An Introduction to the LA Seismology Team
&
Seismic Hazard Briefing

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Outline

– Introduction to the team

– The Method of Seismic Hazard Analysis:
Deterministic, Probabilistic, and Sources of Uncertainty

– PSHA: Inputs and Outputs

– Seismic Hazard in Australia and New Zealand

– Looking Forward

Meet our team

Dr. Paul Somerville
Principal Seismologist

Dr. C.B. Crouse
Principal Engineer

Dr. Hong Kie Thio
Principal Seismologist

Dr. Andreas Skarlatoudis
Principal Seismologist

Dr. Jeff Bayless
Senior Engineering Seismologist

Mark Dober
Senior Seismologist

Dr. Nesrin Yenihayat
Engineering Seismologist

Business Lines We Serve

Water
dams, canals, and related structures

Oil & Gas
onshore and offshore

Buildings + Places
including tall & base isolated

AECOM Seismology Tsunami

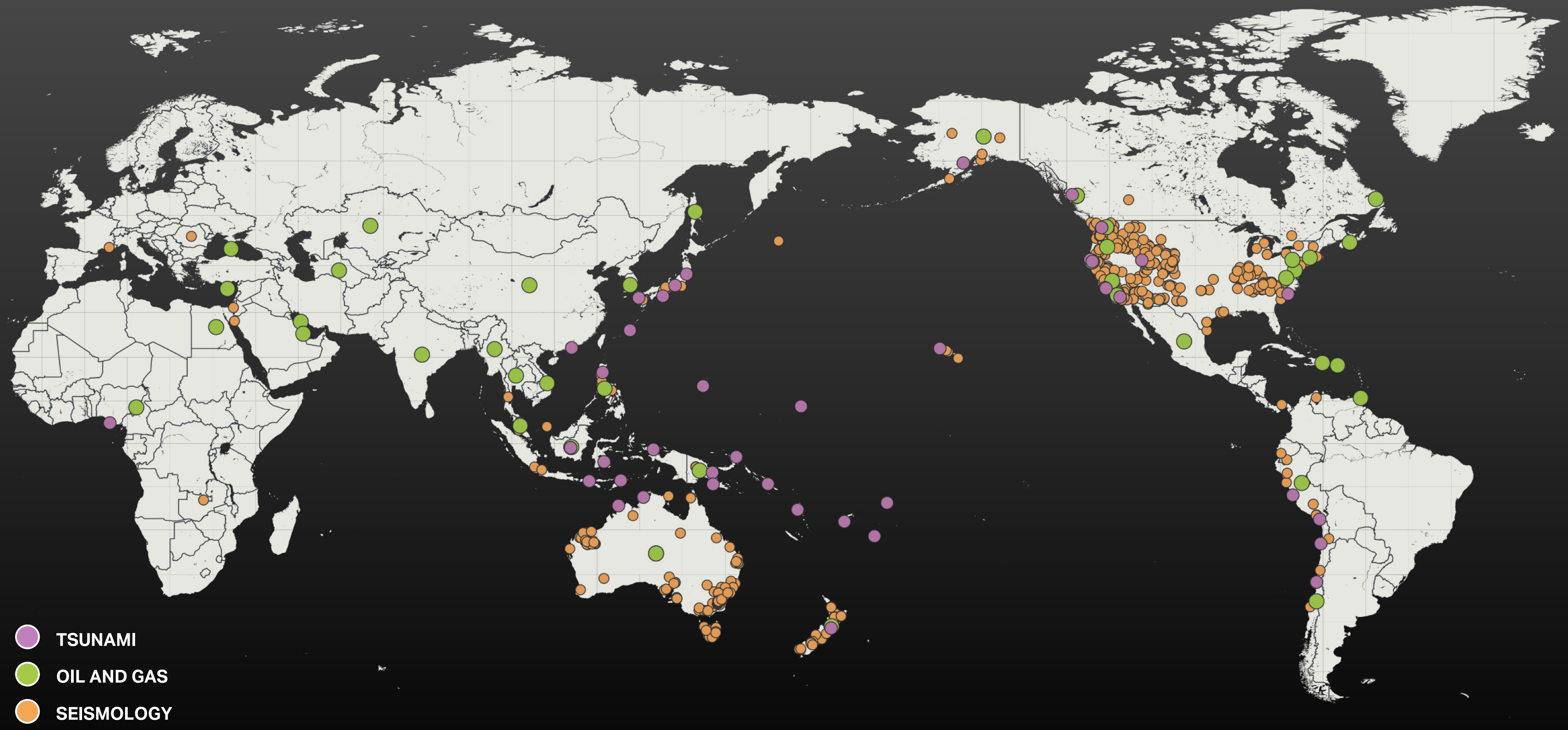
Power & Industrial
nuclear plants

National Government
R&D; FEMA

Transportation
bridges and buildings

Recent Project Locations

We can provide seismic and tsunami hazard information for design at any location on earth



AECOM Seismology

Our group was established in 1980 as an R&D laboratory for transferring advanced theoretical and computational seismology from Caltech into practice in seismic hazard analysis.

Since that time, we have been been applying advanced methods for estimating earthquake (and tsunami) design loads for the design of critical facilities, such as hospitals, bridges, dams and nuclear power plants.

– Probabilistic & Deterministic Seismic and Tsunami Hazard Analysis

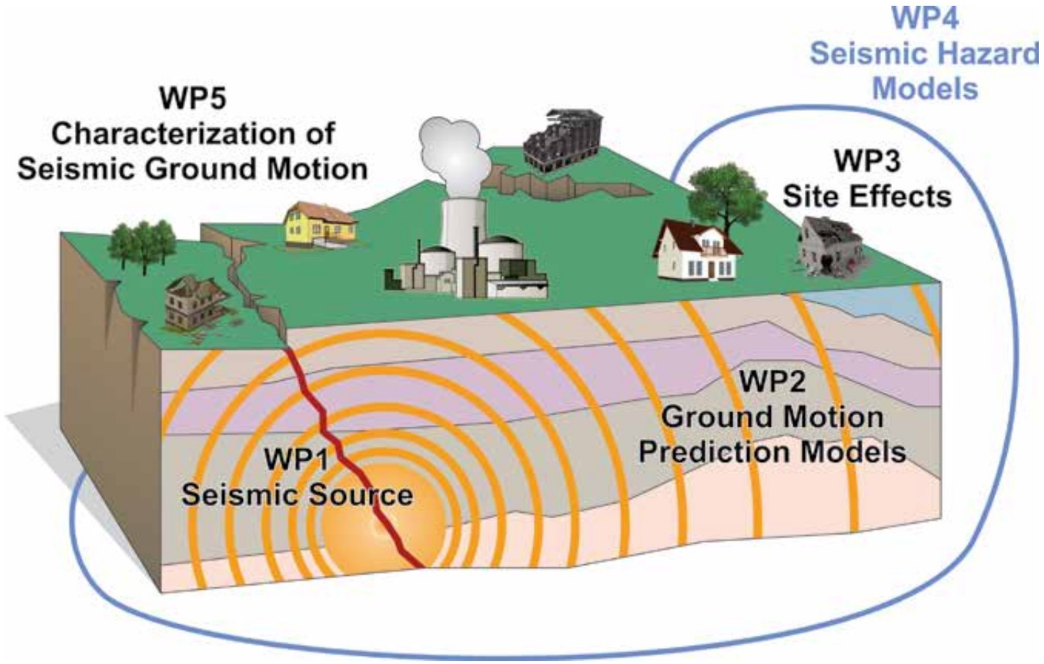
– Fault Displacement Hazard

– Tsunami Wave Heights and Inundation for Design

– Forensic Analyses Following Earthquakes

– R&D in Earthquake and Tsunami Hazards

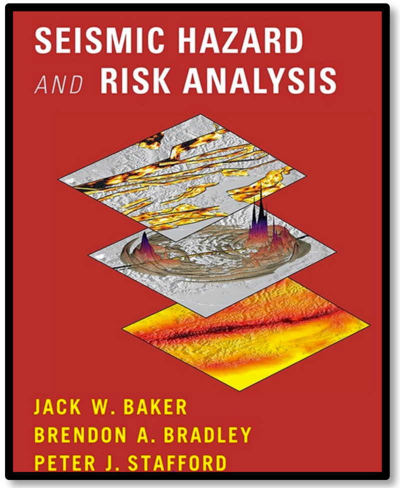
– Participation in building code committees



The PSHA Method

Acknowledgments

- Cornell, C.A. (1968). Engineering seismic risk analysis, Bull. Seism. Soc. Am., 58, 1583-1606.
- Baker, J. W., Bradley, B. A., and Stafford, P. J. (2021).



- Paul Somerville – slides
- Norman Abrahamson – lecture notes

Terminology

PSHA: Probabilistic Seismic Hazard Analysis

DSHA: Deterministic Seismic Hazard Analysis

Seismic Hazard: the characterization of natural phenomena resulting from earthquakes. The phenomenon can be **ground shaking**, tsunami, landslide, or liquefaction

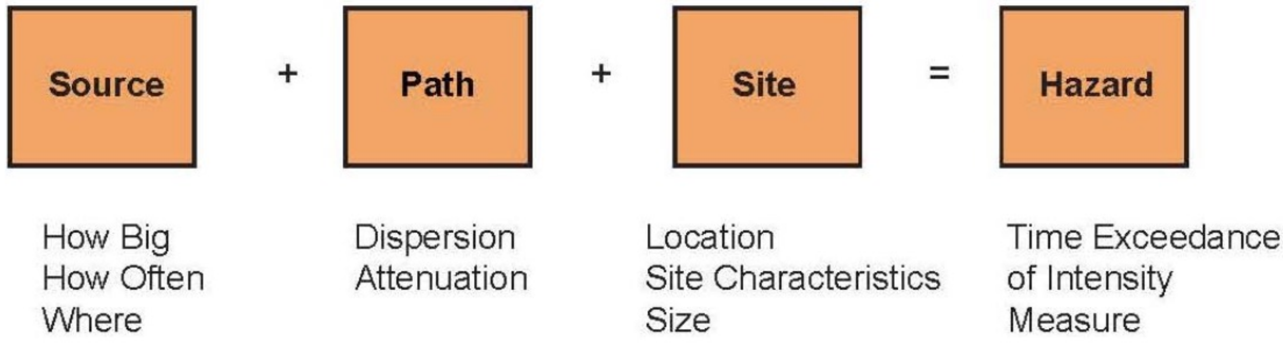
Probabilistic: (Cambridge dictionary) based on or relating to how likely it is that something will happen.

Deterministic: (Cambridge dictionary) believing that everything that happens must happen as it does and could not have happened any other way.

Probabilistic Seismic Hazard Analysis

The mathematical approach for determining the annual rates (or probabilities) of exceeding various levels of ground motion estimated over a specified time period (Cornell 1968).

PSHA considers and incorporates uncertainties in earthquake source, path, and site conditions.



Deterministic Seismic Hazard Analysis

Scenario-based evaluations based on simple rules to define earthquake scenarios (ignoring their likelihood of occurrence) and resulting ground motions.

Fundamentally limited, because it is not a "worst case" approach and therefore requires making decisions of judgment, and the results can be very sensitive to these decisions

Risk: the characterization of the consequences of the hazard, such as structural failures, fatalities, or economic costs.

Risk requires a hazard analysis, as well as an understanding of *exposure* (the presence of assets such as structures and people) and *vulnerability* (the susceptibility of exposed assets to damage from the hazard).

***This presentation focuses mostly on hazard**
(with thoughts on risk-based methods moving forward)

Overview of the PSHA Method

Seismic Source Modeling

- For a given region, model all potential earthquakes of all potential magnitudes on all potential sources – both faults and distributed sources
- Model the frequency of occurrence of these potential earthquakes

Ground Motion Modeling

- For *each earthquake*, estimate the ground motions (and their variability) at the site of interest.

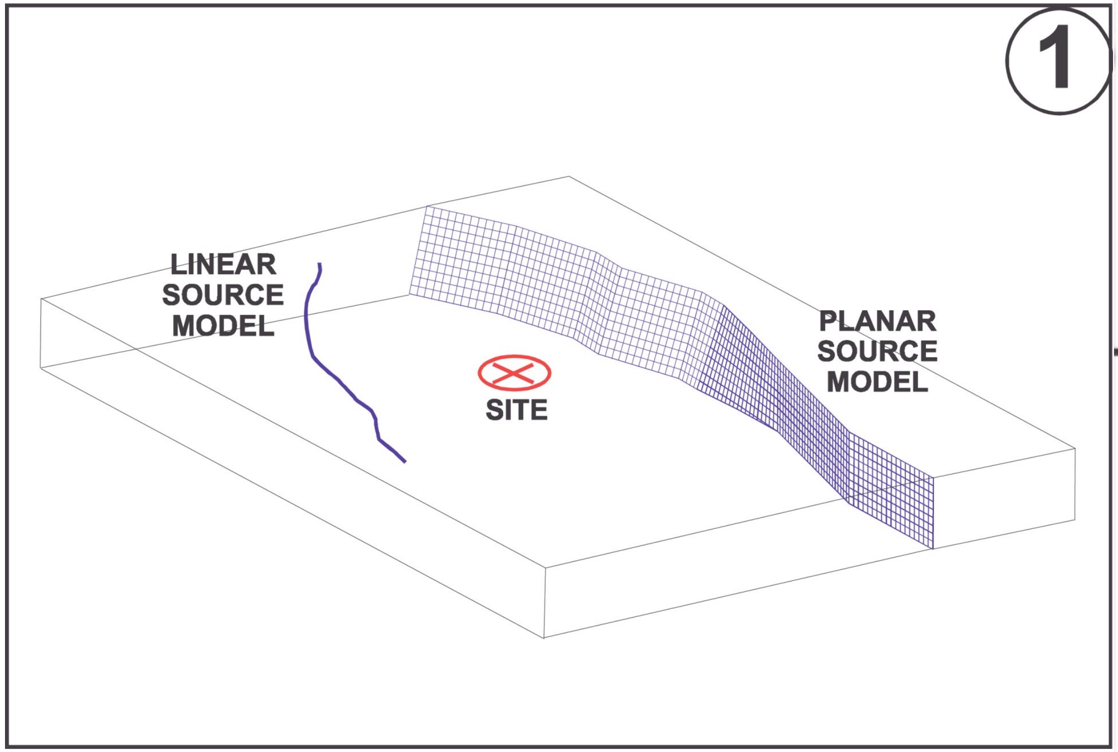
PSHA Calculation

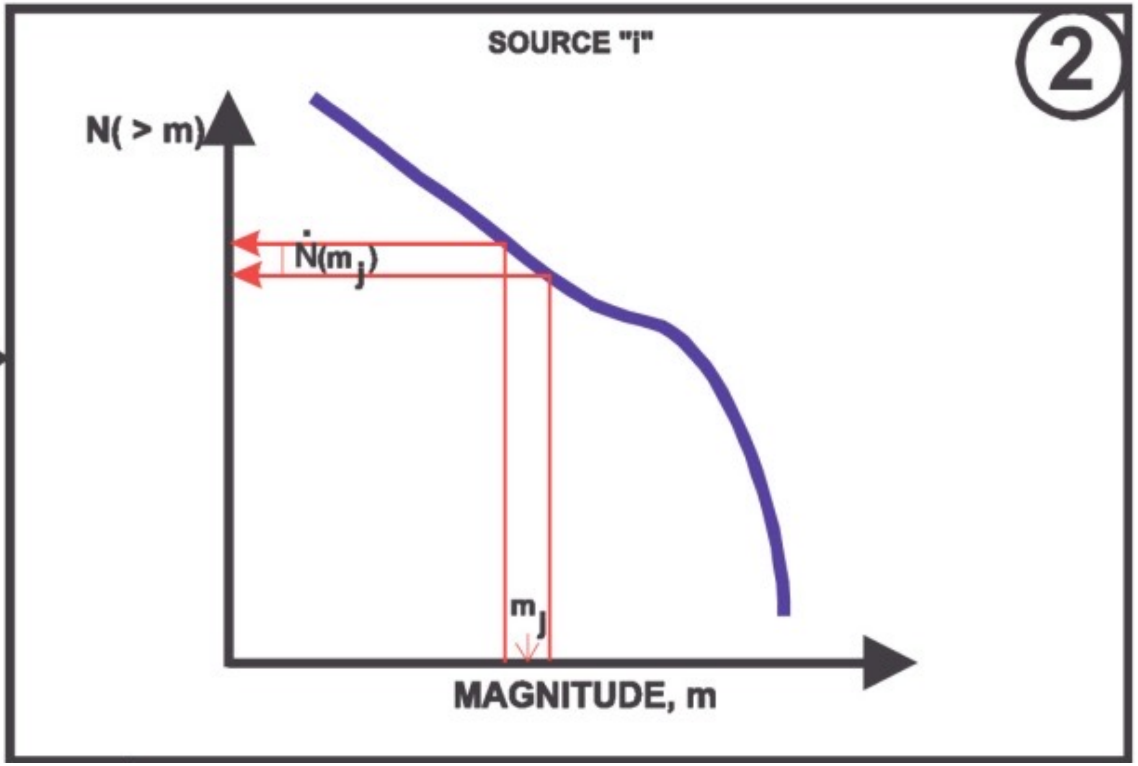
- Tally the frequency with which the ground motion level, e.g. peak ground acceleration (PGA), exceeds some threshold, e.g. 0.1g
  - Repeat for all ground motion levels (e.g. 0.001 to 5g) to get a PGA hazard curve: annual exceedance probability (AEP) vs. PGA
  - Repeat for all ground motion parameters, e.g. PGA plus spectral acceleration for a full range of ground motion periods.

Overview of the PSHA Method

Seismic Source Modeling

- For a given region, model all potential earthquakes of all potential magnitudes on all potential sources – both faults and distributed sources
- Model the frequency of occurrence of these potential earthquakes

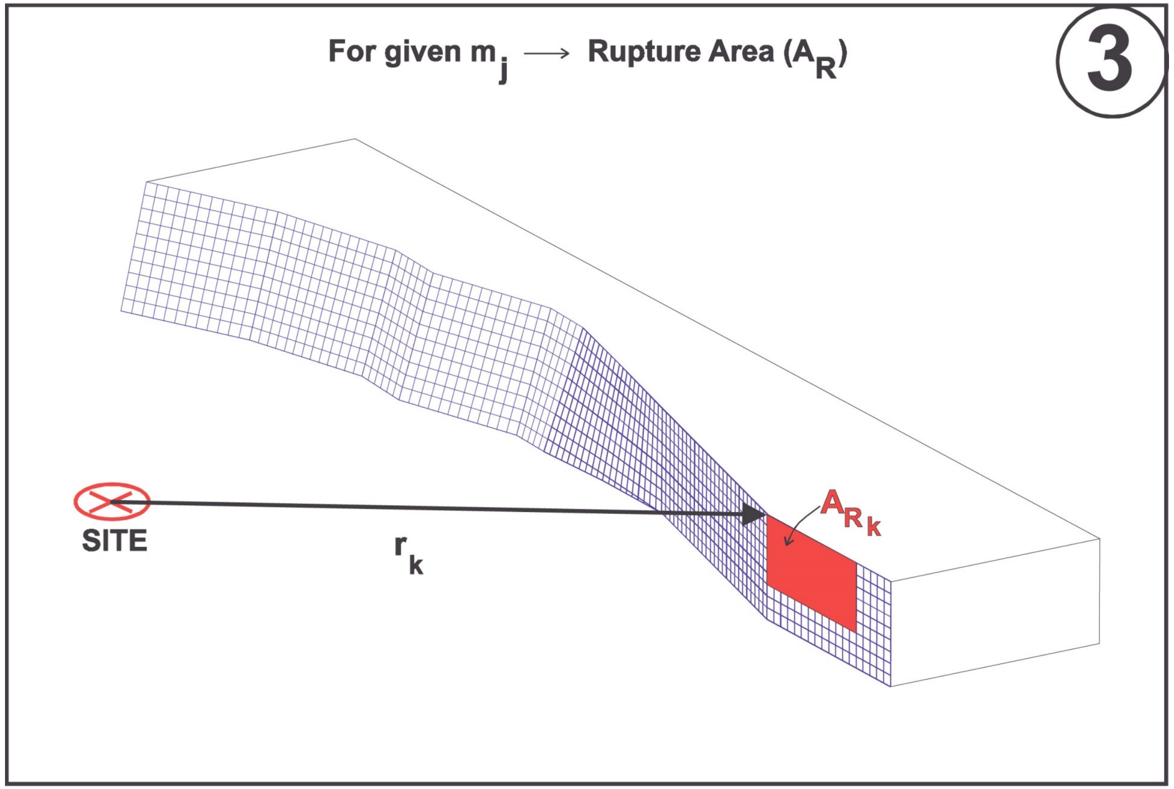


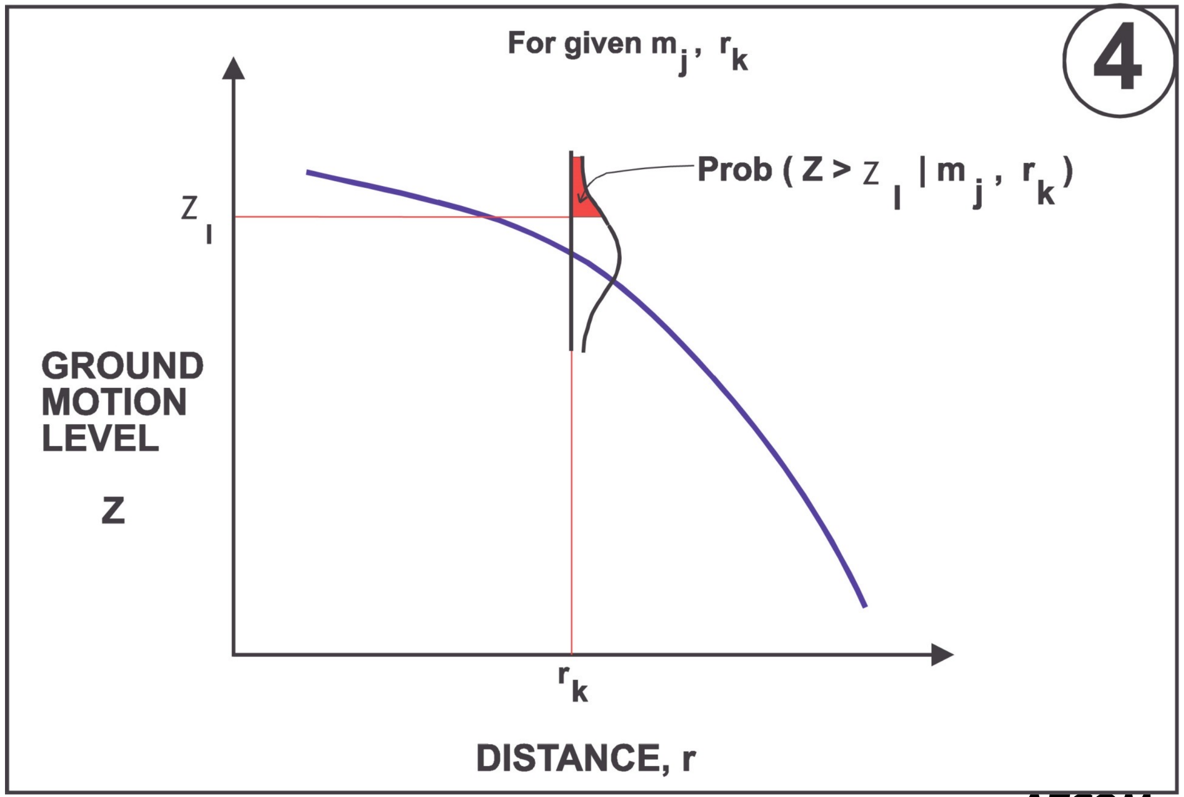


Overview of the PSHA Method

Ground Motion Modeling

– For *each earthquake*, estimate the ground motions (and their variability) at the site of interest.





Overview of the PSHA Method

PSHA Calculation

– Tally the frequency with which the ground motion intensity measure (IM) exceeds some threshold

$$\lambda(IM > x) = \sum_{i=1}^{n_{sources}} \lambda(M > m_{min}) \int_{m_{min}}^{m_{max}} \int_{0}^{r_{max}} \int_{H} P(IM > x|m,r,h) f_M(m,r) f_R(r) f_{HYP}(h)\, dm\, dr\, dh$$

- $\lambda(IM > x)$ is the annual frequency in which IM exceeds the value x.
- $n_{sources}$ is the number of sources considered.
- $\lambda(M > m_{min})$ is the rate of occurrence of earthquakes greater than m_{min} from the ith source.
- $P(IM > x|m,r,h)$ is the conditional probability that IM exceeds x given magnitude m, distance r, and hypocenter h. This probability comes from the GMM and contains an implicit integration over the GMM variability.
- $f_M(m)$, $f_R(r)$, and $f_{HYP}(h)$ are probability density functions for magnitude m, distance r, and hypocenter location h.

Overview of the PSHA Method

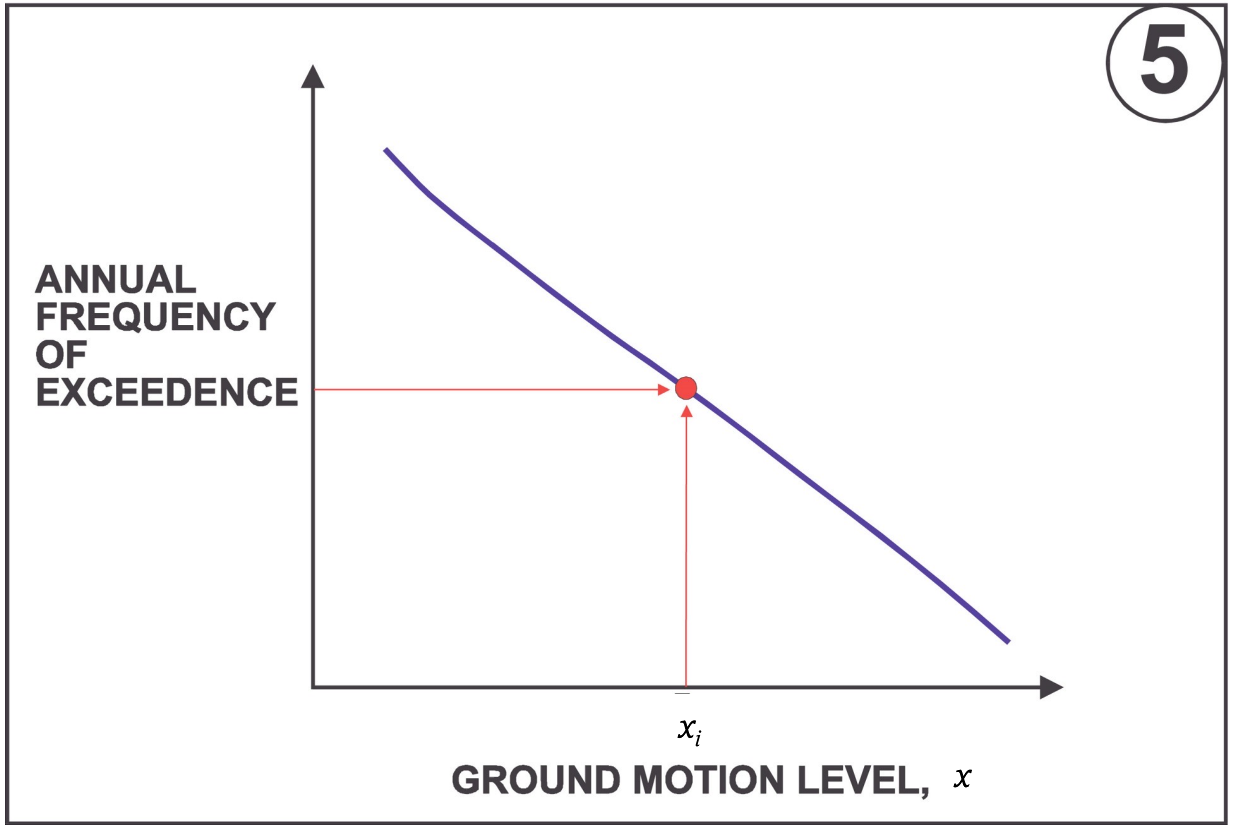
PSHA Calculation

– Tally the frequency with which the ground motion intensity measure (IM) exceeds some threshold

$$\lambda(IM > x) = \sum_{i=1}^{n_{sources}} \lambda(M > m_{min}) \int_{m_{min}}^{m_{max}} \int_{0}^{r_{max}} \int_{H} P(IM > x|m,r,h) f_M(m,r) f_R(r) f_{HYP}(h)\, dm\, dr\, dh$$

This process gets you one point on a hazard curve.

Repeat for multiple ground motion levels and IMs



PSHA Uncertainties

Rather than ignoring uncertainties (DSHA), the PSHA approach incorporates them.
This adds complexity to the procedure, but the resulting calculations are much more defensible for use in engineering decision-making for reducing risk.

Epistemic Uncertainty (from the Greek episteme, “relating to knowledge”)

Uncertainty in the true state of nature.
Alternative models do not coexist, which one is correct?
Treat outside the hazard integral using logic tree branches with weights.
Potentially reducible as we gain more knowledge/data

Examples:

- Maximum magnitude of earthquakes on a fault
- Slip rate on a fault
- Dip angle of a fault

PSHA Uncertainties

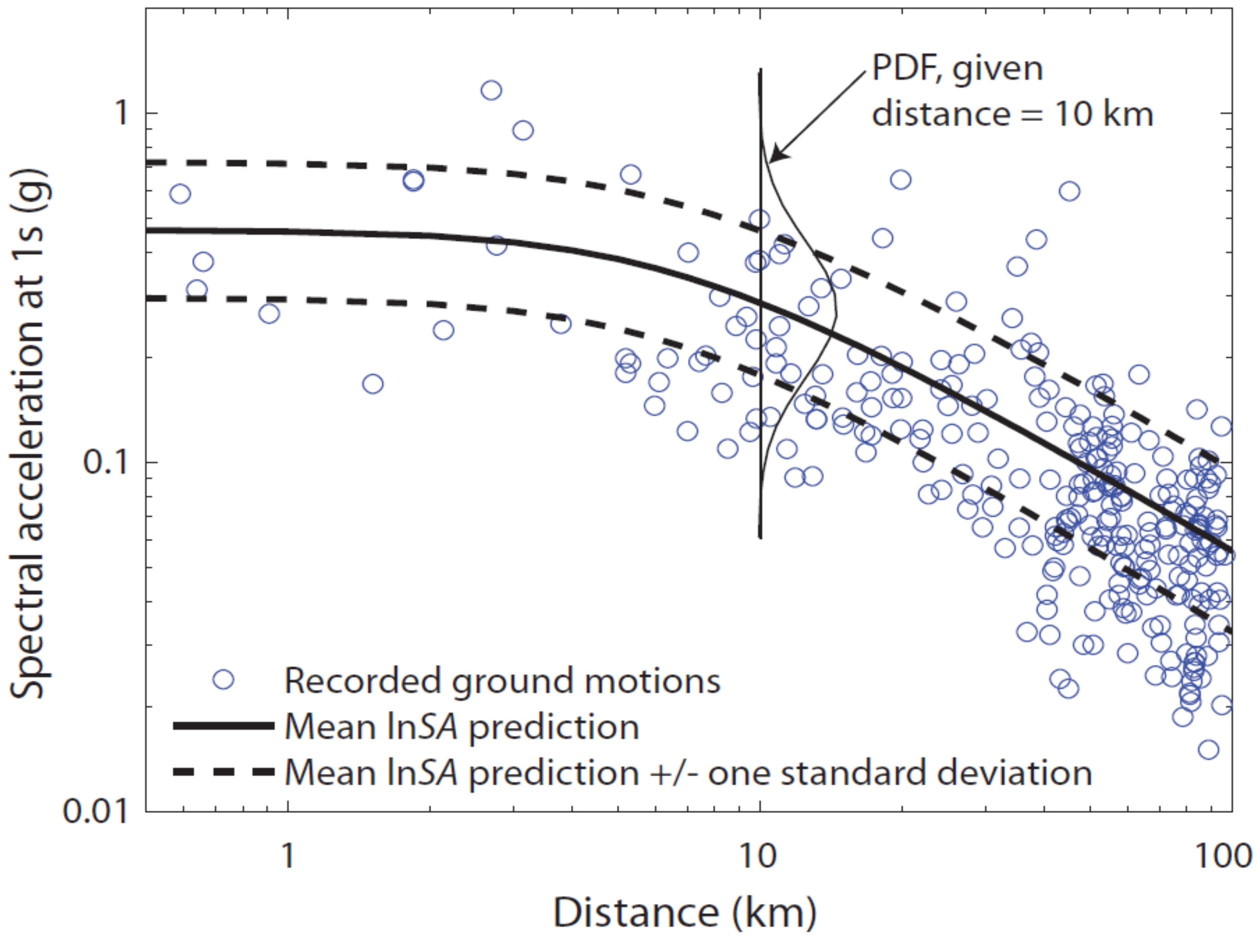
Aleatory Variability
(from the Latin alea, “game of dice”)

Random unexplainable variation.

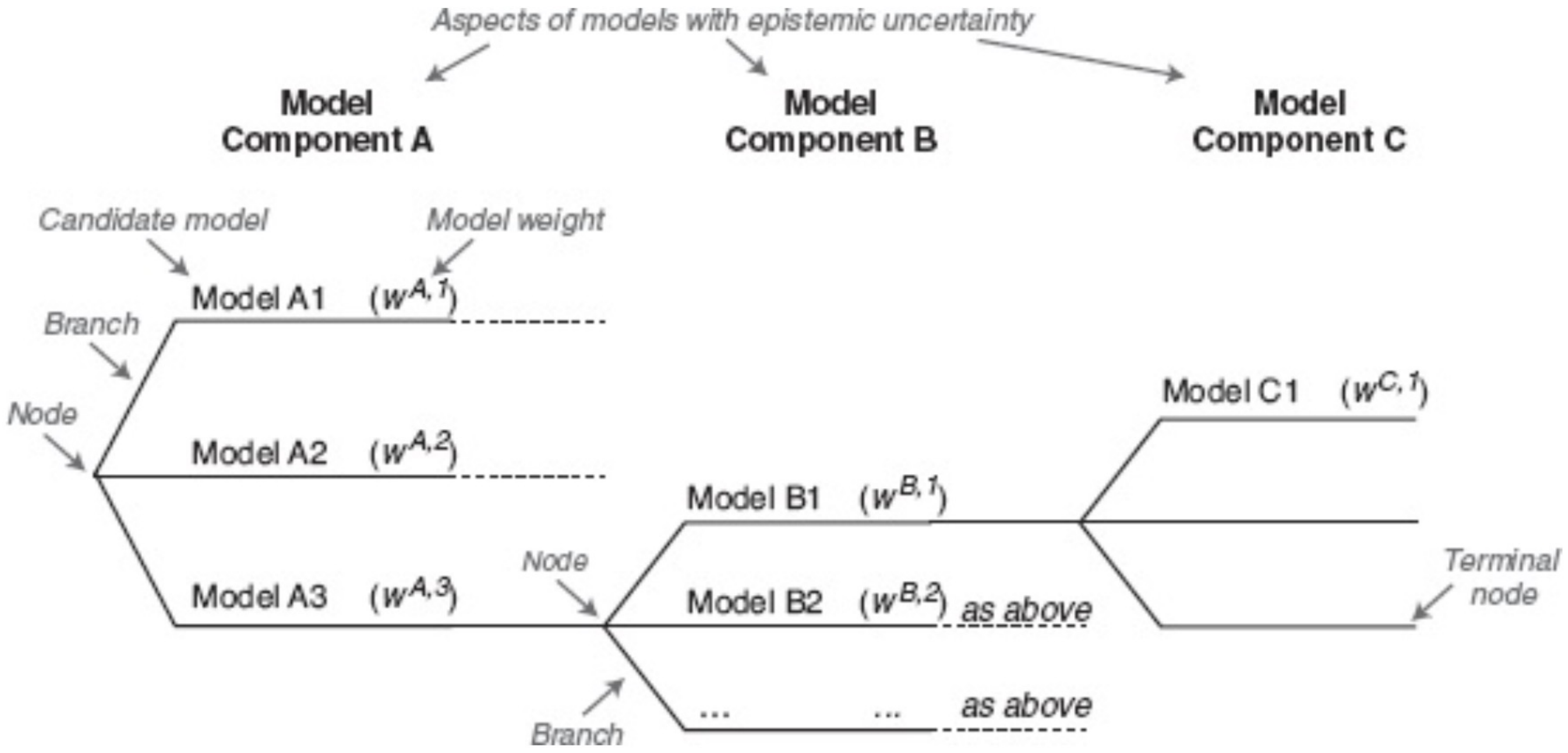
Alternatives coexist.

Treat within the hazard equation using integrals e.g. using lognormal distribution of ground motion levels in a ground motion model

Baker, J. W., Bradley, B. A., and Stafford, P. J. (2021).



Logic Trees Model Epistemic Uncertainty

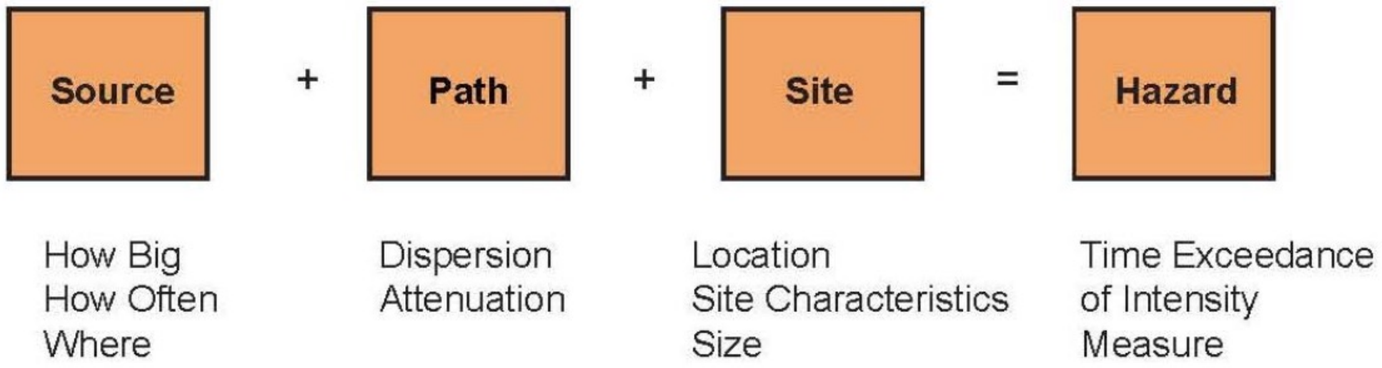


Baker, J. W., Bradley, B. A., and Stafford, P. J. (2021).

Logic Trees Model Epistemic Uncertainty

PSHA: Inputs/Outputs

Summary of PSHA Inputs



Earthquake Forecast (Source)

Fault models and Distributed earthquake source models, include or rely on:

fault geometry models, maximum magnitude models, rupture area models, magnitude-frequency distributions, geological data, recurrence models, slip rates, paleoseismology, etc.

Ground Motion Models (Source + Path + Site)

Selection and weighting of alternative GMMs.
Most GMM parameters are computed within the PSHA program (magnitude, distance, etc).
Input Parameters describing the site: Vs30, Z1.0, Z2.5, usually measured using MASW (multi-channel analysis of surface waves).

Summary of PSHA Inputs

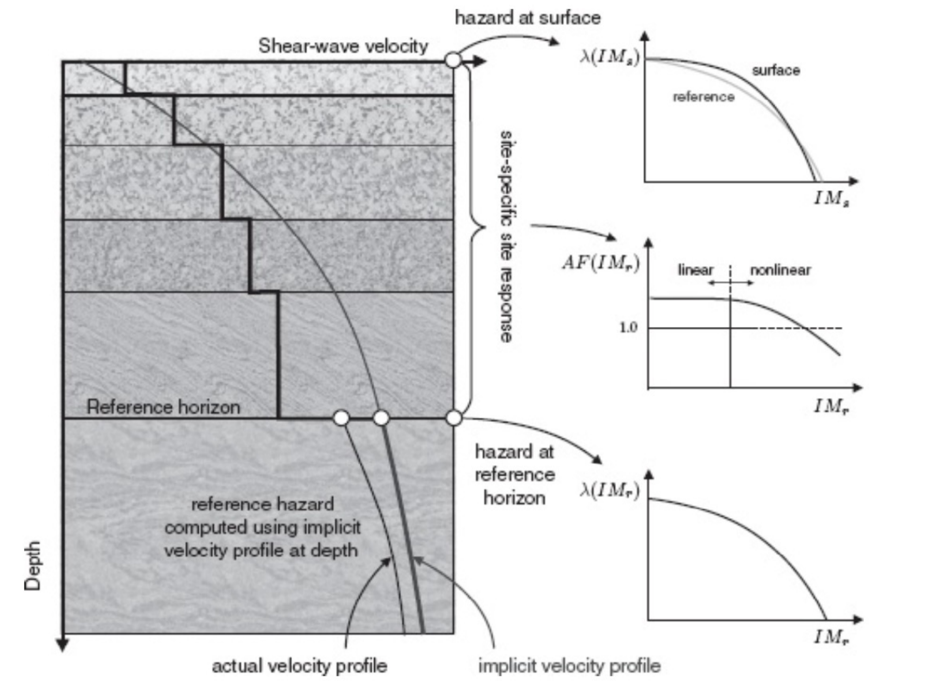
Source + **Path** + **Site** = **Hazard**

Source	Path	Site	Hazard
How Big How Often Where	Dispersion Attenuation	Location Site Characteristics Size	Time Exceedance of Intensity Measure

Site Response (Site)

Nonlinear response of the foundation and overlying soils. Can be 1D (vertical propagation of waves through a horizontally layered medium) or 2D/3D. Requires site-specific soil properties like shear modulus and density.

Baker, J. W., Bradley, B. A., and Stafford, P. J. (2021).

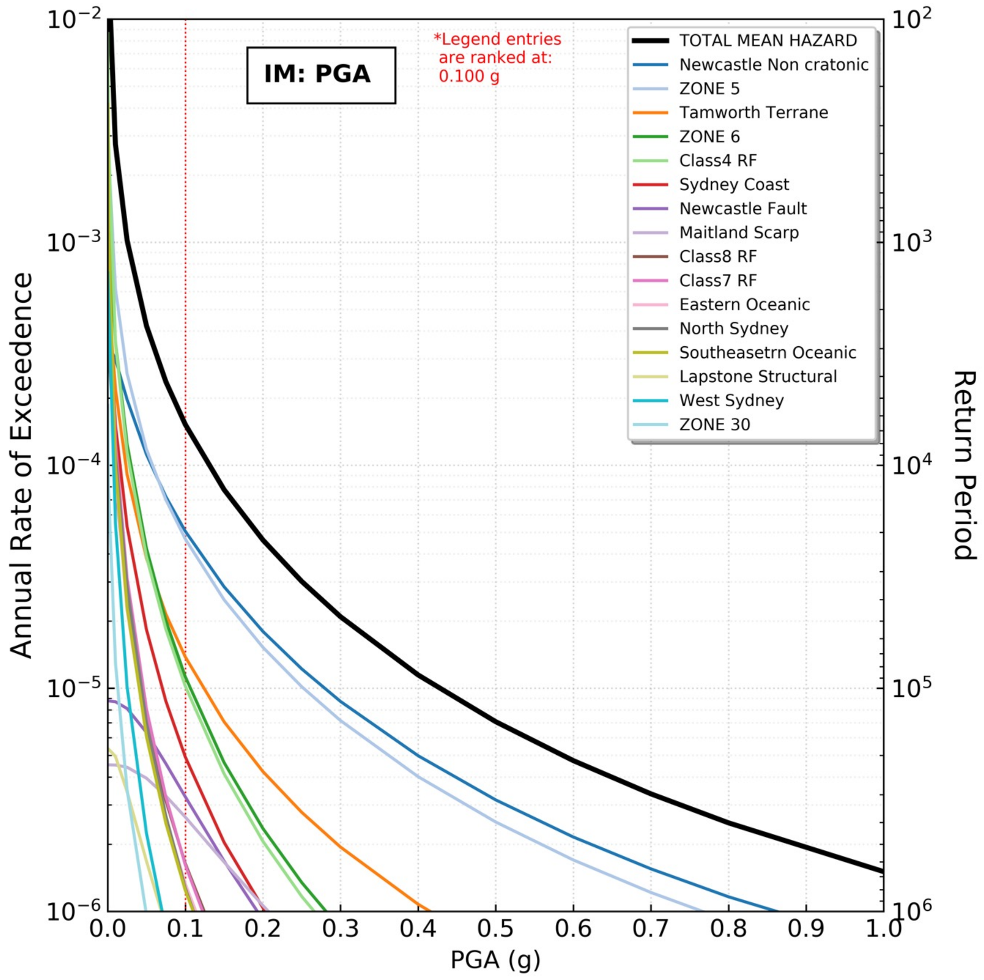


Other Hazard calculation inputs

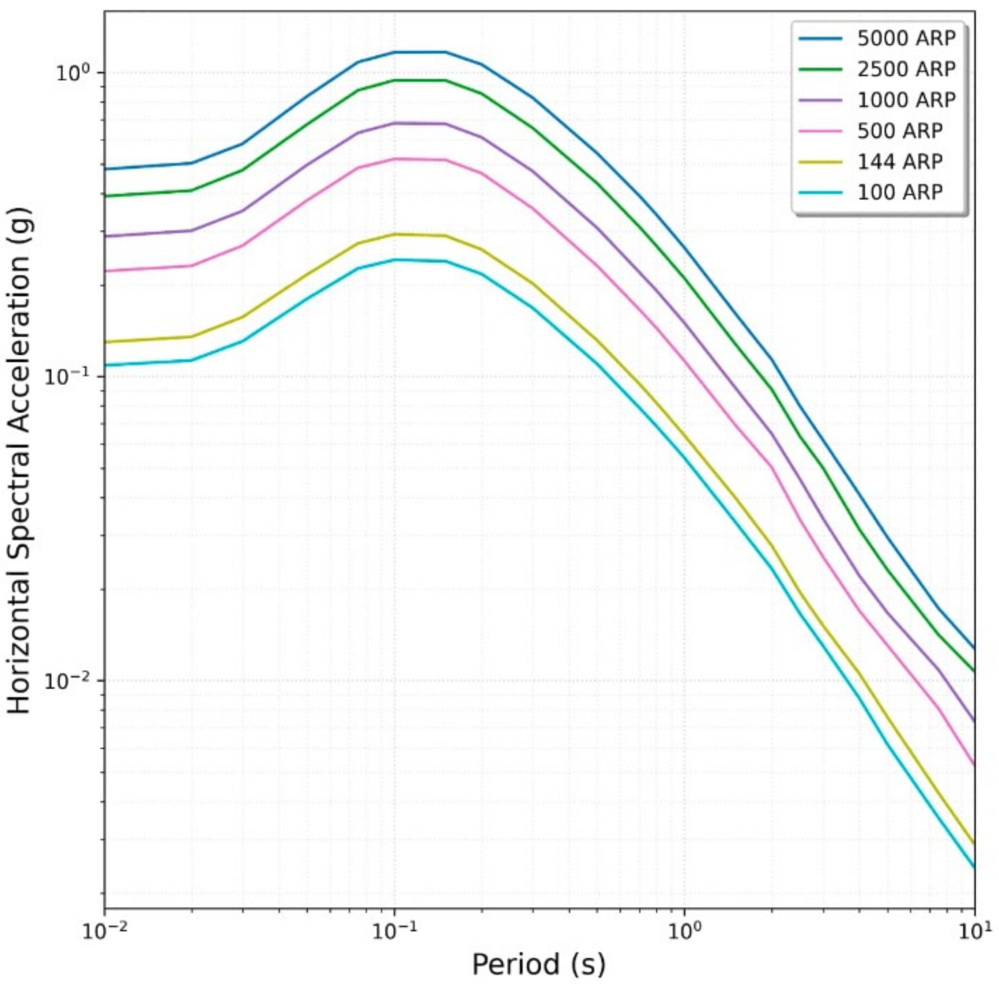
Minimum magnitude, standard deviation truncation

PSHA Outputs

Hazard Curves

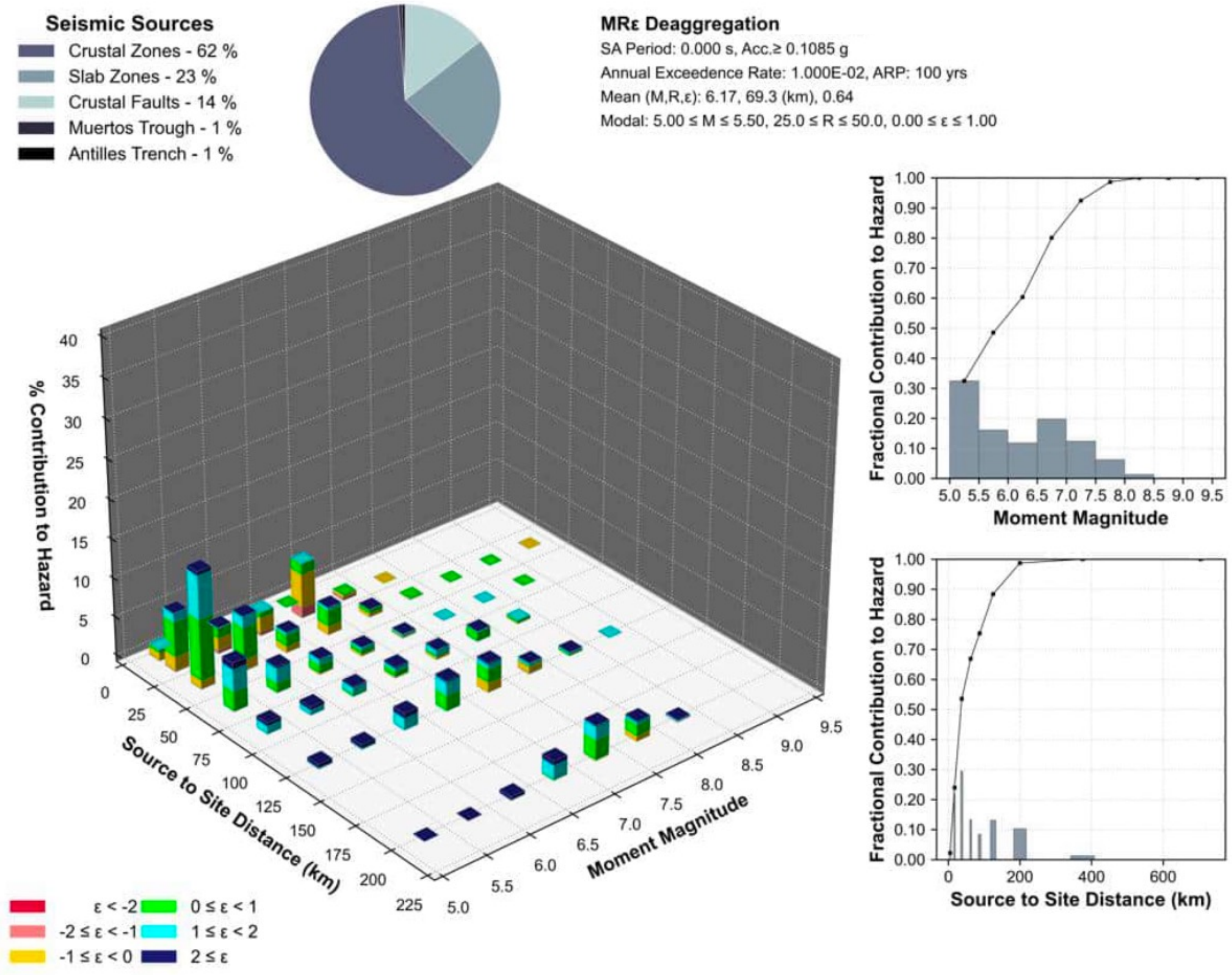


Uniform Hazard Spectra (UHS)



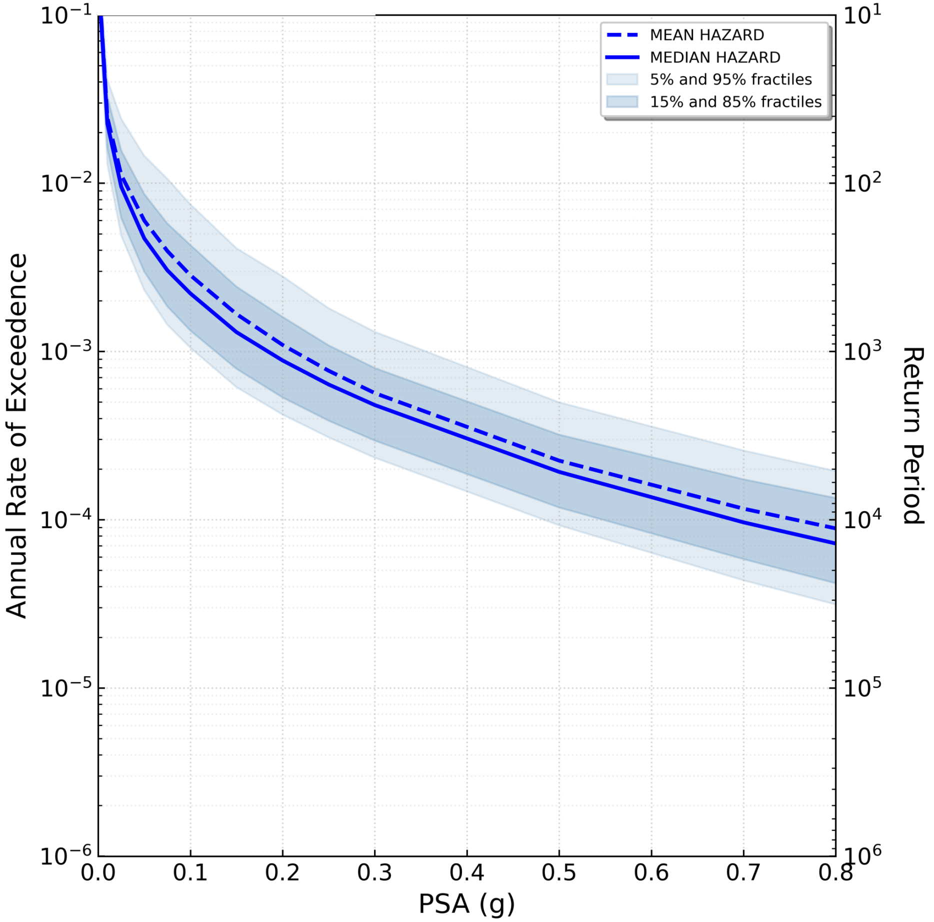
PSHA Outputs

Deaggregation

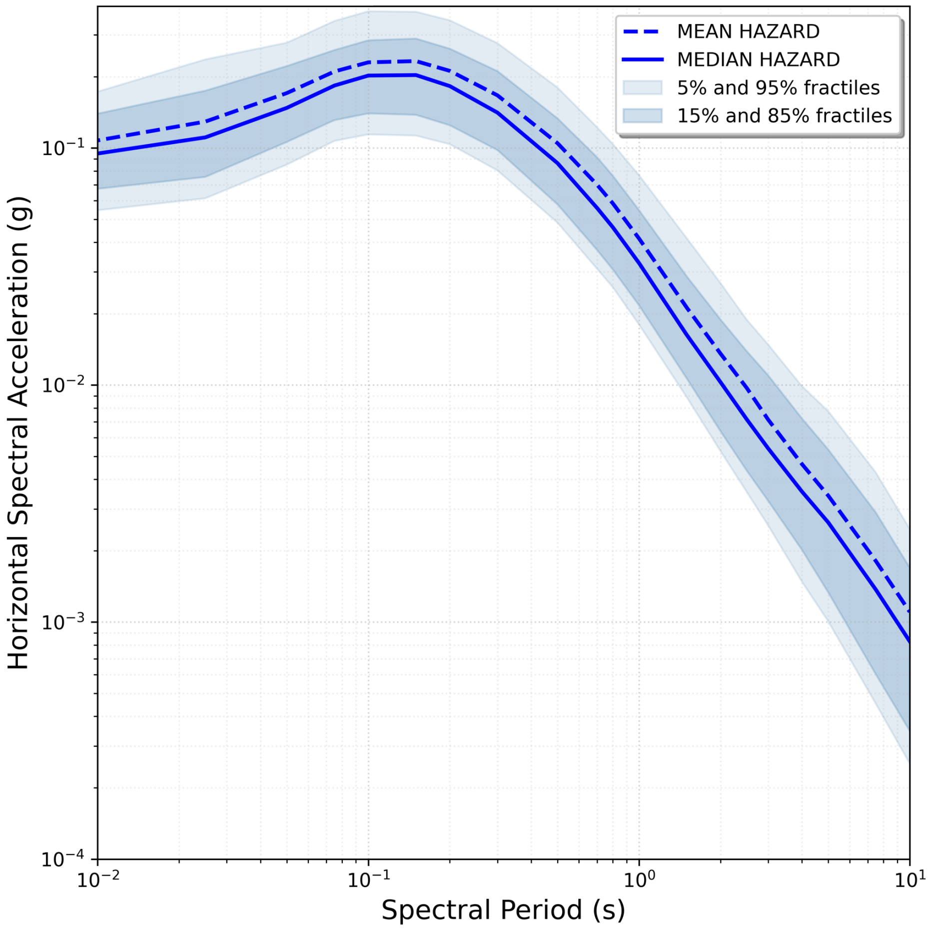


PSHA Outputs

Fractiles of Curves (Epistemic Uncertainty)



Fractiles of UHS

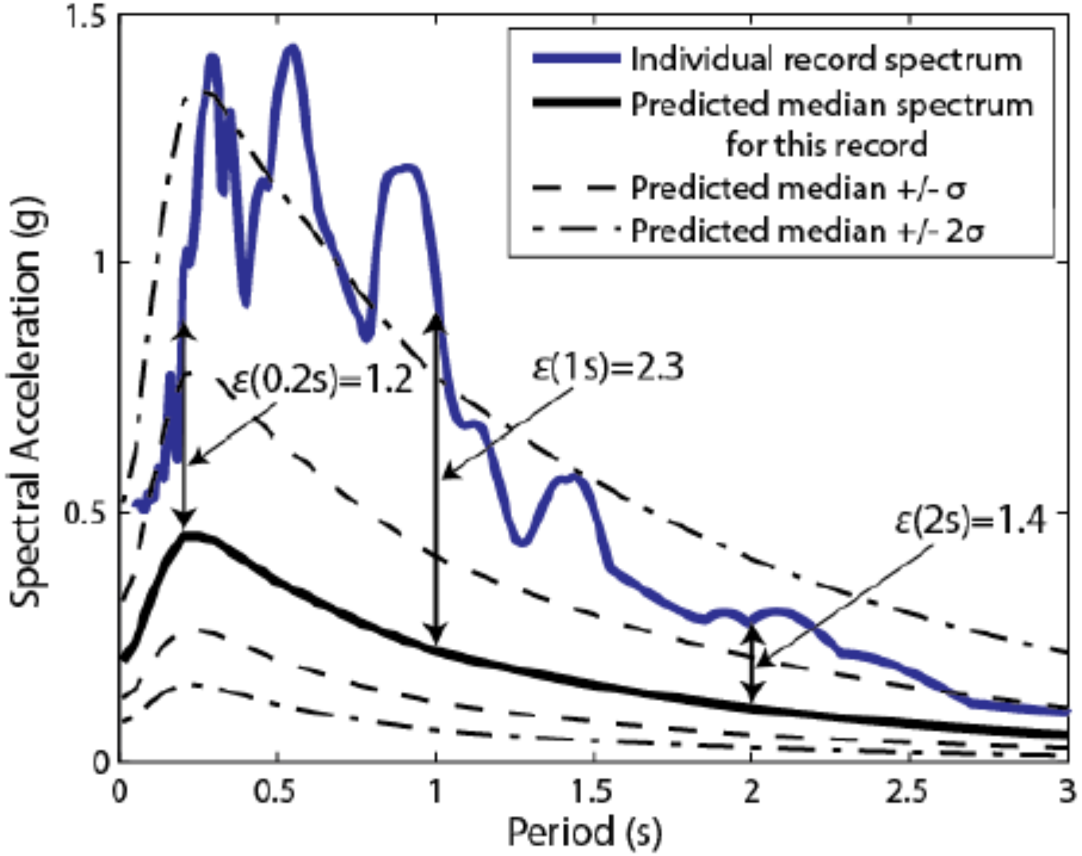


PSHA Outputs

Conditional Mean Spectra

- The uniform hazard spectrum (UHS) obtained from a probabilistic seismic hazard analysis contains contributions (exceedance rates) from many earthquake scenarios.
- But the structure is only exposed to one earthquake at a time
- The UHS is unrealistically broadband (large at all response spectral periods) because real earthquake spectra have peaks (epsilons) and troughs and are not large at all periods.

Baker (2010)



PSHA Outputs

Conditional Mean Spectra

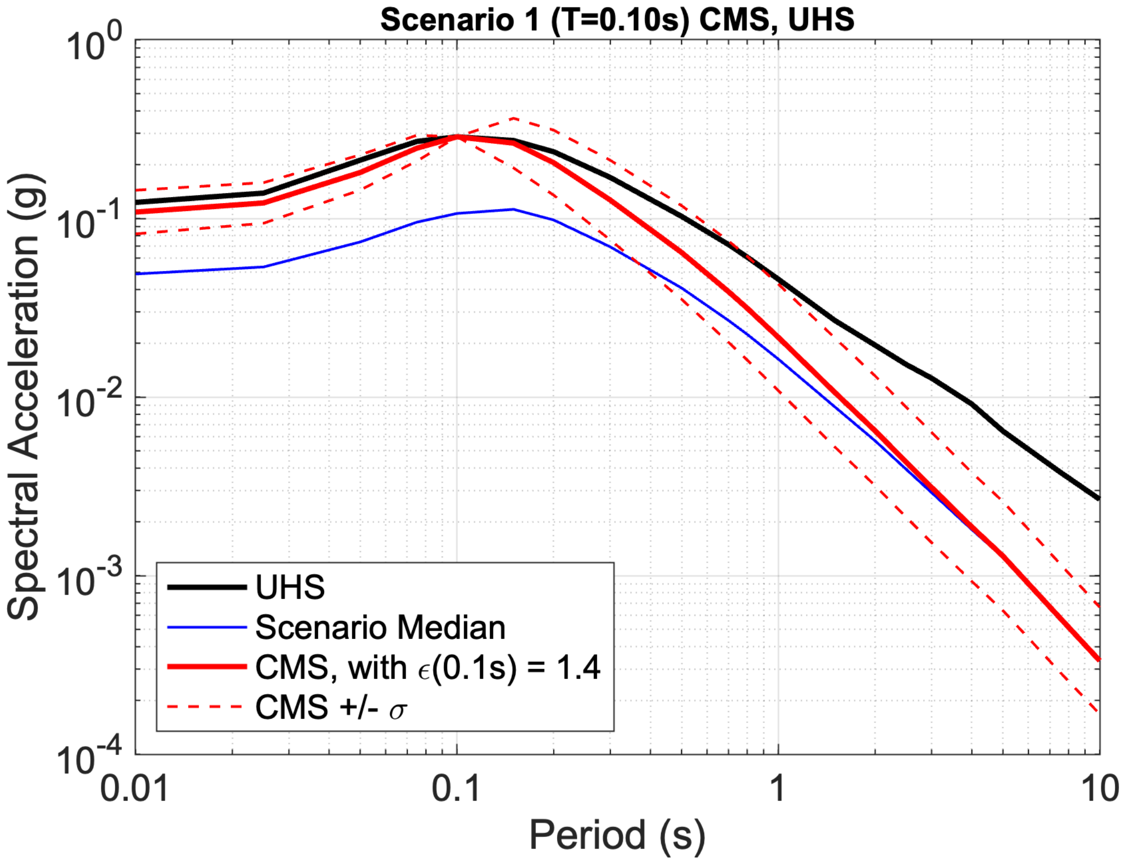
– The conditional mean spectrum (CMS) is conditioned to the UHS at a period of interest (e.g., the fundamental period) and uses the inter-period correlation of epsilon to calculate the spectral acceleration at other periods

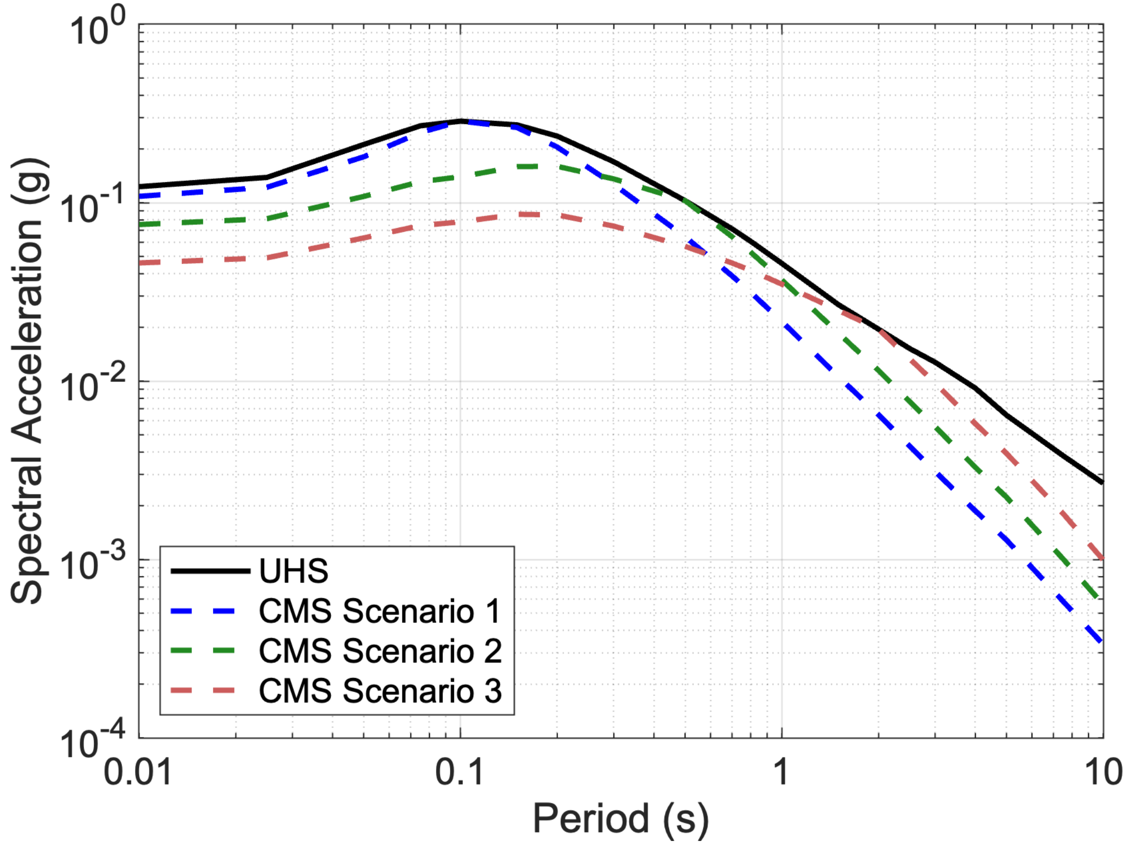
– Sets of CMS, not the UHS, should be used to more accurately represent the design ground motions.

– The CMS approach was adopted for use in ANCOLD (2019), NZSOLD (2024), and ASCE 7-22

PSHA Outputs

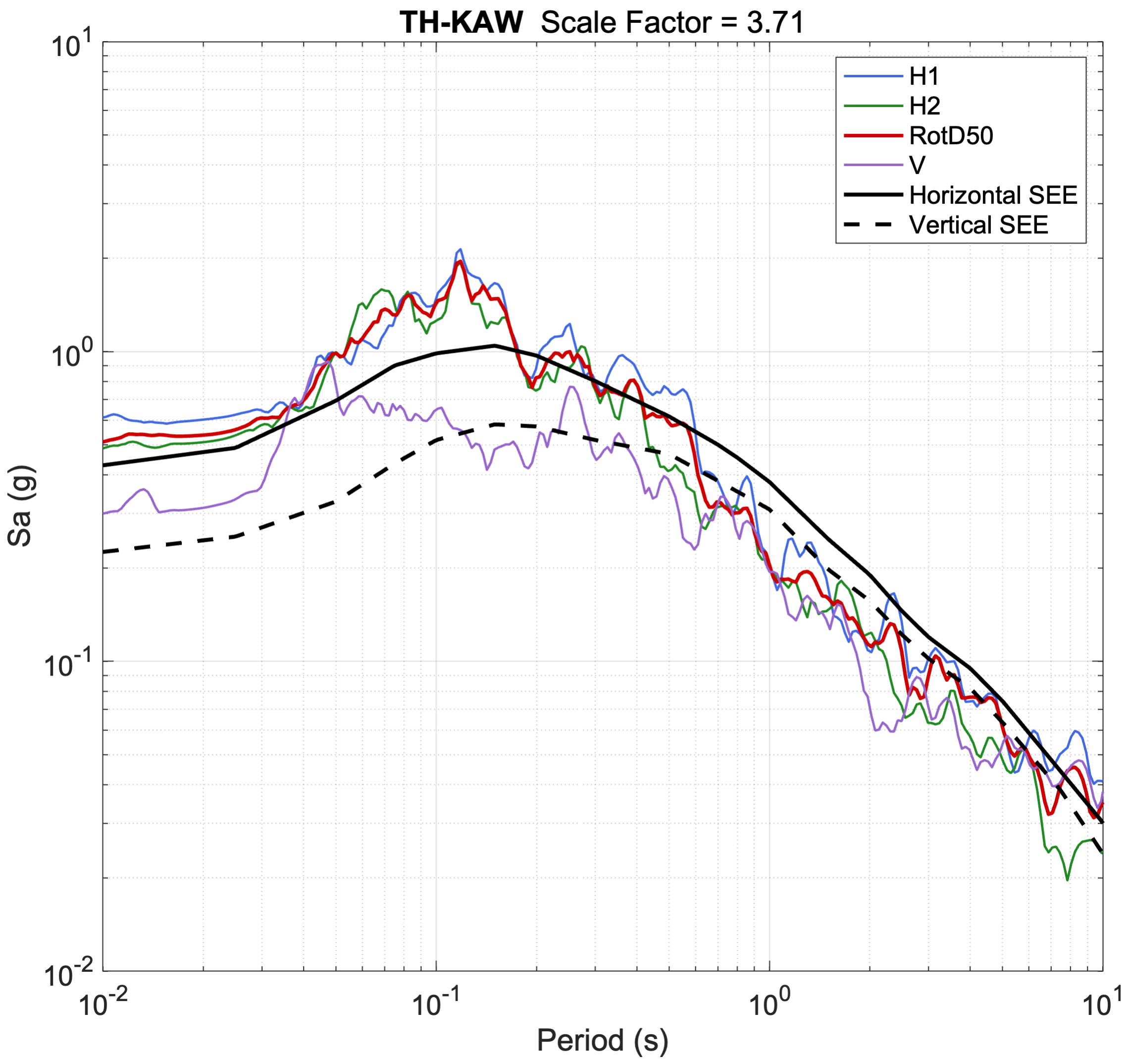
Conditional Mean Spectra

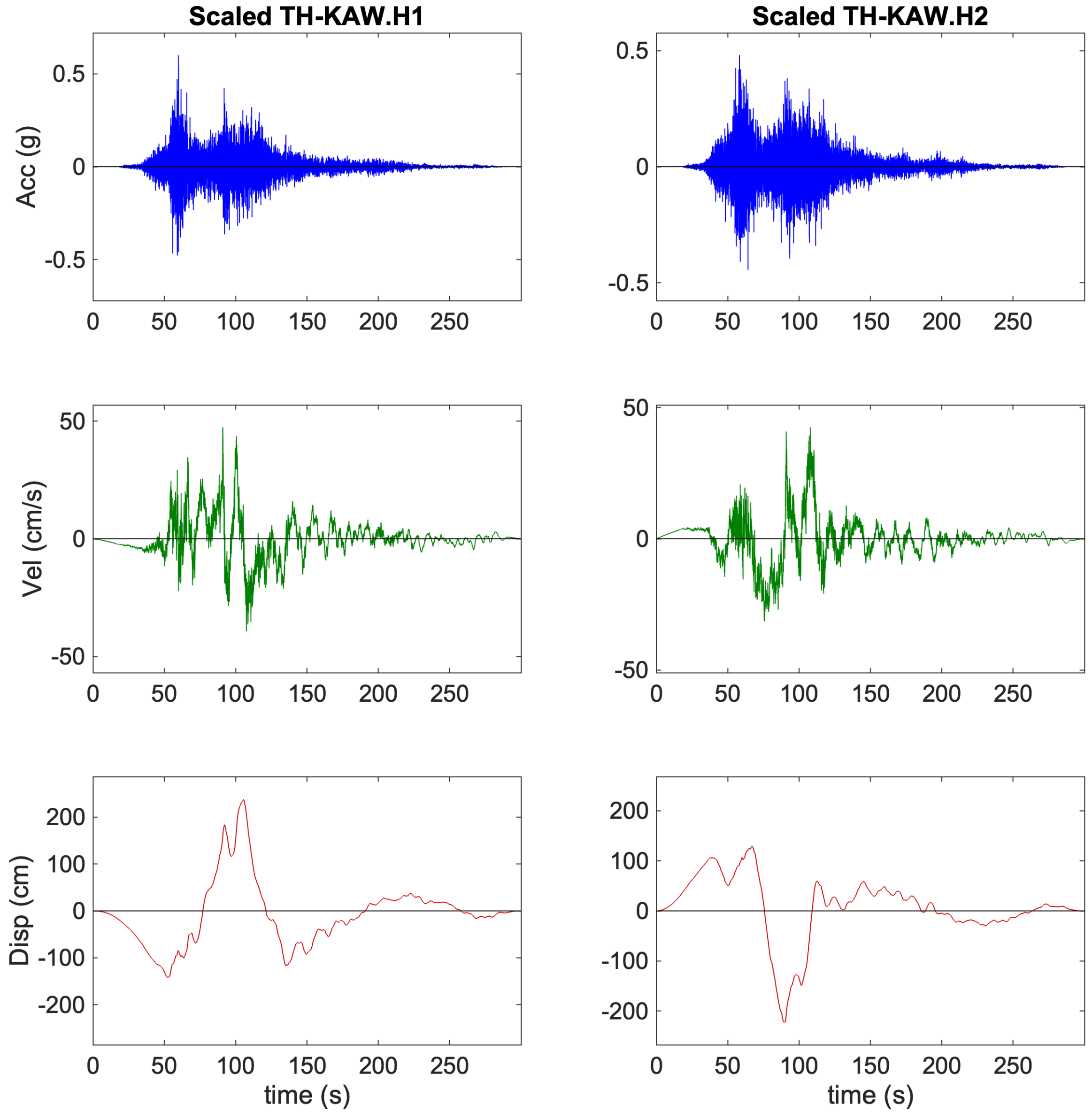




PSHA Outputs

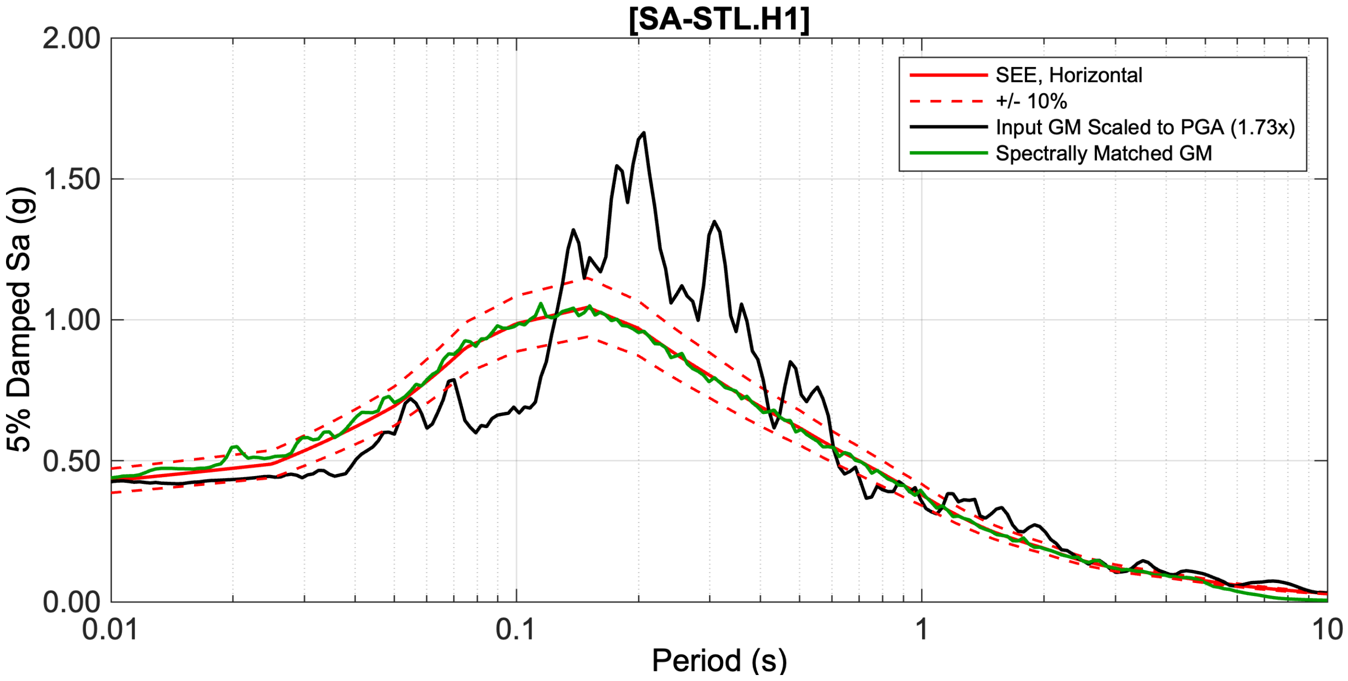
Time Histories: Scaled

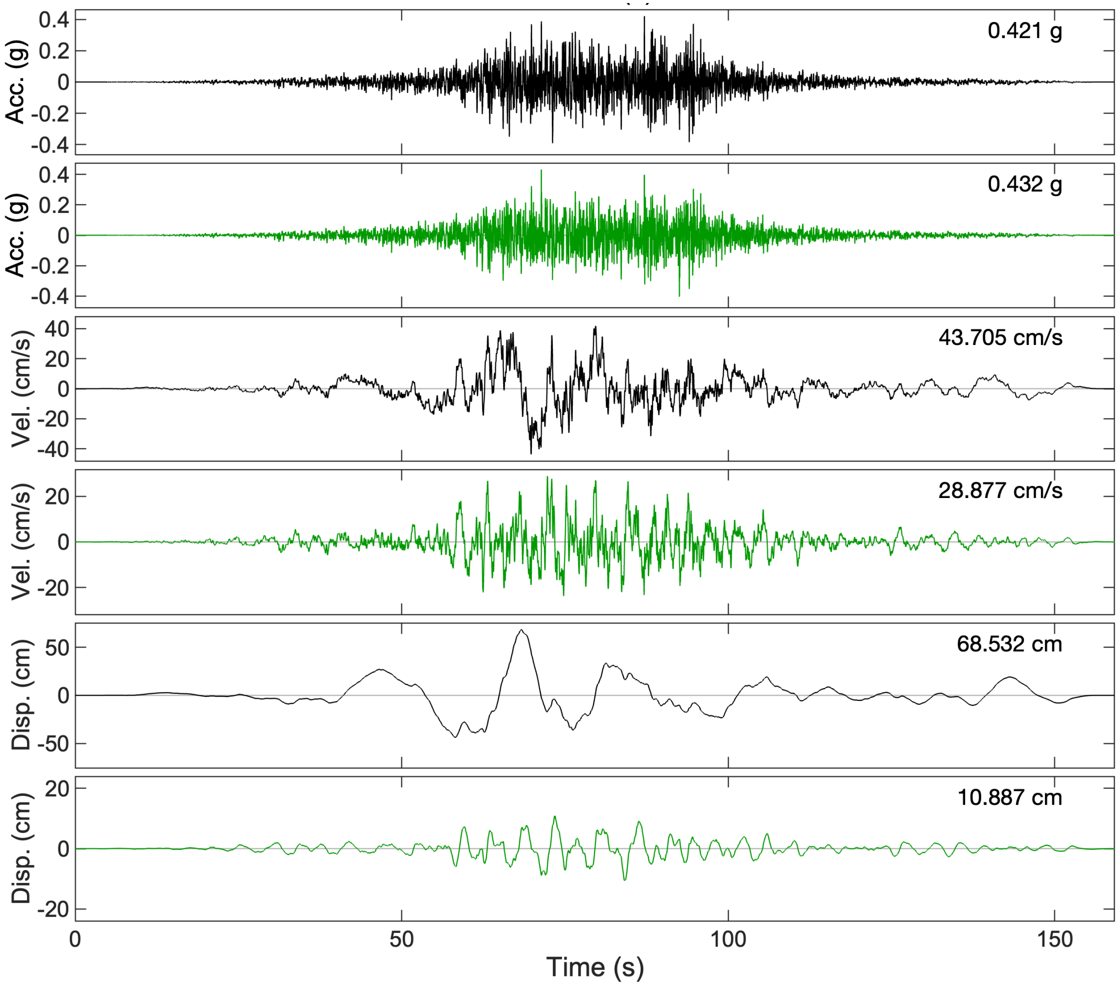




PSHA Outputs

Time Histories: Matched



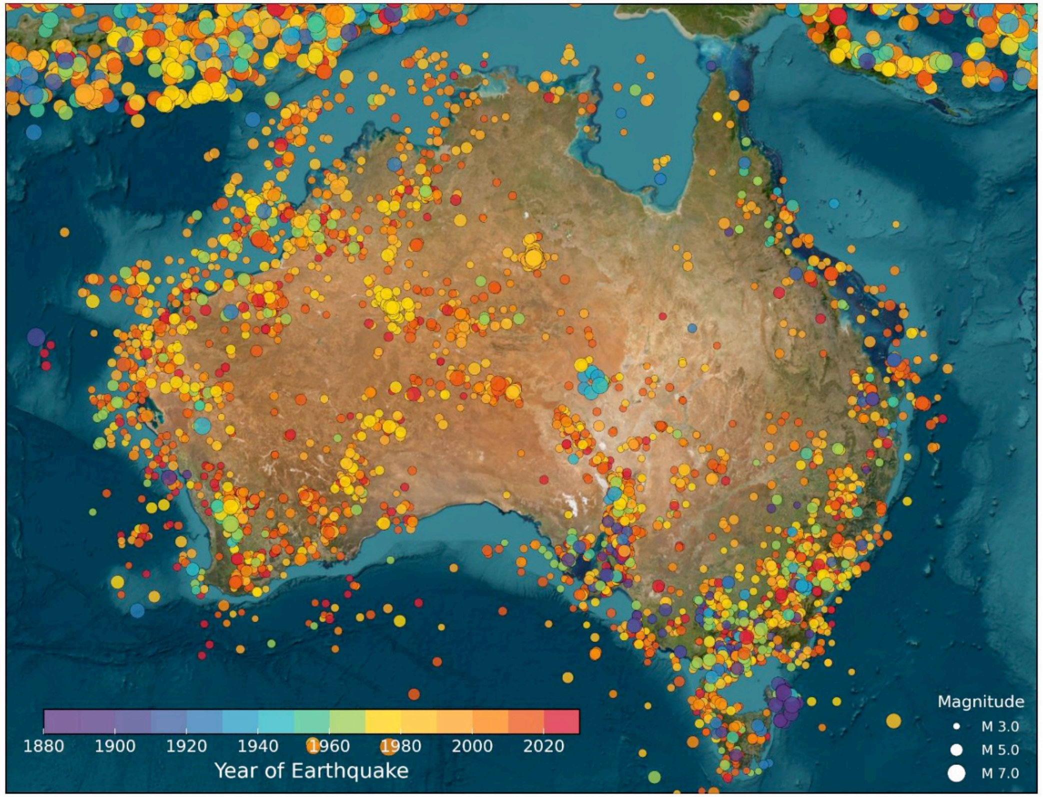


Seismic Hazard in ANZ

Seismicity in Australia

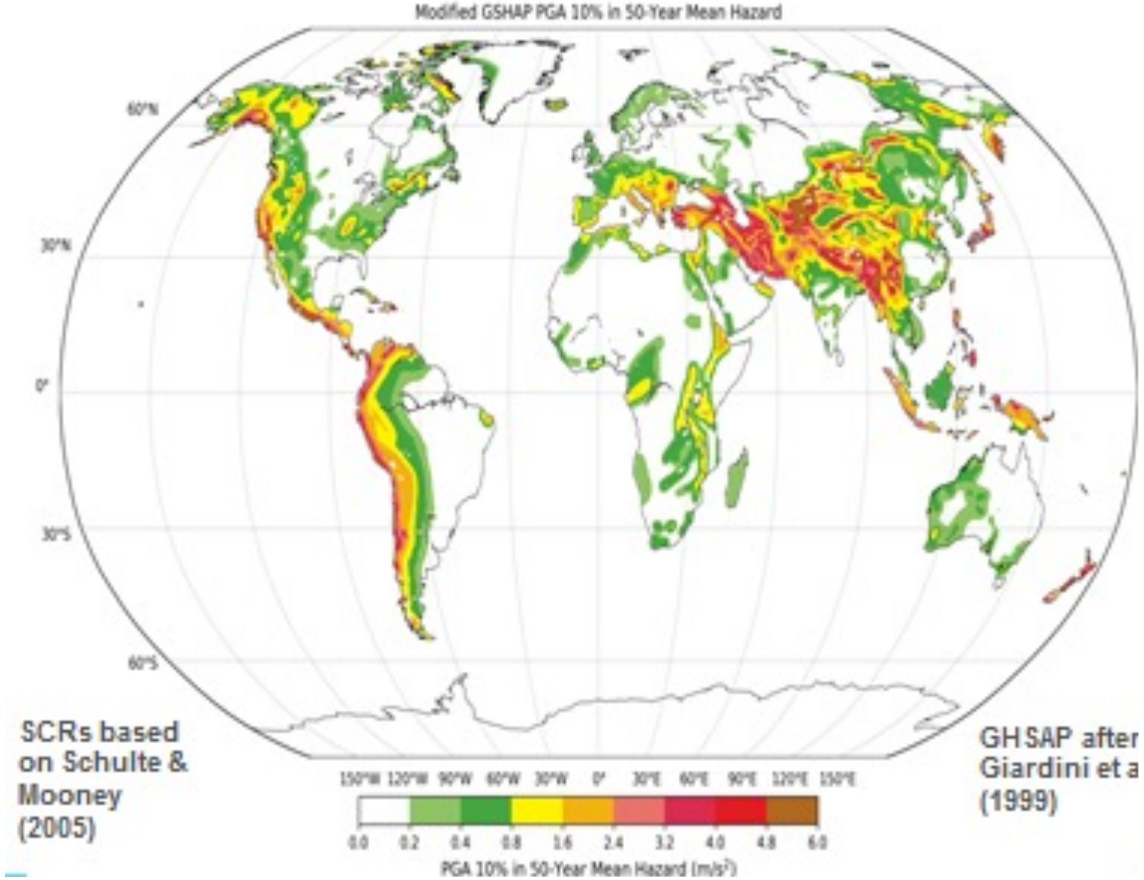
Australia has a low seismicity rate.
So the probabilistic seismic hazard is low (compared to more active regions of the world).
But when earthquakes do occur, they can be just as damaging as elsewhere.

Australia, Indonesia & PNG Seismicity



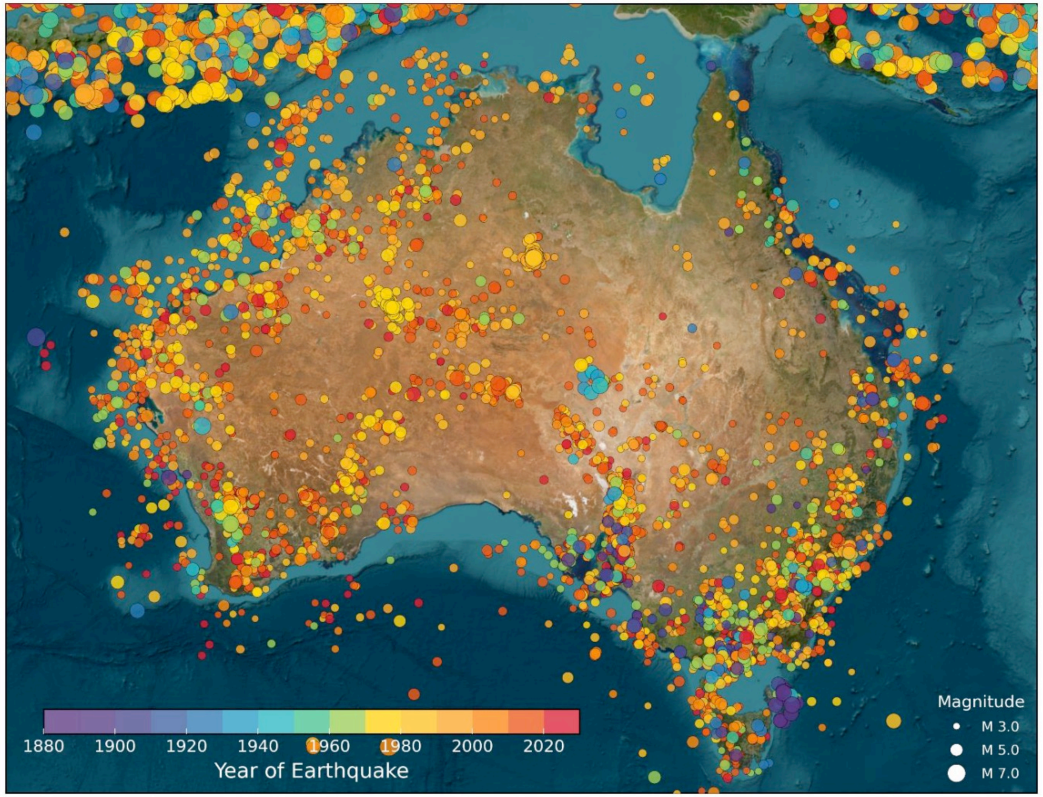
Allen (2018)

Global Seismic Hazard



Seismicity in Australia

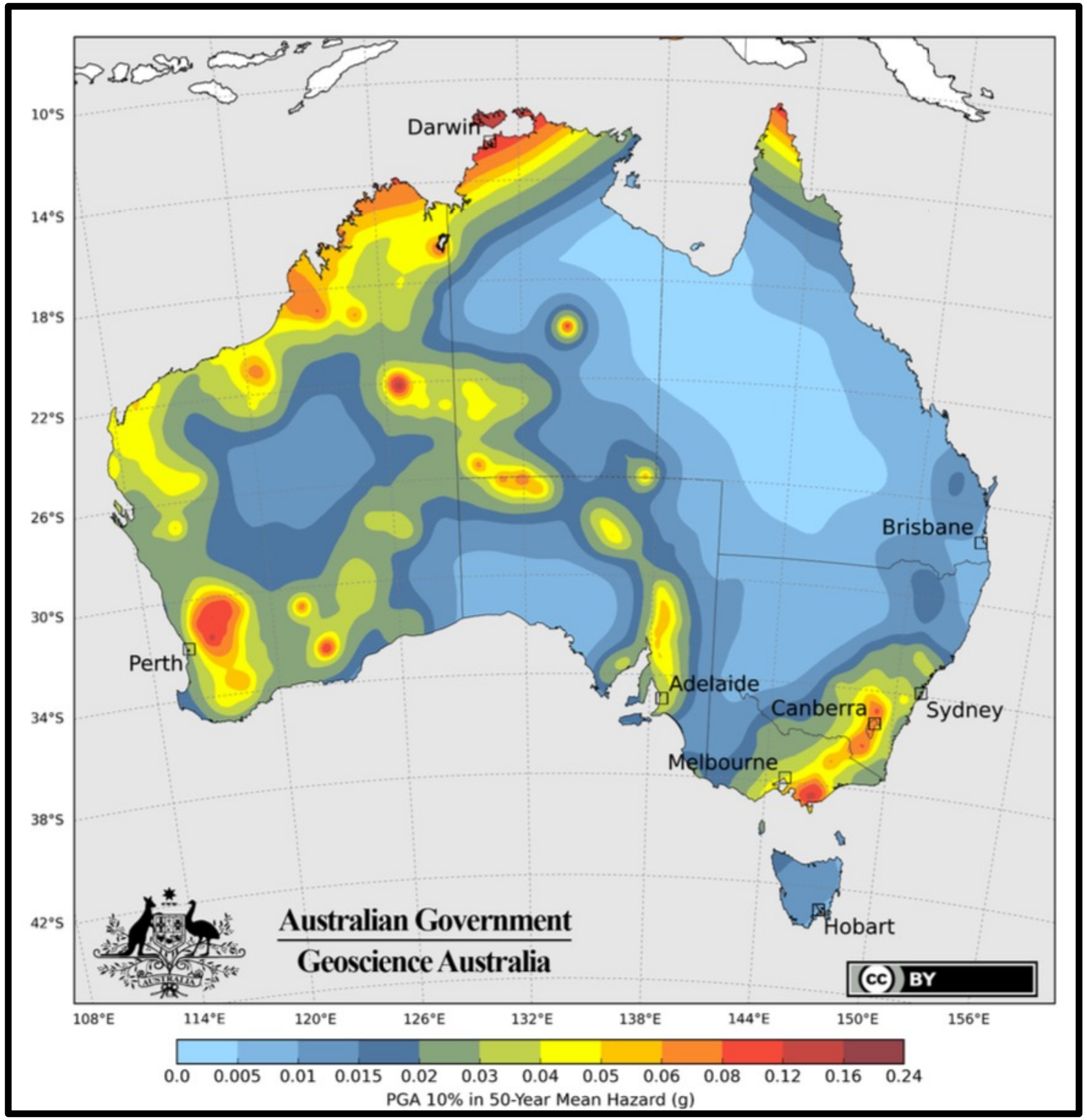
Australia, Indonesia & PNG Seismicity



Allen (2018)

Geoscience Australia: NSHA23

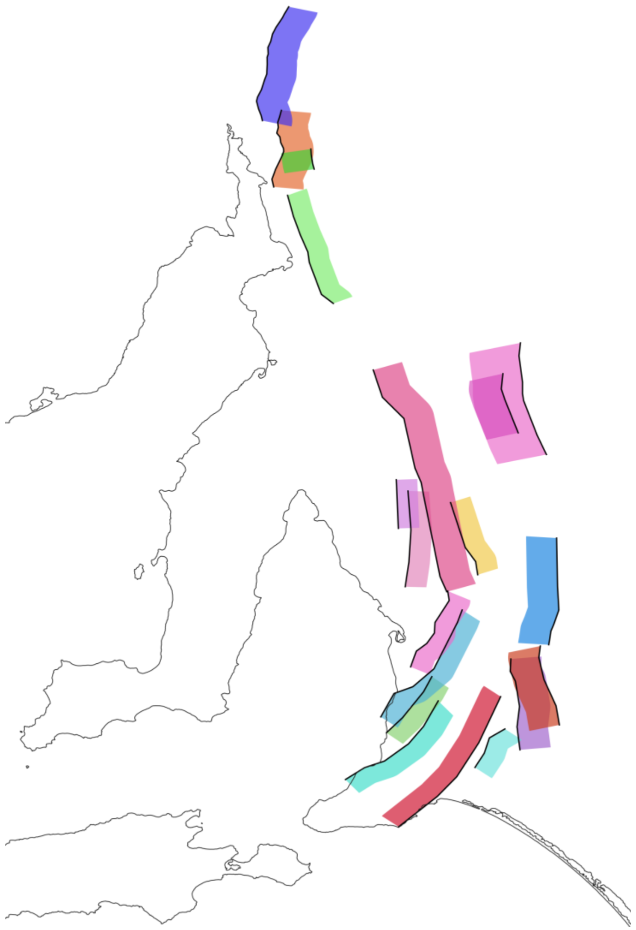
Allen et al. (2023)



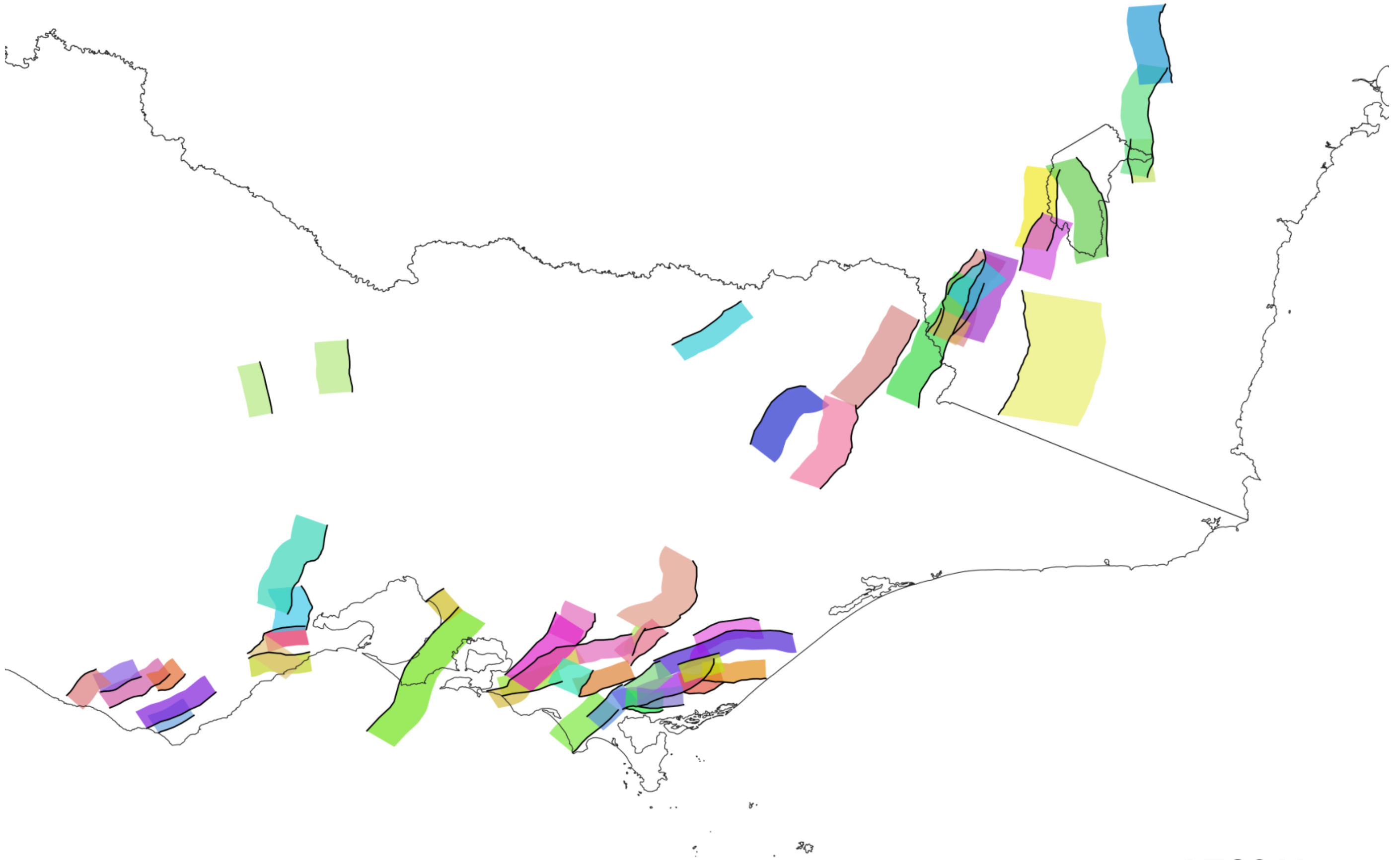
NSHA National Fault Source Model

Fault Source Models are Derived from the Neotectonic Features Database

South Australia



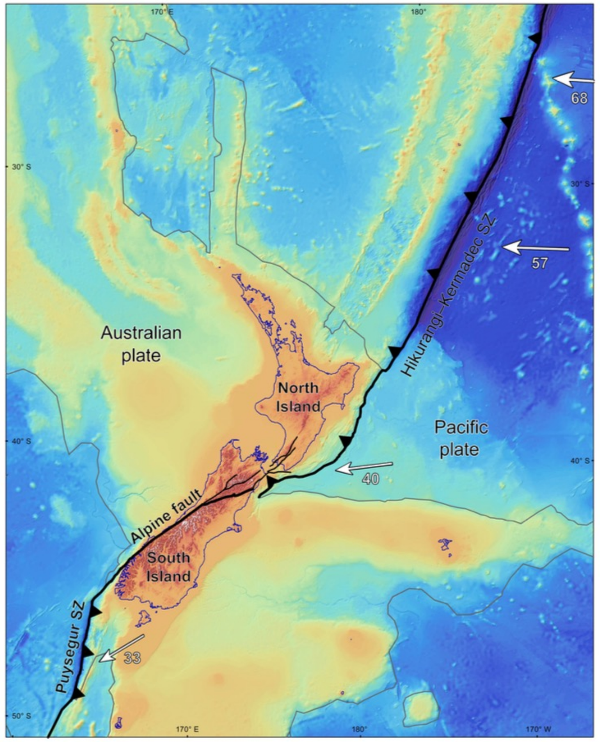
Victoria & Southeastern NSW



Seismicity in New Zealand

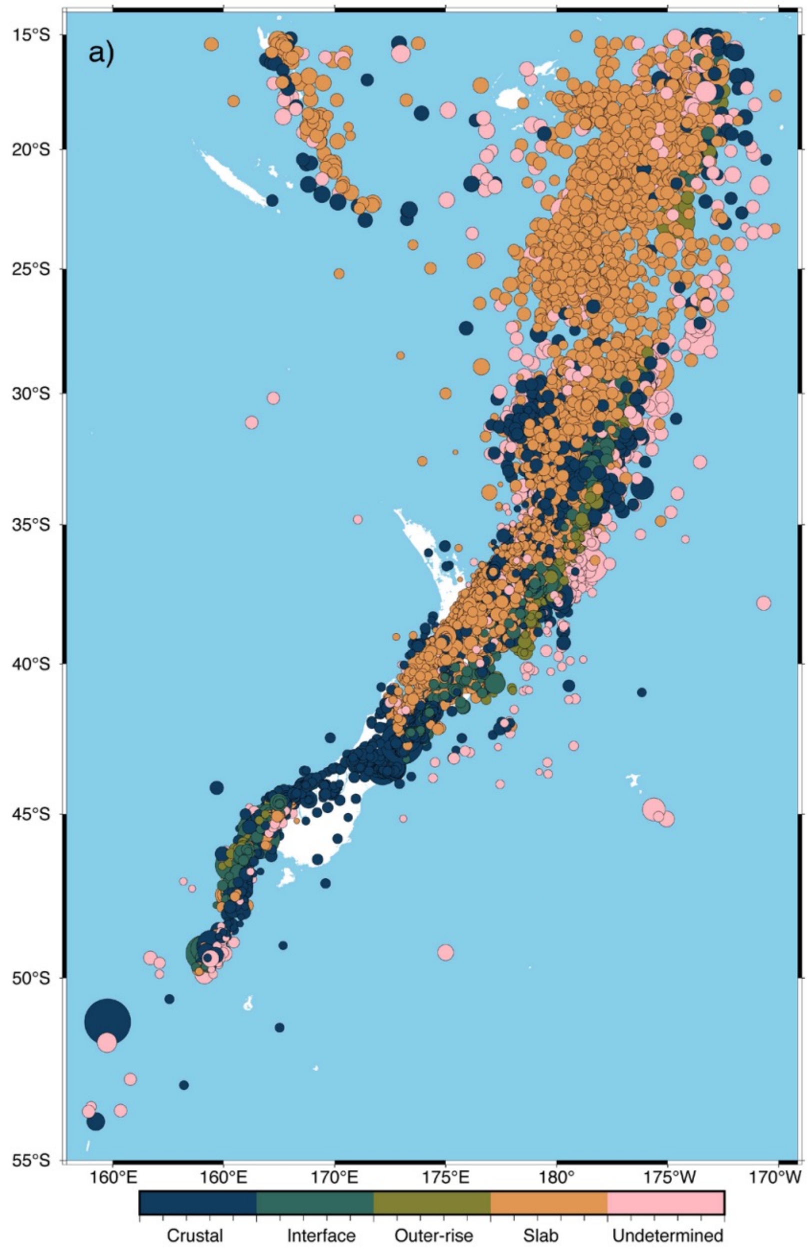
GNS: National Seismic Hazard Model (NSHM23)

Gerstenberger et al. (2022)



The white arrows indicate the relative Pacific plate motion with respect to the Australian plate

Hutchinson et al. (2022)



M > 4.0
2000-2020

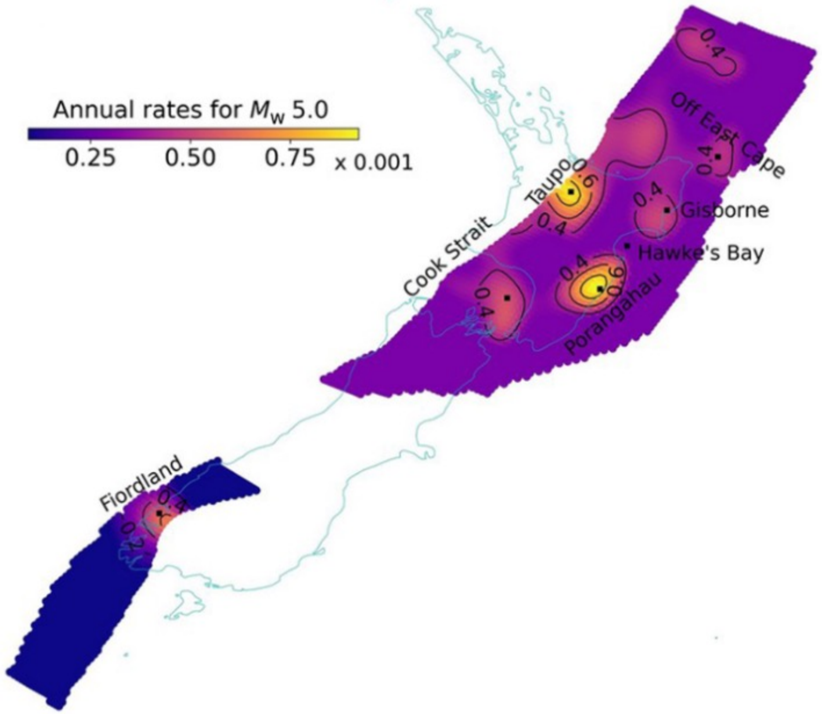
NSHM23 Earthquake Source Models

Gerstenberger et al. (2022)

Crustal (Faults)

Interface (Faults)

Slab (Distributed)



Thingbaijam et al. (2023)

ANZ Dams Guidelines

ANCOLD (2019)

– requires use of the larger of the 84th percentile deterministic MCE and the 85th fractile of the 1:10,000 AEP probabilistic estimate of the SEE for Extreme Consequence dams

When close to an active fault, this can yield very large MCE ground motions having very low probabilities of occurrence, so that the AEP of the MCE may be much lower than 1:10,000 and greatly exceed the probabilistic SEE

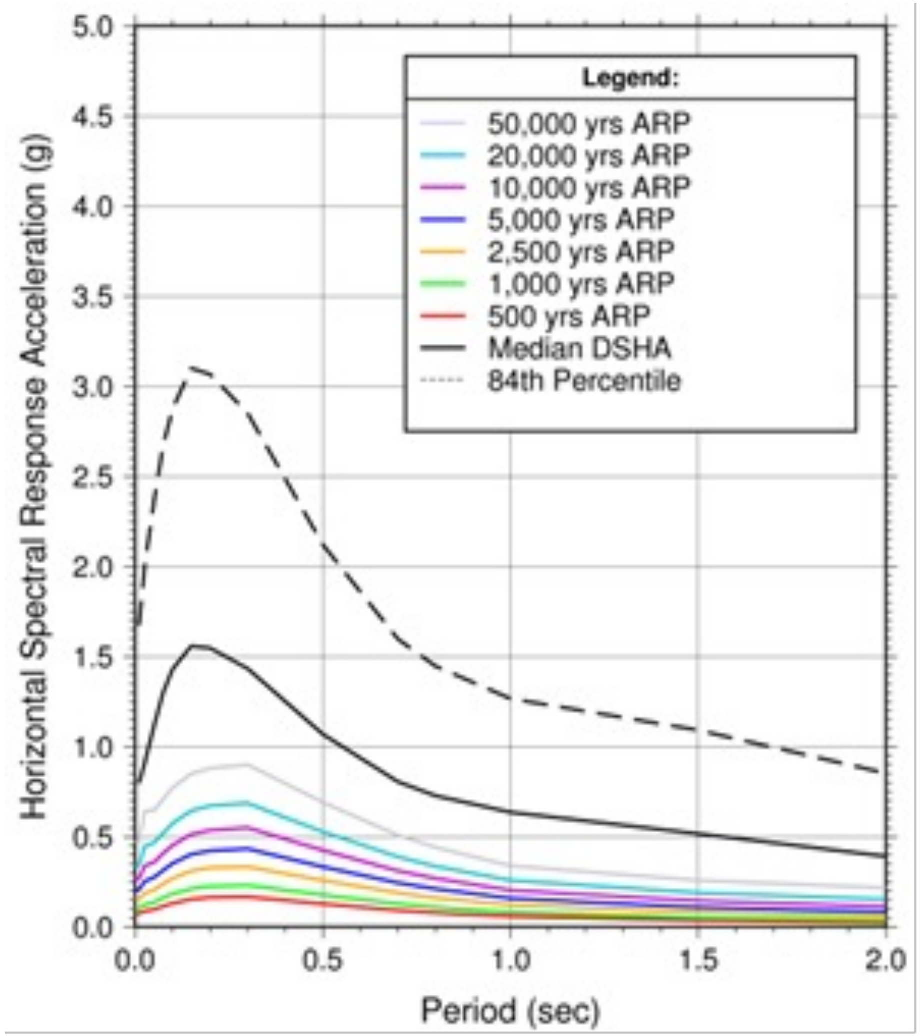
NSOLD (2024)

– allows use of either the 84th percentile deterministic spectrum or the median probabilistic spectrum to represent the SEE for High PIC dams, regardless of which is larger, but the selected spectrum cannot be less than 80% of the larger one

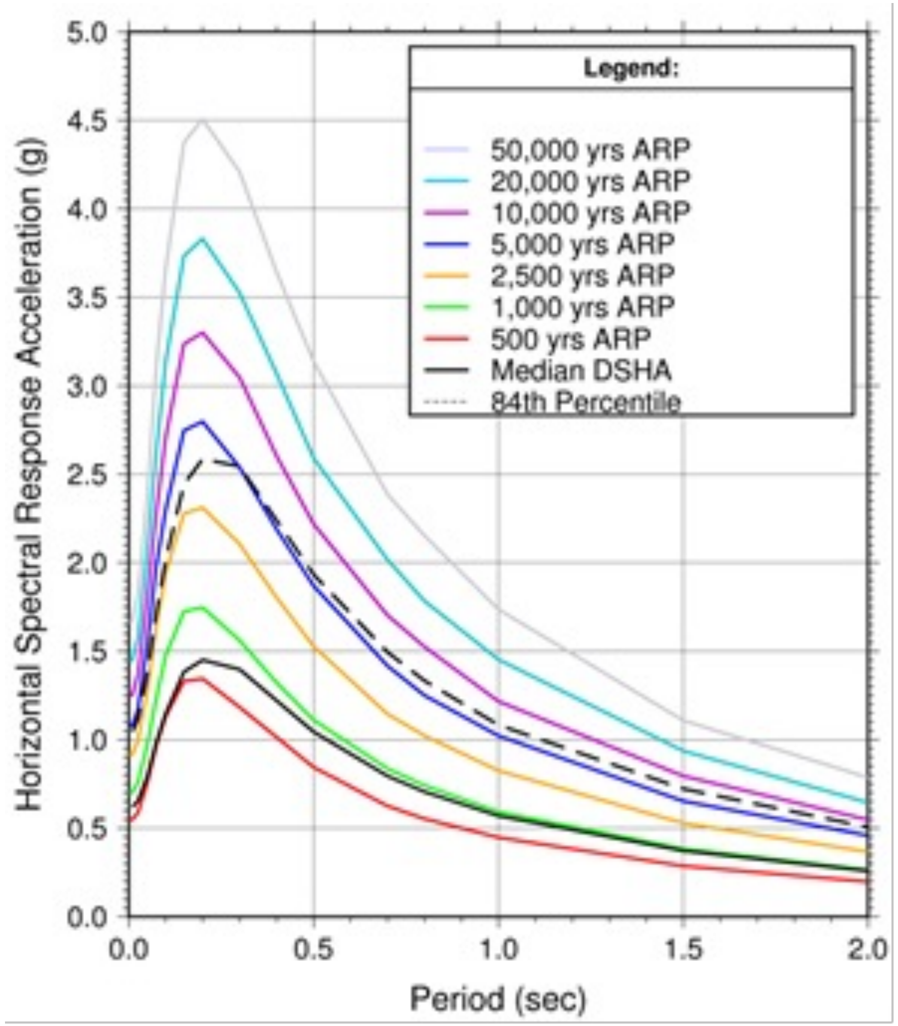
At sites that are distant from faults, the MCE can be much lower than the probabilistic SEE

MCE and UHS close to a long active fault

Australia



New Zealand



Comment on SEE Definition in NZSOLD (2024) and ANCOLD (2019)

– Consideration of scenario earthquakes such as the MCE can be informative for understanding the hazard environment

– However, use of the probabilistic approach for design and analysis of the SEE in both Australia and New Zealand as well as worldwide has the advantage of avoiding the shortcomings in using the MCE in both Australia and New Zealand

– The probabilistic approach forms the basis for performance-based design by providing the likelihood of occurrence of the design event (Baker et al., 2021)

Standards-based vs Risk-based

Standards-based

- Use prescriptive criteria like Design earthquake levels (Operating Basis Earthquake, Maximum Credible Earthquake).
- Clearer requirements and compliance
- Simpler, but less flexible

Risk-based

- Evaluate dam safety in terms of likelihood of failure and consequences
- Assesses the impacts of the full range of hazard levels on the structure/system by convolving the seismic hazard curve (PSHA) with fragility curves
- Allows for performance-based design, where acceptable risk levels are defined, enabling cost-benefit optimization
- More complex in required data, computational tools, and regulations

Standards-based vs Risk-based

– Standards-based methods still dominate today (e.g., ICOLD, ANCOLD, US Bureau of Reclamation, US FERC)

- ANCOLD (2019) has a preference for a risk-based approach
- NZSOLD (2024) has a Risk Informed Decision Making procedure within the context of dam safety deficiency and risk management

– Modern dam earthquake engineering is moving toward hybrid approaches

- using standards for baseline safety, but risk-based methods for prioritization, retrofit, and performance-based design.

– In the future, we anticipate that regulators are expected to adopt risk-based frameworks more, including hybrid approaches

- Computational tools, hazard models, and consequence assessment methods continue to advance

Conclusions

– **Los Angeles Seismology:** We do earthquake (and tsunami) hazard for the design of critical facilities, such as hospitals, bridges, dams and nuclear power plants.

– **The Method of Seismic Hazard Analysis:** Source + Path + Site --> Hazard

- Uncertainties are large, so PSHA is the best method because it systematically incorporates them

– PSHA Inputs and Outputs

- Inputs: models for each hazard component + site information (e.g., Vs30)
- Outputs: hazard curves (annual exceedance probability vs GM level) and their uncertainty, with subsequent products like UHS, deaggregation, CMS, and time histories
- The CMS approach was adopted for use in ANCOLD (2019), NZSOLD (2024), and ASCE 7-22

Conclusions (cont.)

– Seismic Hazard in Australia and New Zealand
  - Both ANCOLD (2019) and NZSOLD (2024) use both probabilistic and scenario-based (MCE) approaches to the assessment of the SEE using Standards-based methods, but the ways in which they are used are quite different.
  - Otherwise, the recent revision of NZSOLD (2024) has brought the two guidelines closer together in several respects

– **Looking Forward:** Prevalence of Risk-Based Approaches
  - In the future, we anticipate that regulators are expected to adopt risk-based frameworks more, including hybrid approaches

AECOM

Imagine it.
Delivered.