PEER

UCSD

Probabilistic Performance-Based Optimum Seismic Design of (Bridge) Structures

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Sponsored by the Pacific Earthquake Engineering Research Center

Outline

(I) PEER Performance Based Earthquake Engineering (PBEE) Methodology

- Probabilistic **Seismic Hazard** Analysis
- Probabilistic **Seismic Demand** Hazard Analysis
- Probabilistic **Seismic Damage** Hazard Analysis
- Probabilistic **Seismic Loss** Hazard Analysis

(II) Parametric PBEE Analysis of SDOF System

- **Yield strength F_y** as varying parameter
- **Hardening ratio b** as varying parameter
- Both **mass m and initial stiffness k_0** as varying parameters (with fixed **k_0/m**)
- **Mass m** as varying parameter
- Initial stiffness **k_0** as varying parameter

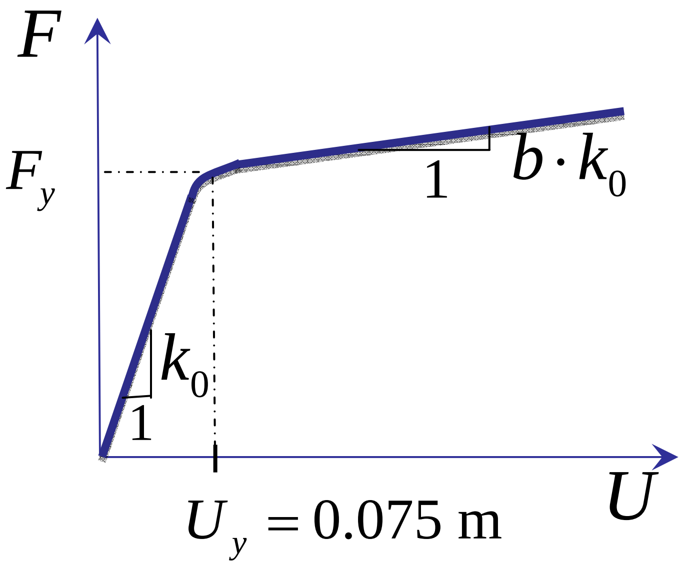
(III) Optimization Formulation for Probabilistic Performance Based Optimum Seismic Design

(I) PEER PBEE Methodology

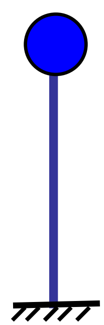
(Forward PBEE Analysis)

SDOF Bridge Model

- **Single-Degree-of-Freedom Bridge Model:**
  - SDOF bridge model with the same initial period as an MDOF model of the Middle Channel Humboldt Bay Bridge previously developed in OpenSees.



SDOF Model
(Menegotto-Pinto)



$T_1 = 1.33$ s

$m = 6{,}150$ tons

$k_0 = 137{,}200$ kN/m

$F_y = 10{,}290$ kN

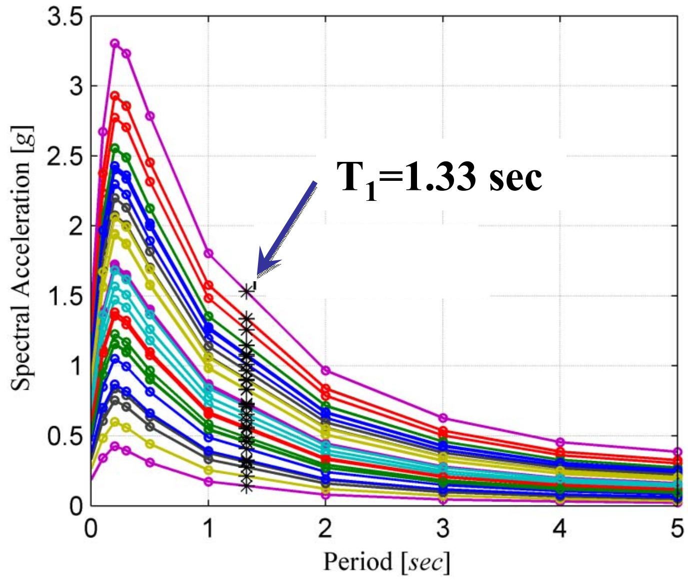
$b = 0.10$

$\xi = 0.02$

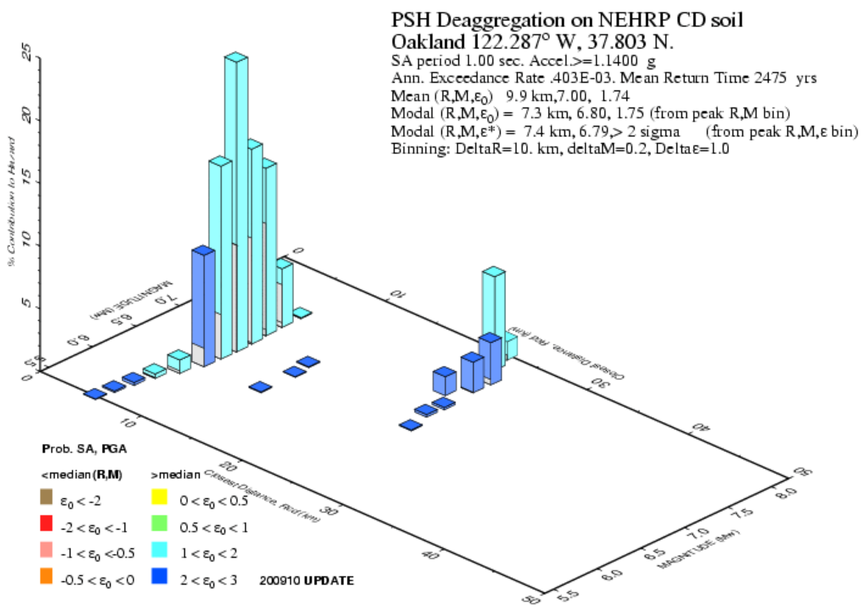
Site Description and Prob. Seismic Hazard Analysis

- **Site Location:** Oakland (37.803N, 122.287W)
- **Site Condition:** V_{s30} = 360m/s (Class C-D)
  - **Uniform Hazard Spectra** are obtained for **30 hazard levels** from the **USGS 2008 Interactive Deaggregation** software/website (beta version)
- **Uniform Hazard Spectra and M-R Deaggregation:**

Uniform Hazard Spectra



Deaggregation (T_1 = 1 sec, 2% in 50 years)

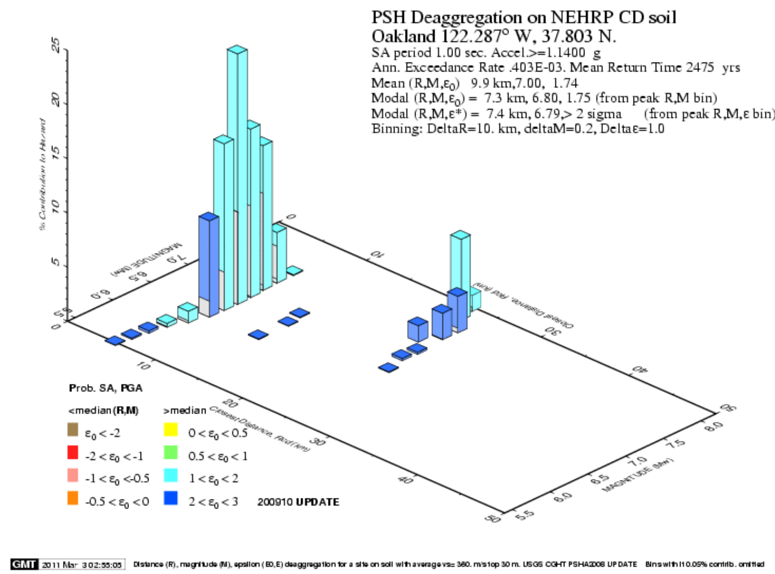


Earthquake Record Selection

- **Earthquake Record Selection:**

  - **Records were selected from NGA database** based on geological and seismological conditions (e.g., fault mechanism), M-R deaggregation of probabilistic seismic hazard results, and local site condition (e.g., V_{s30})

    - NGA Excel Flatfile (3551 records)
    - Mechanism: Strike-slip (➔1004 records)
    - Magnitudes: 5.9 to 7.3 (➔652 records)
    - Distance: 0 – 40 km (➔193 records)
    - V_{s30}: C-D range (➔146 records)



  - **146 horizontal ground motion components were selected from NGA database**

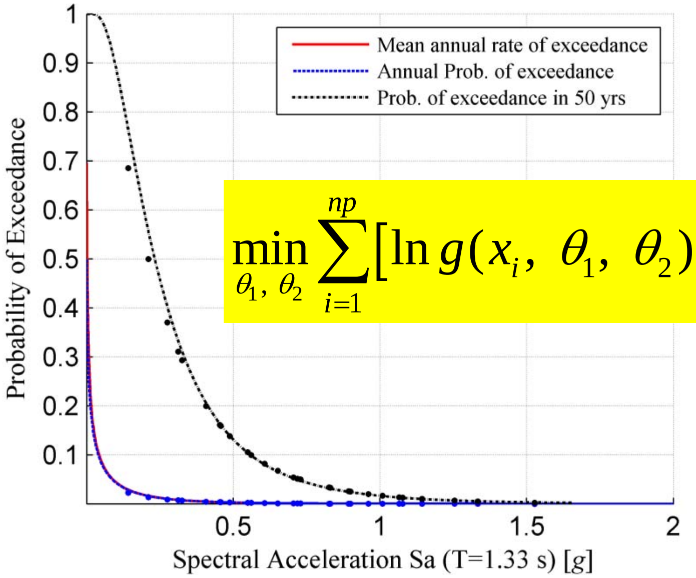
Probabilistic Seismic Hazard Analysis

- **Seismic Hazard Curve (for single/scalar Intensity Measure *IM*):**

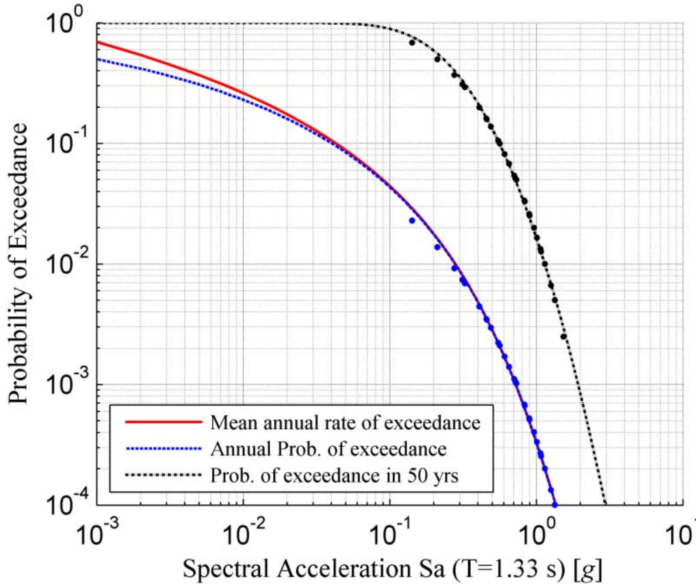
$$\nu_{IM}(im) = \sum_{i=1}^{N_{flt}} \nu_i \cdot \int_{R_i}\int_{M_i} P\left[IM > im \mid m, r\right] \cdot f_{M_i}(m) \cdot f_{R_i}(r) \cdot dm \cdot dr$$

$S_a(T_1,\ \xi = 5\%)$

- **Least Square Fitting of 30 Data Points (IM_i, $MARE_i$) from USGS:**
  - Data Points: $(x_i,\ y_i) = (IM_i,\ PE50_i),\quad i = 1, 2, \cdots, 30$
  - Fitting Function (lognormal CCDF): $g(x,\ \theta_1,\ \theta_2) = 1 - \Phi\left(\dfrac{\ln x - \theta_1}{\theta_2}\right)$



$$\min_{\theta_1,\ \theta_2} \sum_{i=1}^{np} \left[\ln g(x_i,\ \theta_1,\ \theta_2) - \ln y_i\right]^2$$



Probabilistic Seismic Demand Hazard Analysis

- **Demand Hazard Curve:**

$$\nu_{EDP}(edp) = \int_{IM} \underbrace{P\left[EDP > edp \mid IM\right]}_{\text{Complementary CDF of EDP given IM}} \underbrace{\left| d\nu_{IM}(im) \right|}_{\text{Seismic hazard curve}}$$

- **Probabilistic Seismic Demand Analysis conditional on IM:**
  - **"Cloud Method"** based on following assumptions**:**

1. Linear regression after **ln** transformation of predictor and response variables:

$$\hat{\mu}_{EDP|\ln IM} = \mathrm{E}[\ln EDP \mid IM = im] = \hat{a} + \hat{b}\ \ln IM$$

2. Variance of EDP independent of IM:

$$\hat{S}^2 = \frac{\sum_{i=1}^{n} \left(ln\ edp_i - \left(\hat{a} + \hat{b}\ \ln im_i \right) \right)^2}{n-2}$$

3. Probability distribution of EDP|IM assumed to be **Lognormal:**

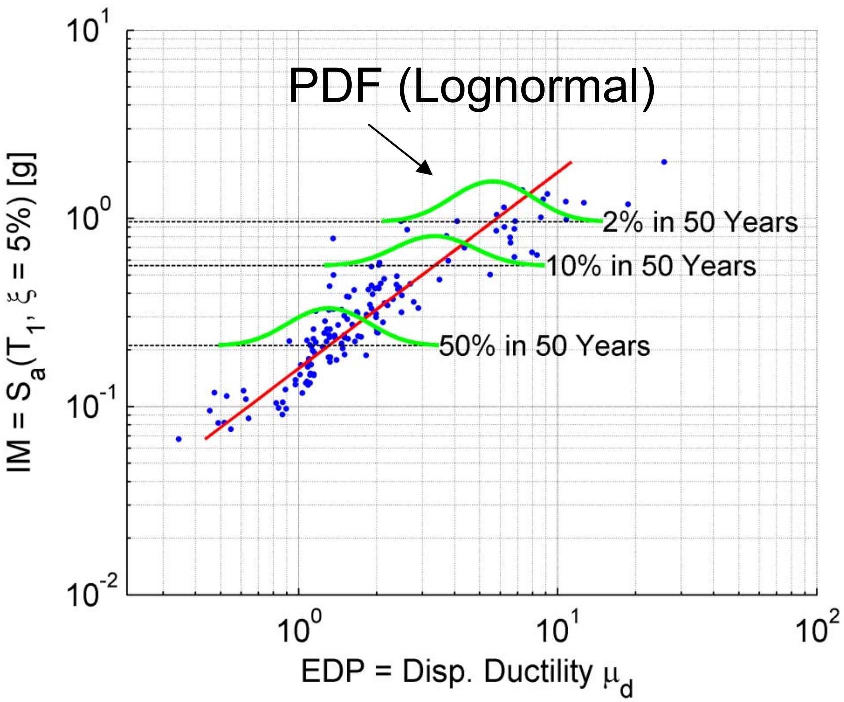
$$EDP \mid IM \sim LN(\lambda,\ \varsigma)$$

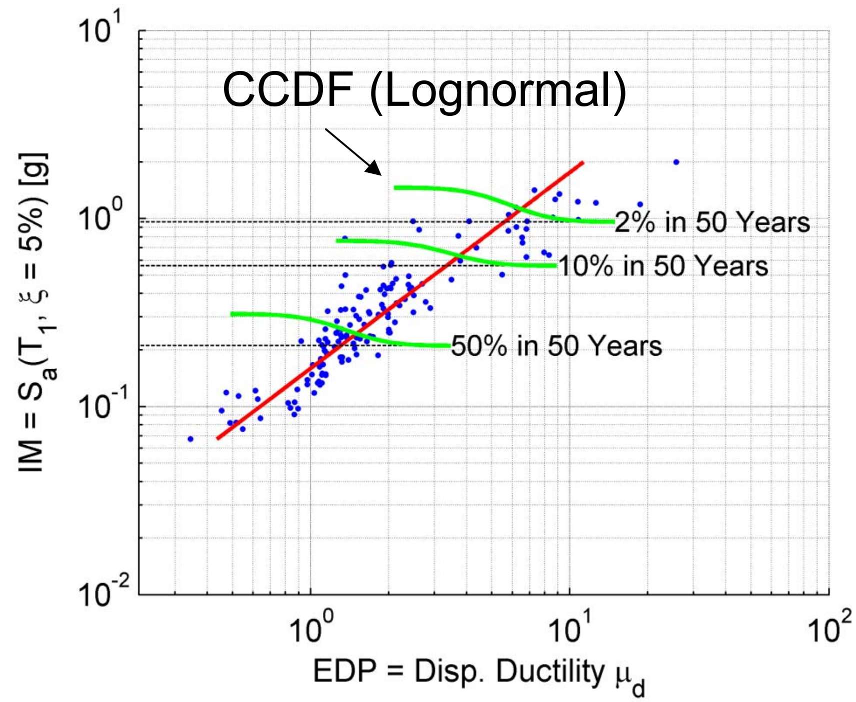
where $\lambda = \hat{\mu}_{\ln EDP|IM} = \hat{a} + \hat{b}\ \ln IM$ and $\varsigma = \hat{\sigma}_{\ln EDP|IM} = \sqrt{\hat{S}^2}$

Probabilistic Seismic Demand Hazard Analysis

• EDP: Displacement Ductility

➢ Regression analysis results and PDF/CCDF for EDP|IM shown at three hazard levels commonly used in Earthquake Engineering:





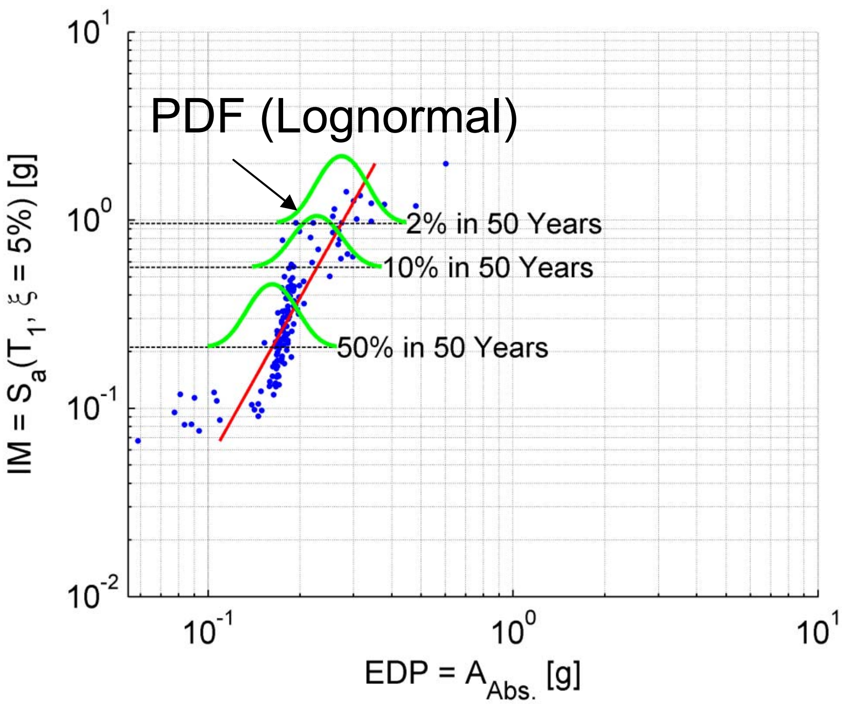
Where the displacement ductility is defined as:

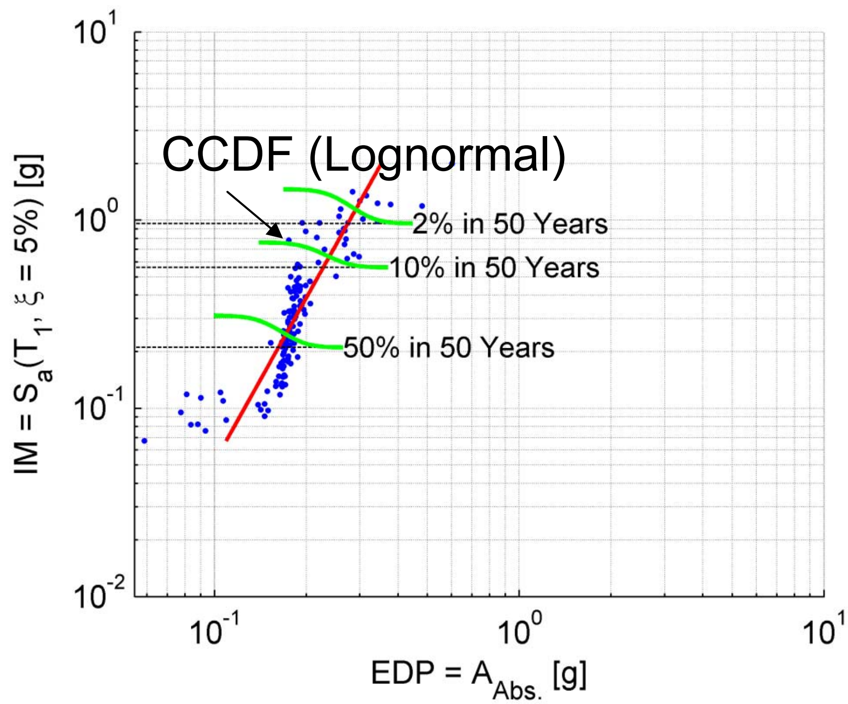
$$\mu_d = \underset{0 < t < t_d}{Max}\left(\frac{u(t)}{U_y}\right)$$

Probabilistic Seismic Demand Hazard Analysis

• EDP: Peak Absolute Acceleration

➢ Regression analysis results and PDF/CCDF for EDP|IM shown at three hazard levels commonly used in Earthquake Engineering:



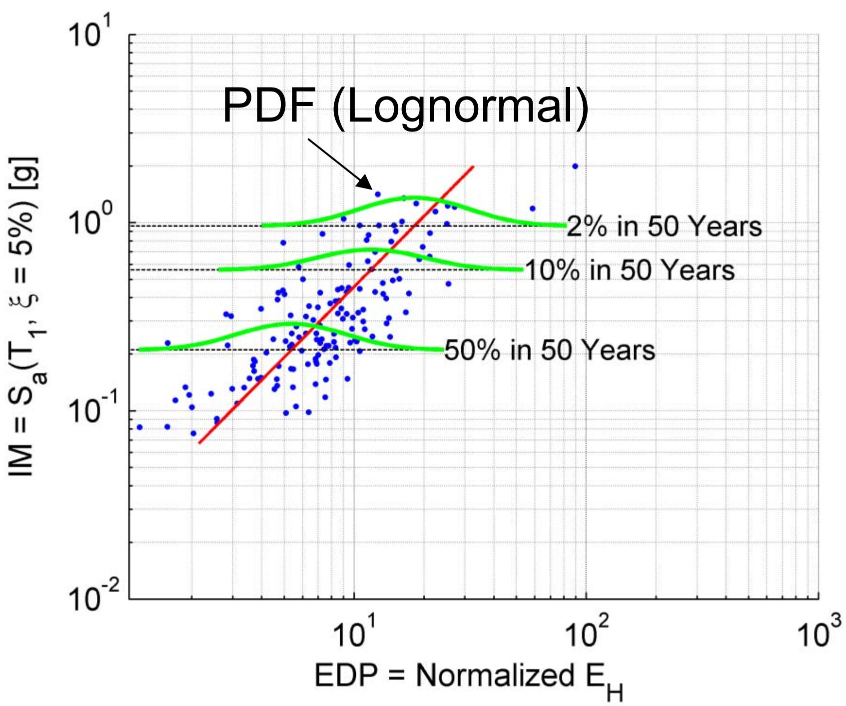


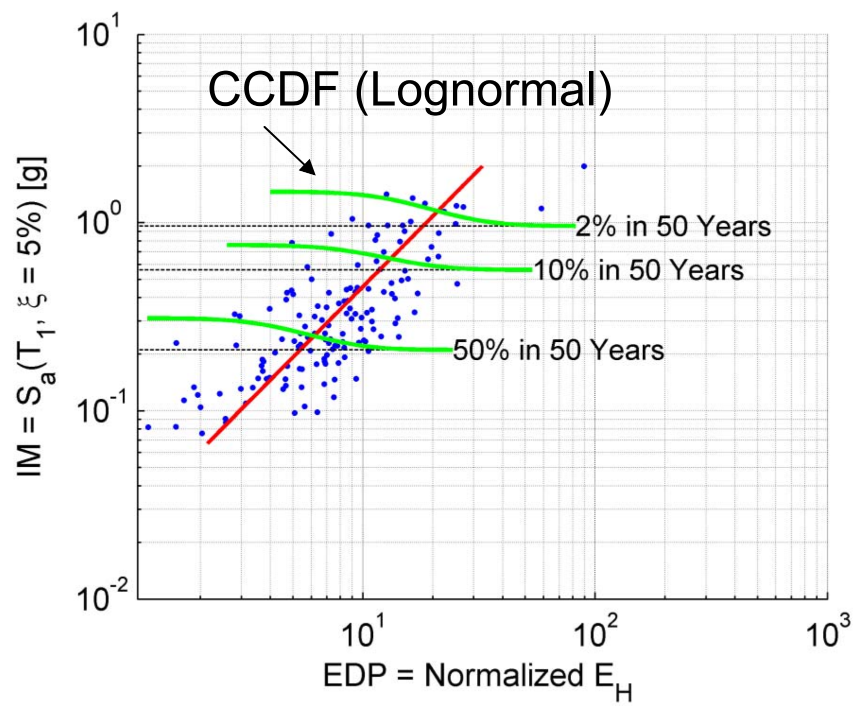
Where the peak absolute acceleration is defined as: $A_{Abs.} = \underset{0 < t < t_d}{Max} \left(\frac{\ddot{u}(t)}{g} \right)$

Probabilistic Seismic Demand Hazard Analysis

• EDP: Normalized Hysteretic Energy Dissipated

➢ Regression analysis results and PDF/CCDF for EDP|IM shown at three hazard levels commonly used in Earthquake Engineering:





Where the Normalized hysteretic energy is defined as: $$E_H = \frac{\int_0^{t_d} R(t)\,du(t) - E_E}{F_y U_y}$$

Probabilistic Seismic Demand Hazard Analysis

- **Demand Hazard Curve:**

$$\nu_{EDP}(edp) = \int_{IM} P\left[EDP > edp \middle| IM = im\right] \left|d\nu_{IM}(im)\right|$$

- **Deaggregation of $\nu_{EDP}(edp)$ with respect to IM:**

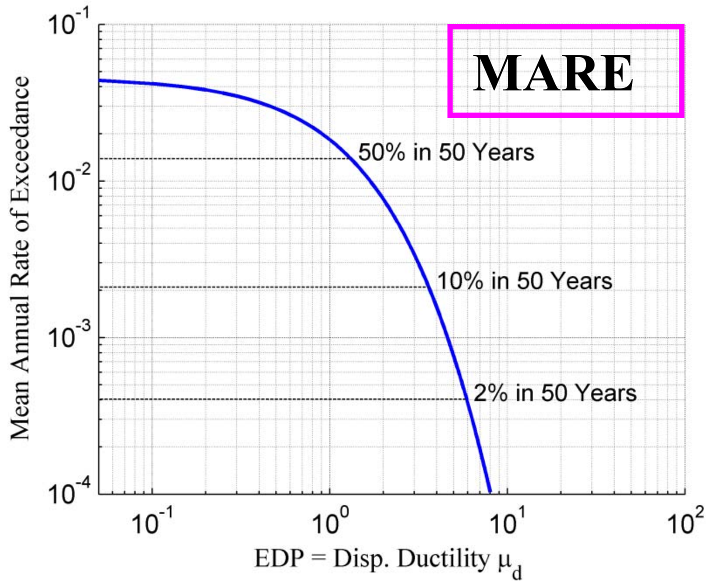
$$\nu_{EDP}(edp) = \int_{IM} P\left[EDP > edp \middle| IM\right] \left|\frac{d\nu_{IM}(im)}{dim}\right| dim$$

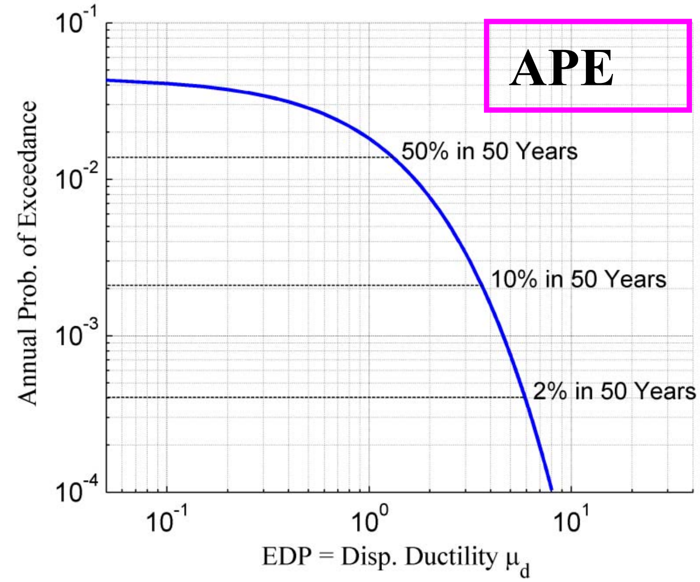
$$= \sum_{i} P\left[EDP > edp \middle| IM = im_i\right] \left|\frac{d\nu_{IM}(im_i)}{\Delta(im)_i}\right| \cdot \Delta(im)_i$$

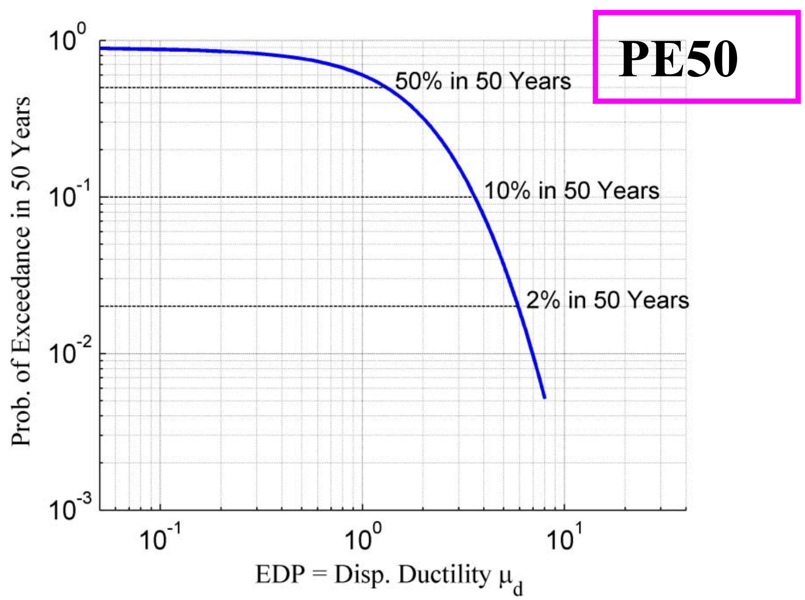
Contribution of bin
***IM = im$_i$* to $\nu_{EDP}(edp)$**

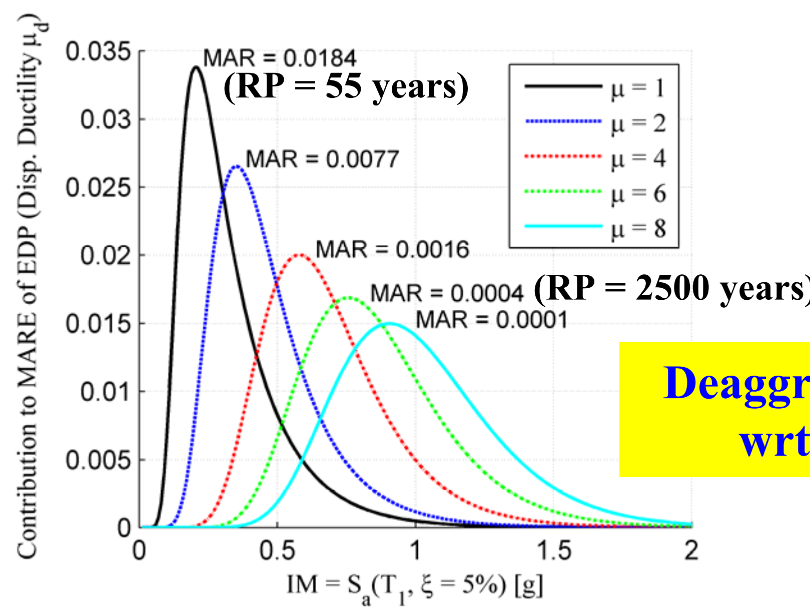
Probabilistic Seismic Demand Hazard Analysis

- Demand Hazard Curve for **EDP = Displacement Ductility μ_d:**





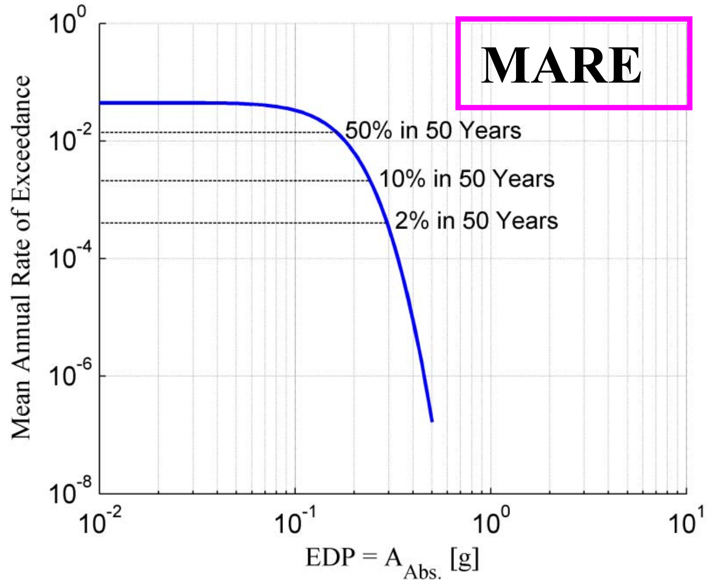


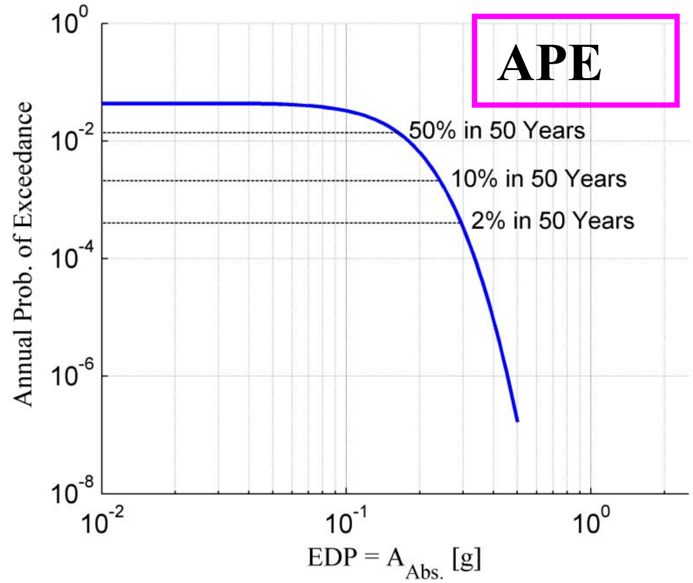


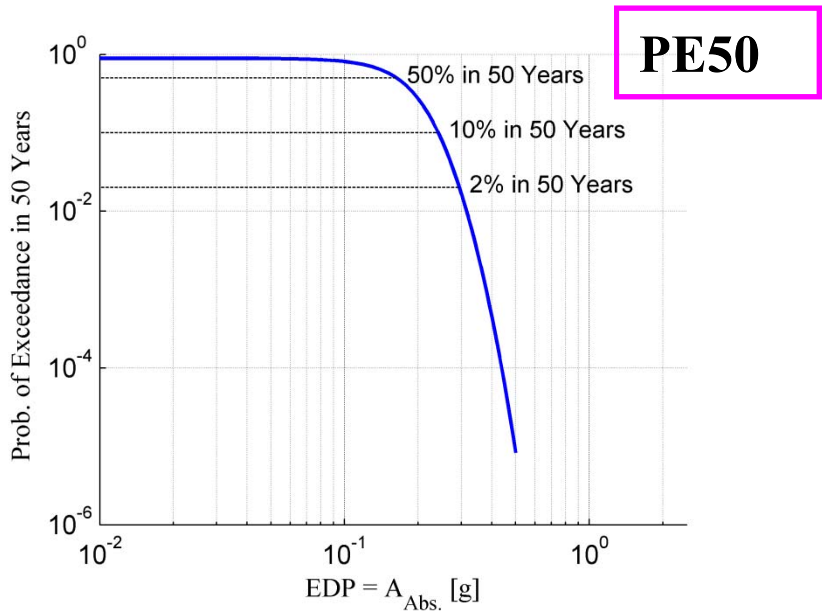
Deaggregation wrt IM

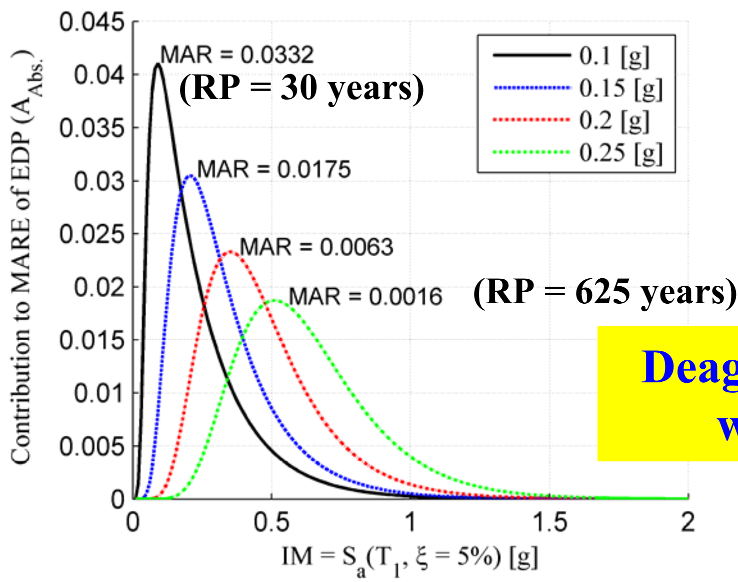
Probabilistic Seismic Demand Hazard Analysis

- Demand Hazard Curve for **EDP = Peak Absolute Acceleration:**





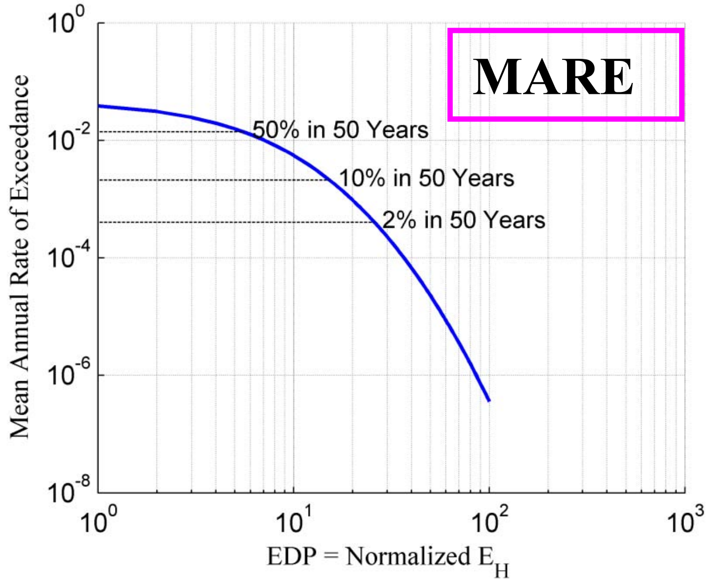


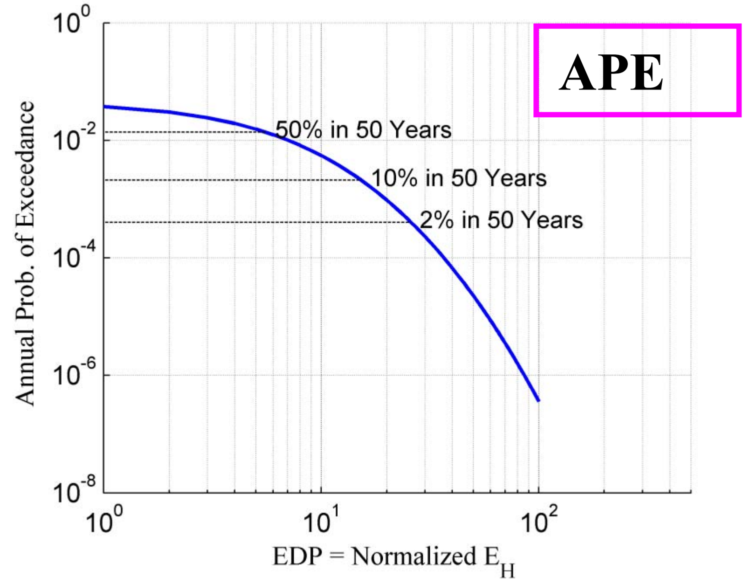


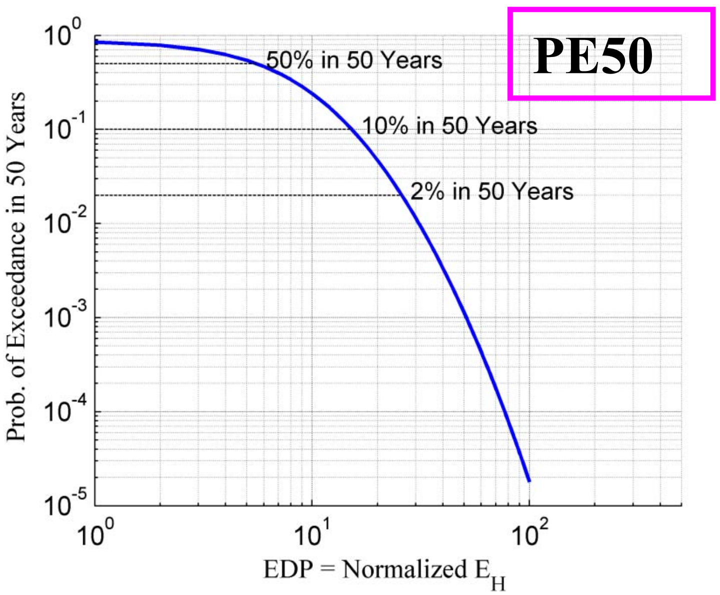
Deaggregation wrt IM

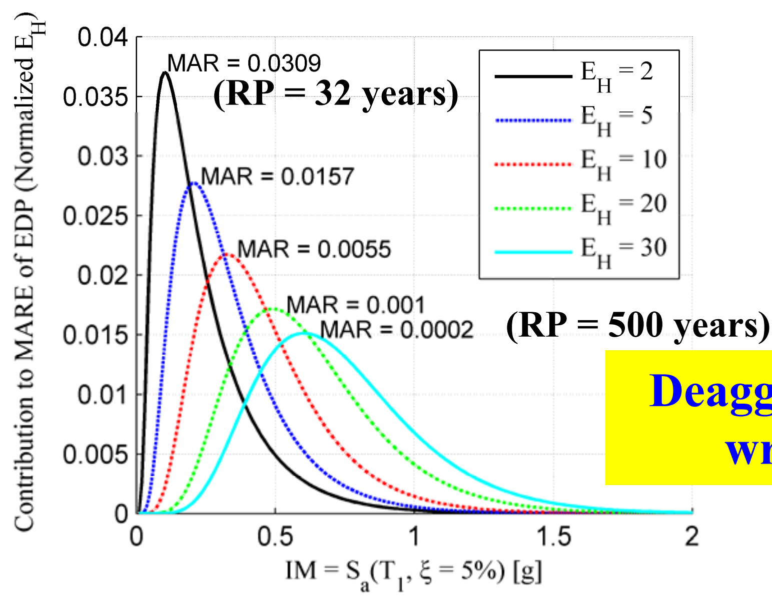
Probabilistic Seismic Demand Hazard Analysis

- Demand Hazard Curve for **EDP = Normalized E_H Dissipated:**









Deaggregation wrt IM

Probabilistic Capacity (Fragility) Analysis

- **Fragility Curves (postulated & parameterized):**
  - Defined as the probability of the structure/component exceeding kth limit-state given the demand.

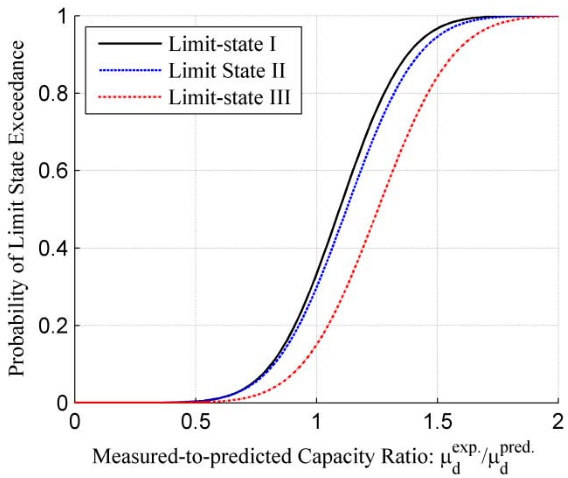
Damage Measure

$$P\left[DM > ls_k \mid EDP = edp\right]$$

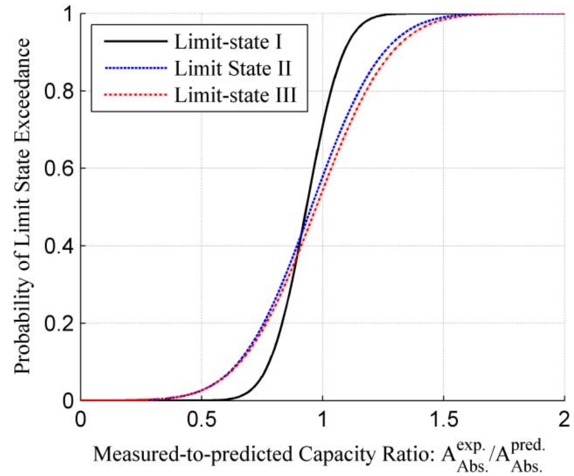
k-th limit state

  - Developed based on analytical and/or empirical capacity models and experimental data.

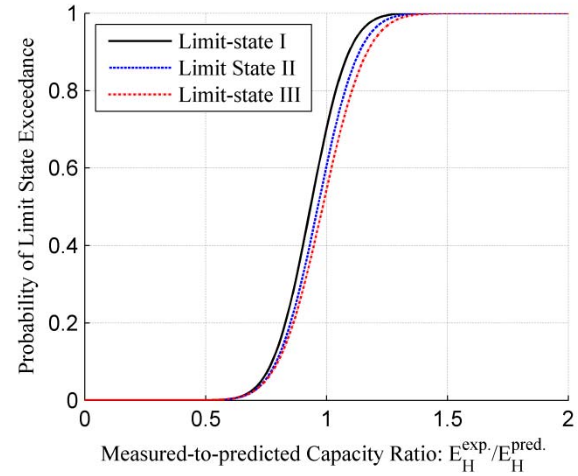
Displacement Ductility



Absolute Acceleration



Normalized E_H Dissipated



Probabilistic Capacity (Fragility) Analysis

- **Fragility Curve Parameters:**

Associated EDP	**Limit-states**	**Predicted Capacity**	**Measured-to-predicted capacity ratio (Normal distributed)**	
			Mean	**c.o.v**
Displacement Ductility	I	$\mu = 2$	1.095	0.201
	II	$\mu = 6$	1.124	0.208
	III	$\mu = 8$	1.254	0.200
Peak Absolute Acceleration [g]	I	$A_{Abs.} = 0.10$	0.934	0.128
	II	$A_{Abs.} = 0.20$	0.952	0.246
	III	$A_{Abs.} = 0.25$	0.973	0.265
Normalized Hysteretic Energy Dissipated	I	$E_H = 5$	0.934	0.133
	II	$E_H = 20$	0.965	0.140
	III	$E_H = 30$	0.983	0.146

Probabilistic Damage Hazard Analysis

- **Damage Hazard (MAR of limit-state exceedance):**

$$\nu_{DS_k} = \int_{EDP} \underbrace{P\left[DM > ls_k \mid EDP = edp\right]}_{\text{Fragility Analysis}} \left| d\nu_{EDP}(edp) \right|$$

Fragility Analysis

- **Deaggregation of Damage Hazard:**

  - with respect to EDP:

Contribution of bin
***EDP = edp**$_i$* **to** ν_{DS_k}

$$\nu_{DS_k} = \sum_i \overbrace{P\left[DM > ls_k \mid EDP = edp_i\right] \frac{\left| d\nu_{EDP}(edp_i) \right|}{\Delta(edp)_i}}^{\text{Contribution of bin } EDP = edp_i \text{ to } \nu_{DS_k}} \Delta(edp)_i$$

  - with respect to IM:

$$\nu_{DS_k} = \sum_i \underbrace{P\left[DM > ls_k \mid EDP\right] \left| \int_{IM} dP\left[EDP > edp \mid IM\right] \right| \frac{\left| d\nu_{IM}(im_i) \right|}{\Delta(im)_i}}_{\text{Contribution of bin } IM = im_i \text{ to } \nu_{DS_k}} \Delta(im)_i$$

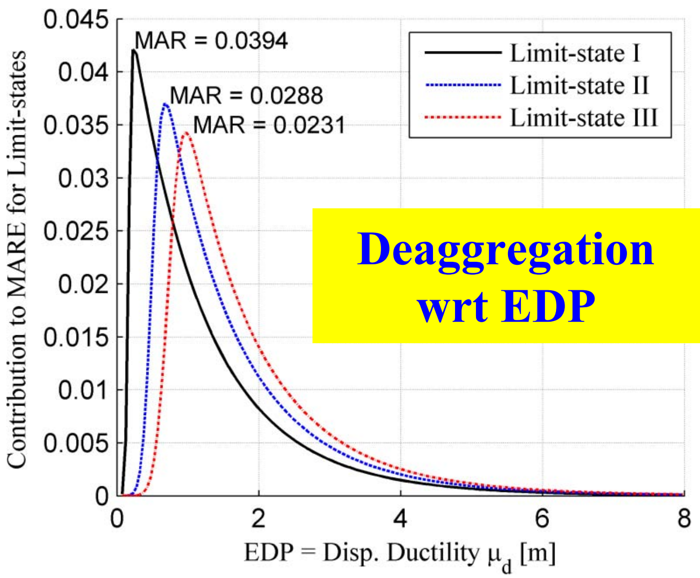
Contribution of bin
***IM = im**$_i$* **to** ν_{DS_k}

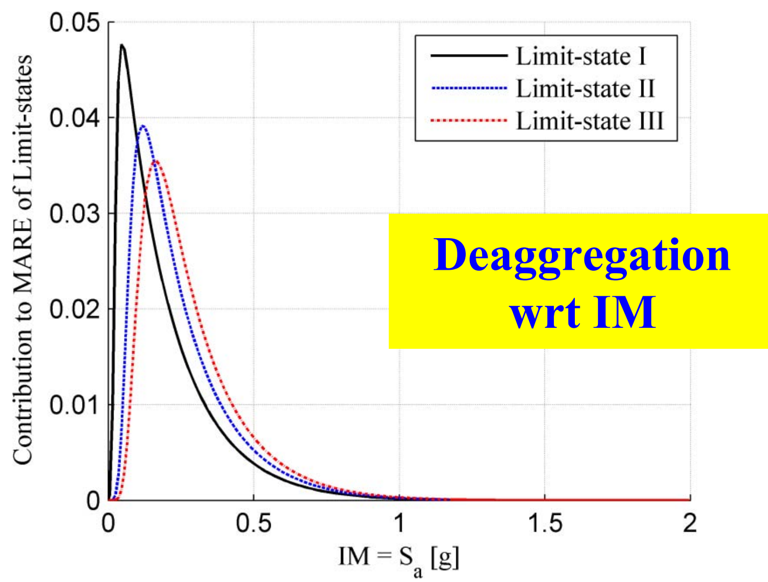
Probabilistic Damage Hazard Analysis

- **Associated EDP = Displacement Ductility:**

Associated EDP	Limit States	MARE	RP	PE50
Displacement Ductility	I (μ_d = 2)	0.0394	26 Years	86%
	II (μ_d = 6)	0.0288	35 Years	76%
	III (μ_d = 8)	0.0231	44 Years	68%

- **Deaggregation Results:**



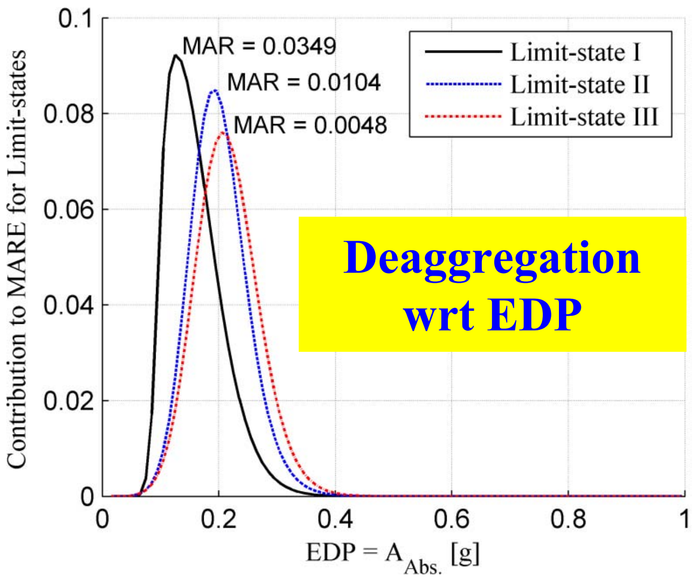


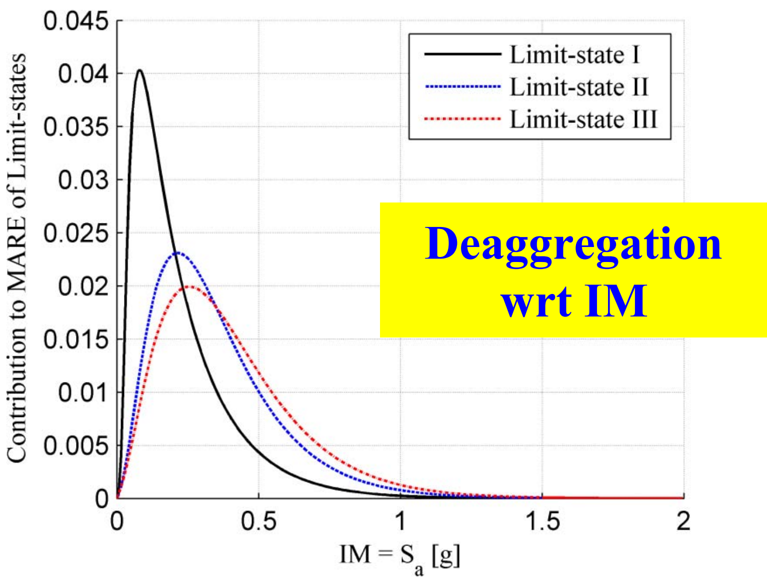
Probabilistic Damage Hazard Analysis

- **Associated EDP = Peak Absolute Acceleration:**

Associated EDP	Limit States	MARE	RP	PE50
Absolute Acceleration	I (A_{Abs} = 0.1g)	0.0349	29 Years	82%
	II (A_{Abs} = 0.2g)	0.0104	96 Years	41%
	III (A_{Abs} = 0.25g)	0.0048	208 Years	21%

- **Deaggregation Results:**



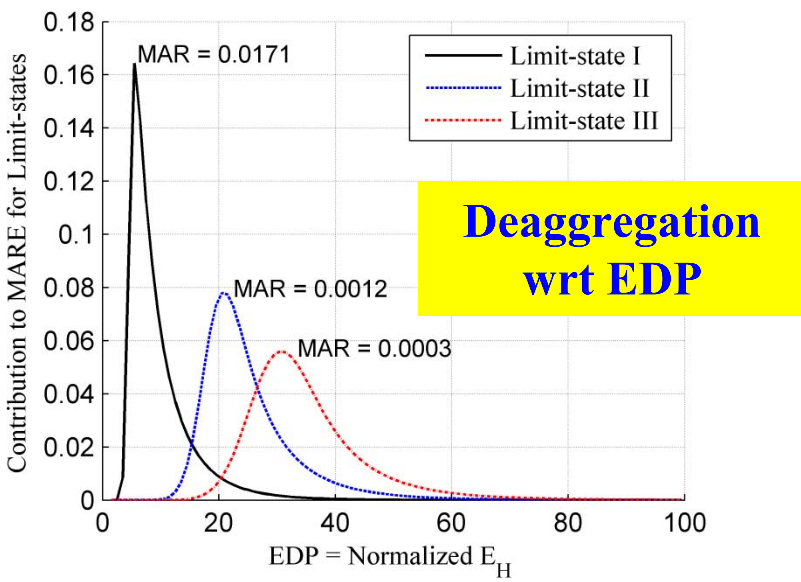


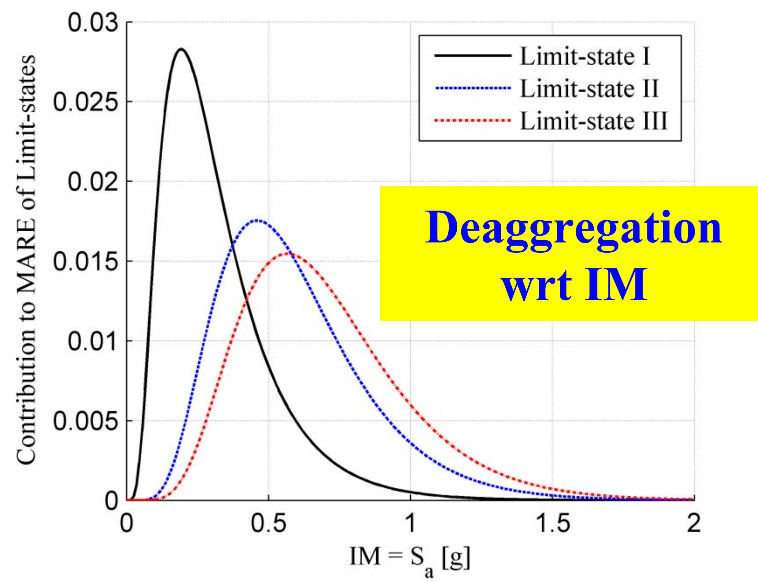
Probabilistic Damage Hazard Analysis

- **Associated EDP = Normalized Hysteretic Energy Dissipated:**

Associated EDP	Limit States	MARE	RP	PE50
Normalized Hysteretic Energy Dissipated	I (E_H = 5)	0.0171	58 Years	57%
	II (E_H = 20)	0.0012	833 Years	6%
	III (E_H = 30)	0.0003	3330 Years	1.5%

- **Deaggregation Results:**





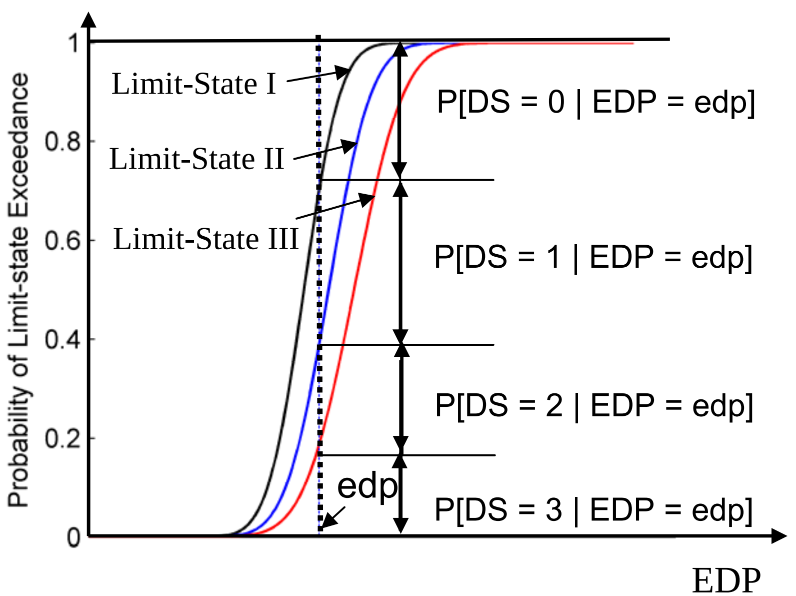
Probabilistic Loss Hazard Analysis

- **Loss Hazard Curve:**
  - Component-wise Loss Hazard Curve:

$$\nu_{L_j}(l) = \int_{DM} P[L_j > l \mid DM] \, |d\nu_{DM}| = \sum_{k=1}^{nls_j} P\left[L_j > l \mid DS = k\right] \left|\nu_{DS_k} - \nu_{DS_{k+1}}\right|$$

nls_j = number of limit states for component j

  - Only discrete damage states are used in practice.
    ν_{DS_k} = MAR of exceeding the k-th limit-state and
    $\nu_{DS_{nls+1}} = 0$

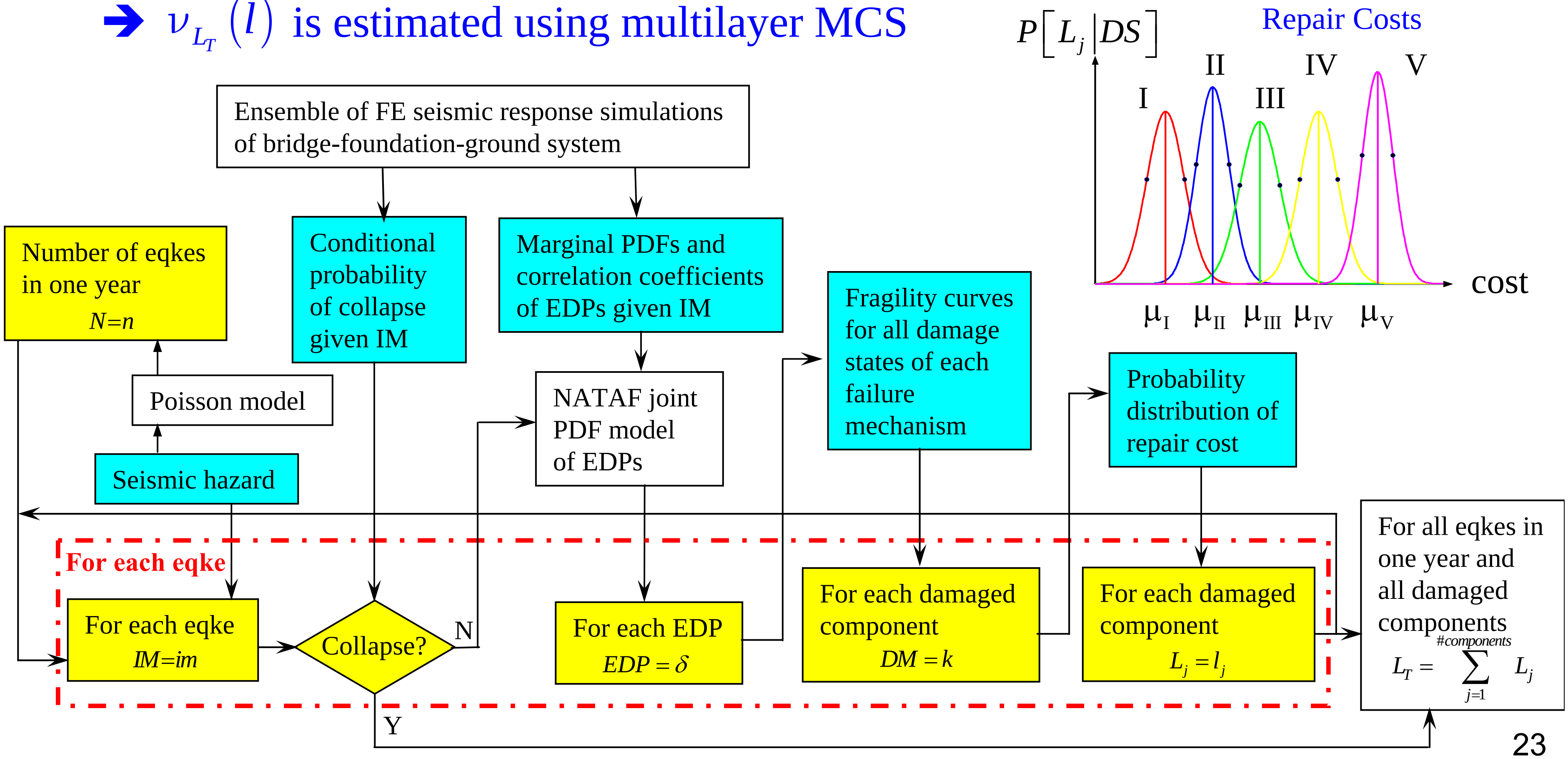


Probabilistic Loss Hazard Analysis

- **Multilayer Monte Carlo Simulation:**
  - **Total Loss (Repair/Replacement Cost):** $$L_T = \sum_{j=1}^{\#components} L_j$$
  - Computation of $\nu_{L_T}(l)$ requires n-fold integration of the joint PDF of the component losses, which is very difficult to obtain.

    ➔ $\nu_{L_T}(l)$ is estimated using multilayer MCS

Probability Distributions of Repair Costs



Probabilistic Loss Hazard Analysis

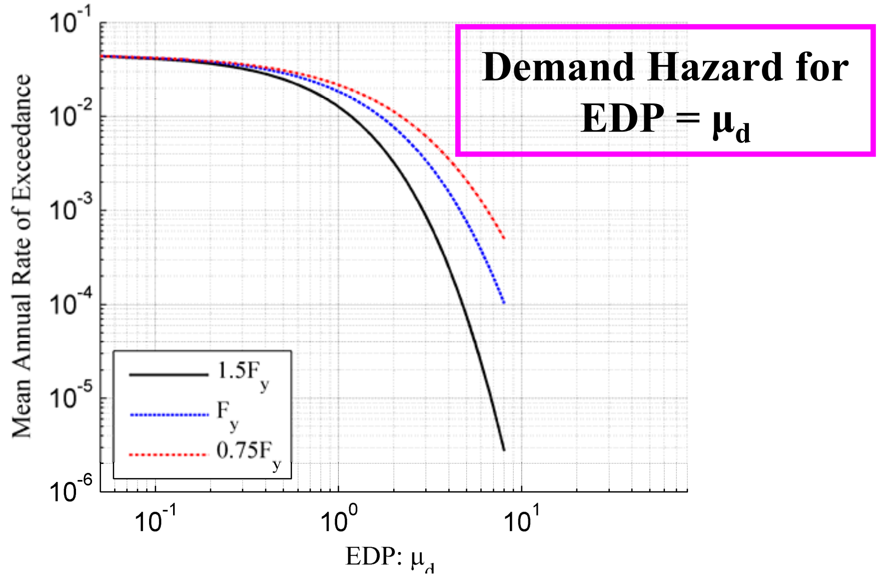
- **Repair/Replacement Cost Parameters:**

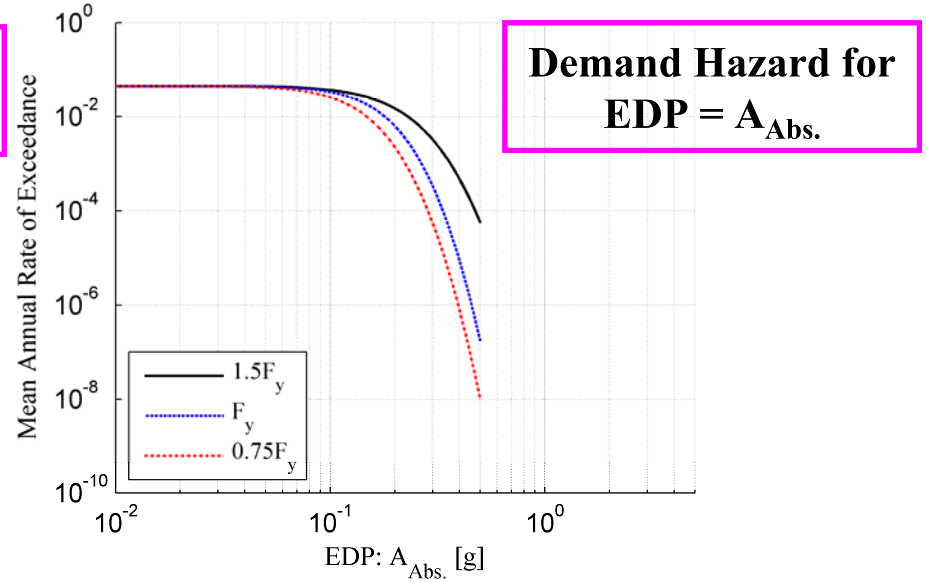
Failure Associated EDP	Limit-states	Repair/Replacement Cost (Normal distributed)	
		Mean ($)	c.o.v.
Displacement Ductility	I	146,500	0.12
	II	246,400	0.25
	III	350,000	0.32
Peak Absolute Acceleration [g]	I	55,000	0.11
	II	100,000	0.20
	III	500,000	0.28
Normalized Hysteretic Energy Dissipated	I	55,650	0.13
	II	110,000	0.22
	III	520,000	0.28

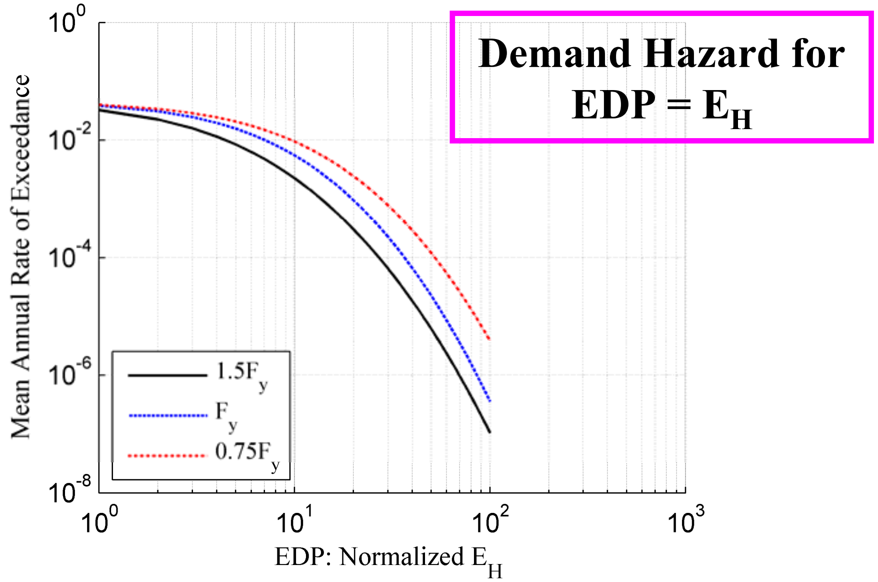
(II) Parametric PBEE Analysis of SDOF System

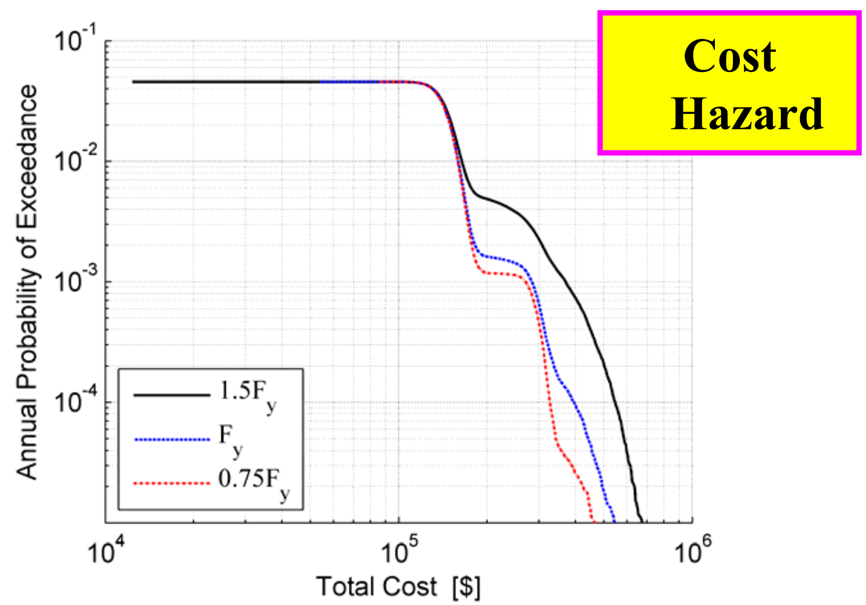
Parametric PBEE Analysis

- Varying Parameter: Yield Strength F_y



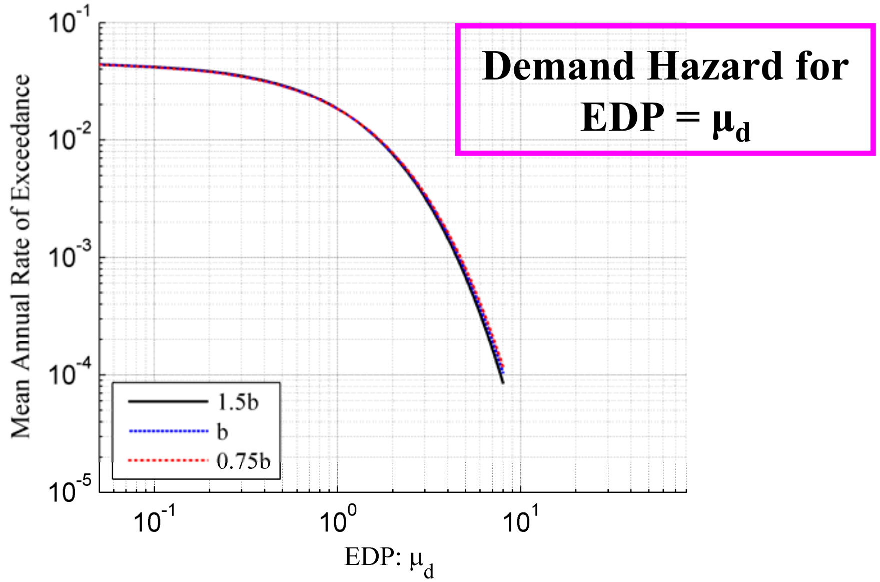


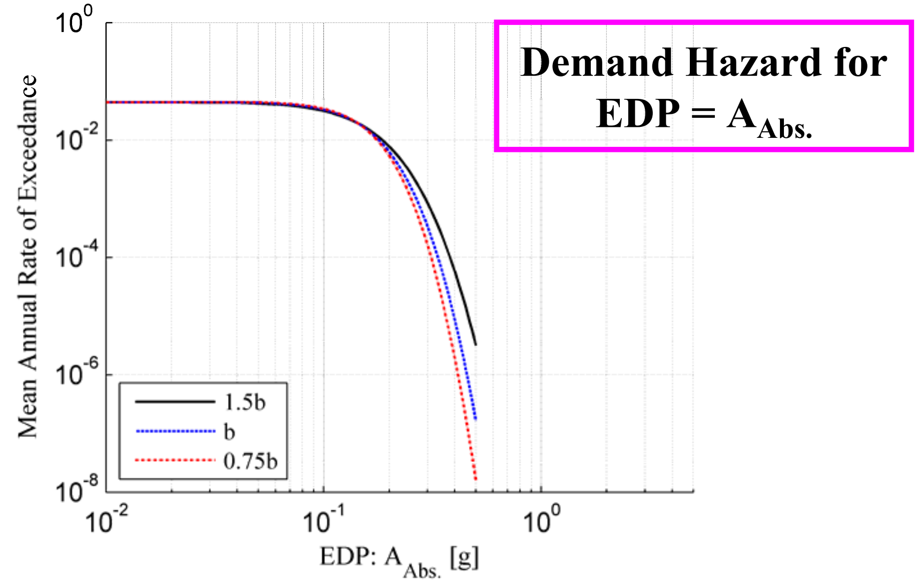


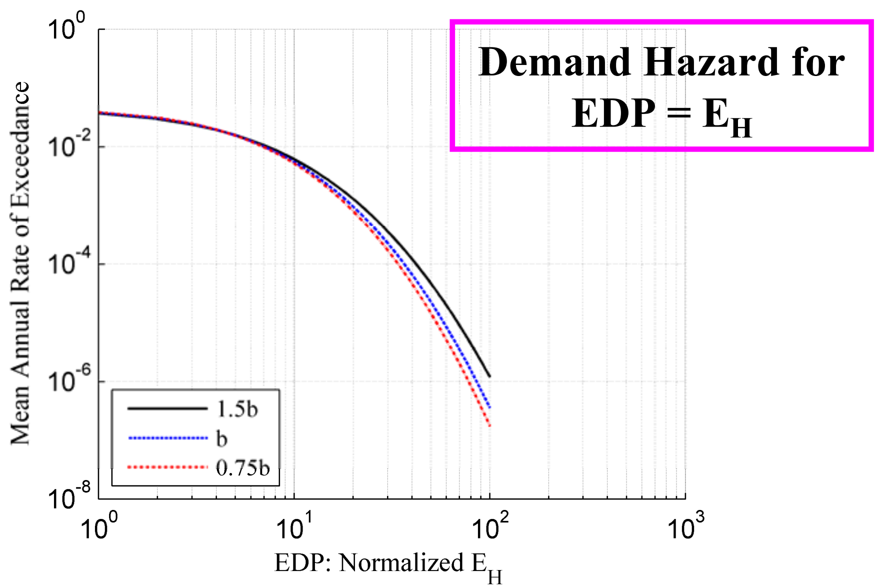


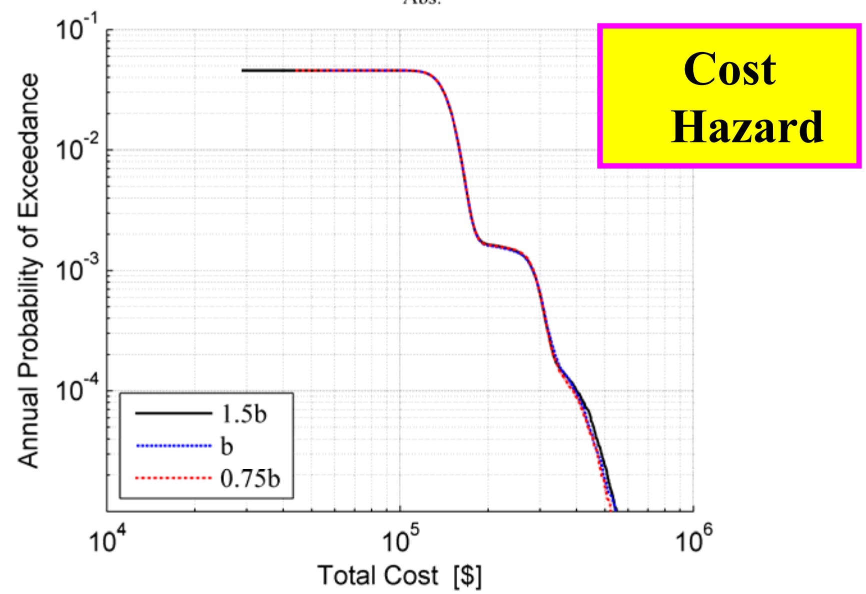
Parametric PBEE Analysis

- Varying Parameter: Hardening Ratio b



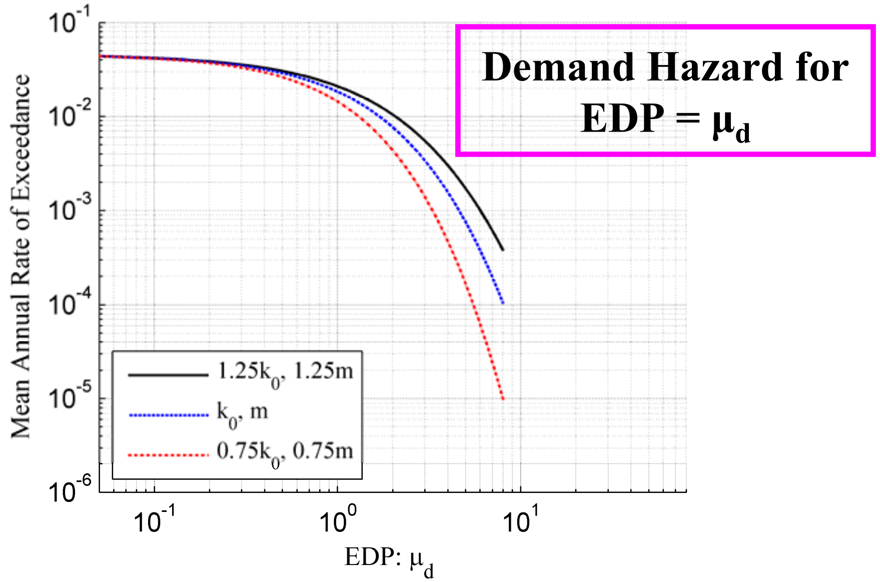


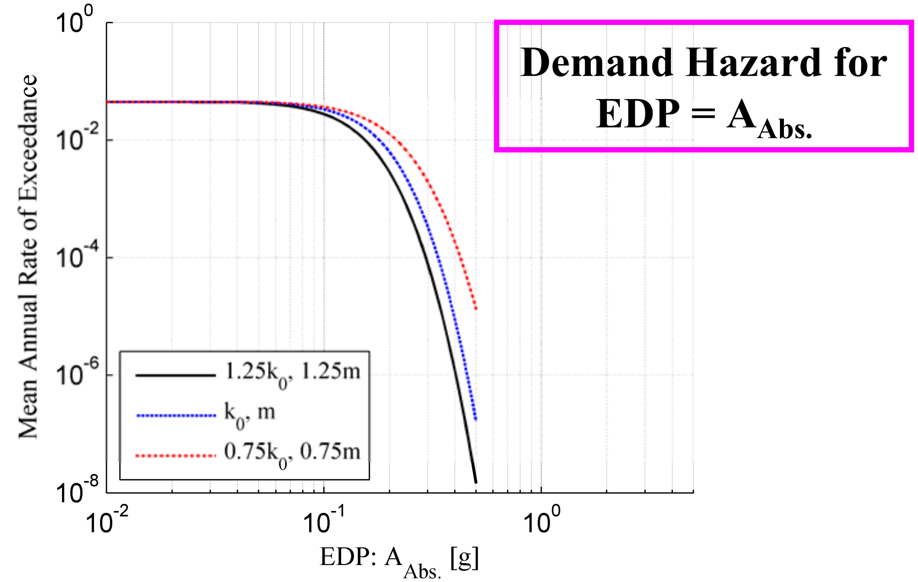


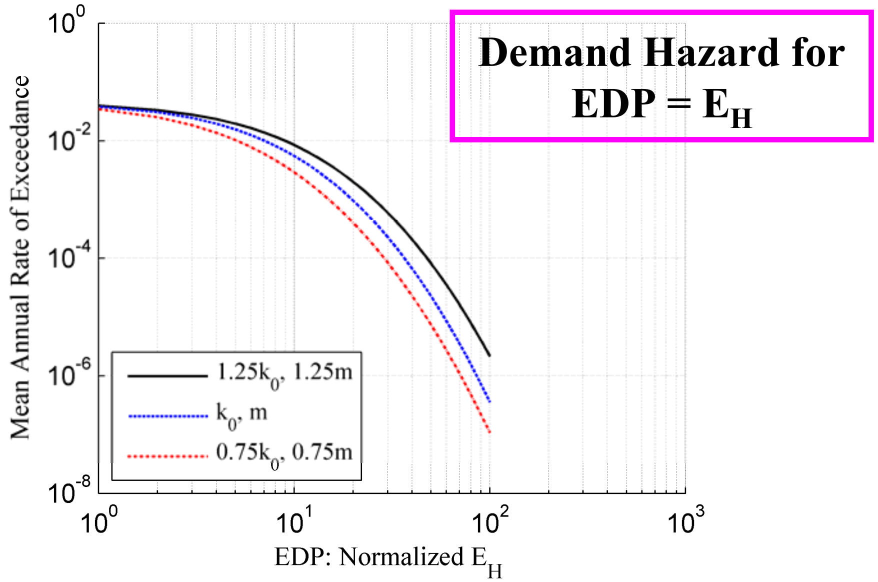


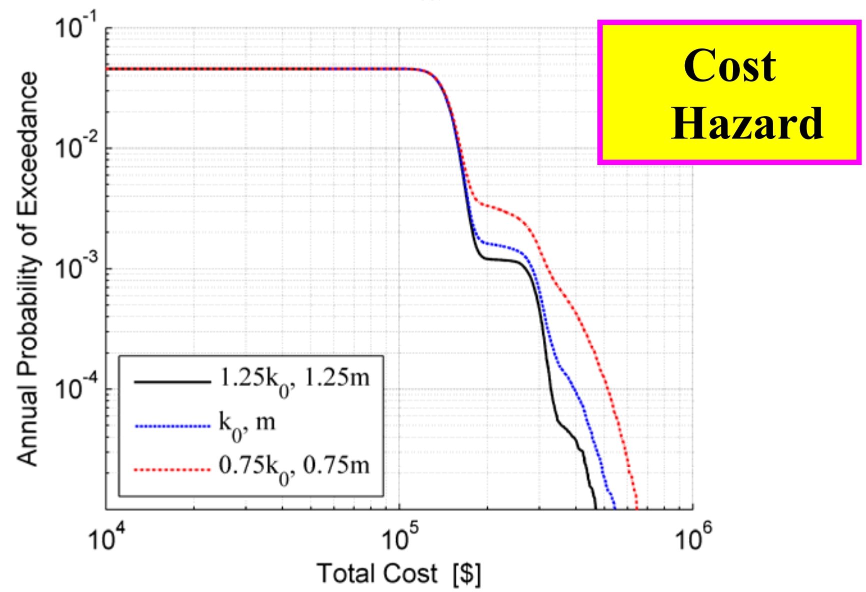
Parametric PBEE Analysis

- Varying Parameters: Both Mass m and Initial Stiffness k_0 (period fixed):



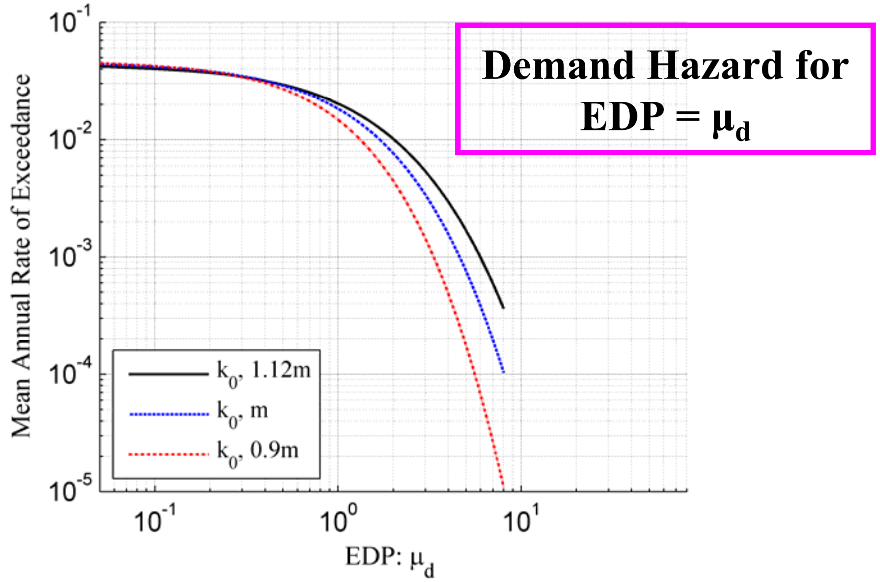


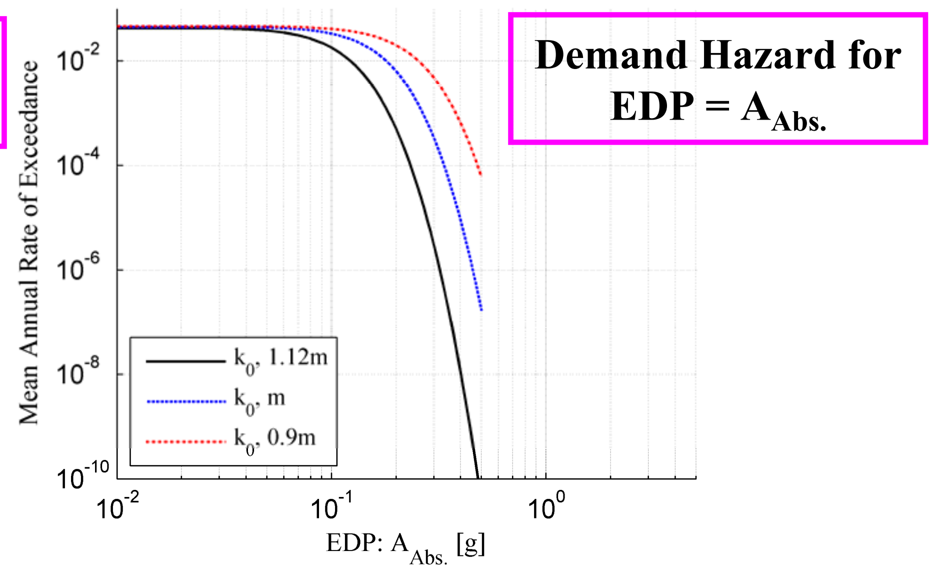


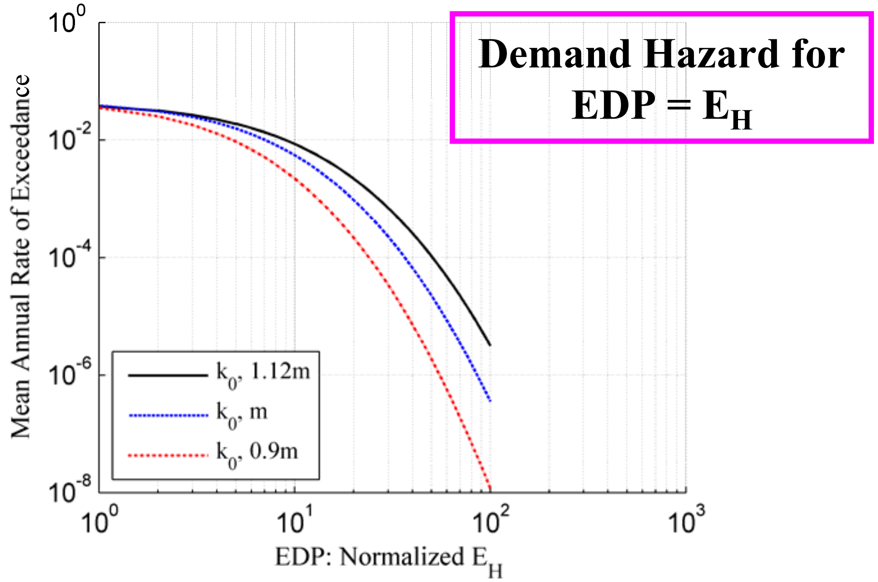


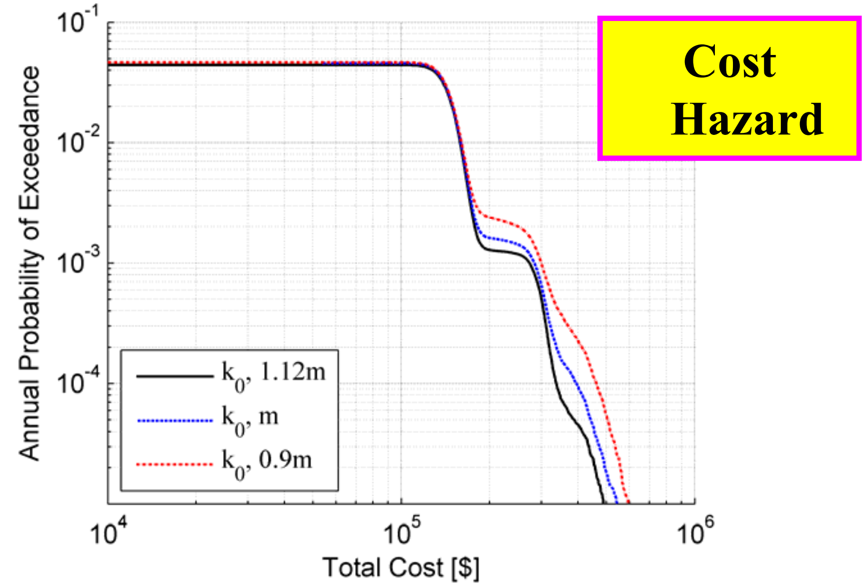
Parametric PBEE Analysis

- Varying Parameter: Mass m



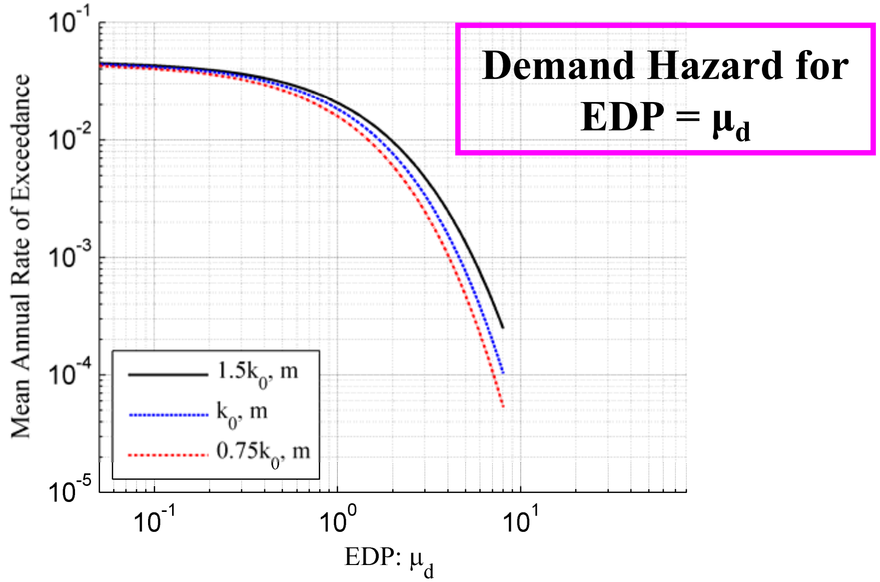


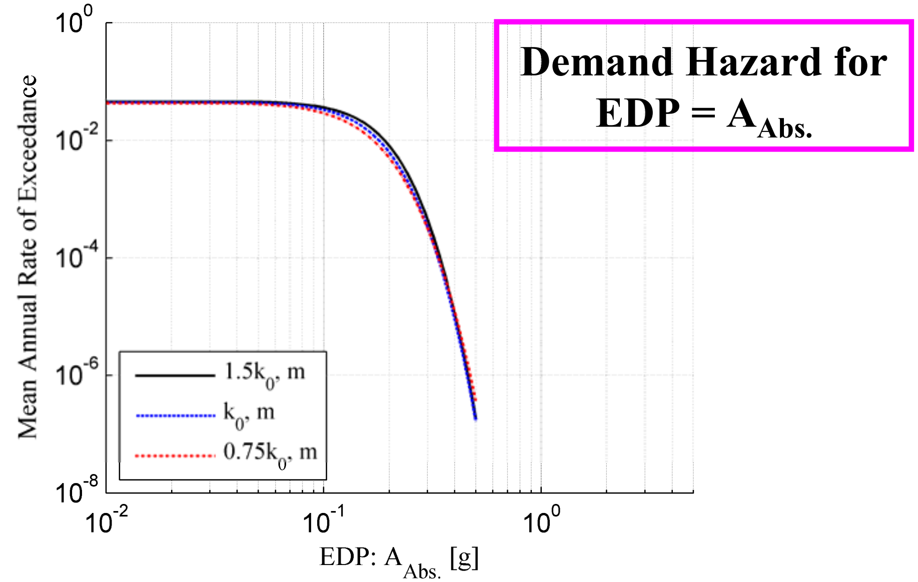


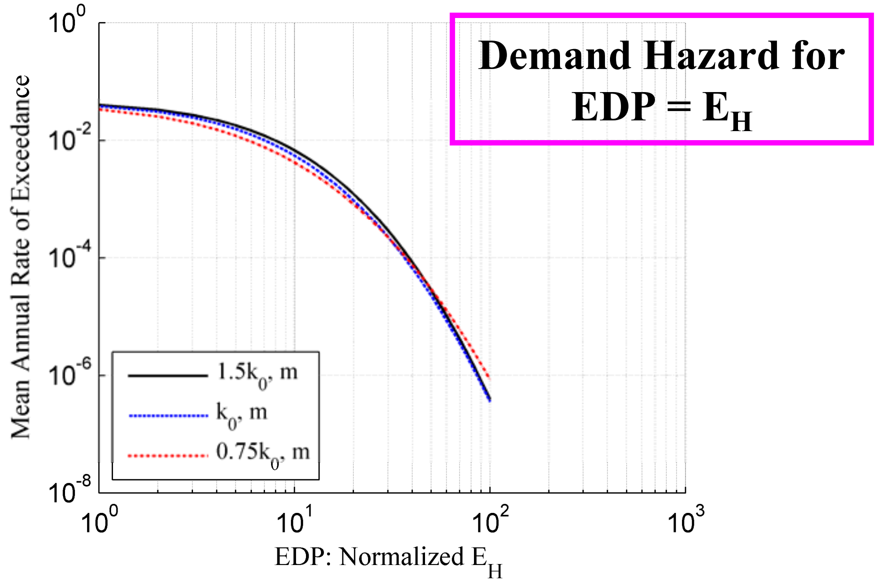


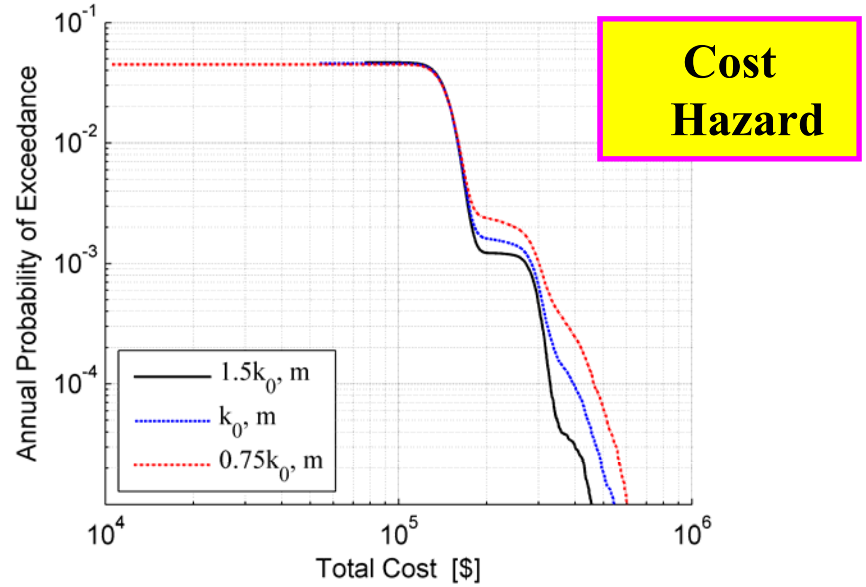
Parametric PBEE Analysis

- Varying Parameter: Initial Stiffness k_0









(III) Optimization Formulation for Probabilistic Performance Based Optimum Seismic Design

(Inverse PBEE Analysis)

Optimization Formulation of PBEE

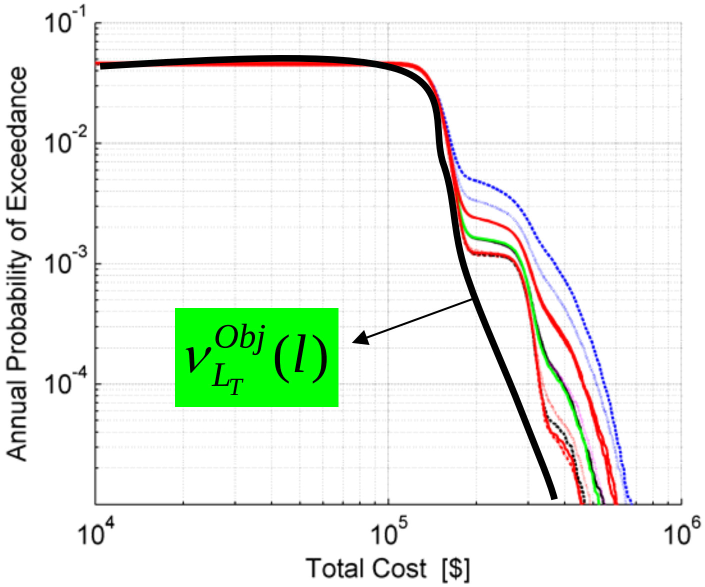
- **Optimization Problem Formulation:**
  - **Objective (Target/Desired)** Loss Hazard Curve: $\nu_{L_T}^{Obj}(l)$
  - Objective function: $f\left(k_0,\ F_y,\ b,\ \cdots\right) = \sum_i |\nu_{L_T}(l_i,\ k_0,\ F_y,\ b,\ \cdots) - \nu_{L_T}^{Obj}(l_i)|^2$
  - Optimization Problem:

$$\underset{\{k_0,\, F_y,\, b,\, \cdots\}}{Minimize}\ f\left(k_0, F_y,\ b, \cdots\right)$$

$$subject\ to:$$

$$\boldsymbol{h}\left(k_0, F_y,\ b, \cdots\right) = 0$$

$$\mathbf{g}\left(k_0, F_y,\ b, \cdots\right) \le 0$$



- Optimization Performed using extended **OpenSees-SNOPT** Framework (ongoing work).

Gu, Q., Barbato, M., Conte, J. P., Gill, P. E., and McKenna, F., "OpenSees-SNOPT Framework for Finite Element-Based Optimization of Structural and Geotechnical Systems," Journal of Structural Engineering, ASCE, under review, 2011.

Thank you !

Any Questions?