Probabilistic Seismic Hazard Analysis (PSHA) for Swiss Nuclear Power Plants: the PEGASOS Project

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PSHA

- Source Characterization
  - Define earthquake scenarios (magnitude, location, rupture geometry, style-of-faulting)
  - Define rates of each earthquake scenario
- Ground Motion Characterization
  - Define the range of possible ground motions for each earthquake scenario (attenuation relation)
  - Define the relative chance of each ground motion for each earthquake scenario (log-normal distribution)
- Hazard Calculation

PSHA - Hazard Calculation

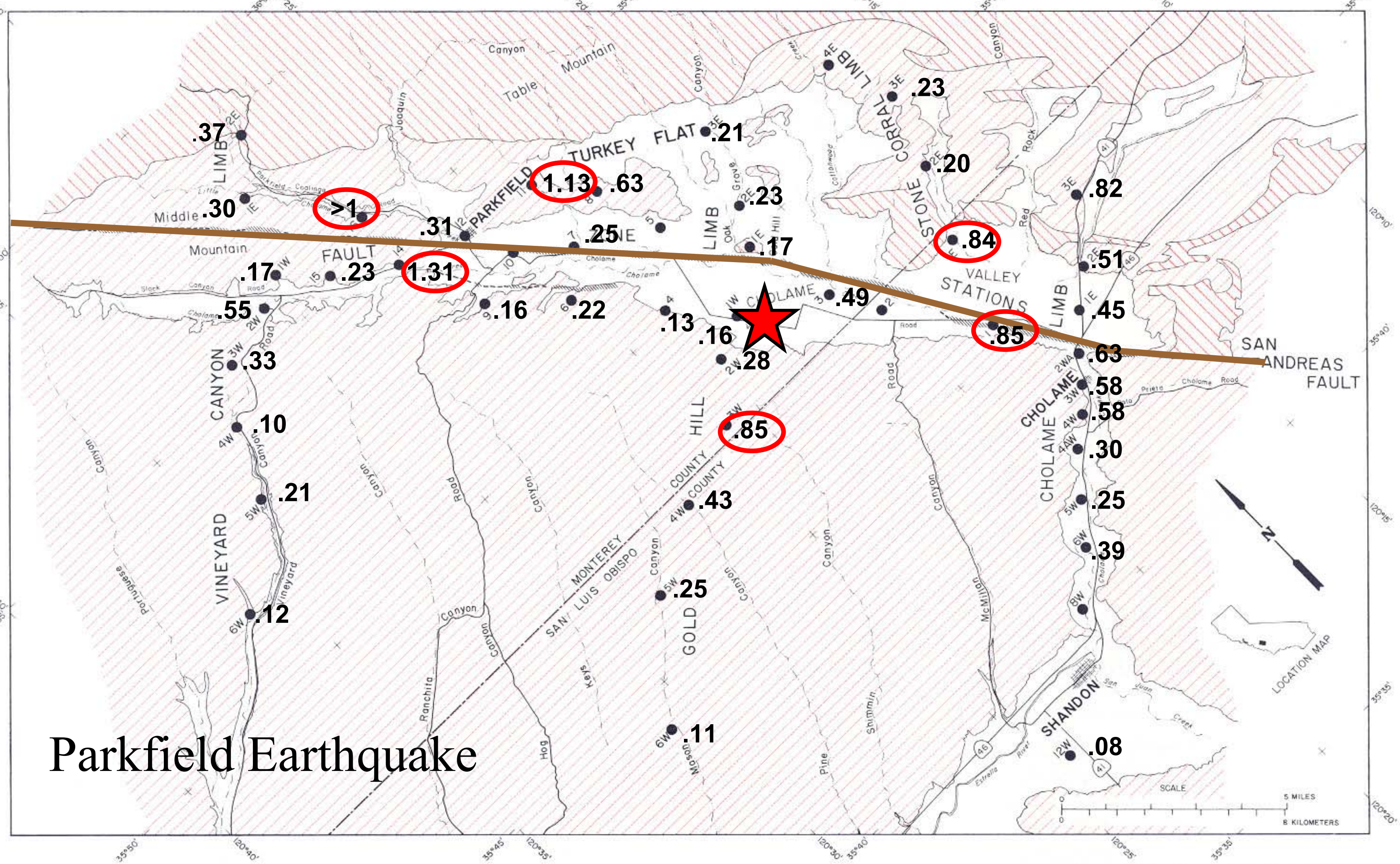
- Suite of deterministic scenarios
  - Earthquake magnitude
  - Earthquake location and rupture dimension
    - Leads to distance
  - Earthquake mechanism (style-of-faulting)
  - Ground motion level (number of std dev)
  - No physically impossible scenarios
- Rates of each deterministic scenario
  - Rate of earthquake
  - Rate of ground motion level
- Rank the deterministic scenarios in terms of strength of ground motion
  - Sum the rates of scenarios to get a hazard curve

Aleatory Variability and Epistemic Uncertainty

- Aleatory variability:
  - Randomness in a earthquake process (magnitude, location, style-of-faulting) and in the ground motion
    - Includes effects of physical attributes not modeled
  - Leads to the shape of the hazard curve
- Epistemic uncertainty
  - scientific uncertainty in the models of the earthquake process and wave propagation
    - Includes uncertainty in the both the median values and degree of randomness
  - Leads to alternative hazard curves
  - Implemented through logic trees

Effect of Log Normal Distribution
Example: M=6.5, R=10 km, Rock

Number of Std Dev	PGA (g)	Probability of Exceeding
0	0.27	0.50
0.5	0.35	0.31
1.0	0.45	0.16
1.5	0.58	0.067
2.0	0.75	0.023
3.0	1.25	0.0013



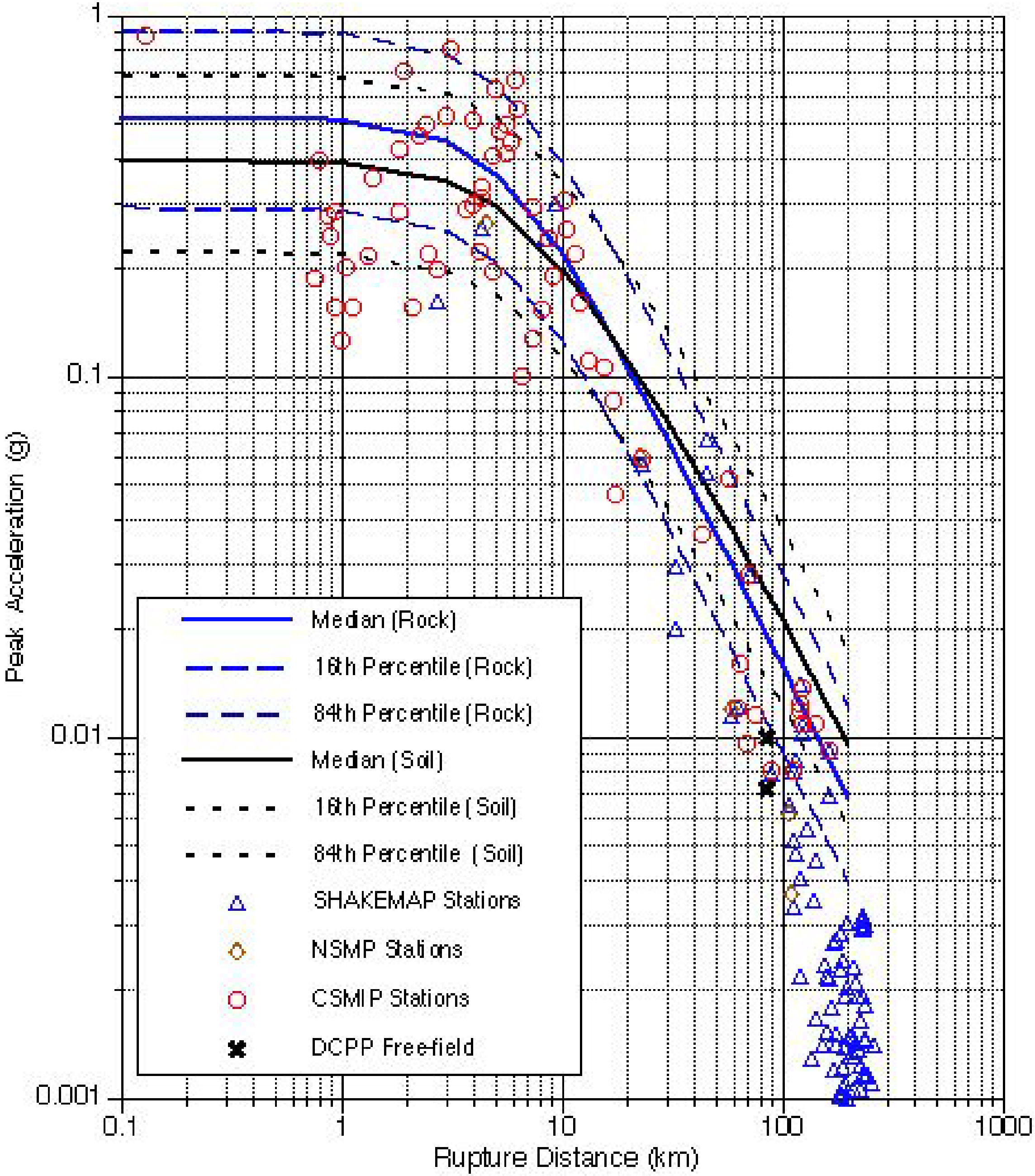
(from McJunkin and Shakal, 1983)

Quaternary Deposits
Unconsolidated stream and floodplain deposits of sand, silt, and gravel and terrace deposits of similar composition. Also includes landslide debris.

Cenozoic Rocks and Deposits
Poorly to well indurated predominantly clastic rocks including sandstone, siltstone, and conglomerate of several formations. Most rocks are marine except for the Plio-Pleistocene Paso Robles Formation which underlies the greatest amount of terrain southwest of the San Andreas fault.

Mesozoic Rocks
Moderately to well indurated marine rocks including predominantly sandstone, siltone, and shale with, in addition, pillow lavas and chert abundant in Franciscan assemblages. Also includes tabular and lenticular bodies of serpentine and intrusive rock.

Parkfield Ground Motion Attenuation (ave Horiz)



Simple PSHA

- Accounts for aleatory variability
  - Earthquake magnitude
  - Earthquake location
  - Ground motion level
- Epistemic uncertainty not considered
  - Single best estimate models are used

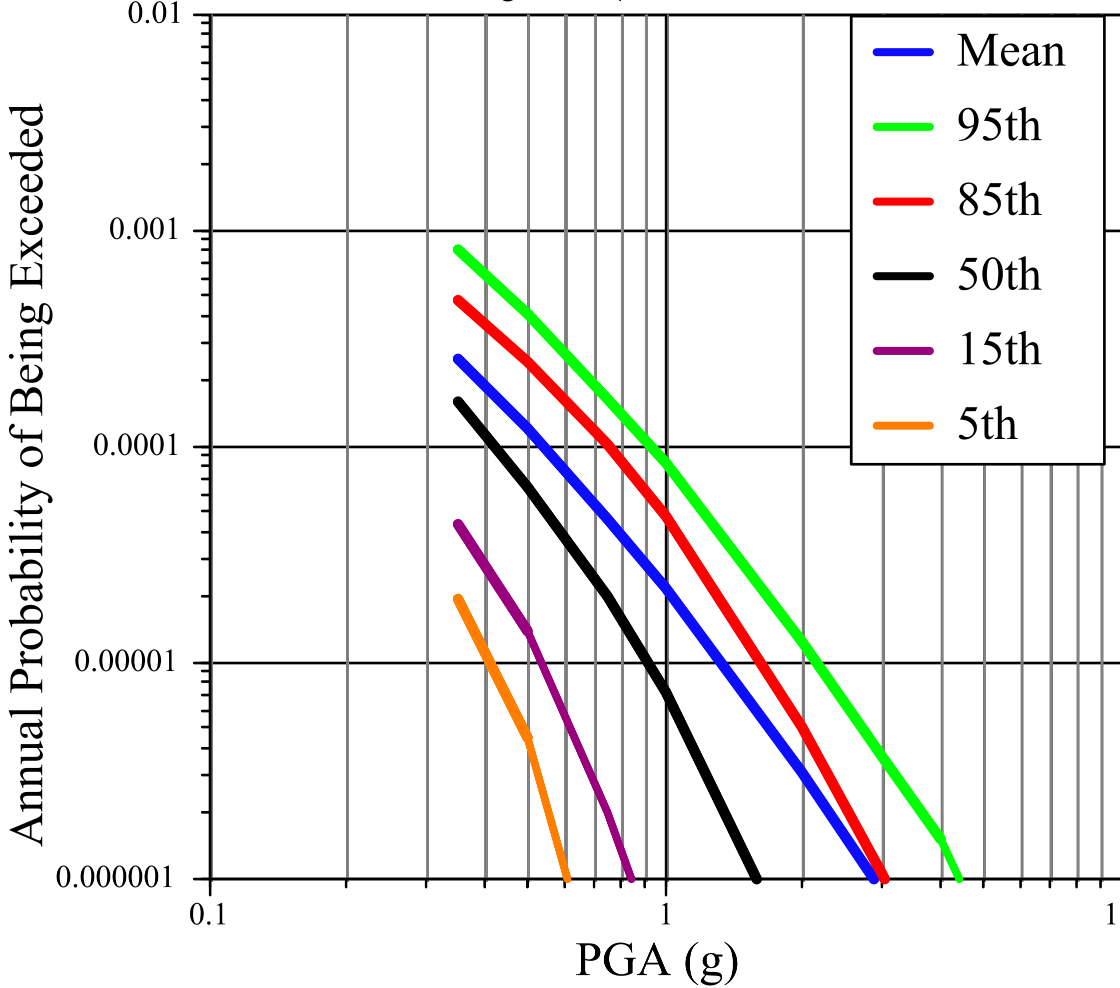
Advanced PSHA

- Separates aleatory variability and epistemic uncertainty
  - Aleatory variability:
    - Randomness in a earthquake process, ground motion
    - Includes effects of physical attributes not modeled
  - Epistemic uncertainty: scientific uncertainty in the model of the earthquake process
    - Includes uncertainty in the models: median values and degree of randomness

Epistemic Example: Ground Motion Models

Ambraseys *et al.* (1996)	Europe
Berge-Thierry *et al*. (2000)	Europe
Sabetta & Pugliese (1996)	Italy
Spudich *et al*. (1999)	Extensional
Lussou *et al*. (2001)	Japan
Abrahamson & Silva (1997)	WUS
Boore *et al*. (1997)	WUS
Campbell, Bozorgnia (2002)	WUS
Ambraseys & Douglas (2000)	World-wide near fault
Atkinson & Boore (1997)	EUS – Emp/Point source
Somerville *et al*. (2001)	EUS (Finite source simulation)
Toro *et al*. (1997)	EUS (point source simulation)
Bay (2002)	Swiss Point Source
Rietbrock (2002)	Swiss Point Source

Example of Epistemic Uncertainty (Yucca Mtn)



SSHAC Level 4 PSHA

- Expert elicitation (opinion) used to quantify epistemic uncertainties
  - Epistemic uncertainty should cover the range of models from the <u>informed</u> scientific community
- Multiple experts / experts groups used
  - Complete alternative models are developed by each expert or expert group
    - Must document technical basis for weights assigned to alternative models
  - Using multiple experts shows the robustness of the results
    - e.g. would we get a different result if different experts were selected
  - Experts provide peer review of each others models

SSHAC Level 4 PSHA Studies

- PEGAOS - Yucca Mtn Differences
  - Site Response
    - Yucca Mtn considered site response effects deterministically (e.g. outside of the PSHA)
    - PEGASOS considered site response effects probabilistically (e.g. as part of the total ground motion model)
  - Maximum Ground Motion
    - Yucca Mtn did not include maximum ground motion on rock
    - PEGASOS explicitly evaluated the maximum ground motions on rock and on soil
      - Avoids extrapolation to unphysical levels of shaking that can result from the extreme tails of the statistical models

PEGASOS Project Steps

- Selection of experts
- Data dissemination
- Meetings of experts
- Elicitation interactive meetings
- Requests for supporting calculations
- Feedback on preliminary results
- Preparation of hazard input documents
- Final documentation of expert models

Selection of Experts

- Formal process for expert selection
  - 109 candidates nominated
  - Factors affecting experts selection:
    - Technical expertise in field
    - Swiss-specific knowledge
    - Willing to work as an evaluator of alternative models, not as proponent of single model
    - Ability to work with other experts in workshops

Selection of Experts

- Three groups of experts:
  - Source characterization (SP1)
    - 4 Expert groups consisted of 3 individual experts due to the range of expertise required to build source models.
  - Ground motion characterization (SP2)
    - 5 ground motion experts
  - Site response characterization (SP3)
    - 4 site response experts

How to Represent the Informed Technical Community?

- All experts have access to same information
- Series of structured workshops attended by experts
  - Present available data and models to the experts
  - Provides feedback to the experts
    - Comments by other experts
    - Feedback on impact on hazard

Data Dissemination

- Data compiled in PEGASOS data base
  - Goal to provide all experts a comprehensive and consistent data set for their evaluations
  - Selection of data input into data base driven by experts requests
    - 134 data requests from experts were met by project

Meetings of Experts (SP1)

- WS#1:
  - Key issues and data needs
- WS#2:
  - Methodologies for defining seismic sources
- WS#3:
  - Feedback on seismic sources and methodologies for maximum magnitude
- WS#4:
  - Feedback on maximum magnitude, recurrence, and hazard

Meetings of Experts (SP2)

- WS#1:
  - Data needs
- WS#2:
  - Evaluation of ground motion models
- WS#3:
  - Feedback on initial expert models (ground motions)
- WS#4:
  - Feedback on revised expert models and hazard
- WS#4a:
  - Style-of-faulting

Meetings of Experts (SP3)

- WS#1:
  - Data needs
- Group Elicitation:
  - Soil properties
- WS#2:
  - Evaluation of site response models
- WS#3:
  - Feedback on initial expert models (surface)
- WS#4:
  - Feedback on revised expert models and hazard
- WS#4a:
  - Maximum ground motions on soil

Experts Not Independent

- SSHAC found that interaction between experts is preferred to independence
  - Experts discuss their interpretations with each other
    - All experts understand the approach and technical basis used by other experts
    - Serves as peer review
    - Helps to achieve goal of representing the informed technical community

Interface Between Expert Groups

- Source - Rock Ground Motion
  - Moment Magnitude
  - Style-of-faulting
  - Depth Distribution
- Rock Ground Motion - Site Response
  - Rock definition: Vs=2000 m/s
- Source - Site Response
  - Source azimuth (for 2-D and 3-D effects)

Adjustments to Rock Ground Motion Models

- Required by Interface with other experts groups
  - SP1 - SP2:
    - Magnitude scale
    - Style-of-faulting
  - SP2 - SP3:
    - Site Condition
      - Vs, Kappa (if correlated to Vs)

Source Characterization

- Earthquake catalog
  - Single earthquake catalog developed for PEGASOS project
- Epistemic Uncertainties
  - Source zones
    - Source zonation approach
    - Spatial smoothing alternatives for activity rate and b-values
    - Local zone boundaries
  - Maximum magnitude
    - Maximum depth of rupture
    - Fault dip
    - Max rupture Length
    - Max magnitude approach

Rock Ground Motion

- Epistemic uncertainties
  - Candidate attenuation relation
  - Magnitude conversion
  - Style-of-faulting scaling
  - Vs30 correction
  - Kappa correction
  - Component conversion

Site Response

- Epistemic Uncertainties
  - Vs profile
  - Non-linear material properties
  - Site response method
  - P-SV effects
  - 2-D and 3-D effects

Combination of Epistemic Uncertainties

- Correlation of epistemic uncertainties is tracked. Examples of correlated uncertainties:
  - Source characterization:
    - b-value with activity rate
  - Rock ground motion
    - Magnitude, Vs, Style-of-faulting with candidate model
    - Kappa correction with Vs

Dominant Epistemic Uncertainties

- Source characterization
  - Maximum magnitude
  - Spatial smoothing
- Rock ground motion
  - Candidate attenuation model
  - Vs, kappa corrections
- Site response
  - Vs profile
  - 2-D effects

Are Results Reasonable?

- Feedback on models and hazard
  - Intended to avoid unintended combinations of parameters that lead to unrealistic results
- In PEGASOS, epistemic uncertainty in the rock ground motion model is the dominant source of uncertainty.
  - Candidate models
  - Vs, kappa corrections

Ground Motion Models

Ambraseys *et al.* (1996)	Europe
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Ground Motion Models

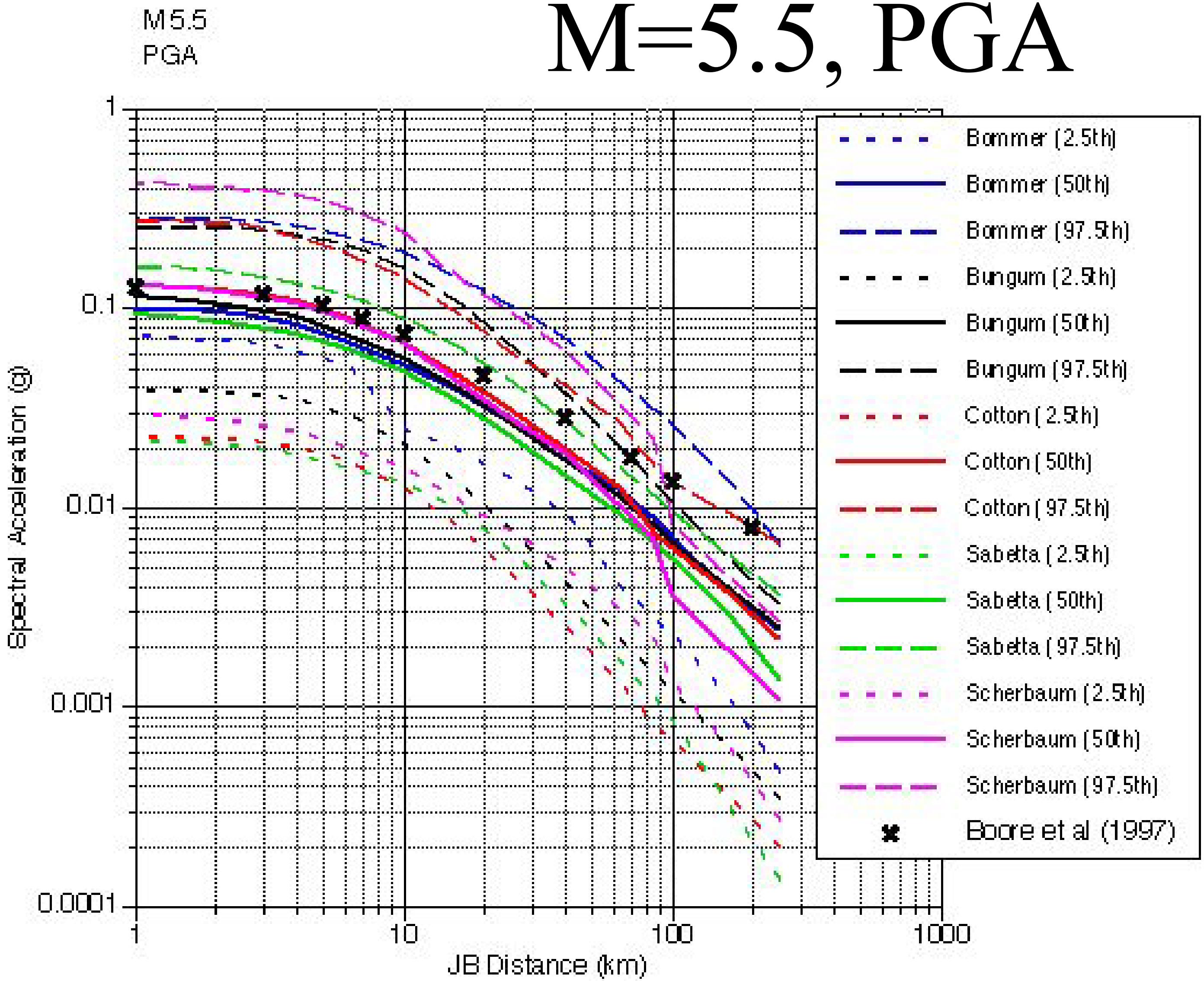
STUDY	Magnitude			Distance[1]			Data	
	Scale	**M_{min}**	**M_{max}**	**Scale**	**R_{min}**	**R_{max}**	**EQs**	**Recs**
Abrahamson & Silva (1997)	M_w	4.4	7.4	R_{rup}	0.1	220	58	655
Ambraseys *et al.* (1996)	M_s	4.0	7.9	R_{jb}	0.0	260	157	422
Ambraseys & Douglas (2000)	M_s	5.8	7.8	R_{jb}	0.0	15	44	186
Atkinson & Boore (1997)	M_w	4.0	7.25	R_{hyp}	10	500	-	-
Berge-Thierry *et al*. (2000)	M_s	4.5	7.3	R_{hyp}	7.0	100	139	483
Boore *et al*. (1997)	M_w	5.3	7.7	R_{jb}	0.0	109	14	112
Campbell, Bozorgnia (2002)	M_w	4.7	7.7	R_{seis}	2.0	60	36	443
Lussou *et al*. (2001)	M_{JMA}	3.7	6.3	R_{hyp}	4.0	600	102	3,011
Sabetta & Pugliese (1996)[2]	M_s,M_L	4.6	6.8	R_{jb},R_{epi}	1.5	180	17	95
Somerville *et al*. (2001)	M_w	5.5	7.5	R_{jb}	0.0	500	-	-
Spudich *et al*. (1999)	M_w	5.1	7.2	R_{jb}	0.0	99.4	38	141
Toro *et al*. (1997)	M_w	5.0	8.0	R_{jb}	1.0	1000	-	-
Bay (2002)	M_w	5.0	7.5	R_{jb}	1.0	500	-	-
Rietbrock (2002)	M_w	5.0	7.5	R_{jb}	1.0	500	-	-

1. Distances defined as in Abrahamson & Shedlock (1997).

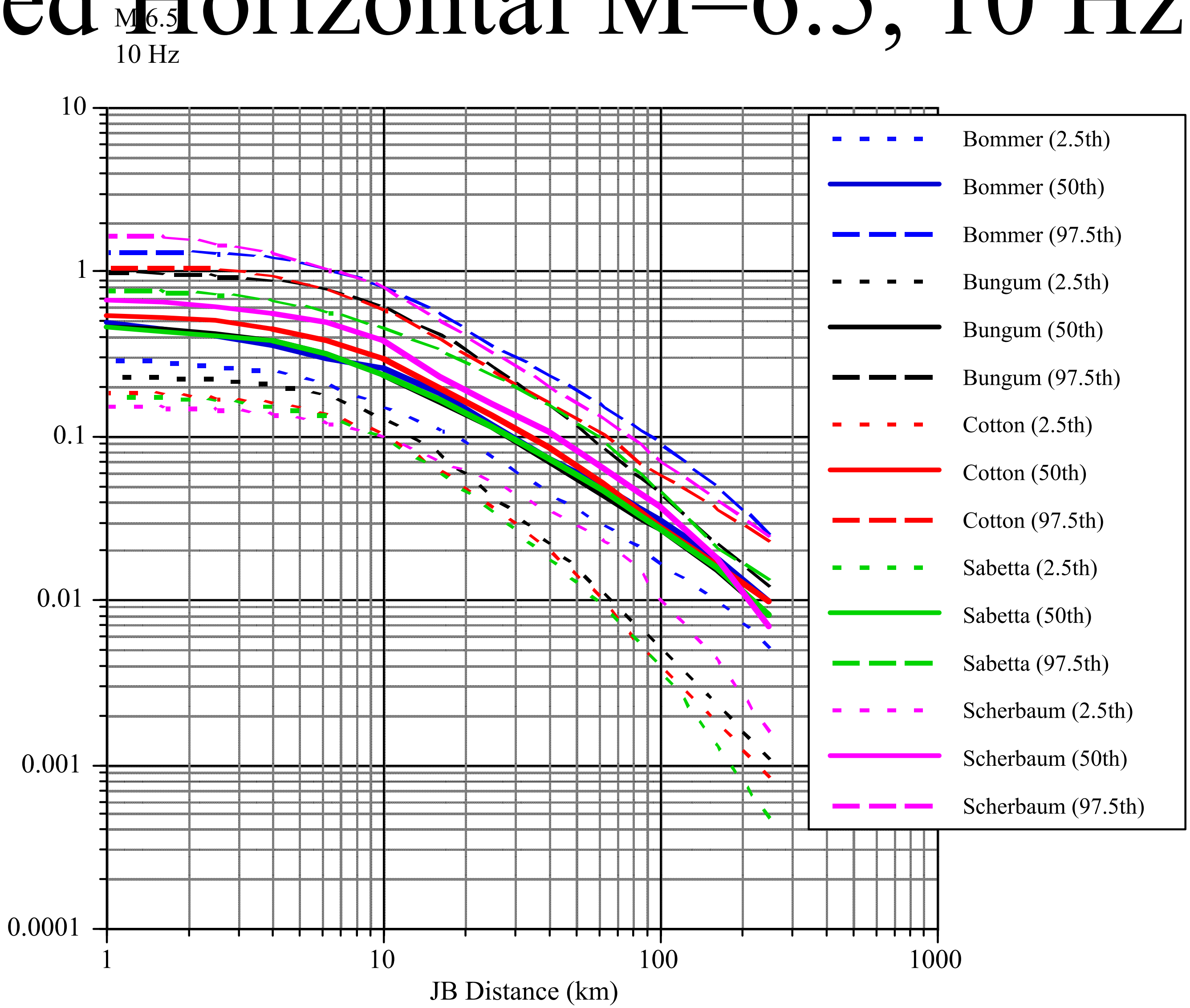
Ground Motion Models Large Range of Vs

Study	Site Class	$V_{s,30}$ (m/s)		
		Lower (w=0.2)	**Central (w=0.6)**	**Upper (w=0.2)**
Abrahamson & Silva (1997)	Rock	450	600	900
Ambraseys *et al.* (1996)	Class R (rock)	550	800	1,200
Ambraseys, Douglas (2000)	Class R (rock)	450	800	1,100
Atkinson & Boore (1997)	-	-	2,800*	-
Berge-Thierry *et al*. (2000)	Rock	550	800	1,200
Boore *et al*. (1997)	Class A (rock)	550	620	750
Campbell, Bozorgnia (2002)	Firm Rock	450	600	900
Lussou *et al*. (2001)	Class B	350	500	900
Sabetta & Pugliese (1996)	Stiff	700	1,000*	1,300
Somerville *et al*. (2001)	-	-	2,800	-
Spudich *et al*. (1999)	Rock	550	800	1,100
Toro *et al*. (1997)	-	-	2,800*	-

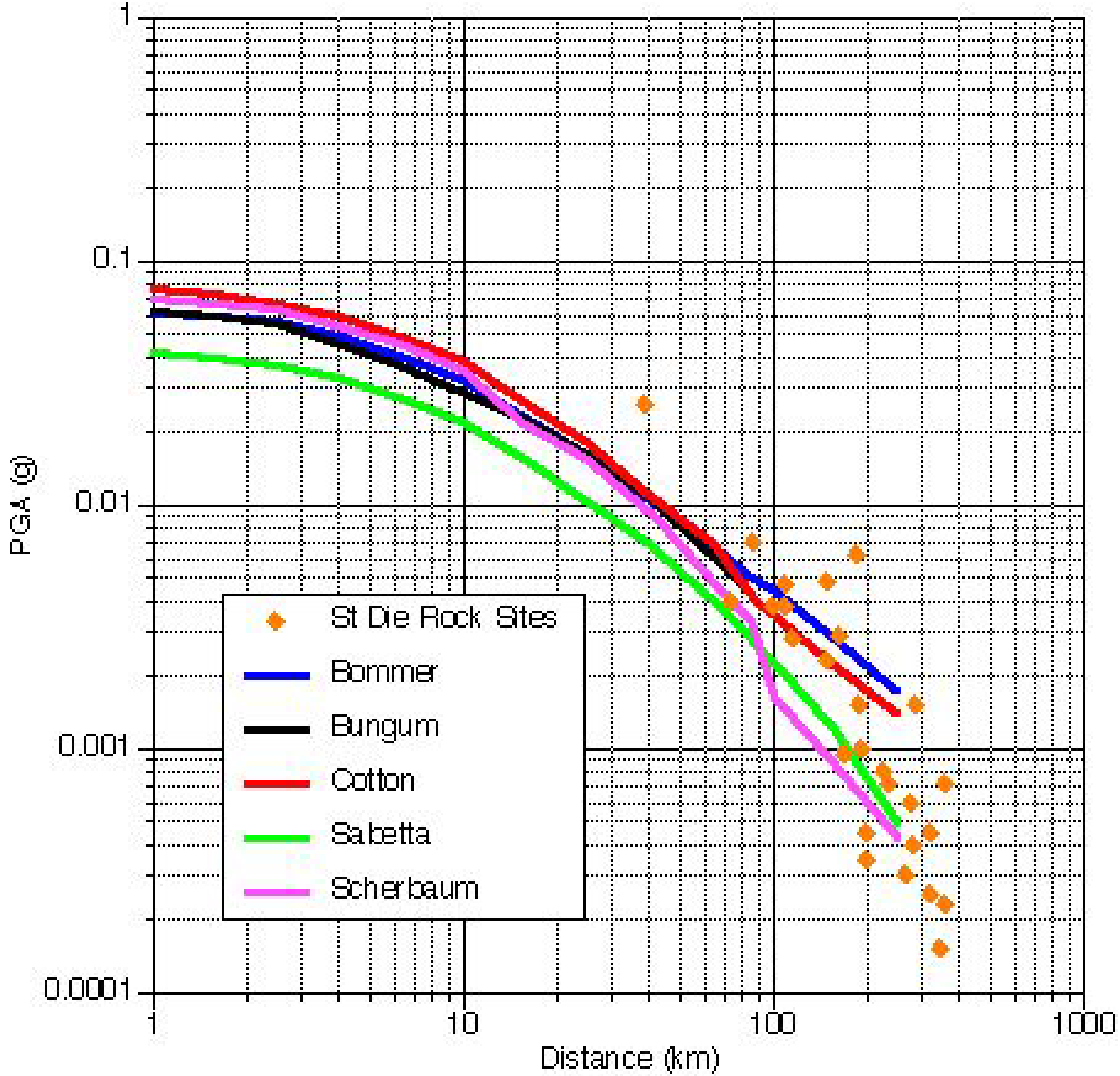
Median Horizontal M=5.5, PGA



Med Horizontal M=6.5, 10 Hz



St Die Earthquake vs Med GM



How Well Do We Know the Ground Motion Model?

- Preliminary results from recent work in CA indicate to up to a factor of 2 changes in the median PGA for large magnitudes (M>7.5), and up to factor of 1.5 for buried moderate magnitudes (M6.3-6.8)
- Vs and kappa values are still not available at most strong motion sites
  - Leads to epistemic uncertainty in the rock ground motion models

Summary

- PEGASOS project captures the current state of knowledge of seismic hazards in Switzerland
- Dominant epistemic uncertainty in ground motion is typical in PSHA
- New standards for a SSHAC level 4 study were established in PEGSOS
  - Inclusion of site response
  - Inclusion of maximum ground motions
  - Development of the Hazard Input Document, providing clear documentation of the implementation of the expert models