

Performance Based Earthquake Engineering of Concrete Dams

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1/6: Introduction and Computational Tools (PPACT)

PFMA vs. PBEE

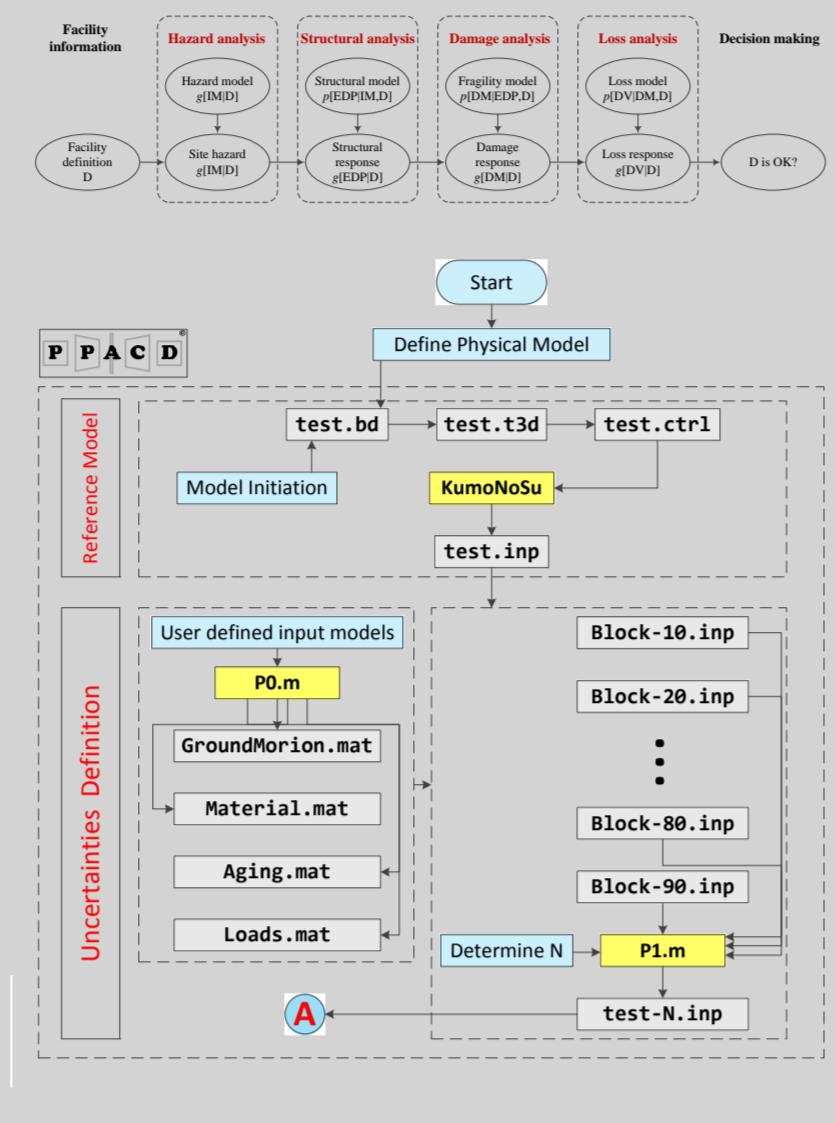
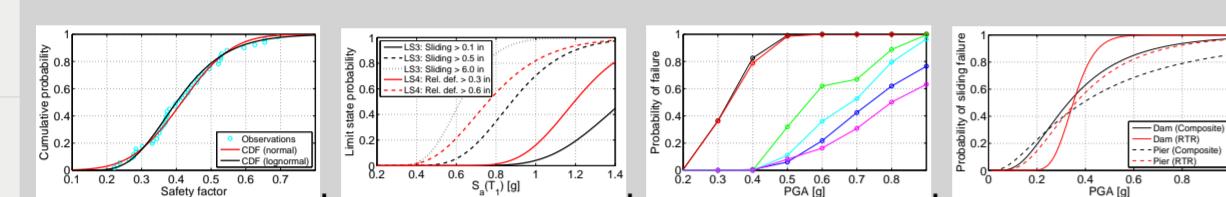
- Potential failure mode analysis: is a chain of events leading to unsatisfactory performance of the dam which could lead to uncontrolled release of the water. Can be very qualitative.
- Performance based earthquake engineering: Performance evaluation under common and extreme loads based on the diverse needs and objectives of owners, users and society.

Merlin and PPACT

- Merlin is a general purpose finite element software originally developed for fracture mechanics based static and dynamic analysis of concrete dams.
- Probabilistic Performance Assessment of Concrete Dams (PPACT): is a Matlab-based toolkit works over Merlin.

Historical Development

- de Araujo and Awruch (1998)
- Ellingwood and Tekie (2002)
- Lupo and Callari (2011)
- Ghanta et al. (2011-2015)



3/6: Sensitivity and Uncertainty Quantification

Nonlinearity of the system

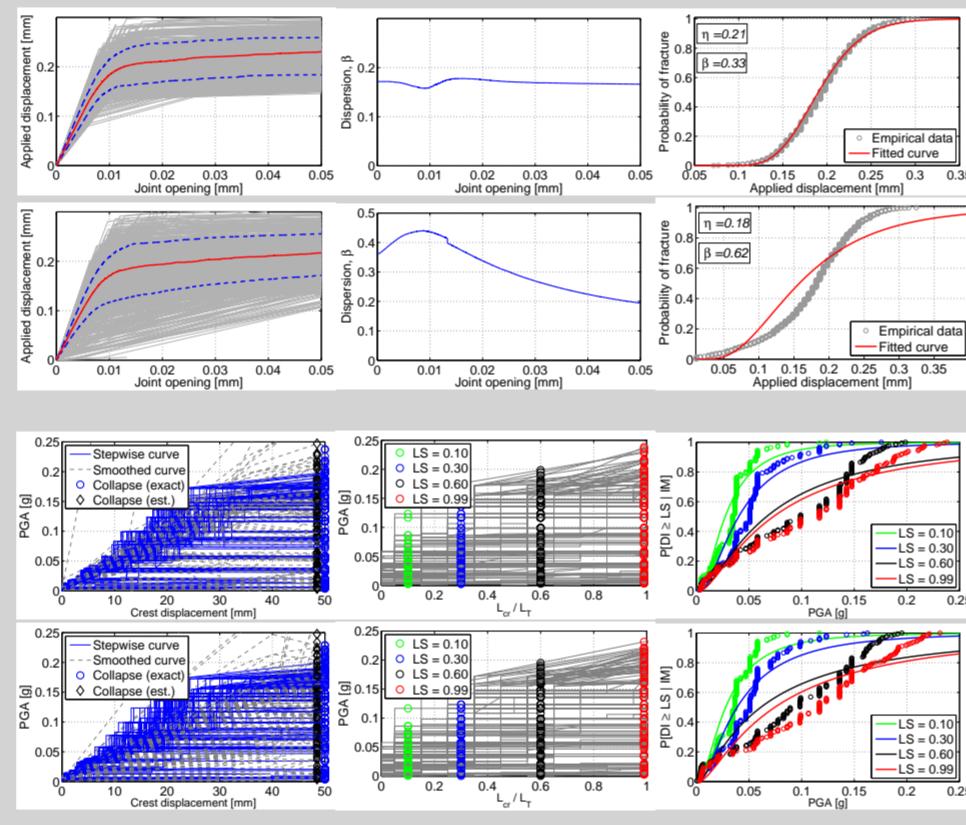
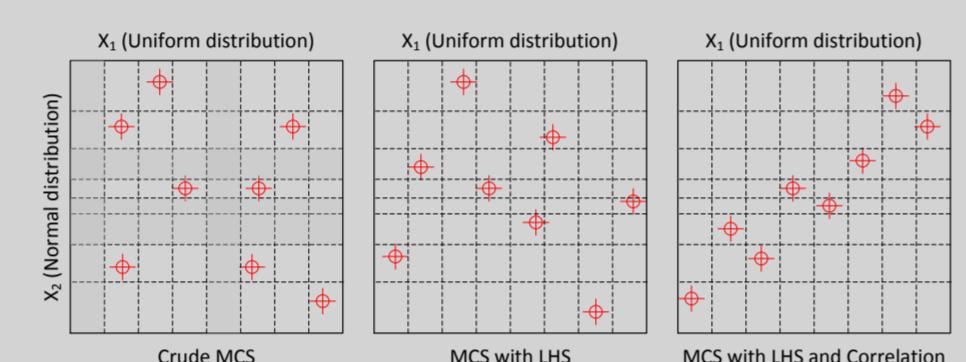
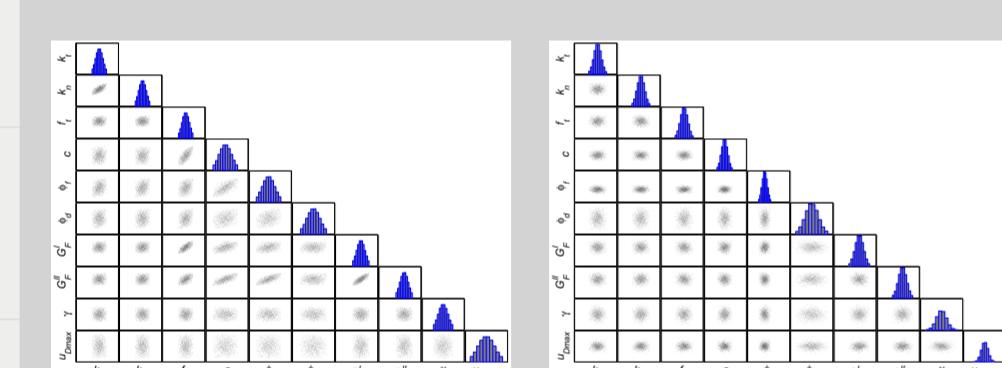
- Fracture mechanics based interface joint model
- The generalized failure surface is given by
$$F = (\tau_1^2 + \tau_2^2) - 2c \tan(\phi_f)(f_t - \sigma) - \tan^2(\phi_f)(\sigma^2 - f_t^2) = 0$$
- A bilinear relationship is used for $c(u^{eff})$ and $\sigma_t(u^{eff})$.

Sensitivity and Uncertainty Analysis

- Aleatory vs. epistemic RVs.
- Sampling is a key element of an uncertainty analysis.
- Monte Carlo Simulation (MCS) vs. Latin Hypercube Sampling (LHS).
- Correlated vs. Uncorrelated RVs.

Models

- Mode I: Static POA
- Mode II: Static POA
- Mixed-Mode: Dynamic POA



5/6: Collapse Fragility Curves for Multiple-Component Ground Motions

Fragility functions

- Empirical: From post-earthquake damage data.
- Analytical: Transient structural analysis.
- Heuristic: Expert opinion.

Lognormal cumulative distribution function (CDF)

$$\Pr[C|IM = im] = \Phi\left(\frac{\ln(im) - \ln(\bar{\eta})}{\beta}\right)$$

Find the parameters

- Method of moments (MM)

$$\hat{\eta} = \exp\left(\frac{1}{n} \sum_{i=1}^n \ln(IM_i)\right), \quad \hat{\beta} = \sqrt{\frac{\sum_{i=1}^n (\ln(IM_i) - \ln(\hat{\eta}))^2}{n-1}}$$

- Sum of squared error (SSE)

$$\{\hat{\eta}, \hat{\beta}\} = \underset{\hat{\eta}, \hat{\beta}}{\operatorname{argmin}} \sum_{i=1}^m \left(\frac{n_i^c}{n_i} - \Phi\left(\frac{\ln(im_i) - \ln(\hat{\eta})}{\hat{\beta}}\right) \right)^2$$

- Maximum likelihood estimation (MLE)

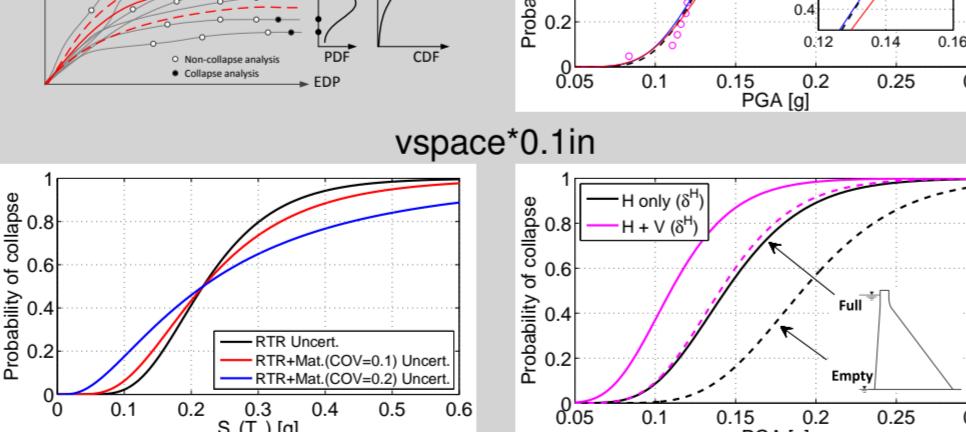
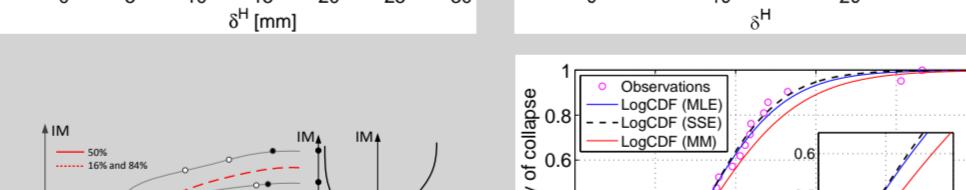
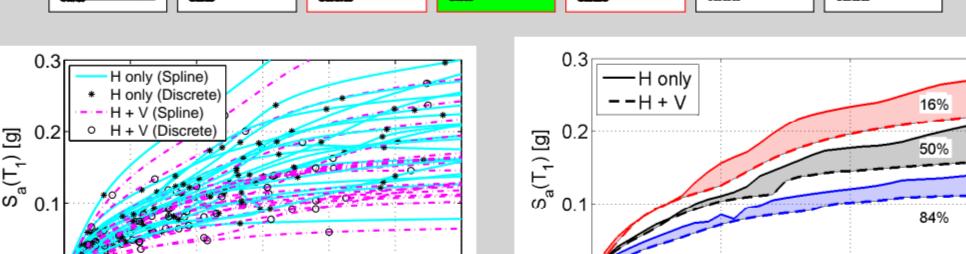
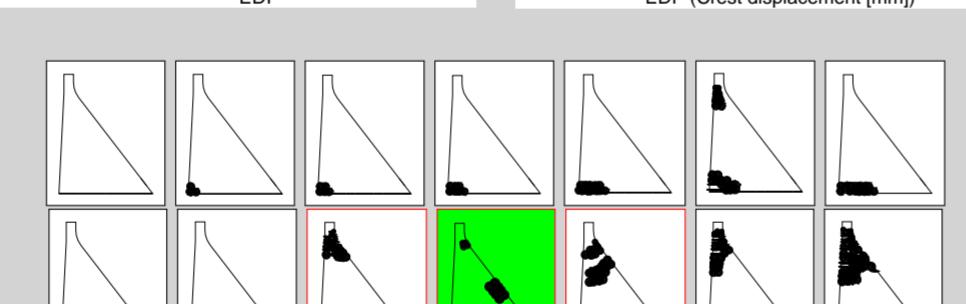
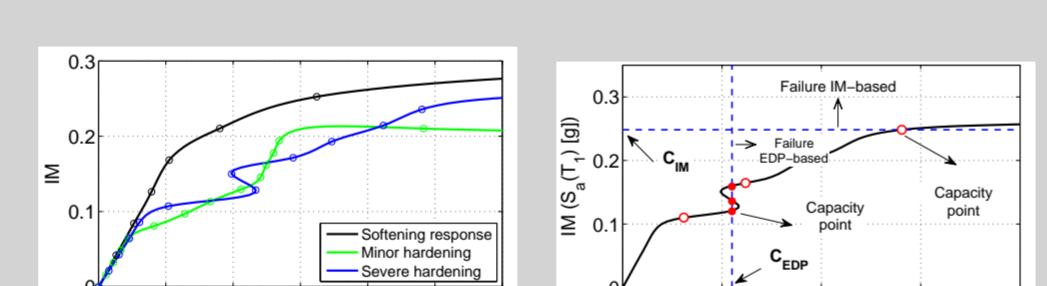
$$\{\hat{\eta}, \hat{\beta}\} = \underset{\hat{\eta}, \hat{\beta}}{\operatorname{argmax}} \sum_{i=1}^m \left(n_i^c \ln \left(\Phi\left(\frac{\ln(im_i) - \ln(\hat{\eta})}{\hat{\beta}}\right) \right) + (n_i - n_i^c) \ln \left(1 - \Phi\left(\frac{\ln(im_i) - \ln(\hat{\eta})}{\hat{\beta}}\right) \right) \right)$$

Anatomy of IDA Curves

- Capacity limit state in SR-IDC: EDP-based vs IM-based rules.
- Hardening in SR-IDC curve based on discrete crack model.
- Resurrection in SR-IDC based on smeared crack model.
- Summarize the MR-IDC curves to some central values, i.e. 16%, 50% and 84% fractiles. Moreover, analyze the EDP-dependent dispersion.

Epistemic and Aleatory Uncertainties

- Epistemic and Aleatory Uncertainties: One may combine the two uncertainties $\beta_{RU} = \sqrt{\beta_R^2 + \beta_U^2}$ assuming independent uncertainties and fixed median.
- Impact of Reservoir Elevation: β_{Full}^{Full} is 0.75 and 0.78 for "H only" and "H + V" cases. β_{Empty}^{Full} is 1.08 in both cases.



2/6: Quantified Potential Failure Mode Analysis

Qualitative vs. Quantitative

- One may perform a potential failure mode analysis either qualitatively (mainly based on site observations) or quantitatively (based on accompanying finite element analyses).

Linear System (Indices)

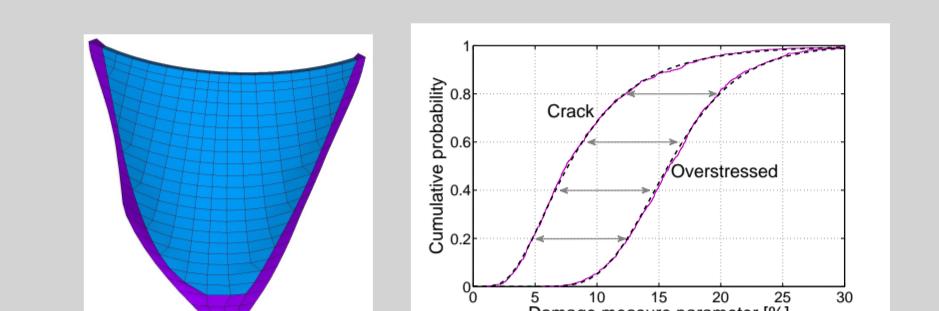
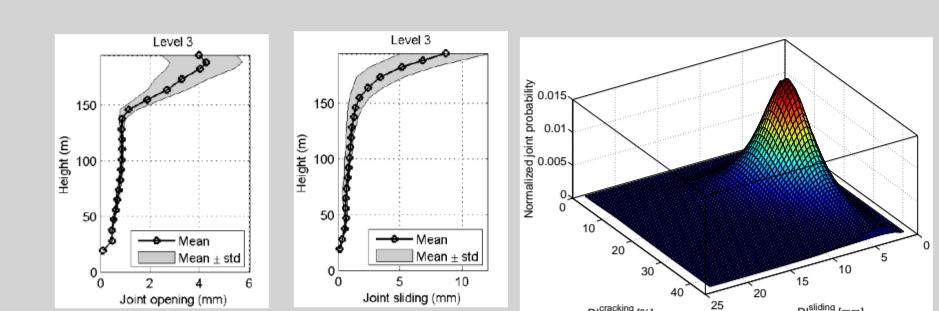
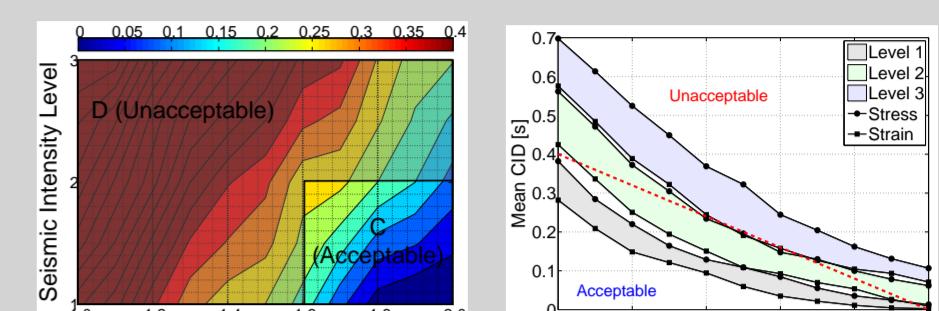
- Demand capacity ratio (DCR)
- Cumulative inelastic duration (CID)
- Cumulative inelastic area (CIA)
- Damage spatial distribution ratio (DSDR)

Linear System

- Multiple Strip Analysis (MSA)
- Akaike Information Criterion (AIC)
- Generate extra EDP based on joint lognormal distribution and Monte Carlo Simulation
- Joint opening/sliding and concrete cracking

Correlation LE vs. NL

- Seek a correlation between linear and nonlinear analyses.



4/6: Probabilistic Seismic Demand Model

PSDM and Cloud Analysis

- PSDM expresses the probability that a system experiences a certain level of demand for a given IM level.
- Cloud analysis is a numerical procedure in which the structure is subjected to a set of un-scaled ground motions.

Criteria for an Optimal IM

- Efficiency: Lower dispersion ($\beta_{EDP|IM}$) \Rightarrow Higher efficiency.
- Practicality: Higher slope (b) \Rightarrow Higher practicality.
- Proficiency: Lower ζ \Rightarrow Higher proficiency.
- Sufficiency: Higher p -value \Rightarrow sufficient IM.
- Hazard compatibility

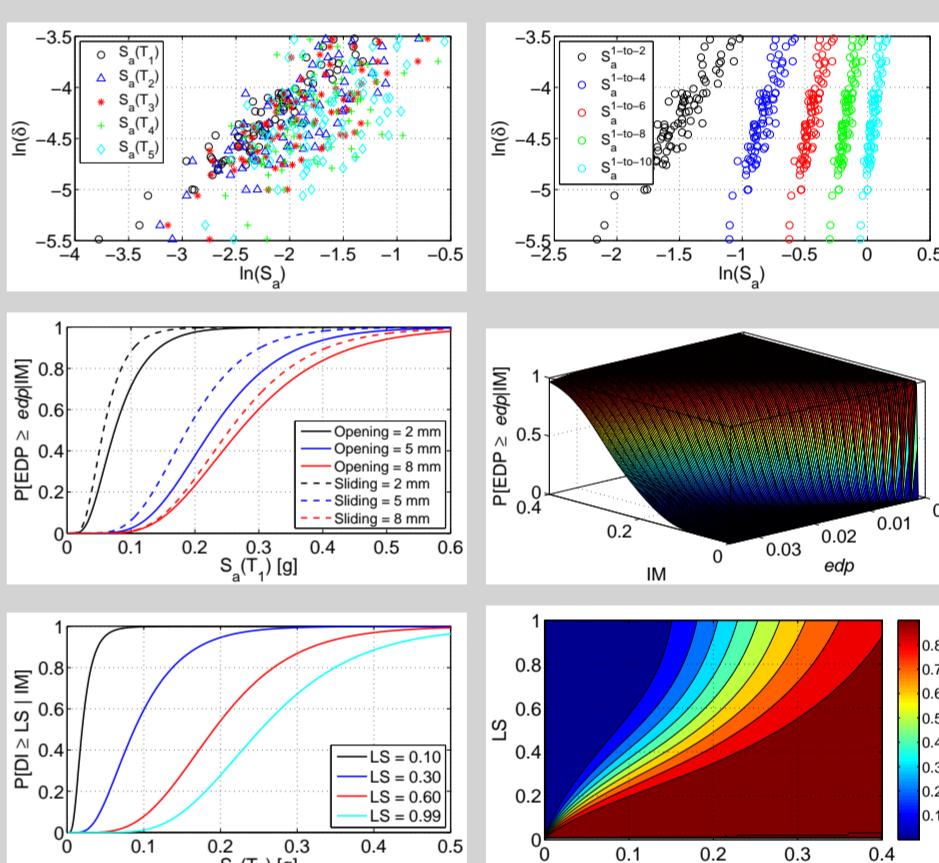
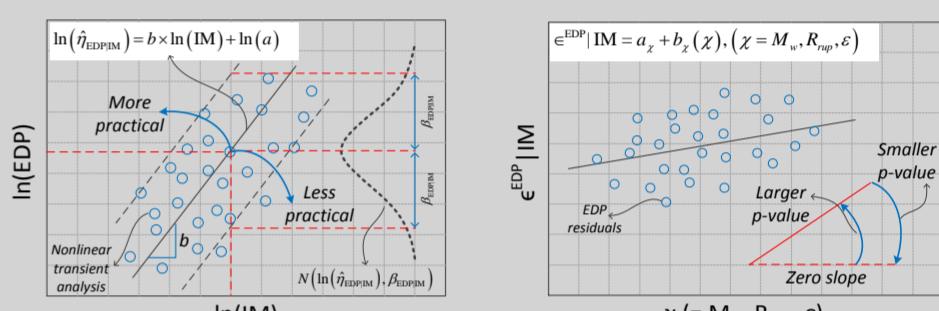
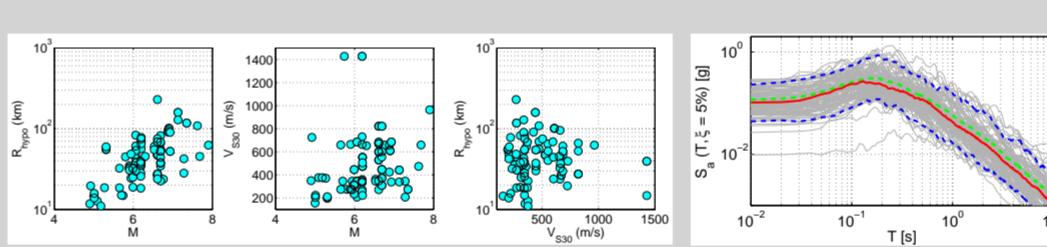
Cloud-based fragility function

- The results, EDP vs. IM form the so-called cloud response (arithmetic or logarithmic scale).

$$\ln(\eta_{EDP|IM}(IM)) = b \cdot \ln(IM) + \ln(a)$$

$$P[EDP \geq edp|IM] = 1 - \Phi\left(\frac{\ln(edp) - \ln(\eta_{EDP|IM})}{\beta_{EDP|IM}}\right)$$

- Fragility curve vs. fragility surface



6/6: Damage Index

- The proposed DI is structural, cumulative, multi-variable, multi-scale. There are three controlling variables

$$DI = f(L^C, E_H, U_{max})$$

- Micro DI for each critical location $DI_i^j = \beta_\Delta \times \frac{L_i^C}{L_j^C}, j = A, B, C, D$
- Meta DI corresponding to each critical location $DI^j = \sum_{i=1}^n DI_i^j \times \zeta_i^j, \zeta_i^j = \frac{(E_H)_i}{E_H}$
- Macro DI for the entire dam or the dam-foundation system $\overline{DI} = \sum_{j=A}^D \overline{DI}^j$

