Earthquake-Soil-Structure Systems

Boris Jeremić and Sashi Kunnath
with
Kallol Sett and Nima Tafazzoli

Department of Civil and Environmental Engineering
University of California, Davis

Outline

Focus

- Steady progress in software and hardware allows high fidelity, detailed performance assessment (simulations) of critical (and other) infrastructure systems (bridges, dams, buildings, ports...)
- Interplay of Earthquake Soil Structure systems seems to play a major role in catastrophic failures (and successes)
- Quantify uncertainty and variablity in soil and structural behavior
- Provide methodology (formulation, implementation) for probabilistic performance based engineering (PEER type)
- Overcome traditional performance assessment approaches used in engineering practice (design using prescriptive code!)

Historical Note (Full Circle?)

- Soil–Structure Interaction phenomena first realized and described by Professor Kyoji Suyehiro
  - Ship engineer (Professor of Naval Arch. at U. of Tokyo),
  - Earthquake engineer (First Director of the Earthquake Research Institute at U. of Tokyo),
  - Was in Tokyo during Great Kantō earthquake (11:58am (–12:08pm! slow?), 1st. Sept. 1923)
  - Saw earthquake surface waves travel and buildings sway (ships in the ocean)
  - Presented his new SSI work in the USA (Caltech, UCB, Stanford, MIT) in 1931...
- Slow and Fast earthquakes
- Uncertainty and variability (source, material...)

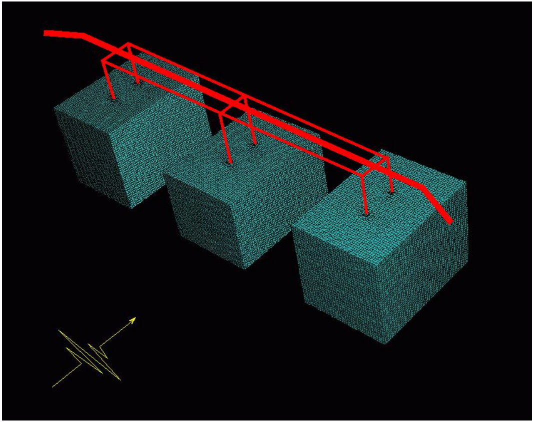
Outline

Detailed 3D, FEM model

- Construction process
- Two types of soil: stiff soil (UT, UCD), soft soil (Bay Mud)
- Deconvolution of given surface ground motions
- Use of the DRM (Prof. Bielak et al.) for seismic input
- Piles $\rightarrow$ beam-column elements in soil holes
- No artificial damping (only mat. dissipation, radiation)
- Structural model: collaboration UCD, UCB and UW
- Element size issues (filtering of frequencies)

model size (el)	el. size	f_{cutoff}	min. $G/Gmax$	γ
12K	1.0 m	10 Hz	1.0	<0.5 %
15K	0.9 m	>3 Hz	0.08	1.0 %
150K	0.3 m	10 Hz	0.08	1.0 %
500K	0.15 m	10 Hz	0.02	5.0 %

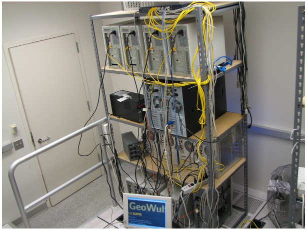
FEM Mesh (one of)

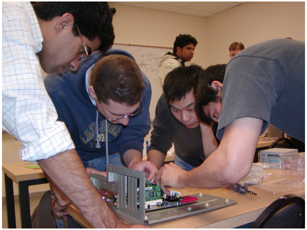


B. Jeremić and G. Jie. "Parallel Soil–Foundation–Structure Computations", Chapter in Book: *Progress in Computational Dynamics and Earthquake Engineering*; Taylor and Francis Publishers, 2008.

Parallel Computer GeoWulf

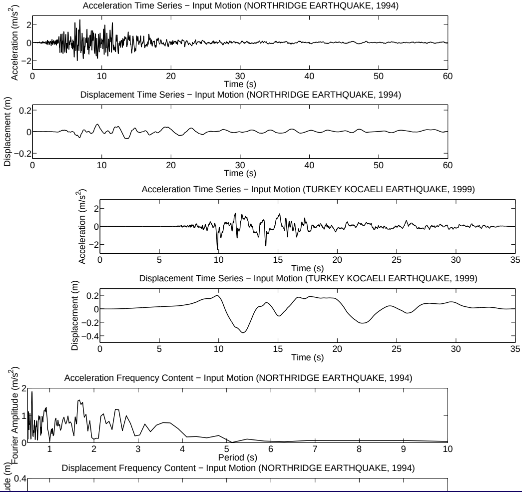
- Distributed memory parallel computer
- Multiple generation compute nodes and networks
- Very cost effective!
- Same architecture as large parallel supercomputers (SDSC, TACC, EarthSimulator...)
- Local design, construction, available at all times!



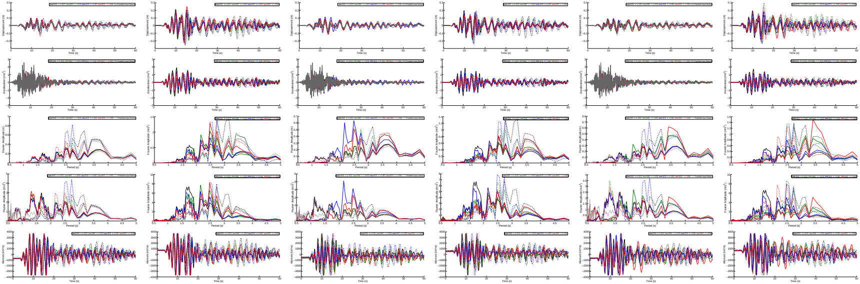


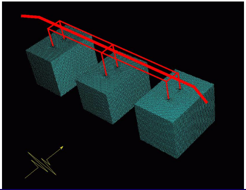
Outline

Northridge and Kocaeli Input Motions

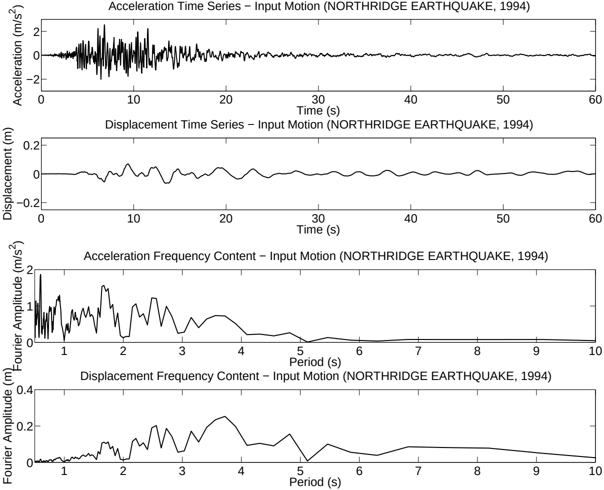


Parametric Simulation Results

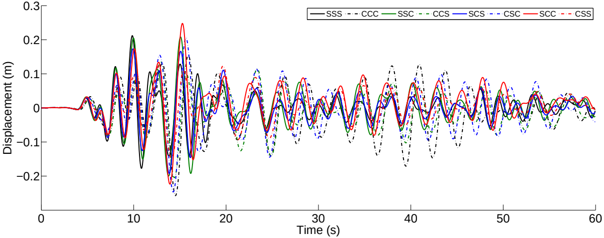


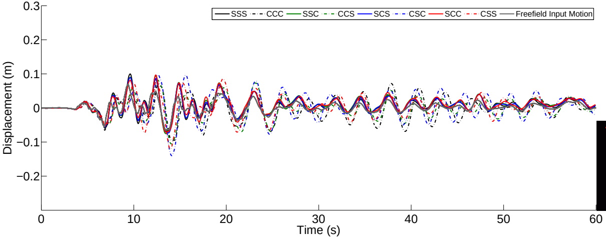


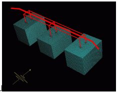
Northridge Input Motions



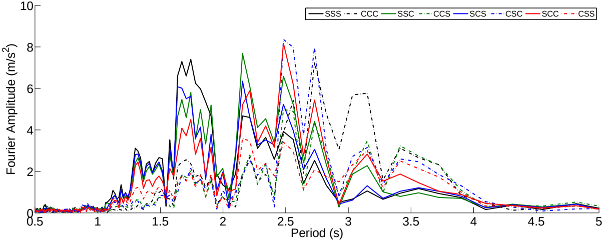
Short Period E.: Left Bent, Structure and Soil, Disp.

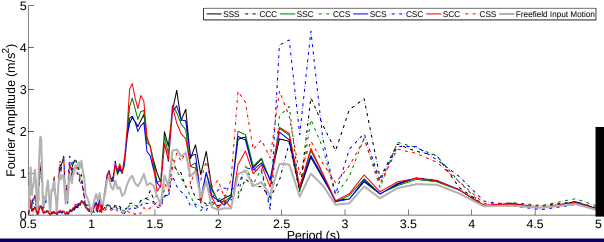


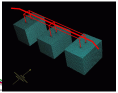




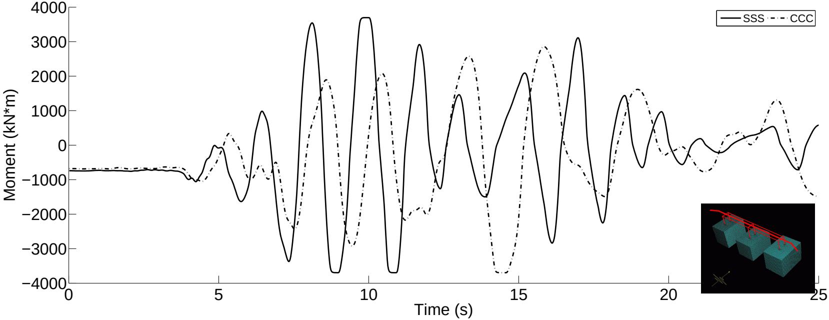
Short Period E.: Left Bent, Structure and Soil, Acc.Sp.





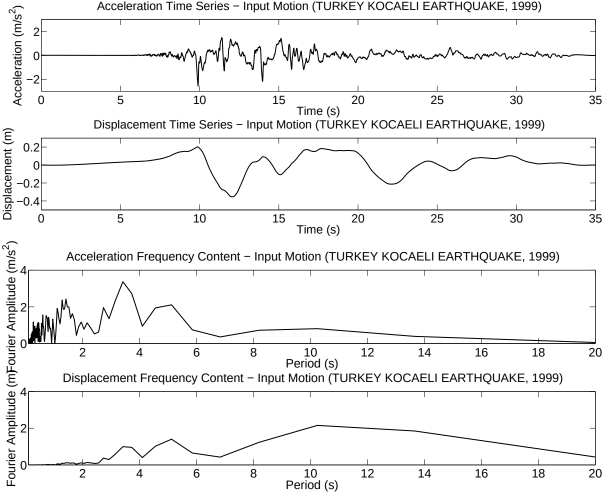


Short Period E.: Left Bent, Structure and Soil, M.

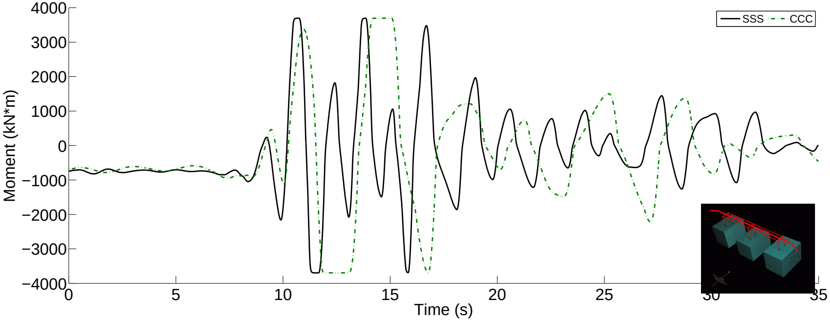


B. Jeremić, G. Jie, M. Preisig and N. Tafazzoli. "Soil–Foundation–Structure Interaction in non–Uniform Soils", in review in *Earthquake Engineering and Structural Dynamics*, 2008.

Kocaeli Input Motions



Long Period E.: Left Bent, Structure and Soil, M.



Outline

Goals

ESS Systems
- High Fidelity, 3D Models
- Behavior for Short and Long Period Motions

Uncertain Seismic Motions
- Constitutive and Spatial Uncertainties
- Seismic Wave Propagation Through Uncertain Soils

Summary

Problem Setup

- Incr. 3D el–pl: $d\sigma_{ij} = \left\{ D^{el}_{ijkl} - \frac{D^{el}_{ijmn} m_{mn} n_{pq} D^{el}_{pqkl}}{n_{rs} D^{el}_{rstu} m_{tu} - \xi_* r_*} \right\} d\epsilon_{kl}$
- phase density ρ of $\sigma(x,t)$ varies in time according to a continuity Liouville equation (Kubo 1963)
- Continuity equation written in ensemble average form (eg. cumulant expansion method (Kavvas and Karakas 1996))
- van Kampen's Lemma (van Kampen 1976) $\rightarrow$ $< \rho(\sigma,t) >= P(\sigma,t)$, ensemble average of phase density is the probability density

Eulerian–Lagrangian FPK Equation

$$
\begin{aligned}
\frac{\partial P(\sigma(x_t,t),t)}{\partial t} &= -\frac{\partial}{\partial \sigma}\left[\left\{\left\langle \eta(\sigma(x_t,t), D^{el}(x_t), q(x_t), r(x_t), \epsilon(x_t,t))\right\rangle\right.\right.\\
&+ \int_0^t d\tau Cov_0\left[\frac{\partial \eta(\sigma(x_t,t), D^{el}(x_t), q(x_t), r(x_t), \epsilon(x_t,t))}{\partial \sigma};\right.\\
&\left.\left.\left.\eta(\sigma(x_{t-\tau}, t-\tau), D^{el}(x_{t-\tau}), q(x_{t-\tau}), r(x_{t-\tau}), \epsilon(x_{t-\tau}, t-\tau)\right]\right\} P(\sigma(x_t,t),t)\right]\\
&+ \frac{\partial^2}{\partial \sigma^2}\left[\left\{\int_0^t d\tau Cov_0\left[\eta(\sigma(x_t,t), D^{el}(x_t), q(x_t), r(x_t), \epsilon(x_t,t));\right.\right.\right.\\
&\left.\left.\left.\eta(\sigma(x_{t-\tau}, t-\tau), D^{el}(x_{t-\tau}), q(x_{t-\tau}), r(x_{t-\tau}), \epsilon(x_{t-\tau}, t-\tau))\right]\right\} P(\sigma(x_t,t),t)\right]
\end{aligned}
$$

B. Jeremić, K. Sett, and M. L. Kavvas, "Probabilistic Elasto–Plasticity: Formulation in 1–D", *Acta Geotechnica*, Vol. 2, No. 3, pp 197-210, 2007.

Euler–Lagrange FPK Equation

- Advection-diffusion equation

$$\frac{\partial P(\sigma,t)}{\partial t} = -\frac{\partial}{\partial \sigma}\left[N_{(1)} P(\sigma,t) - \frac{\partial}{\partial \sigma}\left\{N_{(2)} P(\sigma,t)\right\}\right]$$

- Complete probabilistic description of response
- Solution PDF is second-order exact to covariance of time (exact mean and variance)
- It is deterministic equation in probability density space
- It is linear PDE in probability density space → Simplifies the numerical solution process
- Template FPK diffusion–advection equation is applicable to any material model → only the coefficients $N_{(1)}$ and $N_{(2)}$ are different for different material models

K. Sett, B. Jeremić and M.L. Kavvas, "The Role of Nonlinear Hardening/Softening in Probabilistic Elasto–Plasticity", *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 31, No. 7, pp 953-975, 2007

Spectral Stochastic Elastic–Plastic FEM

$$\sum_{n=1}^{N} K_{mn} d_{ni} + \sum_{n=1}^{N} \sum_{j=0}^{P} d_{nj} \sum_{k=1}^{M} C_{ijk} K'_{mnk} = \langle F_m \psi_i[\{\xi_r\}] \rangle$$

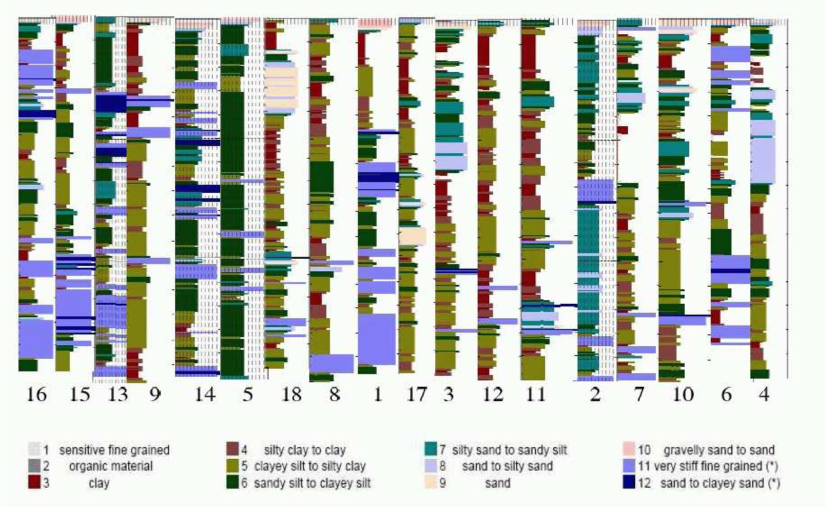
$$K_{mn} = \int_D B_n D B_m dV \qquad K'_{mnk} = \int_D B_n \sqrt{\lambda}_k h_k B_m dV$$

$$C_{ijk} = \langle \xi_k(\theta) \psi_i[\{\xi_r\}] \psi_j[\{\xi_r\}] \rangle \qquad F_m = \int_D \phi N_m dV$$

- SFEM: Ghanem and Spanos 2003
- Material variables random field represented through a finite number of random variables using KL-expansion
- Unknown solution random variables represented using polynomial chaos of (known) input random variables
- Fokker–Planck–Kolmogorov approach based probabilistic constitutive integration at Gauss integration points

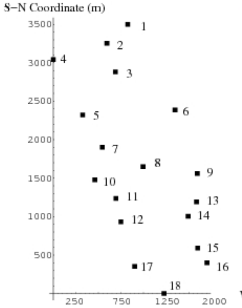
Outline

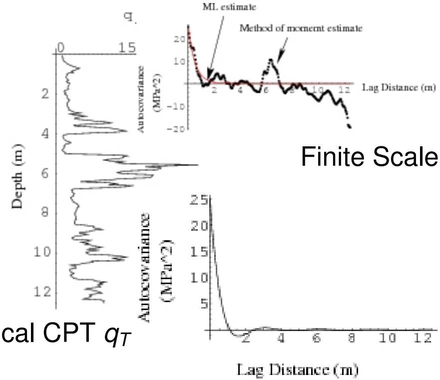
"Uniform" CPT Site Data



Random Field Parameters from Site Data

- Maximum likelihood estimates of correlation length





Finite Scale

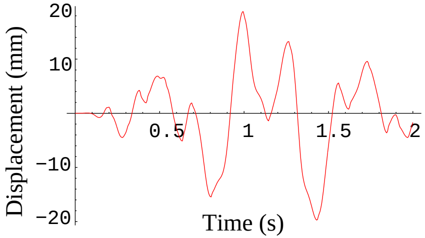
Typical CPT q_T

Fractal

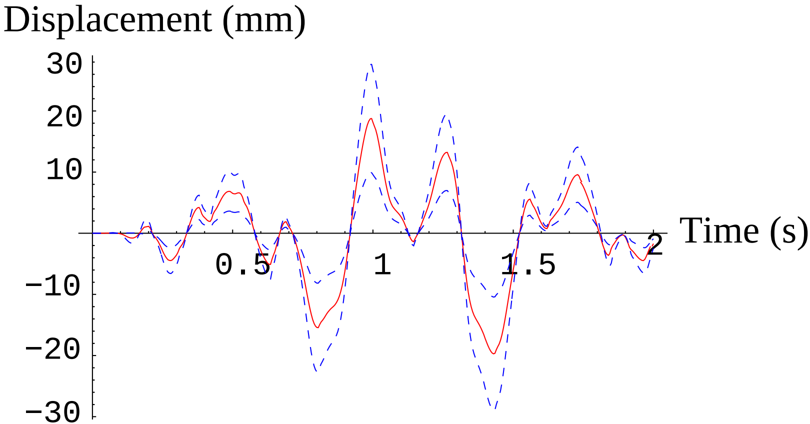
Seismic Wave Propagation through Stochastic Soil

- Soil as 12.5 m deep 1–D soil column (von Mises Material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT q_T
    $\langle q_T \rangle = 4.99\ MPa$; $Var[q_T] = 25.67\ MPa^2$;
    Cor. Length $[q_T] = 0.61\ m$; Testing Error $= 2.78\ MPa^2$
- q_T was transformed to obtain G: $G/(1-\nu) = 2.9 q_T$
  - Assumed transformation uncertainty = 5%
    $\langle G \rangle = 11.57 MPa$; $Var[G] = 142.32 MPa^2$
    Cor. Length $[G] = 0.61 m$
- Input motions: modified 1938 Imperial Valley

Surface Displacement Time History

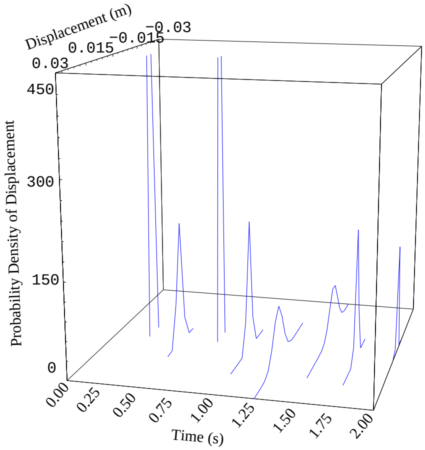


Mean ± Standard Deviation

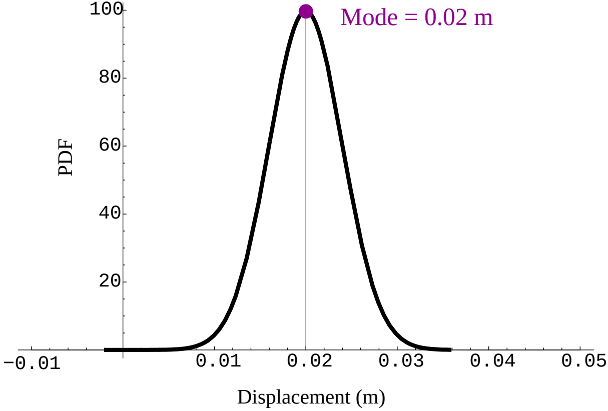


PDF of Surface Displacement Time History

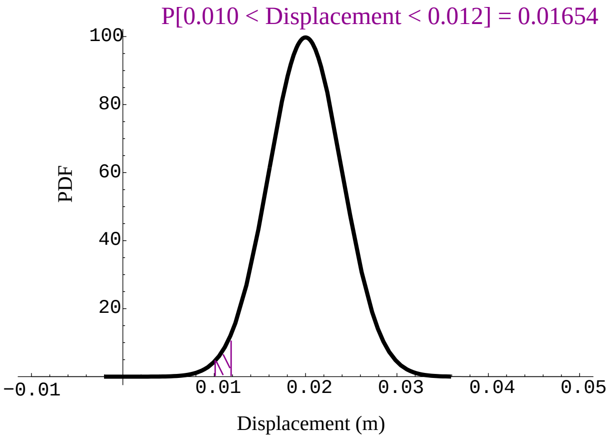
- PDF at the finite element nodes can be obtained using, e.g., Edgeworth expansion (Ghanem and Spanos 2003)
- Numerous applications, especially where extreme statistics are critical



Most Probable Solution

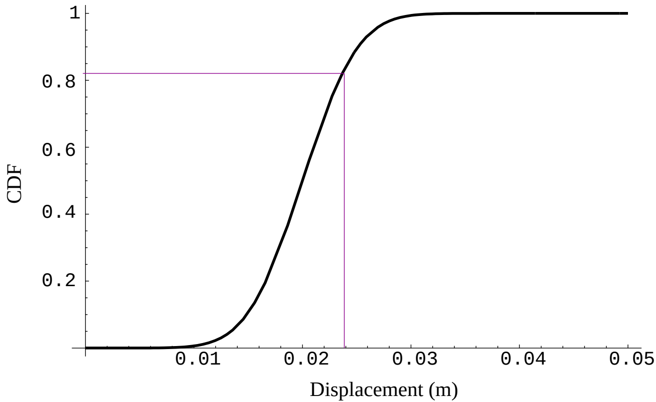


Tails of PDF


P[0.010 < Displacement < 0.012] = 0.01654
100
80
60
40
20
PDF
-0.01
0.01
0.02
0.03
0.04
0.05
Displacement (m)

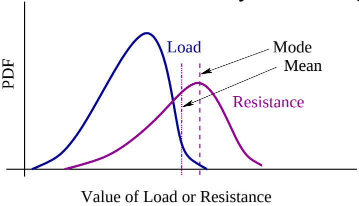
Probability of Exceedance

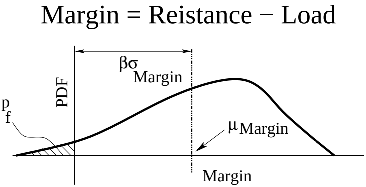
Probability that displacement exceeds 0.025 m = 1 − 0.825 = 0.175



Derivative Applications

- Performance based engineering
  - Reliability index (β)
  - Probability of damage and/or failure (p_f)





- Sensitivity analysis
- Financial risk analysis
- In general, useful for applications where mean, mode and extreme statistics are important

Summary

- **Steady progress** in software and hardware allows for high fidelity Model Based Simulations for performance assessment of infrastructure systems
- **Interplay** of **Earthquake(s)** with **Soil** and **Structure Systems** plays a major role in catastrophic failures (and successes)
- **Probabilistic** performance based engineering (uncertainty in soil and structural behavior, earthquake motions...)
- **Overcome** traditional performance assessment approaches used in engineering practice (design using prescriptive code!)