consulting engineers and scientists

Seismic Hazard, Design Ground Motions and Input Motion

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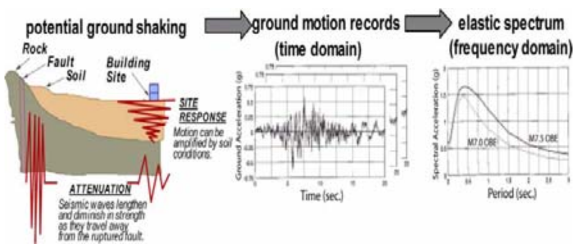
San Juan, Argentina April 28-29

Evaluating seismic hazard



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Evaluating seismic hazard

- Select the approach for the seismic hazard analysis
- Characterize the seismic sources
- Characterize the ground motion attenuation
- Perform the seismic hazard analysis
- Develop design response spectra for a reference site condition
- Develop design time histories for the reference site condition

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Seismic hazard analysis

- **Seismology**: study of earthquakes and seismic waves
- **Geology**: location, configuration, and potential of seismic sources
- **Geophysics**: definition of seismic sources not observable at earth's surface
- **Mathematics**: probability and statistics
- **Geotechnical engineering**: effects of local soil conditions on ground motion
- **Structural engineering**: application to seismic design of structures
- **Economics, Sociology and Political Science**

Hazard vs. Risk

Probabilistic Seismic Hazard
(frequency of exceedance vs. ground motion)

Damage Functions
(damage vs. ground motion)
Loss Functions
(loss vs. ground motion; loss vs. damage)

→ Seismic Risk Analysis
(frequency of exceedance vs. damage or loss)

Hazard vs. Risk (McGuire 2004)

Seismic Hazard

A property of an earthquake that *can cause* damage and loss.

Examples are a ground motion amplitude in a certain range, or a fault displacement larger than a specified amount on a known fault.

A PSHA determines the frequency (*the number of events per unit of time*) with which a seismic hazard will occur.

Seismic Risk

The probability that some humans will incur *loss* or that their built environment will be *damaged*.

These probabilities usually represent a level of *loss or damage* that is equaled or exceeded over some time period. The loss or damage must be quantified; it might be monetary loss, the number of casualties in a region, or the cost to repair a facility as a percentage of replacement cost.

Approaches to seismic hazard analysis

Deterministic
"The earthquake hazard for the site is a PGA of 0.35g resulting from an earthquake of magnitude 6.0 on the Balcones Fault at a distance of 12 miles from the site"

Probabilistic
"The earthquake hazard for the site is PGA of 0.28g with a 2 percent probability of being exceeded in a 50-year period"

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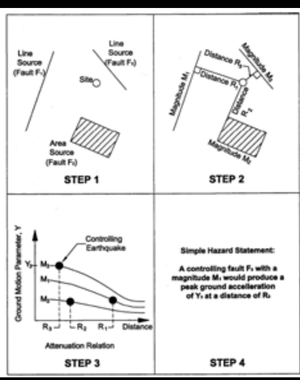
Deterministic seismic hazard analysis



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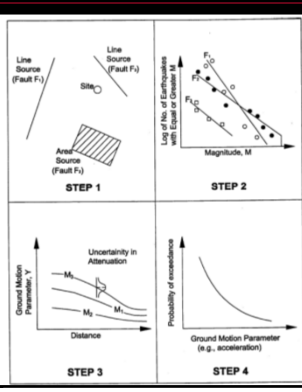
Probabilistic seismic hazard analysis



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Probabilistic seismic hazard analysis

First addressed in 1968 by C. Allin Cornell in "Engineering Seismic Risk Analysis," an article in The Bulletin of the Seismological Society of America (Vol. 58, No.5, October, pp. 1583-1606)

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Gutenberg and Richter (1944)

"The expected occurrence of about four great earthquakes per century in the California region by no means excludes the possibility that double that number might occur in a given century, or that a whole century might pass without even one"

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Introduction

Several types of ground motions parameters can be calculated from a recorded EQ time history.

But what do you do if you want to estimate what the ground motion parameters are going to be from an earthquake that hasn't happened yet?

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Introduction

ANSWER:
Use the data that we've collected so far and fit equations to them for predicting future ground motions.

These equations are often called **attenuation relationships.**

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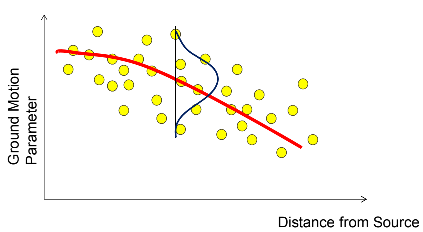
Attenuation Relationships



Initial relationships were just based on Magnitude (M) and Distance (R), but equations become much more complex as researchers looked for ways to **minimize data scatter.**

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Attenuation Relationships

Modern attenuation relationships have terms that deal with such complexities as:

1) **Fault type**
2) **Fault geometry**
3) **Hanging wall/Foot wall**
4) **Site response effects**
5) **Basin effects**
6) **Main shock vs. After shock effects**

Pretty complex …. Hard to do by hand!!

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Attenuation Relationships

Ideally, every geographic area that experiences EQs would have its own set of attenuation relationships. WHY?

Scatter in the data could be minimized!

…But we can't really produce site-specific attenuation relationships for places other than those that have a lot of frequent earthquakes. WHY?

Not enough recorded data!

So we start combining earthquake records from geographically different areas with the assumption that the ground motions should be similar despite the differences in location.

Ergodic Assumption

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NGA=Next Generation "Attenuation" Relations

Three NGA projects:

- For **active crustal** Eqs (California, Middle East, Japan, Taiwan,…): **NGA-West**
- For **subduction** Eqs (US Pacific Northwest and northern California, Japan, Chile, Peru,…): **NGA-Sub**
- **Stable continental** regions (Central and Eastern US, portion of Europe, South Africa,…): **NGA-East**

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Attenuation Relationships (GMPEs)

For crustal faults in the Western US and other high- to moderate- seismicity areas, most professionals currently use:

Next Generation Attenuation Relationships (NGAs)

NGA West 1: 5 separate research teams were given the same set of ground motion data and were asked to develop relationships to fit the data. Their results were published in 2008.

- **-Abrahamson & Silva**
- **-Chiou & Youngs**
- **-Campbell & Bozorgnia**
- **-Boore & Atkinson**
- **-Idriss (rock only)**

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NGA-West

NGA-West 1: 2008
NGA-West 2: 2014

Data set	No. EQs	No. Rec	Sa Type	Damping (%)	Periods (sec)
NGA-West 1	173	3,551	AR, GMRotI50	5	0.01 - 10
NGA-West 2	610	21,331	AR, RotDnn	0.5 - 30	0.01 - 20

AR= as-recorded

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RotDnn

Rotate horizontal components, at each period compute:

- RotD50 = 50 percentile
- RotD100 = max
- RotD00 = min

- ❑ RotD50 is the main intensity measure
- ❑ PGA, PGV and Sa at 21 periods: 0.01, 0.02,……,5, 7.5, 10 sec
- ❑ No GMPE for PGD

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NGA West-2 ranges of applicability

- Applicable magnitude range:
  - M ≤ 8.5 for strike-slip (SS)
  - M ≤ 8.0 for reverse (RV)
  - M ≤ 7.5 for normal faults (NM)
- Applicable distance range:
  - 0 – 200 km (preferably 300km)

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Horizontal NGA-West 2 GMPEs parameters

Parameter	AS	BSSA	CB	CY	I
Magnitude	M_w	M_w	M_w	M_w	M_w
Top of rupture	Z_{tor}		Z_{tor}	Z_{tor}	
Style of faulting	RV, NM, SS	RV, NM, SS	RV, NM, SS	RV, NM, SS	RV, NM, SS
Dip	Yes		Yes	Yes	
Downdip fault width	Yes		Yes		
Closest distance to rupture	R_{rup}		R_{rup}	R_{rup}	R_{rup}
Hor. dist. to surface proj.	R_{jb}	R_{jb}	R_{jb}	R_{jb}	
Hor. dist. Perpendicular to strike	R_x, R_y		R_x	R_x	
Hanging wall model	Yes	(R_{jb})	Yes	Yes	
V_{s30}	V_{s30}	(760m/s)	V_{s30}, (S_j)	V_{s30}	V_{s30}≥450
Depth to Vs	$Z_{1.0}$		$Z_{2.5}$	$Z_{1.0}$	
Hypocentral depth			H_{hyp}		
Vs30 for reference rock (m/s)	1,100	760	1,100	1,130	

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NGA West 2 Five models

- Abrahamson-Silva-Kamai (ASK)
- Boore-Stewart-Seyhan-Atkinson (BSSA)
- Campbell-Bozorgnia (CB)
- Chious-Youngs (CY)
- Idriss (I)

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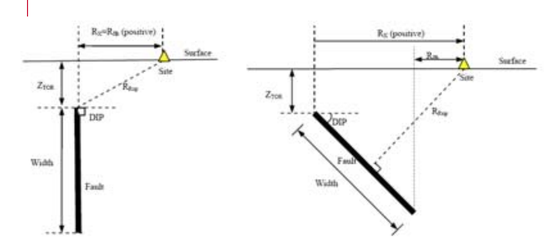
NGA Distance Notations



(a) Strike slip faulting (b) Reverse or normal faulting, hanging-wall site

R_{Rup} = *Closest distance to rupturing fault plane*

R_{JB} = *Boore–Joyner distance*

R_X = *Closest horizontal distance to the top of rupture*

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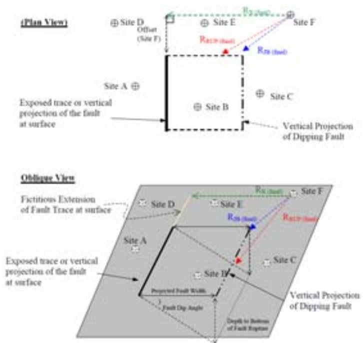
More on distances

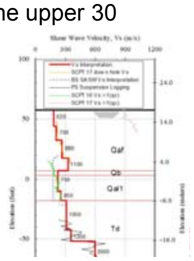


- Geotechnical Services Design Manual, Version 1.0, 2009, Caltrans
- Development of the Caltrans Deterministic PGA Map and Caltrans ARS Online, 2009, Caltrans

NGA Soil vs. Rock

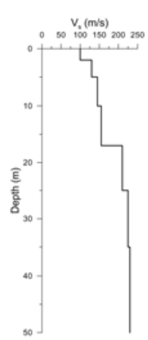
NGA equations don't have a "trigger" for soil or rock. They just rely on the V_{S30}, which is the average shear wave velocity in the upper 30 meters of the ground.

V_{S30} (m/s)	Type	Site Class
>1500	Hard Rock	A
760-1500	Firm Rock	B
360-760	Soft Rock	C
180-360	Regular Soil	D
<180	Soft Soil	E



What is V_{s30}?

- Not an average velocity in upper 30 m
- Ratio of 30 m to shear wave travel time

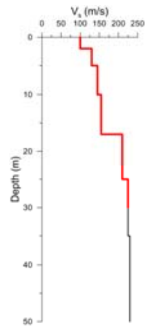


(Stewart 2011)

What is V_{s30}?

- Not an average velocity in upper 30 m
- Ratio of 30 m to shear wave travel time

$$V_{s30} = \frac{30m}{\sum_i \Delta t_i}$$



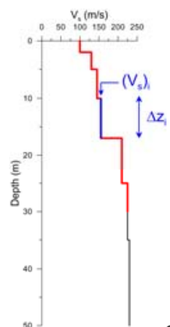
(Stewart 2011)

What is V_{s30}?

- Not an average velocity in upper 30 m
- Ratio of 30 m to shear wave travel time

$$V_{s30} = \frac{30m}{\sum_i \Delta t_i} \qquad \Delta t_i = \frac{\Delta z_i}{(V_s)_i}$$

- Emphasizes low V_s layers



(Stewart 2011)

Subduction Zones

Subduction zone sources have been observed to produce their own seismic “signature” and should be treated differently than crustal fault sources.

Do not use NGA West for Subduction Zone sources!

Commonly Used Subduction GMPEs

1. **BC Hydro [2012]:**
   Worldwide
2. **Arroyo *et al*. [2010]:**
   Interface model for Mexico (complementary to Garcia *et al.* [2005])
3. **Atkinson & Boore [2003]:**
   Worldwide
4. **Garcia *et al*. [2005]:**
   Intraslab model for Mexico (complementary to Arroyo *et al.* [2010])
5. **Kanno *et al*. [2006]:**
   Japan
6. **Lin & Lee [2008]:**
   Taiwan
7. **McVerry *et al*. [2006]:**
   New Zealand
8. **Youngs *et al*. [1997]:**
   Worldwide
9. **Zhao *et al*. [2006]:**
   Japan

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Commonly Used Subduction GMPEs

MODEL	RECORDS	EVENTS	M_w	DIST. (km)	H (km)	SITE Parameters
BC Hydro (2012)	Interface 1378 Intraslab 3946	Interface 46 Intraslab 76	Interface 6.5 - 8.4 Intraslab 5 - 7.9	Interface 5 - 551 Intraslab 34 – 991	Interface < 30 Intraslab > 30	Continuous (V_{s30})
Arroyo et al (2010)	Interface 418	Interface 40	Interface 5.0 - 8.0	Interface 20 - 400	Interface 10 – 29	N/A (NEHRP B only)
Atkinson & Boore (2003)	Interface 349 Intraslab + crustal 761	Interface 49 Intraslab + crustal 30	Interface 5.5 - 8.3 Intraslab 5 - 7.9	Interface 5 – 420 Intraslab 34 – 575 (r300)	Interface < 50 Intraslab 50 – 100	4 (Vs30; NEHRP B to E)
Garcia et al. (2005)	Intraslab 267	Intraslab 16	Intraslab 5.2 - 7.4	Intraslab 40 – 400	Intraslab 35 - 138 (m75)	N/A (NEHRP B only)
Kanno et al. (2006)	Interf. + cr. 3769 Intraslab 8150	Interf. + cr. 83 Intraslab 111	Interf.+ cr. 5.2 - 8.2 Intraslab 5.5 – 8	Interface 1 - 400 Intraslab 30 – 500	Shallow < 30 Deep 30 - 180	Continuous (V_{s30})

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Commonly Used Subduction GMPEs

MODEL	RECORDS	EVENTS	M_w	DIST. (km)	H (km)	SITE Parameters
Lin & Lee (2008)	Interface 873 Intraslab 3950	Interface 17 Intraslab 37	Interface 5.3 - 8.1 Intraslab 4.1 – 6.7	Interface 20 - 40 Intraslab 40 - 600	Interface 4 - 30 Intraslab 43 - 161	2 (Vs30; NEHRP B,C or D,E)
McVerry et al. (2006)	535 Subduct. + crustal	Interface 6 Intraslab 19	5.08 – 7.09	6 - 400	Interf. 15 – 24 Intrasl. 26 - 50 50 - 149	3 (NZ classes)
Youngs et al. (1997)	Interface 181 Intraslab 53	Interface 57 Intraslab 26	Interface 5 - 8.2 Intraslab 5 - 7.8	Interface 8.5 - 551 Intraslab 45 – 774	10 – 229 (not distinguished)	2 (Rock/Soil)
Zhao et al. (2006)	Interface 1508 Intraslab 1725 Crustal 1285	289 (not distinguished)	5.0 - 8.3 (not distinguished)	0 - 300 (not distinguished)	Interf. 10 - 50 Intraslab 15–162 (c125)	5 (HR + 4 Jap. Rail. Ass., Tg)

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Observations on Existing Subduction GMPEs

- All existing GMPEs were developed before the 2010 Chile and 2011 Japan subduction earthquakes
  - Except one (BC Hydro) that the model was adjusted based on the new data
- Some GMPEs are based on very old databases
- Median predictions and standard deviations of some GMPEs can be very different than others

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Latest GMPE: BC Hydro Model

Combined available data through 2007

- – Youngs et al (1997) - global
- – Atkinson & Boore (2003) - global
- – Zhao et al (2006) - Japan
- – Lin and Lee (2008) – Taiwan
- – Macias & Atkinson (2009) – Central America
- – Other available data
- – About 6000 recordings from 292 earthquakes in full set

2010 Chile and 2011 Tohoku

- – Not included in data set, but model adjusted based on these data

Ref.: Abrahamson, March 2012, Seattle

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Model Features

Magnitude Scaling

- Includes break in magnitude scaling at large magnitudes (C1) based on simulations
- Revised based on 2010 Chile and 2011 Tohoku

Depth

- Only applies to slab events

Site

- V_{S30} with non-linear site response based on AS08 and CB08 NGA-West models

Forearc/backarc

- Includes different rates of attenuation for forearc and backarc sites

Sigma

- Both traditional and single-station sigma

Epistemic Uncertainty

- Includes range of constants to capture range of constant terms from different regions

Ref.: Abrahamson, March 2012, Seattle

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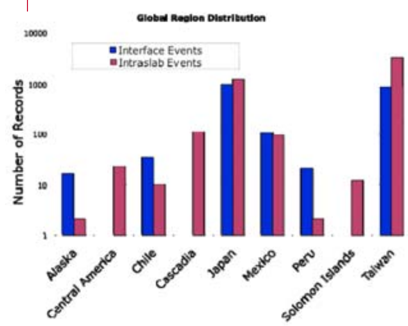
BC Hydro Database



292 Earthquakes (9946 record pairs

163 Interface (3557 record pairs

129 Intraslab (6389 record pairs

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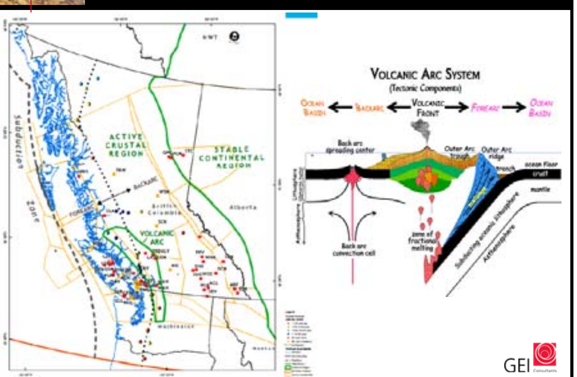
Forearc or backarc?



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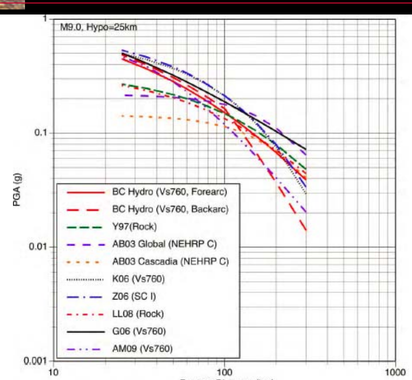
Interface M = 9.0 (PGA)



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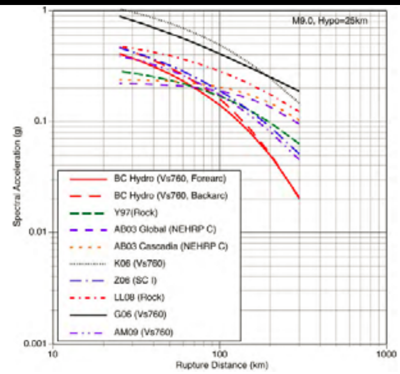
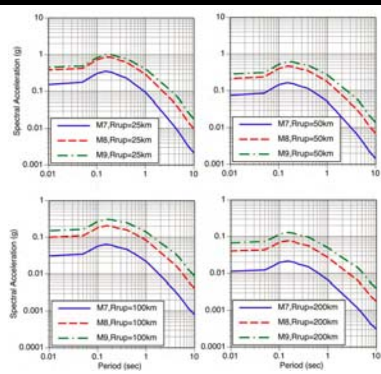
Interface M = 9.0 (Sa 1 second)

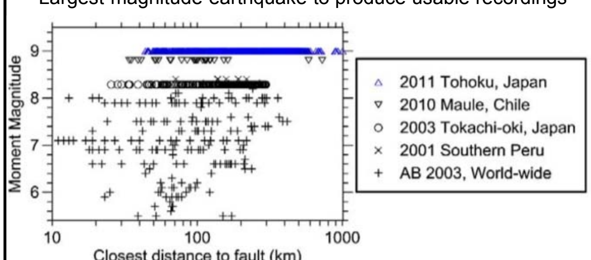


Magnitude scaling, Interface, forearc station locations



Strong Motion Data for Interface Subduction Earthquakes

Largest-magnitude earthquake to produce usable recordings

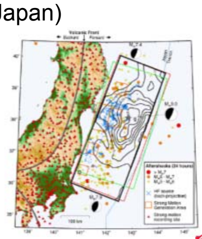


(Stewart et al. 2013)

Ground Motion Prediction Equations for Interface Subduction Zone

- Atkinson and Boore (2003, 2008) (USGS 2008)
- Abrahamson et al. (2013) (USGS subsequent)
- Zhao et al. (2006) (USGS 2008)
- Si and Midorikawa (2000) (Japan)

- NGA Sub ?



High-frequency ground motions demonstrate faster attenuation with distance in backarc than in forearc regions, which is only captured by Abrahamson et al. (2013)

(Stewart et al. 2013)

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NGA-Sub

- PEER has just initiated a multidisciplinary multi-year research program to develop **N**ext **G**eneration **A**ttenuation models for **Sub**duction earthquakes: **NGA-Sub**
- **NGA-Sub** has three parallel phases

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NGA-Sub: Phase I

- Collection of recorded data and metadata from the
  - Feb 2010 Maule, Chile (M 8.8), and
  - March 2011 Tohoku, Japan (M 9.0)

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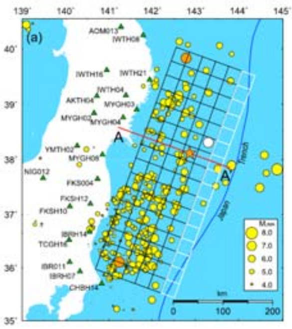
NGA-Sub: Phase I

- For Tohoku EQ, PEER **already processed**:
  - More than 570 recordings for the main shock (three-component each)
  - 7 foreshocks (about 600 recordings total)
  - 45 aftershocks from M 6–7.7 (>3000 recordings)



Courtesy: Yokota, et al (2011)

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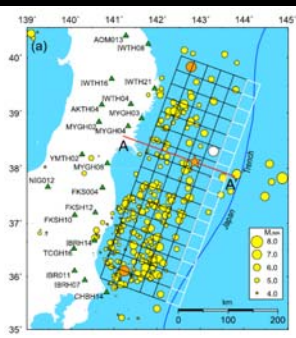
NGA-Sub: Phase I

- For Tohoku EQ:
- In collaboration with Japanese colleagues another set of:
  - 1,190 recordings from JMA and other local networks for the main shock
- In the entire set:
  - PGA > 0.5g was recorded at 210 sites
  - PGV > 50 cm/sec was recorded at 110 sites



Courtesy: Yokota, et al (2011)

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NGA-Sub: Phase I

- **Phase I**: Comparison of the data with current GMPEs used in the USGS National Seismic Hazard Map for subduction area
- Phase I is funded by USGS/NEHRP; and PEER Transportation Systems Program
- Started Jan 2012; was completed by Early 2013

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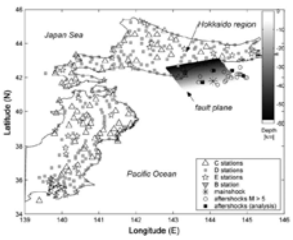
NGA-Sub: Phase II

- **Phase II**: Collection and processing of data and metadata from other subduction earthquakes worldwide:
  - Other Japan EQs, e.g., 2003 Tokachi-Oki EQ, M 8.3
  - Alaska, Chile, Mexico, Peru, Taiwan, CSZ, …
- Collect and process aftershock data



Reference: Tokachi-Oki EQ, by Macias, Atkinson, and Motazedian (2008)

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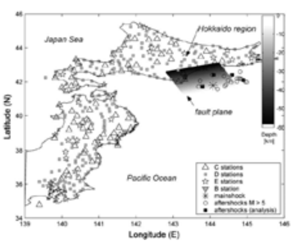
NGA-Sub: Phase II

- **Phase II**: Develop/update one GMPE for subduction earthquakes
- Funded by FM Global
- With supplemental funding from Caltrans
- With in-kind from: BC Hydro, Validus Research, PG&E
- To be completed by May 2016



Reference: Tokachi-Oki EQ, by Macias, Atkinson, and Motazedian (2008)

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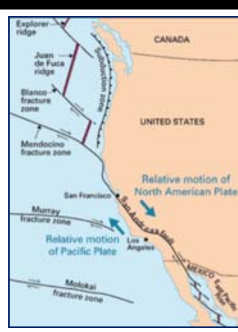
NGA-Sub: Phase III

- **Phase III**:
- Carry out validated simulations to fill the gap in empirical data
- Develop multiple GMPEs by multiple developer teams (epistemic uncertainty)
- Examine directivity,…
- They are working to secure funding
- To start February 2013 and complete by May 2016



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Continental Seismic Sources

NGA West equations were developed specifically for the western US and other areas of high seismicity. How do we represent seismic sources in the central and eastern US?

It's complicated!!!

Refer to the USGS 2008 seismic source model write-up to see what they currently recommend.

The same NGA research teams are currently working on NGA equations for the central and eastern US!!!

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Introduction

The process of predicting strong ground motions for a given site is called

Seismic hazard analysis

There are two basic types of seismic hazard analysis:

Deterministic Seismic Hazard Analysis (DSHA)

Probabilistic Seismic Hazard Analysis (PSHA)

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Deterministic Seismic Hazard Analysis

DSHA is the 'original' seismic hazard analysis. It represents a single **scenario** and is intended to be conservative.

1. Identify the "active" sources and magnitudes

2. Compute the closest source-to-site distances

3. Use attenuation relationship(s) to compute ground motions

4. Identify the "governing" ground motions (i.e., the largest ground motion)

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Deterministic Seismic Hazard Analysis

There are two major problems with DSHA:

1. **Doesn't deal explicitly with uncertainty**
2. **Only deals with the possibility of EQ, not the likelihood**

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Probabilistic Seismic Hazard Analysis

PSHA was developed in the 1970s as a means for accounting for most of the uncertainties involved with seismic hazard. PSHA acknowledges that we don't know certain important aspects to the problem:

1. **Where the EQ will occur**
2. **How big the EQ will be**
3. **The intensity of ground motions at the site**
4. **When the EQ will occur**

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Probability Theory

In order to understand PSHA, we need to talk briefly about a few important principles related to probability.

PSHA is based on the **Total Probability Theorem** which states that we can compute the total probability of a system by summing the individual probabilities from each contributing part.

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Probability Theory

Probability Nomenclature:

P[A] = Probability of A

P[A|B] = Probability of A given "B"

P[A=a|B=b] = Probability that A=a given B=b

μ or $\overline{x}$ = mean value

σ or s = standard deviation

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Probability Theory

Total Probability Theorem:

$$P[Y] = \sum_{i=1}^{n} P[Y|X_i]P[X_i]$$

Let's look at an example application of how the total probability theorem works….

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Example of total probability

You have been asked to compute the probability that Dam T collapses during the next earthquake in the region. You do not know with certainty if the next earthquake will be strong, medium or weak, but ***seismologists*** have estimated the following probabilities:

P(strong) = 0.01
P(medium) = 0.1
P(weak) = 0.89

Additionally, ***geotechnical earthquake engineers*** have performed analyses and estimated the following:

P(collapse|strong) = 0.9
P(collapse|medium) = 0.2
P(collapse|weak) = 0.01

P(collapse)=
P(collapse|strong)P(strong)+P(collapse|medium)P(medium)+P(collapse|weak)P(weak)

P(collapse) = 0.90(0.01) + 0.2(0.1) + 0.01(0.89) = 0.0379

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Total probability

The total probability theorem:

- breaks the problem into two parts (size of the earthquake and capacity of the dam)
- compute probabilities for those parts, and
- re-combine them to answer the original question.

This not only facilitates solution of the problem in pieces, but it allows different specialists (e.g. seismologists and geotechnical engineers) to work on different aspects of the problem

PSHA is a direct application of the total probability theorem (except that it uses random variables, instead of random events).

The distribution of earthquake magnitudes and distances are studied independently of the conditional distribution of ground motion intensity, and this probabilistic framework allows to re-combine the various sources of information in a rigorous manner.

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Probability Theory

So how do we compute individual probabilities?

Probability Density Function, *f*(x)

There are three main types of PDFs that we use regularly in earthquake engineering:

1. **Uniform Distribution**
2. **Normal Distribution**
3. **Lognormal Distribution**

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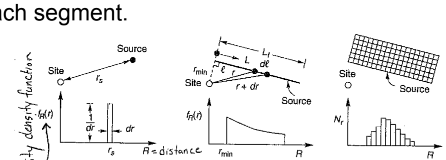
Where will the EQ Occur?

Spatial Uncertainty is the uncertainty associated with not knowing where an EQ will occur. We typically divide the source up into small segments and compute the likelihood that it could come from each segment.



Examples of variations of source-to-site distance for different source zone geometries. The shape of the probability distribution can be visualized by considering the relative portions of the source zone that would fall between each of a series of circles (or spheres for three-dimensional problems) with equal differences in radius.

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How Big Will the EQ Be?

We typically deal with uncertainty in EQ size by using **Recurrence Laws.**

There are three general types of recurrence laws:

1. **Slip-Dependent Laws**
2. **Gutenberg-Richter Laws**
3. **Characteristic EQ Laws**

How Big Will the EQ Be?

Recurrence Law Terminology:

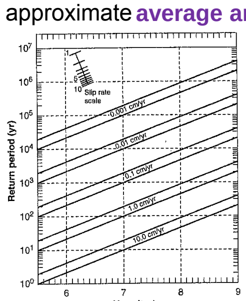
Annual Rate of Exceedance, λ_m = the number of earthquakes larger than a specified magnitude that occurs each year on average.

Return Period, T_R = the number of years on average before an earthquake larger than a specified magnitude occurs

$$\lambda_m = \frac{1}{T_R}$$

How Big Will the EQ Be?

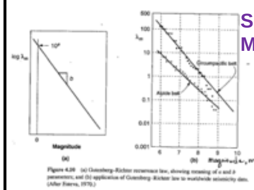
Slip-Dependent Recurrence Laws are typically assigned to faults that are known to have an approximate **average annual slip rate.**



Effects of fault slip and M on Return Period (Slemmons 1982)

How Big Will the EQ Be?

Gutenberg-Richter Recurrence Laws have been around for awhile, but they are still very widely used. They essentially state that the number of EQs occurring annually from a given source is a log-linear function of the magnitude



Sometimes called Time-Dependent Models

$$\log\lambda_m = a - bm$$

$$\lambda_m = 10^{a-bm}$$

Also…..

$$\lambda_m = \exp(\alpha - \beta m)$$

$$\alpha = 2.303a,\ \beta = 2.303b$$

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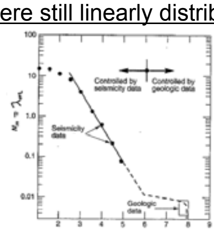
How Big Will the EQ Be?

Characteristic Earthquake Recurrence Laws:
In the 1980s, Paleoseismologists began to note that some faults seemed to have a "characteristic earthquake" instead of a linear distribution of big EQs. Small EQs were still linearly distributed, just not the big ones.



Characteristic EQ model for some fault (after Youngs and Coppersmith 1985)

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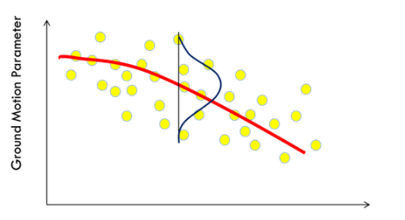
How Big Will My Ground Motions Be?



Recall from earlier that attenuation relationships have quite a bit of scatter associated with them

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How Big Will My Ground Motions Be?

Instead of forcing ourselves to blindly pick a level of certainty to apply in computing our EQ ground motions (like in a deterministic analysis), probabilistic methods let us account for all possible ground motions and weight them accordingly.

How Big Will My Ground Motions Be?

Example:

For simplicity, let's assume that a simple attenuation relationship solves for the ln(SA). At a period of T=0 seconds, the mean computed spectral acceleration from one of the seismic sources is SA=0.162g (….note that the spectral acceleration at T=0sec is the same as the PGA!). Let's assume that the standard deviation is $\sigma_{\ln(SA)} = 0.39$

Find the probability that the SA will exceed 0.25g.

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How Big Will My Ground Motions Be?

Example:

$$\overline{X} = \overline{\ln(SA)} = \ln(0.162) = -1.82$$

$$X = \ln(0.25) = -1.386$$

$$z = \frac{X - \overline{X}}{\sigma_{\ln(SA)}} = \frac{(-1.386) - (-1.82)}{(0.39)} = 1.1128$$

$$P[SA > 0.25g] = 1 - F(z) = 1 - 0.8671 = \mathbf{0.1329}$$

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Tying It All Together…….

Ok, in the previous example we computed the probability that the PGA exceeded 0.25g.

BUT WAIT.....

The mean acceleration SA=0.162g was computed with a single pair of magnitude and distance values. What about spatial uncertainty and size uncertainty? How do we account for that?!!!

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Tying It All Together…….

Remember what we learned about the Total Probability Theorem: As long as we track our individual conditional probabilities, we can compute the final overall probability.

So how do we do this? We need to (1) compute the probability of exceeding 0.25g for every possible combination of magnitude and distance, (2) multiply it by the probability of having those particular values of magnitude and distance, and (3) sum it all together.

$$\sum_{j=1}^{N_M}\sum_{k=1}^{N_R} P\left[SA > 0.25g \mid m_j, r_k\right] P\left[M = m_j\right] P\left[R = r_k\right]$$

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Tying It All Together…….

If we multiply the preceding summation by the mean annual rate of exceeding the minimum magnitude for our seismic source, ν we get the mean annual rate of exceeding 0.25g.

$$\lambda_{SA=0.25g} = \nu \sum_{j=1}^{Nm}\sum_{k=1}^{N_R} P\left[SA > 0.25g \mid m_j, r_k\right] P\left[M = m_j\right] P\left[R = r_k\right]$$

"So…….are we done yet?"

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Tying It All Together…….

Of course not!! What if there are more than just one seismic source? Don't they contribute to the hazard, too?!!

Repeat the process for all of the possible seismic sources and then sum the results!!

$$\lambda_{SA=0.25g} = \sum_{i=1}^{N_S} \nu_i \sum_{j=1}^{Nm} \sum_{k=1}^{N_R} P\left[SA > 0.25g \mid m_j, r_k\right] P\left[M = m_j\right] P\left[R = r_k\right]$$

"So….NOW are we done yet?.....Please?!!"

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Tying It All Together……

NO!!! The best part is still coming! Most engineers aren't interested in just a peak acceleration of 0.25g, but they want to know the mean annual rate of exceeding <u>any</u> peak acceleration value at their site,

$$\lambda_{y^*} = \sum_{i=1}^{N_S} \nu_i \sum_{j=1}^{Nm} \sum_{k=1}^{N_R} P\left[Y > y^* \mid m_j, r_k\right] P\left[M = m_j\right] P\left[R = r_k\right]$$

So if you computed a wide range of λ_{y^*} and plotted them against their corresponding accelerations (i.e. y^*), you would develop the **Seismic hazard curve** for the site.

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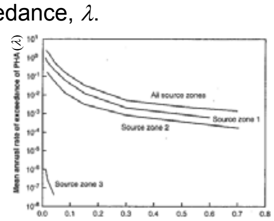
Seismic Hazard Curves

A seismic hazard curve is a function relating a given ground motion parameter to its mean annual rate of exceedance, λ.

Return Period, T_R = 1/λ



In a PSHA, the seismic hazard curves computed for each source are summed together to provide the **Total Seismic Hazard**

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When Will the EQ Occur?

Temporal uncertainty

is the uncertainty associated with when an EQ of a given size will occur.

Because EQs occur infrequently relative to the lifetime of our designs, we can treat them as **random** and **independent** processes. We can then apply the

Poisson Probability Model

Same model that applies to rolling dice

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When Will the EQ Occur?

Poisson Probability Model:

$$P\left[Y_T > y^*\right] = 1 - e^{-\lambda_{y*}T}$$

$P[Y_T > y^*]$ = the probability of exceeding y* in a specified time frame, T

λ_{y^*} = the mean annual rate of exceeding y* (….from the seismic hazard curve)

T = the time frame of interest (years)

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When Will the EQ Occur?

Example:

Assume that a PSHA was performed and that the mean annual rate of exceedance associated with PGA=0.3g is equal to 0.0013. (T_R = 1/0.0013 = 770 years).

Compute the probability of exceeding PGA=0.3g at the site in 50 years.

$$P\left[PGA > 0.3g\right] = 1 - e^{-(0.0013)(50\,yrs)}$$

$P\left[PGA > 0.3g\right] =$ **0.0629 = 6.29%**

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When Will the EQ Occur?

However, is the Poisson assumption about random occurrence valid? What about seismic gaps and elastic rebound theory? What do you think?

Error is negligible in the majority of cases.

Be careful using Poisson model if:

1. **The structure has an unusually long design life**
2. **Previous seismicity shows strong time-dependence between events (e.g. Parkfield, CA)**
3. **One or more of the significant sources is well overdue**

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Characterizing Seismic Sources

Up to this point, we have talked about seismic sources as if their characteristics were well-known and easily-obtained parameters.

The Truth:

Characterizing the seismic sources is the most difficult aspect to performing a PSHA.

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Characterizing Seismic Sources

Typically, specialized engineering geologists or paleoseismologists develop the parameters associated with various seismic sources.

The collection of seismic sources and their corresponding magnitude and distance probability distributions is called the **Seismic source model** of a PSHA.

Having a good seismic source model is **ALL** of the battle.

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Characterizing Seismic Sources

How do engineering geologists and paleoseismologists evaluate seismic sources?

Geologic Evidence

This type of evidence involves "reading" the history recorded in the ground and in the geomorphology.

- Aerial photos & remote sensing
- Surficial reconnaissance
- Fault trenching
- Geophysical methods

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Characterizing Seismic Sources

How do engineering geologists and paleoseismologists evaluate seismic sources?

Historical Evidence

This type of evidence involves researching historical accounts of pre-instrumental earthquakes. May incorporate intensity records if available. Often involves old newspaper articles.

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Characterizing Seismic Sources

How do engineering geologists and paleoseismologists evaluate seismic sources?

Instrumental Evidence

Since the 1930s, more and more information regarding seismic sources is becoming available. This type of evidence will only improve with time.

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Characterizing Seismic Sources

How do engineering geologists and paleoseismologists evaluate seismic sources?

Academic Literature Review

MUCH of the seismic source characterization available to us today was developed through university research projects. Searching through student theses and dissertations could yield some fabulous results. Beware of quality, however.

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Characterizing Seismic Sources

So if you want to perform a PSHA and you need a seismic source model, what can you do?

1. **Hire an engineering geologist to build your own model ($$$)**
2. **Use a publicly available seismic source model like those developed by USGS**
3. **Use the results of previous private studies if those results are available to you**

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Characterizing Seismic Sources

The United States Geological Survey has done A LOT of work to characterize many of the most common seismic sources here in the US.

For deterministic analyses, the Quaternary Fault and Fold database is very helpful.

For probabilistic analyses, the 2008 USGS seismic source model map is great.

https://geohazards.usgs.gov/hazfaults/map2008.php

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Seismic Source Uncertainty

We spent some time discussing how PSHA accounts for the various uncertainties related to computing ground motions. BUT THOSE WERE ASSUMING THAT WE WERE 100% CONFIDENT WITH OUR SEISMIC SOURCES.

What happens if we are not completely confident with our seismic source model or with which attenuation relationships to use to represent them?

Seismic Source Uncertainty

There are 2 general types of uncertainties:

1. **Aleatory uncertainty**

   Deals with random variability in nature. For example, EQ magnitude, location, and ground motion intensity.

2. **Epistemic uncertainty**

   Deals with a lack of understanding of how to represent the system. For example, which attenuation relationship would best represent a particular fault or seismic source?

Seismic Source Uncertainty

How do we deal with these uncertainties:

1. Aleatory uncertainty

   Within the hazard integral itself.
   Iterate through all possible values.

2. Epistemic uncertainty

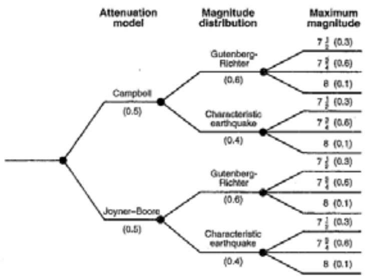
   Incorporate logic trees.

Seismic Source Uncertainty

Logic Trees:

Each "level" deals with a different aspects of epistemic uncertainty. The weighting factors from each level must sum to 1.0.

Each "branch" represents a viable alternative within a given level. Each branch represents its own PSHA.



Simple logic tree for incorporation of model uncertainty

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Seismic Source Interpretation from PSHA Results

We learned last week that PSHA represents a huge probabilistic conglomeration from all of the individual sources. Is it possible to use the PSHA results to infer the amount of risk associated with each seismic source?

Yes!

1. **Seismic hazard curves from Individual sources**
2. **Deaggregation plot**

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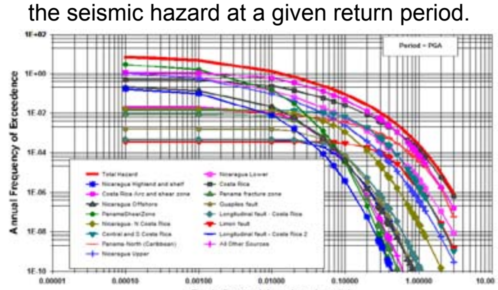
Seismic Source Interpretation from PSHA Results

Seismic Hazard Curves for Sources:
Can be used to see which sources govern the seismic hazard at a given return period.



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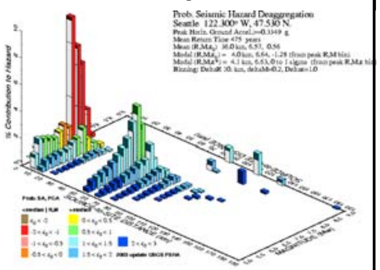
Seismic Source Interpretation from PSHA Results

Deaggregation:
Break the probabilistic "aggregation" back down to individual contributions based on magnitude and distance.



Provides:

- Mean M,R: weighted average

- Modal M,R: Greatest single contribution to hazard

Wrapping Up Seismic Hazard Analysis….

We have discussed both PSHA and DSHA. Which one is better?

Neither is better. Each has its useful applications.

A good seismic hazard analysis will include both DSHA and PSHA. Only after comparing the results from both you can make an informed decision regarding which to use in design.

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Wrapping Up Seismic Hazard Analysis….

Most building codes allow you to select the **lesser** of the probabilistic and deterministic ground motions. WHY?

In general, PSHA will govern:

In the majority of cases, particularly in regions of low to moderate seismicity.

DSHA will be used:

As an upper bound for the seismic hazard. Most often used in areas of high seismicity or if designing a critical structure.

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Wrapping Up Seismic Hazard Analysis….

If performing a site-specific PSHA, what should your report include:

1. **Regional and historical seismicity**
2. **Seismic source model and logic tree**
3. **Description of attenuation relationships used**
4. **Seismic hazard curve(s)**
5. **Uniform Hazard Response Spectra for return periods of interest**
6. **Deaggregation(s) from return period(s) of interest**
7. **Interpretation of results**

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