Epistemic Uncertainty Reduction in the PSA of Nuclear Power Plant using Bayesian Approach and Information Entropy

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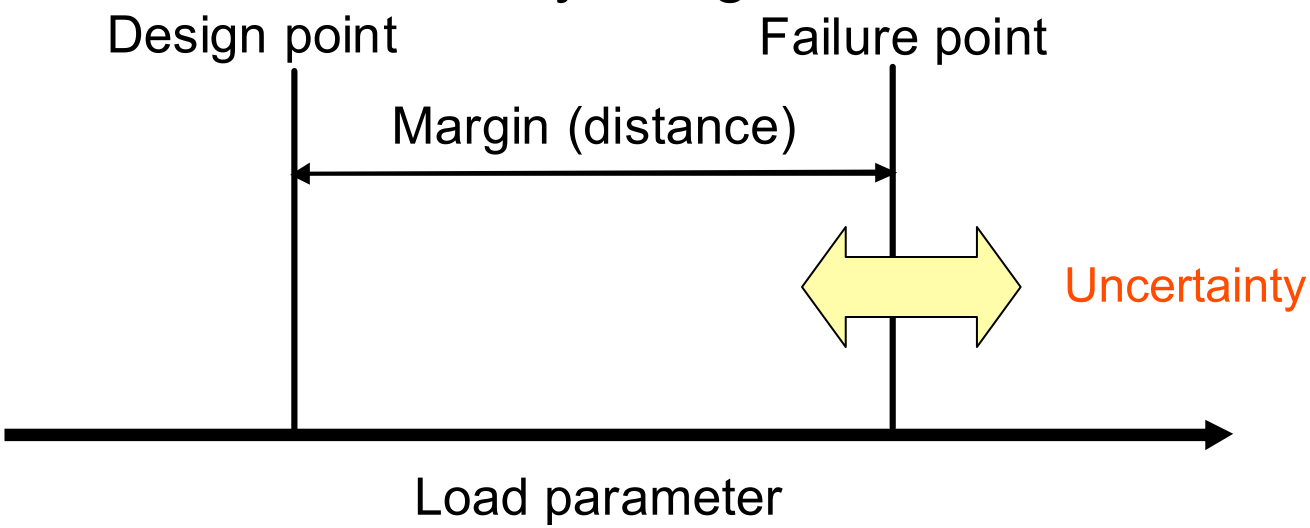
Introduction

- Residual risk of nuclear power plants is mostly caused by rare events and lack of data is a major problem
- How to overcome the lack of data
  - Statistics, as a subject, is the study of frequency type information. That is, it is the science of handling data.
  - Probability, as a subject, we might say is the science of handling the lack of data. (Kaplan And Garrick, 1982)
- Some experienced earthquakes that exceed the design earthquake level
  - Tyuetsu-Oki earthquake in July 2007
  - Great East Japan earthquake in March 2011
- A methodology to utilize all the information is needed, that maximizes uncertainty reduction

Distance between DP and FP

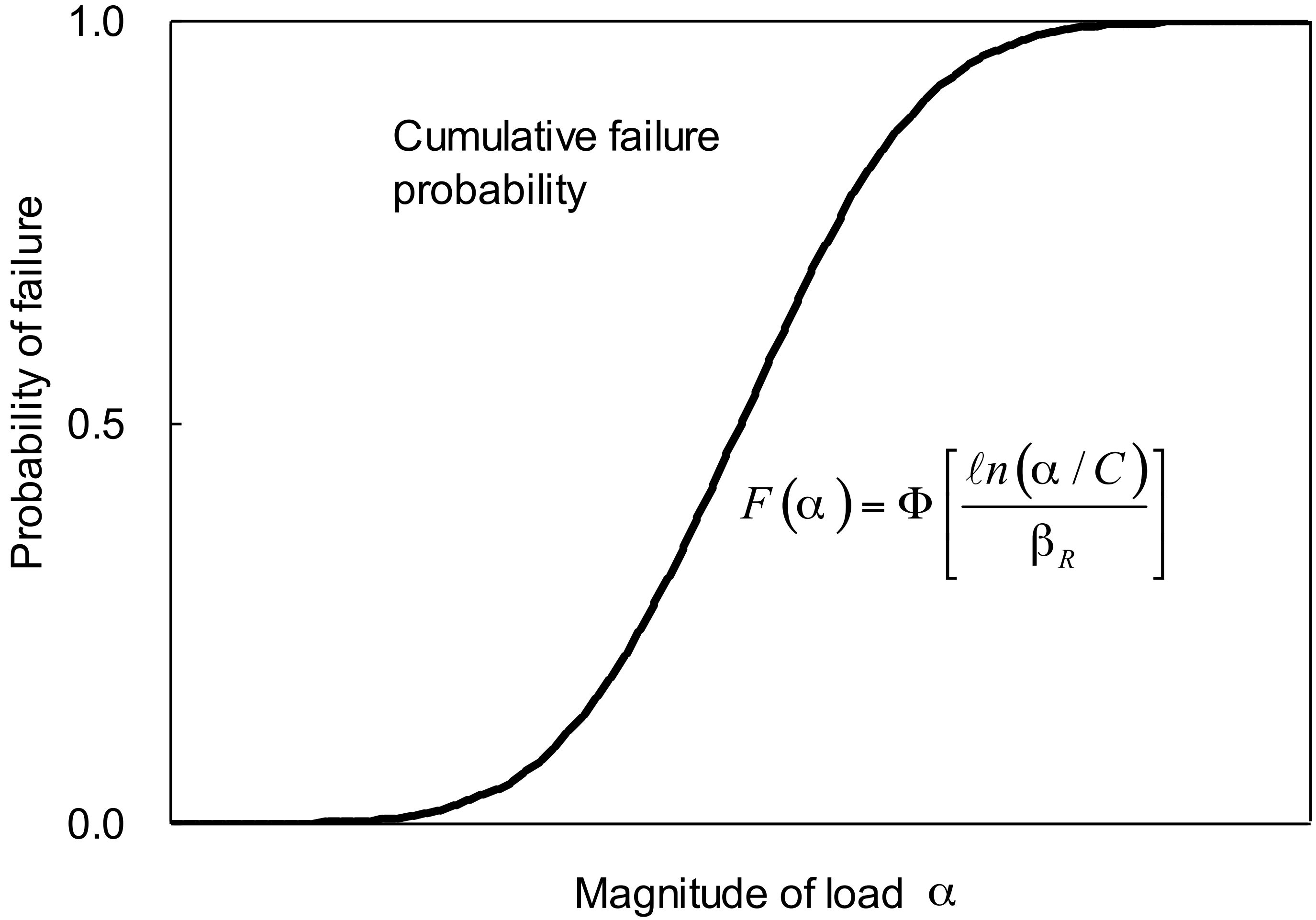
- Safety is assured by DBE as well as margins
- Uncertainty reduction
  - Failure limit and safety margin



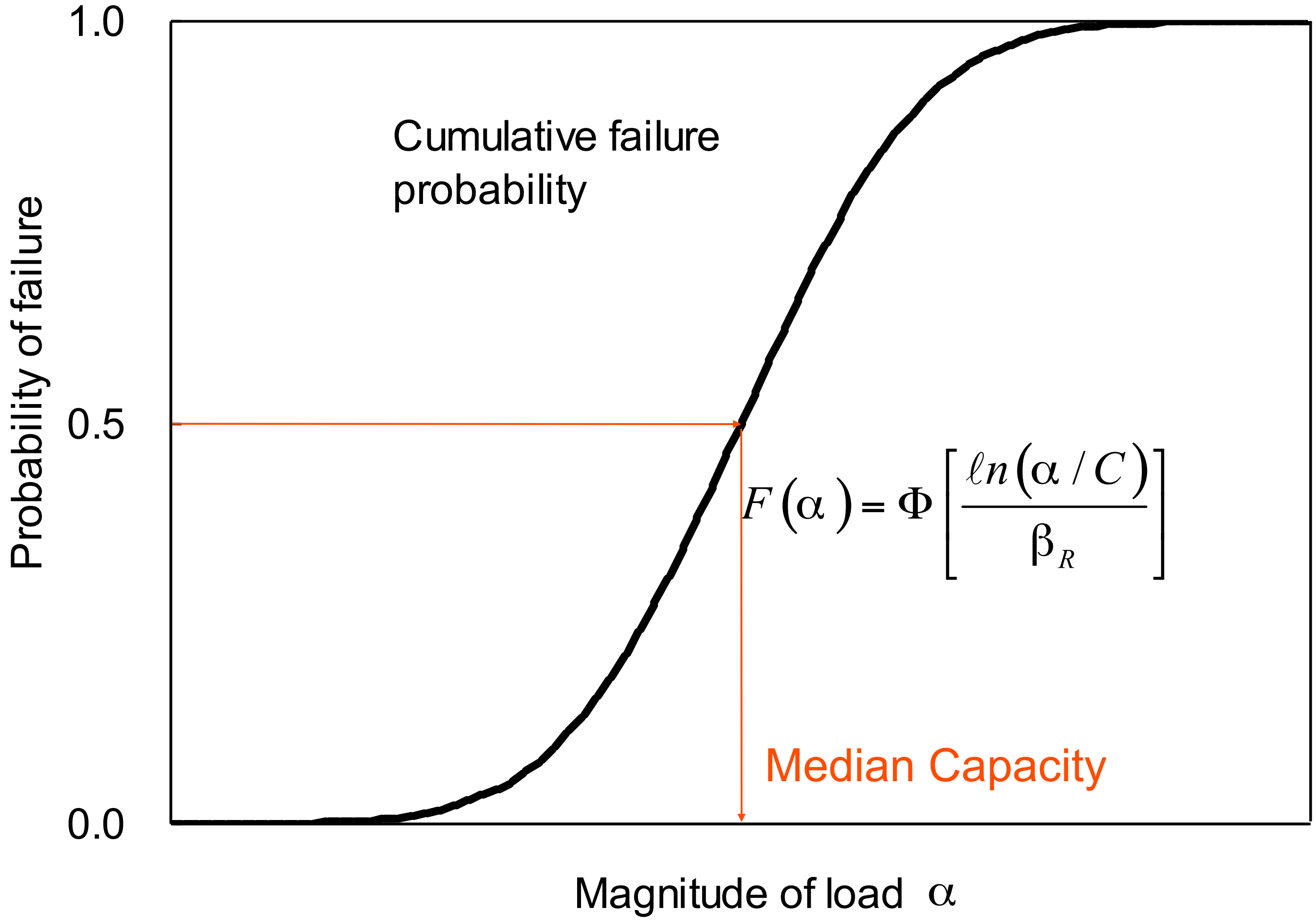
- Seismic capacity test (e.g. vibration table test)
  - Obtain additional information

Limited number of the test..... Best test conditions

Mathematical model for seismic margin



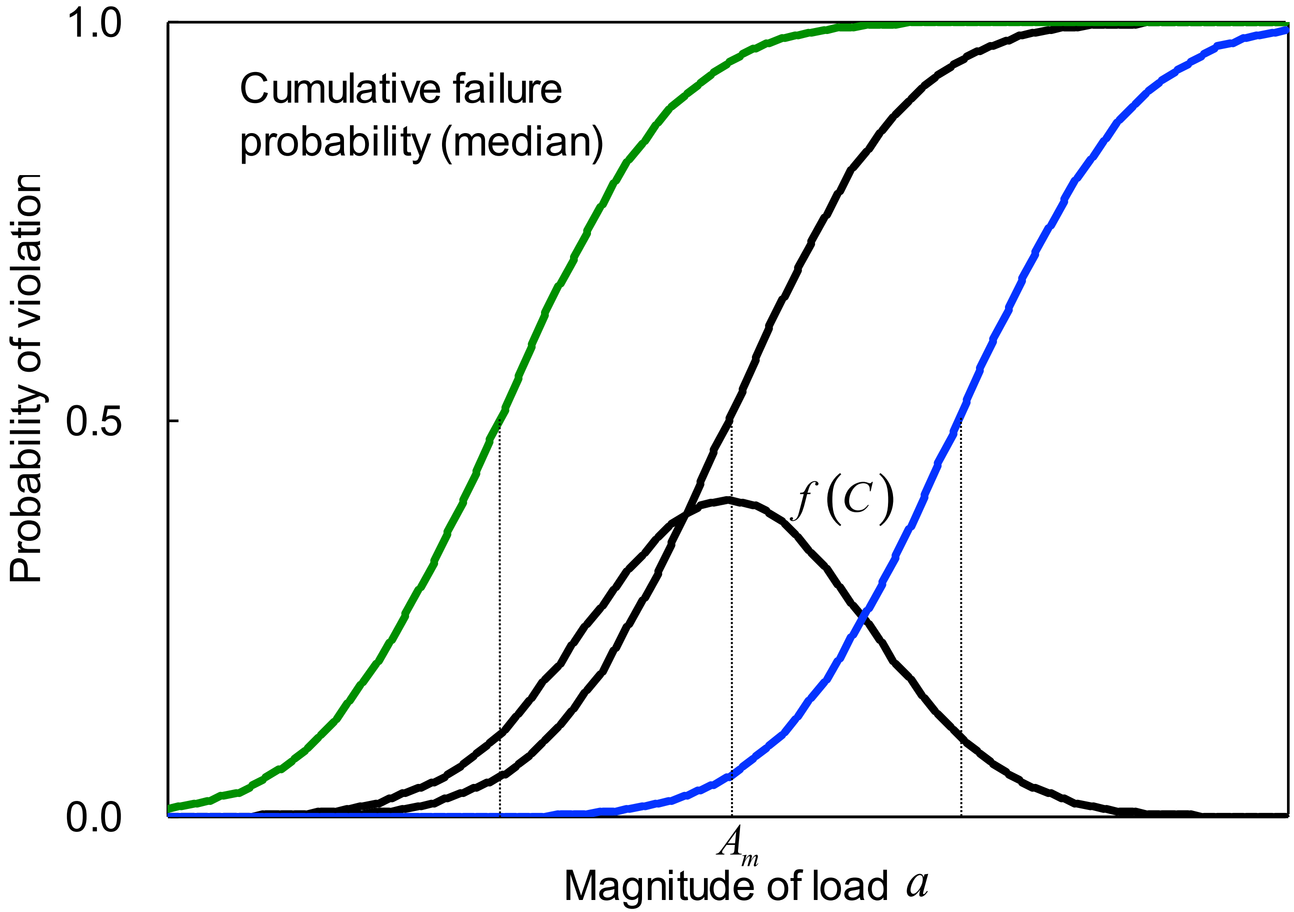
Mathematical model for seismic margin



$$F(\alpha) = \Phi\left[\frac{\ell n(\alpha / C)}{\beta_R}\right]$$

Mathematical model for seismic margin and uncertainty

$$f(C)=\frac{1}{\sqrt{2\pi}\,\beta_U C}\exp\left[-\frac{1}{2}\left\{\frac{\ell n\left(C/A_m\right)}{\beta_U}\right\}^2\right] \qquad F(\alpha)=\Phi\left[\frac{\ell n\left(\alpha/C\right)}{\beta_R}\right]$$



Response-Strength Model

$$\boxed{\xi = R / S}$$

$$R = LN(R_m, \beta_{Res})$$

応答の確率分布

$$S = LN(S_m, \beta_{Str})$$

強度の確率分布

損傷パラメータ

$$\xi \geq 1: \ failure\,criterion$$

$$f(\xi) = \phi\left[\frac{\ell n(\xi / \xi_m)}{\beta_\xi}\right]$$

$$\xi_m = R_m / S_m$$

$$\beta_\xi = \sqrt{\beta_{Res}{}^2 + \beta_{Str}{}^2}$$

Conditional failure probability fragility and R-S model

Fragility model

$$F(\alpha) = \Phi\left[\frac{\ell n(\alpha / A_m) - \beta_U \cdot \Phi^{-1}(p))}{\beta_R}\right]$$

Response-strength model

$$F(\alpha) = \Phi\left[\frac{\ell n\left(\alpha / A_m\right) - \ell n\left(C / A_m\right)}{\beta_\xi}\right]$$

$$\beta_R = \beta_\xi = \sqrt{\beta_{Res}{}^2 + \beta_{Str}{}^2}$$

Variability of response to strength (random)

$$\beta_U = \frac{1}{\Phi^{-1}(p)} \ell n \frac{C}{A_m}$$

Uncertainty of equipment capacity

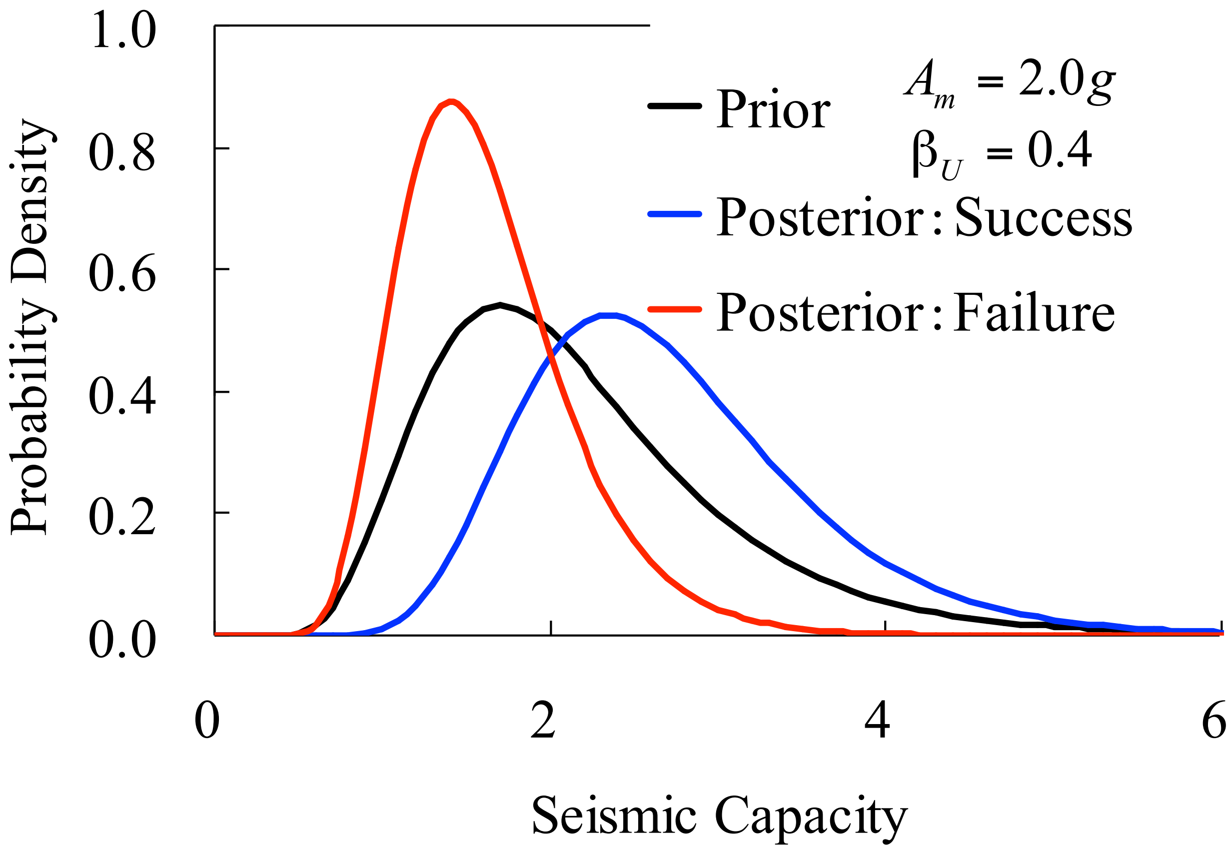
Bayesian Update of Capacity

Bayes Equation

$$f\left(C|E\right)=\frac{f\left(C\right)L\left(E|C\right)}{\int_0^{\infty} f\left(C\right)L\left(E|C\right)dC}$$

Shaking table test (Bernoulli trial)

$$L_k\left(\alpha, N|C\right)=\binom{N}{k}F\left(\alpha|C\right)^k\left\{1-F\left(\alpha|C\right)\right\}^{N-k}$$



N=1 (single test)

$$L_0\left(\alpha|C\right)=1-F\left(\alpha|C\right)$$

$$L_1\left(\alpha|C\right)=F\left(\alpha|C\right)$$

α: test acceleration
What the test level should be?

Conclusions

- Epistemic uncertainty reduction is necessary in seismic PSA
- Extension of our knowledge concerning uncertain failure phenomena reduces the epistemic uncertainty
- Bayesian method updates seismic fragility based on additional information (seismic test)
- Effective seismic test condition can be determined by information entropy
- Reduction of fragility uncertainty can be predicted by generalized uncertainty Index