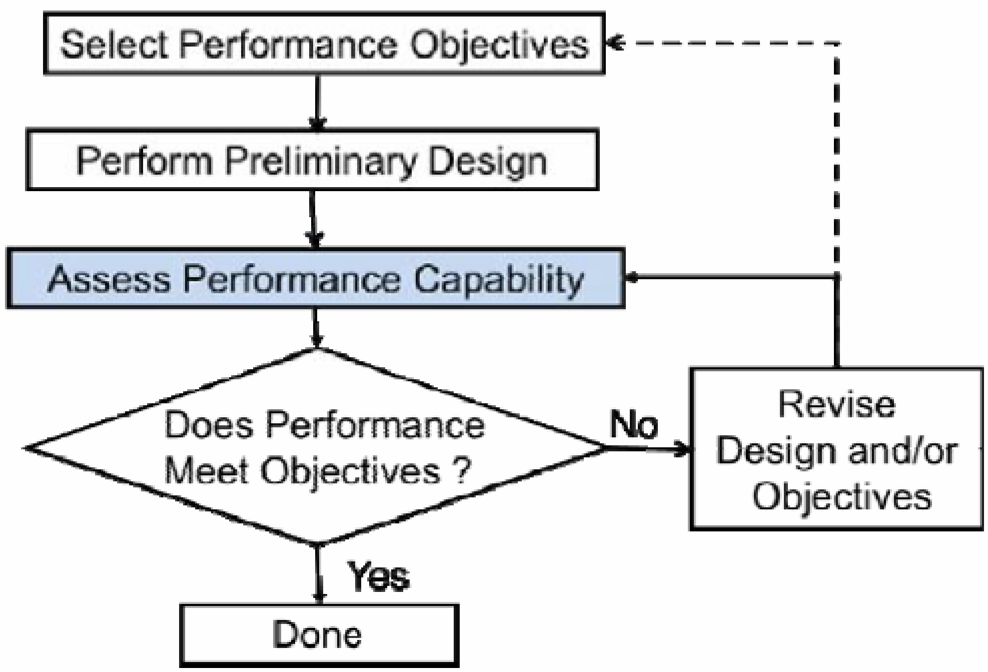
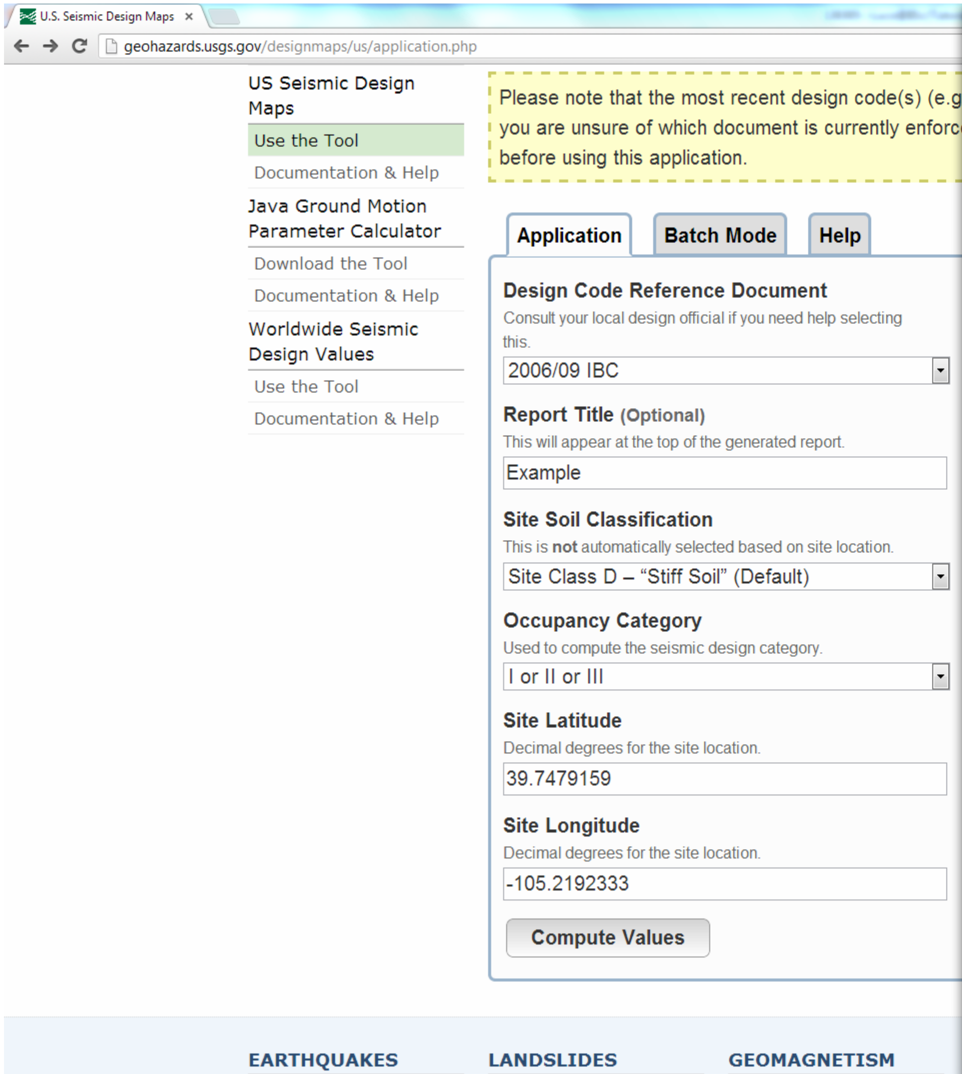


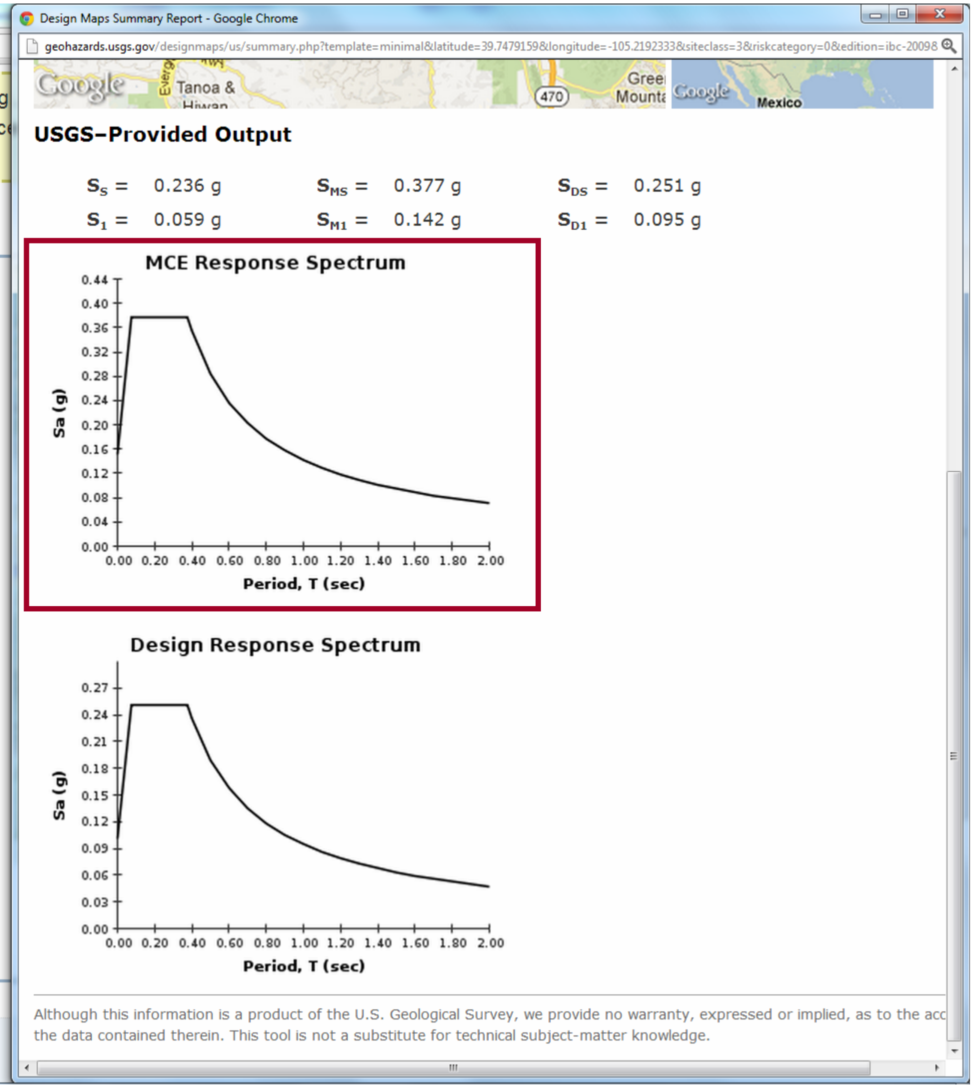

Figure 1-1 Performance-based design flow diagram

# ATC-58 Performance Assessments

- Three types of quantitative performance assessments:
  - **“Intensity-Based”** (for a user-selected acceleration response spectrum; a.k.a., code-based)
  - **“Scenario-Based”** (for a user-defined earthquake magnitude and site distance; a.k.a., deterministic)
  - **“Time-Based”** (considering all possible earthquakes and their prob. of occurrence; a.k.a., probabilistic/risk-based)
- Ground motions for all three assessment are in the form of response spectra or hazard curves (for time-based) <u>and</u> corresponding ground motion time series.

# ATC-58 Intensity-Based Assessment



# ATC-58 Scenario-Based Assessment

- From *Deterministic* Seismic Hazard Analysis …

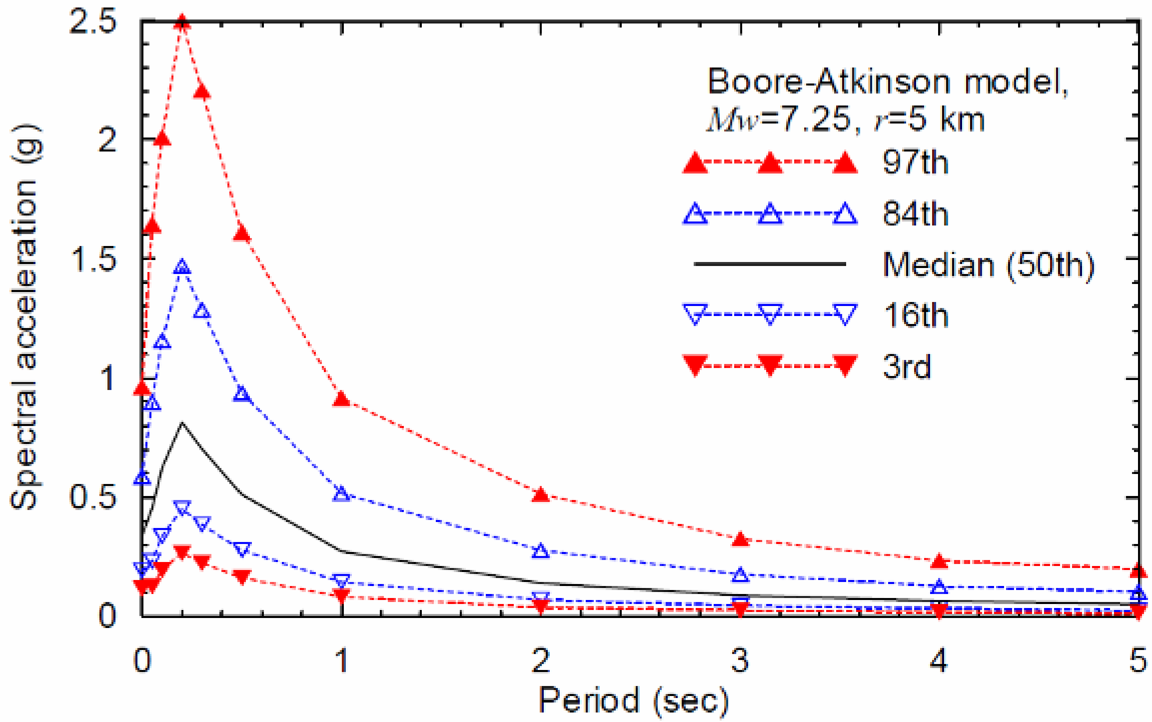



Figure 4-2 Response spectra with different probabilities of exceedance derived from a single ground motion prediction equation for an earthquake scenario.

# ATC-58 Time-Based Assessment

- From *Probabilistic* Seismic Hazard Analysis …

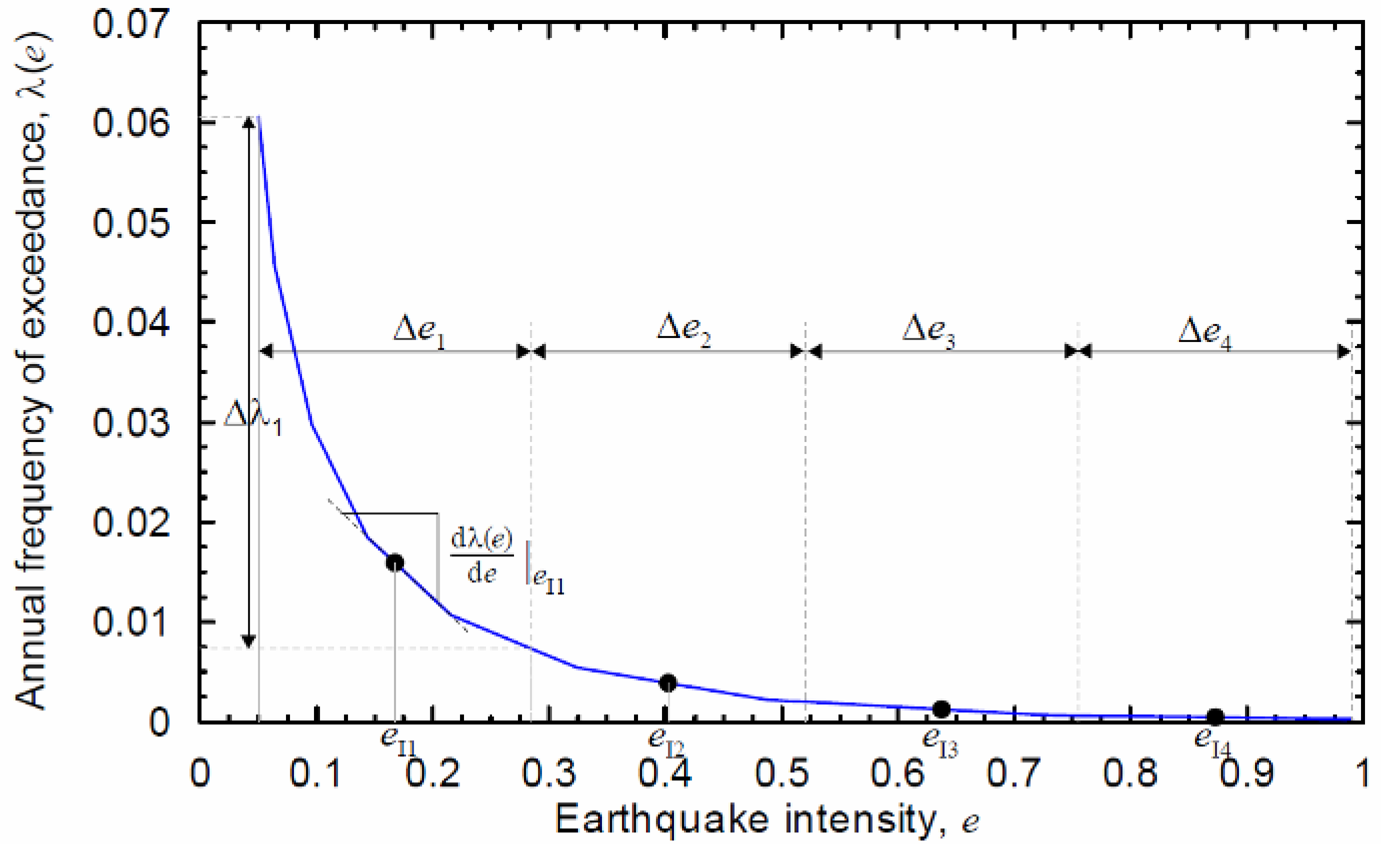



Figure 7-9 Seismic hazard curve and time-based loss calculations

# ATC-58 Performance Metrics

- All three types of performance assessments quantify probabilities of earthquake-induced casualties (Deaths), repair costs (Dollars), and occupancy loss (Downtime).
- For intensity-based and scenario-based assessments …

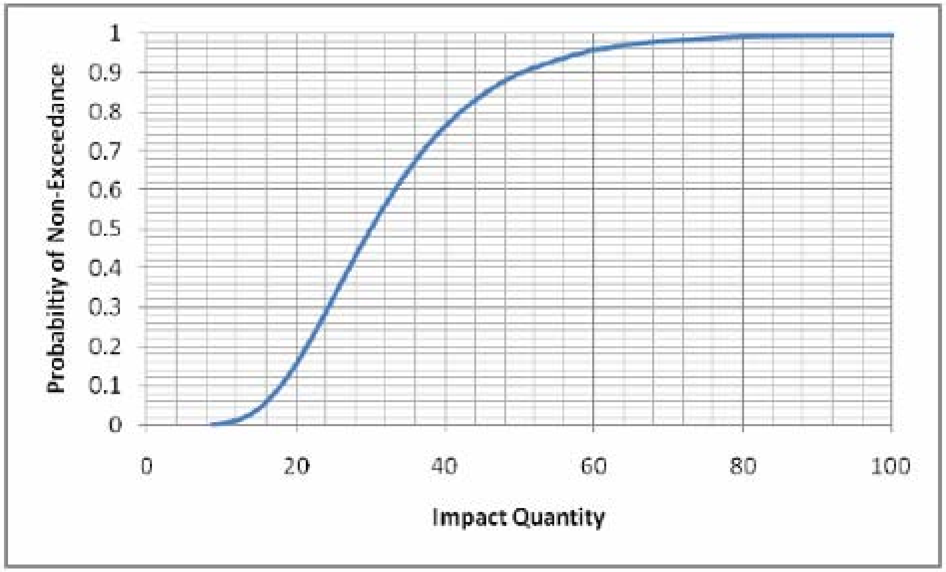



Figure 2-1 Hypothetical Performance Building Function

# ATC-58 Performance Metrics

- For time-based (or “risk-based”) assessments …

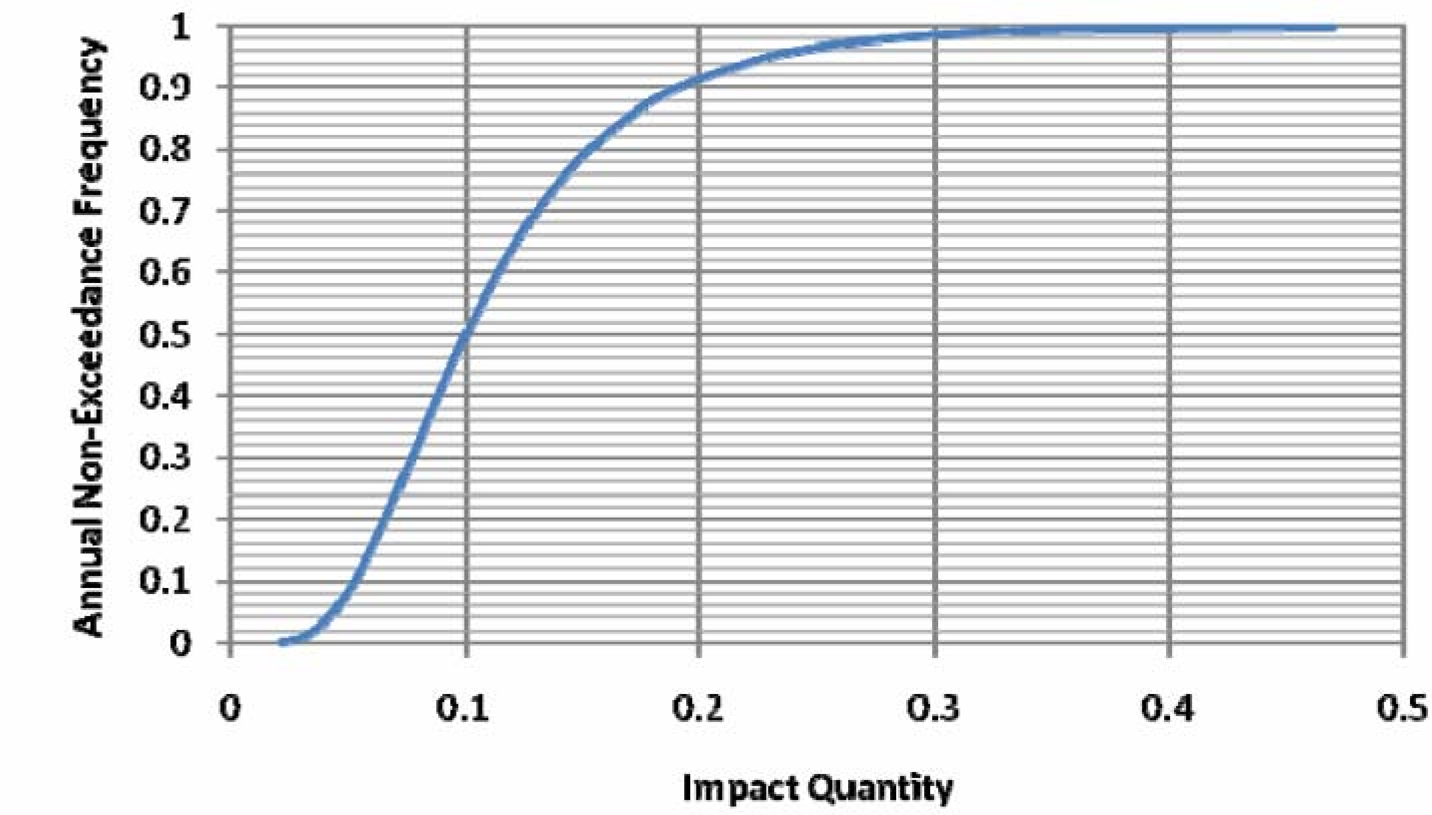



Figure 2-7 Example time-based performance curve

# ATC-58 Performance Simulations

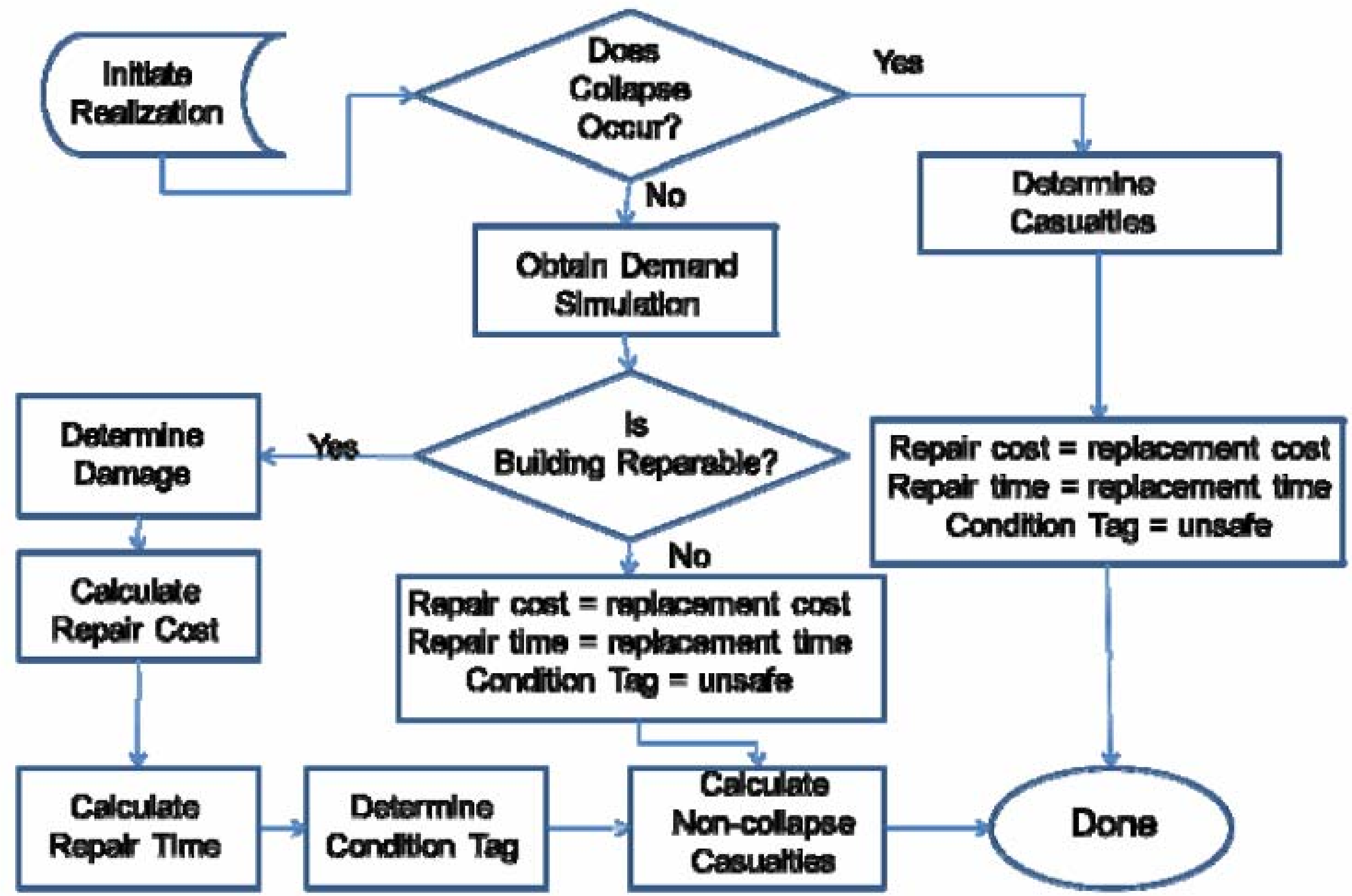



Figure 2-4 Realization flow chart

# ATC-58 Characterization of Damage

*A series of discrete damage states representing the different levels of possible damage.*

For example, for an exterior cladding component …

1)No damage (and no consequences with regard to repair actions, occupancy, or casualties).

2)Cracking of sealant joints, permitting moisture and/or air intrusion. Such damage will have no consequence with regard to casualties, safety placard placement or long-lead times. However, over the long term, the damage will present building maintenance issues, and therefore result in small repair and environmental costs with an associated short repair time.

# ATC-58 Characterization of Damage

3) Damage consisting of visible cracking of the panels. To repair this unsightly damage, the cladding must be removed from the building and replaced. This damage will likely have more severe cost and environmental consequences and will result in a longer repair time. Casualties, safety placards and or long-lead times are not impacted in this damage state.

4) Damage consisting of panel connection failure, and pieces of the cladding falling off the building. This damage will likely have similar repair consequences as that above, but will also have potential casualty impacts, and may have severe occupancy impacts as the building might be deemed unsafe for occupancy and placarded as such, until the cladding is repaired.

# Summary of Presentation

**Probabilistic Seismic Hazard Analysis (PSHA)**

•Couples models for earthquake sources (including frequencies) and ground motions to produce “hazard curves”

**Previous “uniform-hazard” maps in USA building codes**

•Based primarily on PSHA, with details designed for USA

**Ground motions for Next Generation Performance-Based Seismic Design Procedures for New and Existing Buildings (“ATC-58 Project”, funded by FEMA)**

•Procedures explicitly quantify performance in terms of “deaths, dollars, downtime”

•Hazard curves the basis of time/risk-based assessment