Seismic Probabilistic Risk Assessment (SPRA) – Quo Vadis?

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Overview

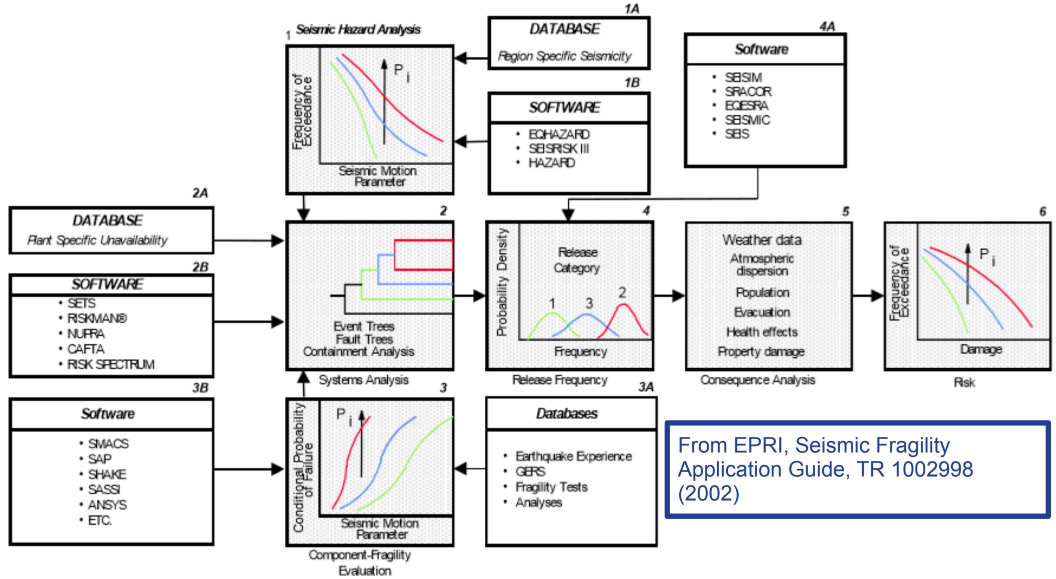
- On the Relationship between SPRA and Risk – Correction of a Myth
  - Is a Uniform Hazard – Uniform?
  - The fragility model.
    - Missing scaling factor!!!
    - Does infinite load capacity exist? (lognormal model)
  - Do SPRA results reflect the “real” risk profile of a NPP?
- Alternative approaches to SPRA
  - The damage-consistent (intensity-based) approach (intensity-based hazard curves)
  - The damage-consistent (intensity-based) scenario-based approach (analogy to LOCA PRA)

Current SPRA-Methodology - Summary

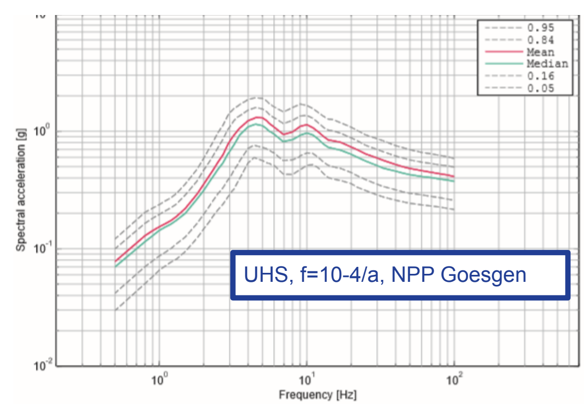
- SPRA-Methodology is based on
  - Seismic Hazard Curves
  - Uniform Hazard Spectra (UHS) and Seismic Fragility Analysis;

UHS are expressed in terms of spectral accelerations, component capacity is expressed in terms of PGA or SA for a dedicated spectral frequency

  - Risk Integration



From EPRI, Seismic Fragility Application Guide, TR 1002998 (2002)



UHS, f=10-4/a, NPP Goesgen

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Is a Uniform Hazard Spectrum – Uniform?

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Vol. 1

Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Main Report

Manuscript Completed: April 1997
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Prepared by
Senior Seismic Hazard Analysis Committee (SSHAC)
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Under Contract to:
Lawrence Livermore National Laboratory
Livermore, CA 94550

$$\lambda(a) = \sum_{i=1}^{S} \nu \int\int \Phi'\left(\frac{\ln a - g(m,r)}{\sigma}\right) f_R(r|m) f_M(m)\, dr\, dm \qquad (2.2)$$

Mean exceedance frequency for acceleration **a**

Summation of contributions of many different earthquake (scenarios)

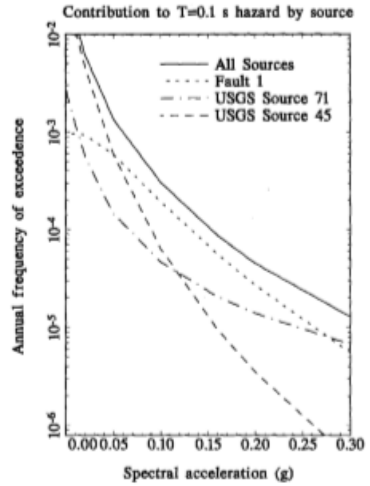


Figure 2. Contribution to hazard by source for $T = 0.1$ sec, example 1.

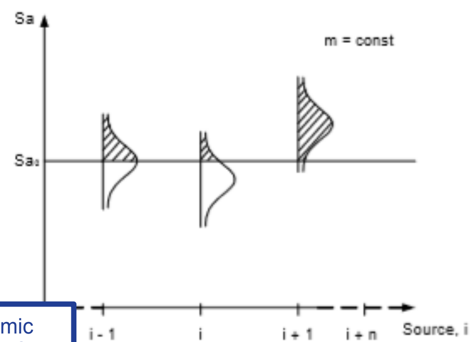
R.K. McGuire, Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop (1995)

Contribution of the different sources to hazard is different (different exceedance probabilities)

Does equal frequency of exceedance mean the hazard is uniform?

Certainly it does not!!!

Is a Uniform Hazard Spectrum Uniform?



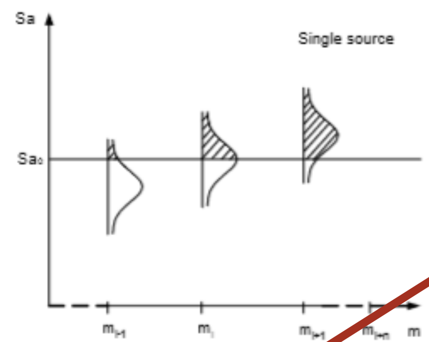
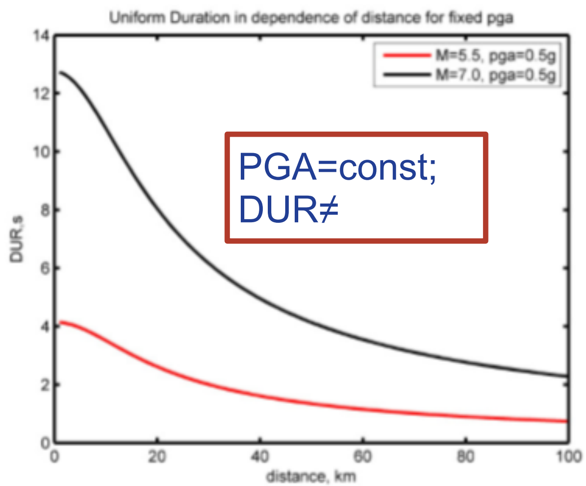


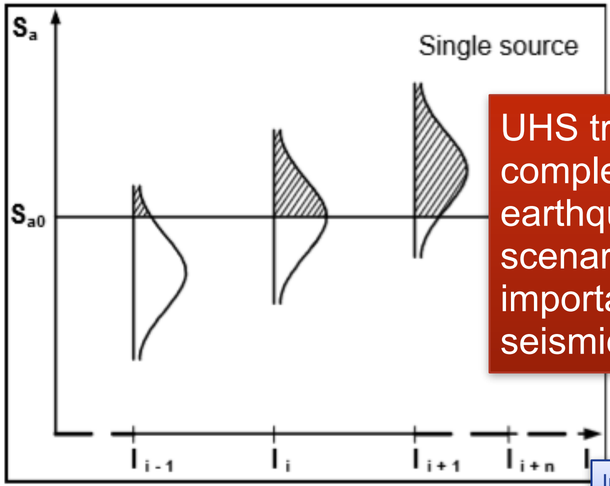
Illustration of summation process in PSHA for a UHS

But the damaging effects of the different summands is different, because of their different strong motion durations, different energy content

J.-U. Klügel, Seismic Hazard Analysis – Quo Vadis?, Earth Science Reviews (2008)



PGA=const;
DUR≠



UHS treats completely unequal earthquake scenarios as equally important for seismic hazard

Intensity

J.-U. Klügel, How to eliminate non-damaging earthquakes from the results of a Probabilistic Seismic Hazard Analysis – A comprehensive procedure with site-specific application, Nuclear Engineering& Design (2009)

Is a Uniform Hazard Spectrum – Uniform?- Summary

- The answer is: Not at all!!!
- An UHS treats earthquakes (scenarios) leading to completely different consequences but exceeding the same level of spectral acceleration as equally important for risk;
- assessing the consequences of the hazard just by probability of exceedance means **that elementary physics are ignored,**
  - risk analysis is interested in negative consequences that means in damage,
  - for causing damage energy is needed
  - PSHA sums up contributions of completely non-uniform elements with respect to damage
- The consequence is that an UHS
  - in seismic active regions with big faults leads mathematically to a dilution of the seismic hazard (confirmed by many examples, L'Aquila 2014, Haiti 2010, Chile 2010) by overestimating the importance of weak earthquakes
  - In regions of moderate and diffuse seismicity leads mathematically to an overestimation of the seismic hazard (low intensity events are summed up)

The Fragility model – Scaling factor approach, missing scaling

$$F = \frac{\text{Actual seismic capacity of element}}{\text{Actual response due to SSE}}$$

This relationship is typically expanded to identify the conservatism or factor of safety in both the strength and the response.

$$F = \frac{\text{Actual capacity}}{\text{Design response due to SSE}} \times \frac{\text{Design response due to SSE}}{\text{Acctual response due to RE}}$$

$$F = F_C F_{SR} \qquad \textbf{Equation 2-4}$$

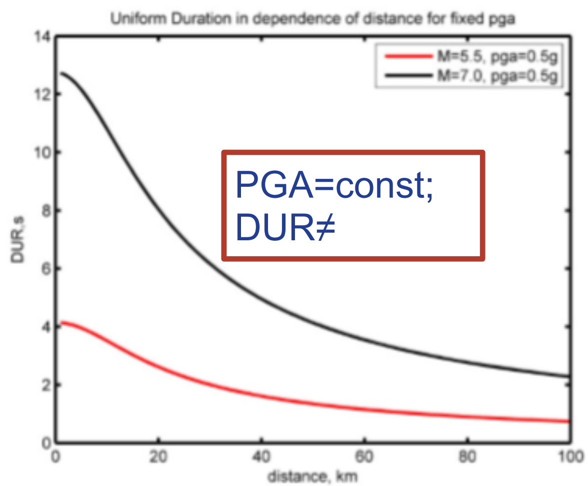
where F_c is the capacity factor, F_{SR} is the structural response factor and RE is the reference earthquake spectrum derived from the probabilistic hazard study, anchored to the same pga as the SSE.

EPRI, Seismic Fragility Application Guide, TR 1002998 (2002)

Standard Fragility Method (Scaling Method) is based on the evaluation of a Safety Factor

Scaling does not include the difference in energy content between the design response to SSE and the response to RE.→ Simplification forced by lack of nonlinear analysis for the original design response. (the true design response is not known).
→ **Importance of large earthquakes underestimated, of small earthquakes overestimated**

Simple structural (macro- and micro-mechanic) models indicate the existence of an **additional scaling factor**, that scales approximately with the square root of uniform strong motion duration for a fixed response spectrum (e.g. equal (normalized) spectra of SSE and RE))



J.-U. Klügel, How to eliminate non-damaging earthquakes from the results of a Probabilistic Seismic Hazard Analysis – A comprehensive procedure with site-specific application, Nuclear Engineering & Design (2009)

Does infinite load capacity exist? – The lognormal model

$$A = A_M \times \varepsilon_R \times \varepsilon_U$$

Lognormally distributed with unity median

Theoretically an infinite capacity is possible

May be of less practical importance (HCLPF-values are mainly used, probabilities may not change significantly), but

How can we conclude, that a model which allows for impossible results (infinity) is realistic enough for practical applications?

Furthermore: Median capacities can be very high (large safety factors), but the limit loading state of any SSC is approached by nonlinear response of the SSC. ***What is the basis of linear scaling (multiplication by safety factor) for estimating its ultimate capacity?***

Do SPRA results reflect the "real" risk profile of a NPP for earthquakes?

The answer can be given by remembering the quantitative definition of risk!

The current methodology uses an hazard input that represents a weighted mixture of "earthquake scenarios" with significantly different consequences (damaging effects)

This contradicts to the definition of risk as we use it in the nuclear industry; scenarios with the same (or nearly the same) consequences are binned together, **not mixtures!**

Development of the risk curve is part of the risk integration process, not part of hazard definition

On The Quantitative Definition of Risk

Stanley Kaplan[1] and B. John Garrick[2]

Received July 14, 1980

A quantitative definition of risk is suggested in terms of the idea of a "set of triplets." The definition is extended to include uncertainty and completeness, and the use of Bayes' theorem is described in this connection. The definition is used to discuss the notions of "relative risk," "relativity of risk," and "acceptability of risk."

KEY WORDS: risk; uncertainty; probability; Baye's theorem; decision.

Table I. Scenario List

Scenario	Likelihood	Consequence
S_1	p_1	x_1
S_2	p_2	x_2
⋮	⋮	⋮
S_N	p_N	x_N

Table II. Scenario List with Cumulative Probability

Scenario	Likelihood	Consequences	Cumulative probability
s_1	p_1	x_1	$P_1 = P_2 + p_1$
s_2	p_2	x_2	$P_2 = P_3 + p_2$
⋮	⋮	⋮	
s_i	p_i	x_i	$P_i = P_{i+1} + p_i$
⋮	⋮	⋮	
s_{N-1}	p_{N-1}	x_{N-1}	$P_{N-1} = P_N + p_{N-1}$
s_N	p_N	x_N	$P_N = p_N$

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What are the alternatives? The damage-consistent approach

Based on the definition of risk we have to return to a seismic parameter which adequately reflects the physical

The seismological parameter which allows to characterize the physical effects of earthquakes is **Intensity** (in Europe in the EMS-98 scale)

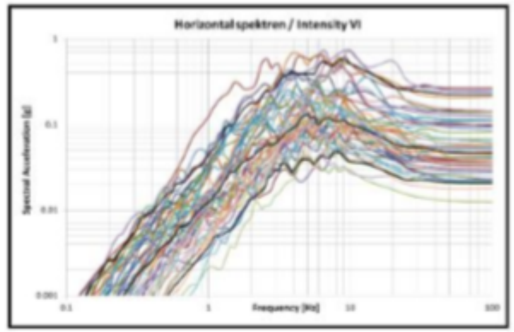
Intensity can easily be transformed into engineering parameters (e.g. ground – motion time-histories) using registered time-histories classified by site intensity or/and waveform modeling techniques (synthetic seismograms or kinematic models) and damage calibration

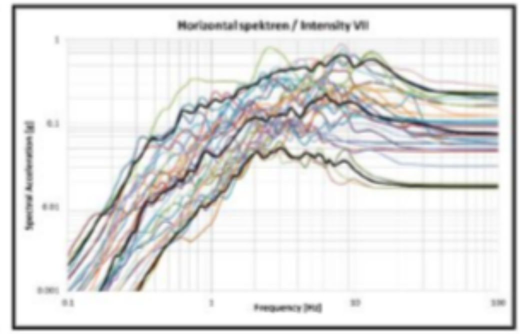
Recorded Time-histories INTENSITY VII-VIII, Resorce-Database (2013)

16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

SEISMIC SAFETY REASSESSMENT OF NPP GOESGEN AFTER COMPLETION OF SITE-SPECIFIC PROBABILISTIC SEISMIC HAZARD ANALYSIS

Sunay STAEUBLE-AKCAY[1], Andrii NYKYFORCHYN[2], Jens Uwe KLUEGEL[3]





Advantage: The Time-Histories (or Response Spectra) reflect **observed damage** and **observed variability (uncertainty)** of ground motion

Alternatives- a) Use of intensity-based hazard curves

- PSHA and SPRA can be performed in terms of Intensity
- Hazard curves are directly determined in terms of Intensity-→ Empirical Ground Motion Equations are replaced by Intensity Attenuation Equations.
- This is just the way how PSHA once started
- One reference value (e.g. exceedance frequency of 10^{-5}/a) can be used as reference point to define a fragility case, conversion of Intensity to time-histories / Response spectra using recorded time-histories and or waveform modeling

Intensity- Exceedance Rate

Example, PSHA in terms of Intensity, for NPP Goesgen, Dr. Rosenhauer, 2008, VGB (Germany)

All other essential elements of SPRA can be maintained

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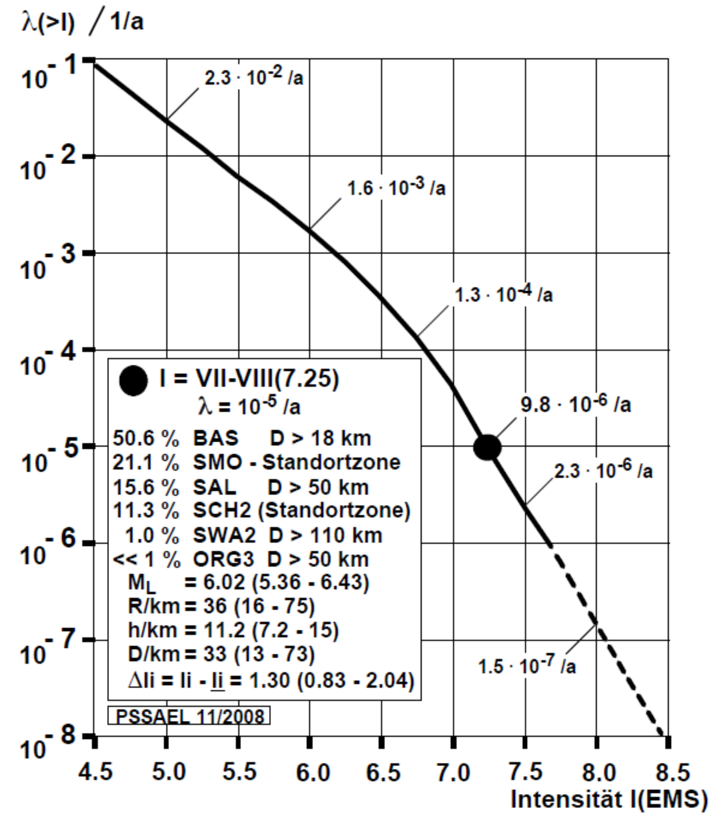

All other essential elements of SPRA can be maintained

Alternatives b) Damage- consistent (scenario-based approach)

- SPRA is performed in analogy to LOCA PRA,
  - We do not model each and any LOCA, but we group the possible LOCA – scenarios in different classes assigning different success criteria to each of the classes (small breaks, medium breaks …) but compute the frequency from all possible scenarios within the class
- We define different damaging scenarios (e.g. site intensity VII-XII) (classes IC) and calculate for all sources the frequency that the source can contribute to the corresponding site intensity, adding them gives the frequency of each intensity category

$f_{IC} = \sum f_i$


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A scenario-based procedure for seismic risk analysis

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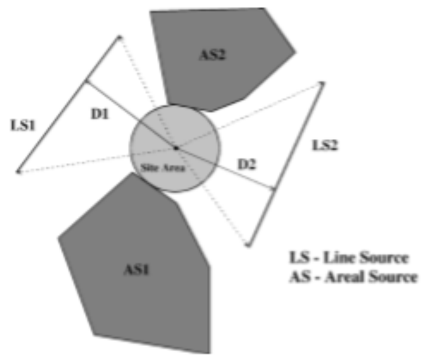

Simplified example (but using spectral acceleration instead of intensity) included contained

Conversion of I to time-histories /response spectra again based on recorded time histories or waveform modeling using damage calibration

Alternatives b) Damage- consistent (scenario-based approach) – Risk integration

- Risk integration is performed by defining a fragility reference case for each of the intensity classes; each fragility case is related to a single seismic initiator
  - The use of multiple fragility cases gives a numerically better representation of the risk curve;
  - standard or alternative formulations of fragility functions can be used
- Seismic initiators are quantified in the risk model like other initiating events

Methods a) and b) can be combined, e.g. the frequency of each Intensity class can be calculated using Intensity-based hazard curves
→ But alternative probabilistic models can be used to compute frequencies (e.g. Non-Poissonian models) if available

Summary

- The current practice of SPRA based on UHS in terms of ground motion accelerations is not able to provide technically meaningful risk assessment results;
  - Its methodology does not comply with the definition of risk as used in nuclear industry elsewhere because it mixes earthquake scenarios with different consequences into a joint initiating event
- A significantly improved methodology is the damage-consistent (Intensity-based) approach which avoids the problem of mixing different earthquake scenarios of different physical impact
- The conversion of Intensity into engineering parameters today can be performed easily by using recorded time-histories (categorized into intensity classes) or waveform methodology and damage calibration