Seismic Probabilistic Risk Assessment (SPRA) – Quo Vadis?

J.-U. Klügel¹, A. Nykyforchyn¹

¹ NPP Goesgen-Daeniken, Seismic Competence Center of Swiss NPPs
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;
  - Risk Integration

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

Is a Uniform Hazard Spectrum – Uniform?

Mean exceedance frequency for acceleration $a$

Summation of contributions of many different earthquake (scenarios)

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, 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)

PGA=const; DUR≠

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

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.
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 effects of earthquakes. 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, Resource-Database (2013)

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

All other essential elements of SPRA can be maintained
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.

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

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

\[ f_i = \sum f_s \]

- 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

Available online at www.sciencedirect.com

A scenario-based procedure for seismic risk analysis

J.-U. Klügel \(^{a, *}\), L. Mualchin \(^b\), G.F. Panza \(^c,d\)

\(^a\) Kernkraftwerk Gösgen-Dauendorf, Kraftwerkkonzepte, 6358 Dauendorf, Switzerland

\(^b\) Retired from the California Department of Transportation (Caltrans), Sacramento, California, United States

\(^c\) Dipartimento di Scienze della Terra – Università di Trieste, Italy

\(^d\) The Abdus Salam International Centre for Theoretical Physics – Miranor, Trieste, Italy

Received 10 March 2006; received in revised form 4 July 2006; accepted 18 September 2006

Available online 18 September 2006
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