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Estimates of Mean Consequences and Confidence Bounds on the Mean Associated With Low-Probability Seismic Events in Total System Performance Assessments

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Outline

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- Assumptions
- Mathematical Approach
- Results
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Introduction

- U.S. regulations for high-level radioactive waste disposal require that a mean dose to members of the public does not exceed a prescribed value
- A possible mechanism for early breaching of engineered barrier system components is drift degradation and seismic events of high magnitude (i.e., low recurrence rate)

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Introduction (Continued)

- Consequence estimates can be obtained using a performance assessment (PA) model
  - A large number of variables affecting the potential repository performance are considered
  - Propagation of input uncertainty is accomplished using Monte Carlo sampling
  - Only few hundreds to few thousands of Monte Carlo realizations are typically performed
- Special methodologies are needed to derive confidence bounds on mean consequences of low probability events

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Objectives

- Present an approach to estimate consequences of low recurrence rate seismic events with a limited number of Monte Carlo realizations for a particular type of PA model
  - PA model of interest: consequences per waste package (WP) are independent of the process causing waste package failure (e.g., the consequence per waste package is the same for high and low intensity seismic events)
- Develop formulas for confidence bounds on mean consequences

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Assumptions

- Only events of recurrence rates, λ, less than a threshold (e.g., $\lambda<10^{-4}$ yr^{-1}) damage the waste package
  - Facilities/structures are assumed to have been designed and built to withstand events of $\lambda \geq 10^{-4}$ yr^{-1}
- The probability for an event, p_e, to cause waste package failure is time independent
- A waste package can be in two states: breached or not

Assumptions (Continued)

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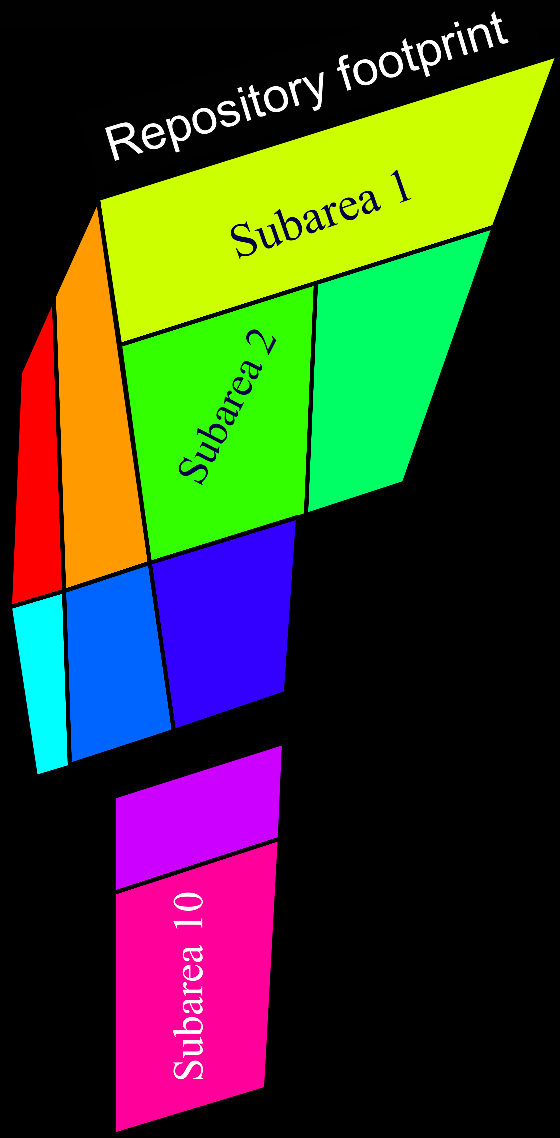
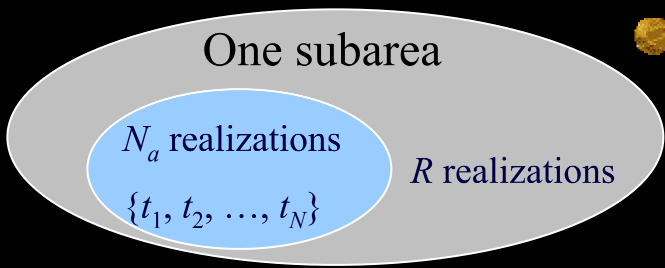


One representative waste package is used to simulate a set

- All waste packages in a subarea are assumed simultaneously breached
- Conditions controlling radionuclide releases (temperature, water flow rates, in-package chemistry) are assumed identical for all waste packages in a subarea

Problem Description



Probability for a realization to include a waste package breaching event:

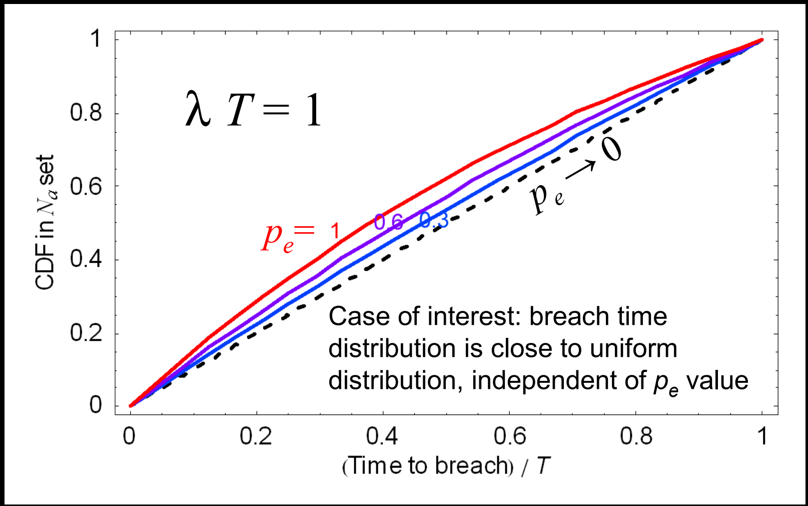
$$p = 1 - e^{-p_e \lambda T} \approx \frac{N_a}{R}$$

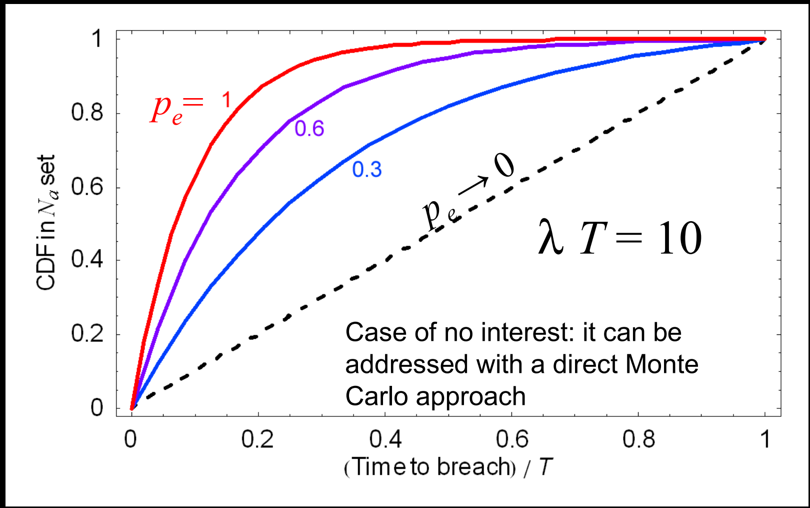
T: simulation time

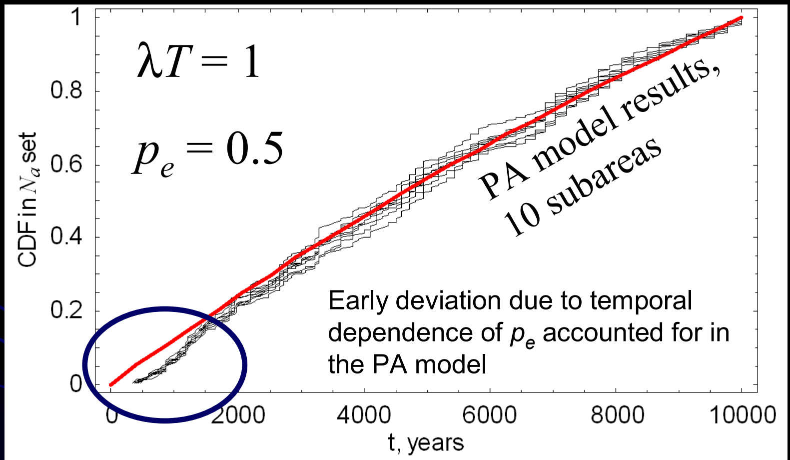
λ: recurrence rate

- In most realizations, there is no waste package breaching (because λ and p_e are small for the case of interest)
- $\{t_1, t_2, \ldots, t_N\}$ is the collection of breach times in the set N_a (one subarea)
  - Breach times follow a truncated exponential distribution with recurrence rate equal to $p_e\,\lambda$
- If product $p_e\,\lambda$ is small, there are not enough realizations (set N_a is too small) to compute converging statistics on consequences

Breach Time Distribution







In the N_a set (one subarea) for the case of interest ($\lambda T \leq 1$), the cumulative distribution of breach times is quasi-independent of the value of p_e

Mathematical Approach

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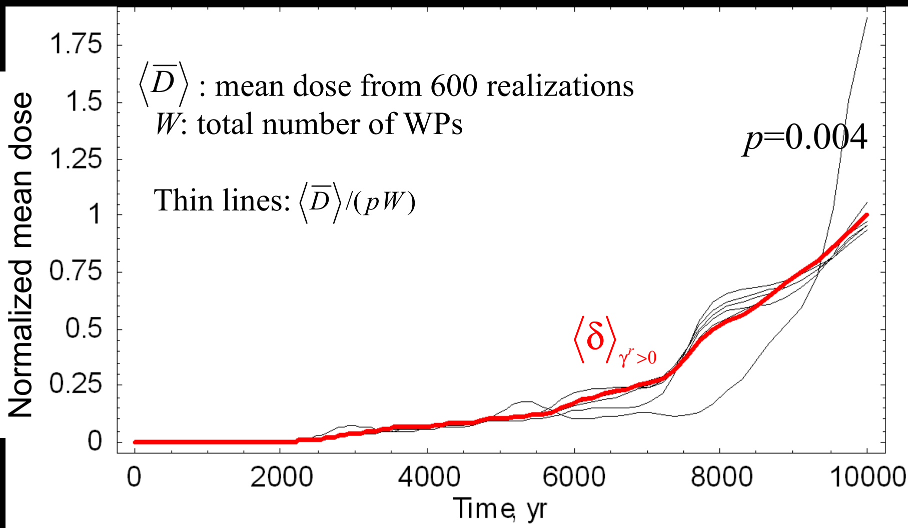
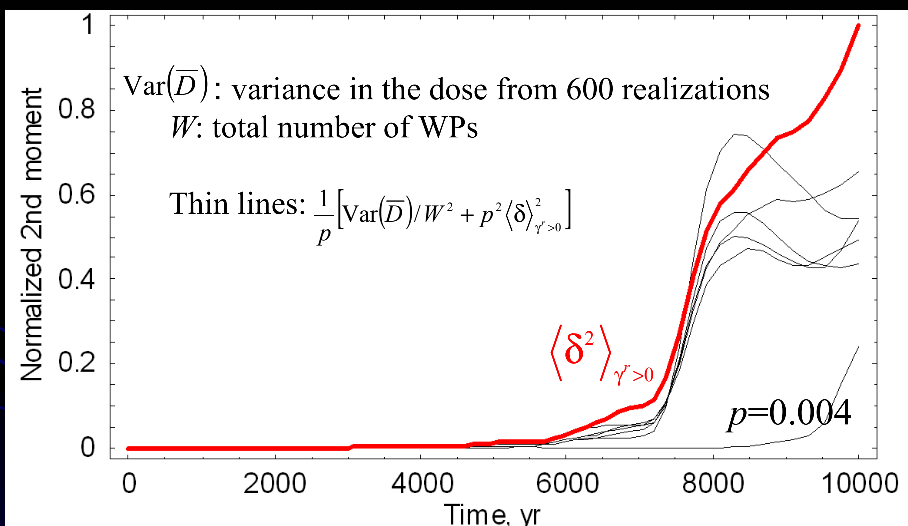
- Run the PA model with a high value of p_e (or p)
- Derive statistics in the N_a subset (one subarea only)
  - Moments of the dose per waste package: $\left\langle \delta^m \right\rangle_{\gamma^r>0}$, m=1, 2, 3, …
  - Statistics are independent of the value of p
- Derive statistics for the complete R set (case of interest: low value of p) from the N_a subset statistics
  - Total mean dose (aggregated from all subareas)
  - Analytical upper bound in the standard deviation
    - Derived by assuming perfectly correlated subareas
    - Used to assist in the understanding of the significance of the seismic scenario

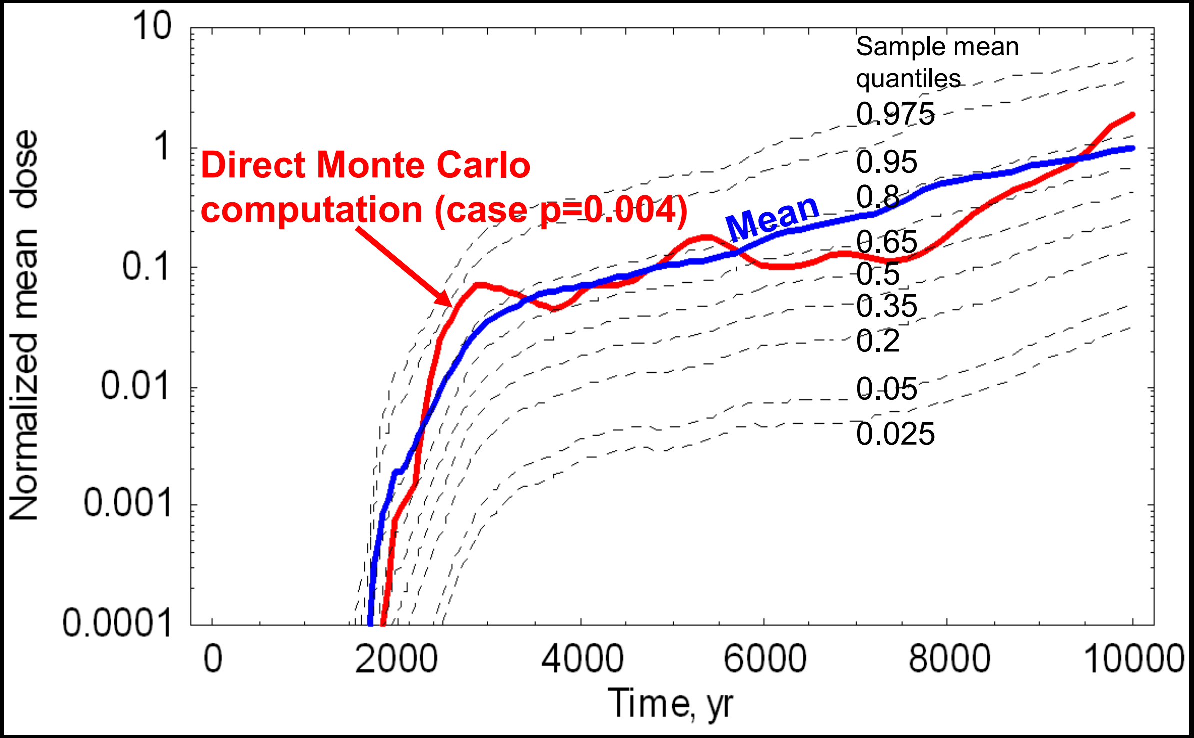
Results





- Similar results of the mean dose per waste package in the N_a set were derived independently of the value of p
- The reference red line was computed with the case p=0.4

Results



Confidence interval computed by assuming that, for every time step, the mean and standard deviation in the sample mean are computed as (case p=0.004)

$$\langle \overline{D} \rangle = p \langle \delta \rangle_{\gamma' > 0} \sum_{a=1}^{A} w_a = p \langle \delta \rangle_{\gamma' > 0} W$$

$$\mathrm{SDev}\left(\langle \overline{D} \rangle \right) \leq \frac{W}{\sqrt{R}} \sqrt{p \langle \delta^2 \rangle_{\gamma' > 0} - p^2 \langle \delta \rangle_{\gamma' > 0}^2}$$

w_a: WPs in a subarea

W: Total WPs in repository

$\langle \delta^n \rangle_{\gamma' > 0}$: n moment (dose per WP) in set N_a

(moment computed with case p=0.4)

A More General Case

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- The previous derivation assumed that all of the waste packages in a subarea were breached once an event of sufficient magnitude occurred
- If only a fraction, *n*, of the waste packages in a subarea is breached then the formulas are modified as
  - Sample mean: $\langle \overline{D} \rangle = p W \langle n \delta \rangle_{\gamma^r > 0}$
  - Sample variance: $\mathrm{Var}(\overline{D}) = \langle \overline{D}^2 \rangle - \langle \overline{D} \rangle^2 \leq W^2 \left(p \langle n^2 \delta^2 \rangle_{\gamma^r > 0} - p^2 \langle n \delta \rangle^2_{\gamma^r > 0} \right)$
  - SDev in the sample mean: $\mathrm{SDev}(\langle \overline{D} \rangle) \leq \frac{W}{\sqrt{R}} \sqrt{p \langle n^2 \delta^2 \rangle_{\gamma^r > 0} - p^2 \langle n \delta \rangle^2_{\gamma^r > 0}}$
  - The distribution for the fraction, *n*, is assumed independent of the subarea, but could be a function of other factors (e.g., event intensity)

Results

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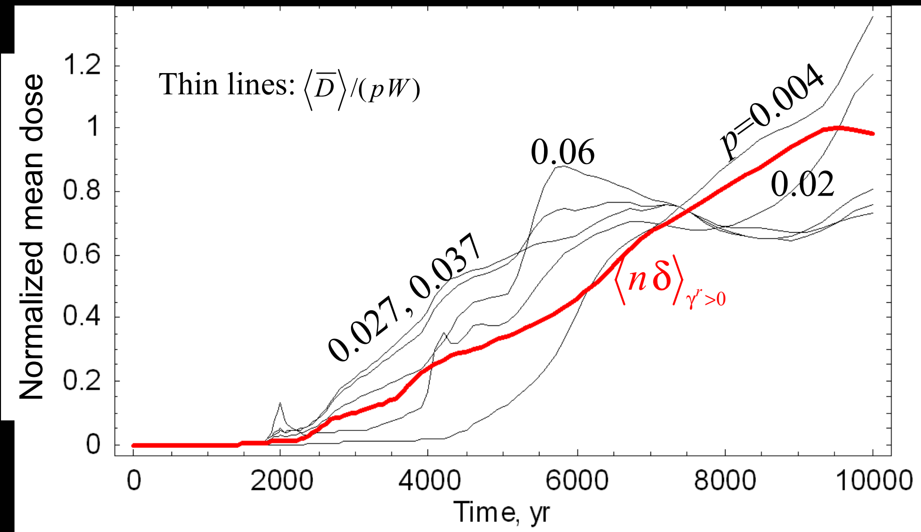
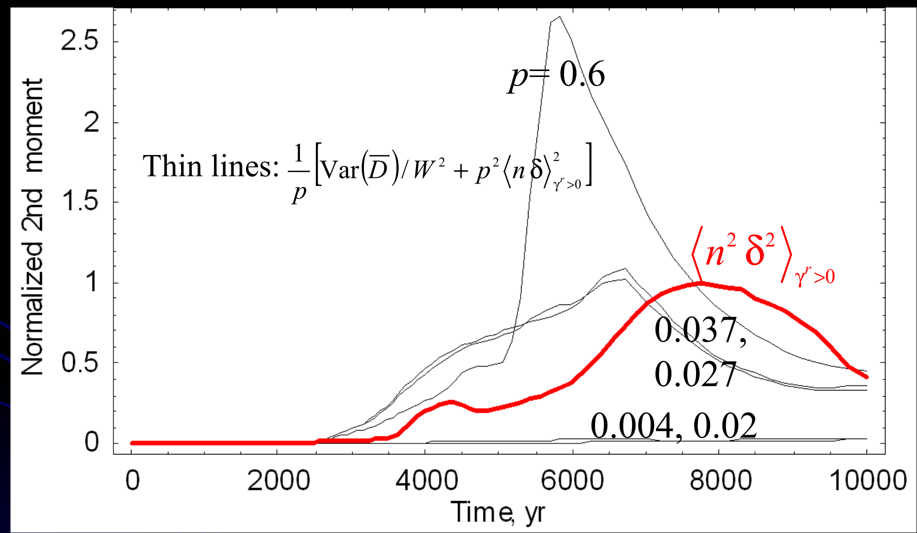
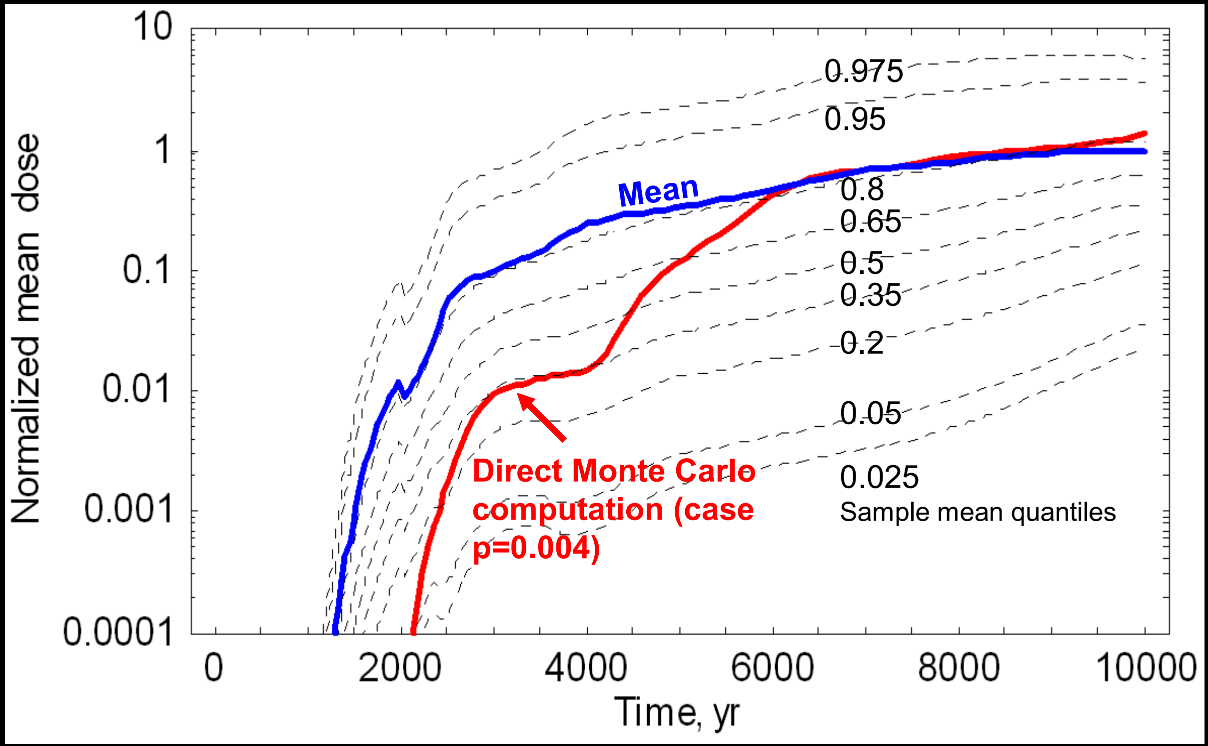




- The fraction, *n*, randomly sampled in this example, is a source of extra variance in the mean dose
- The reference red line was computed with a stylized 500-realization run
  - Breach times uniformly distributed
  - One breaching event in each realization (i.e., N_a=*R*)

Results



Confidence interval computed by assuming that, for every time step, the mean and standard deviation in the sample mean are computed as (case p=0.004)

$$\langle \overline{D} \rangle = p W \langle n \delta \rangle_{\gamma^r > 0}$$

$$\mathrm{SDev}(\langle \overline{D} \rangle) \le \frac{W}{\sqrt{R}} \sqrt{p \langle n^2 \delta^2 \rangle_{\gamma^r > 0} - p^2 \langle n \delta \rangle^2_{\gamma^r > 0}}$$

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Conclusions

- An approach was developed to estimate mean consequences of seismic events in a performance assessment model
- The approach was extended to account for the case where only a fraction (defined by a distribution function) of the waste packages in a subarea may be breached
- Mean consequences can be derived with stylized runs
  - Breach times uniformly distributed
  - One waste package breaching event in each realization
- Derived equations can be used to estimate mean consequences without the need for a large number of PA model realizations

Disclaimer

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