G.A. Leonards Lecture
April 26, 2019

Performance-Based Geotechnical Seismic Design

Steve Kramer

Professor of Civil and Environmental Engineering
University of Washington
Seattle, Washington

Acknowledgments

Pacific Earthquake Engineering Research (PEER) Center

Washington State Department of Transportation

University of Washington

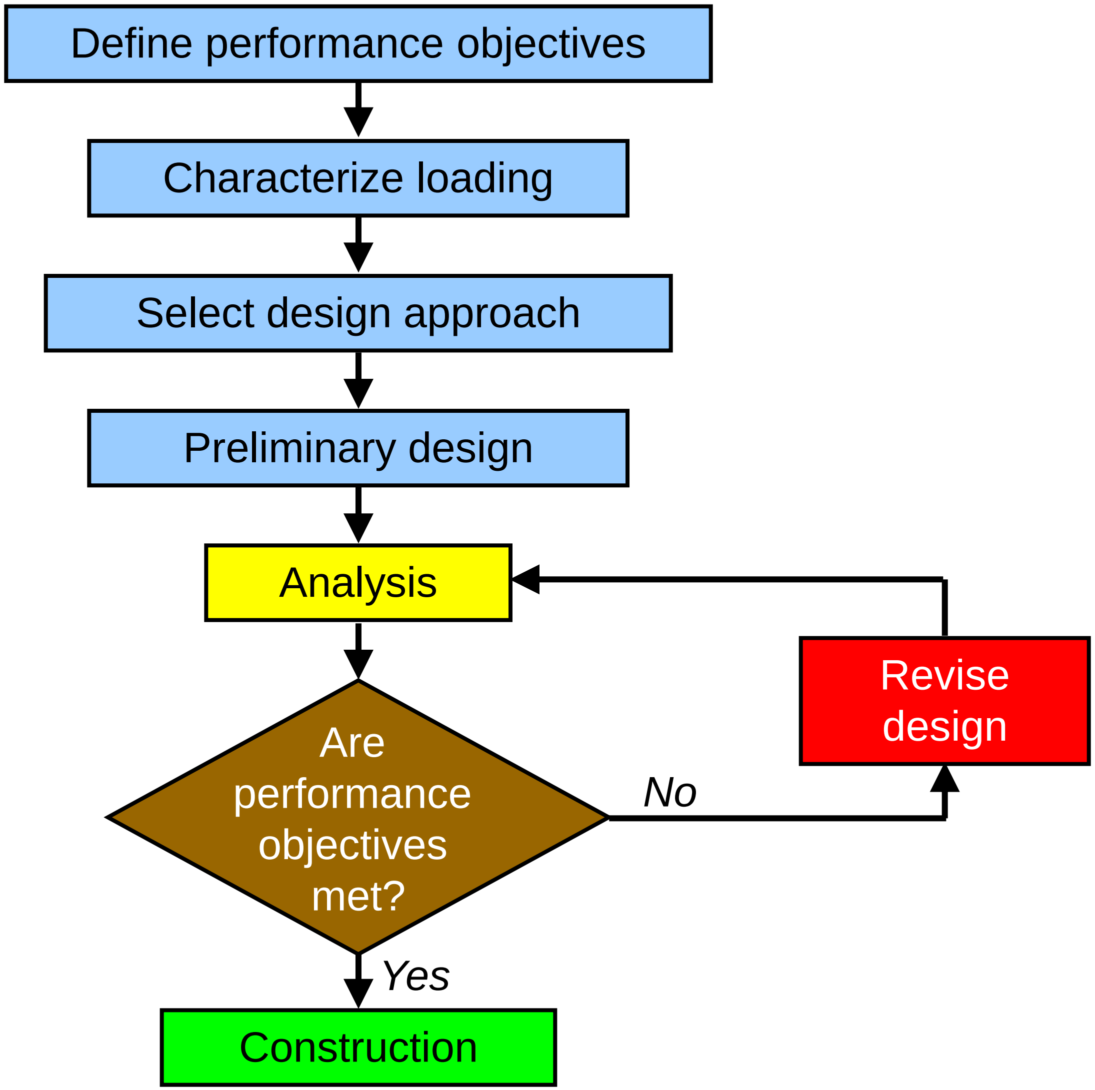
- Pedro Arduino
- Roy Mayfield
- HyungSuk Shin
- Kevin Franke
- Yi-Min Huang
- Sam Sideras
- Mike Greenfield
- Andrew Makdisi

Outline

- Introduction
- Geotechnical Design
- Seismic Design
  - Historical Approaches
  - Code-Based Approaches
- Performance-Based Design
  - Response-Level Implementation
  - Damage-Level Implementation
  - Loss-Level Implementation
- Advancing Performance-Based Design
  - Consideration of Capacity
  - Load and Resistance Factor Framework
  - Demand and Capacity Factor Framework
  - Application to Pile Foundations
- Summary and Conclusions

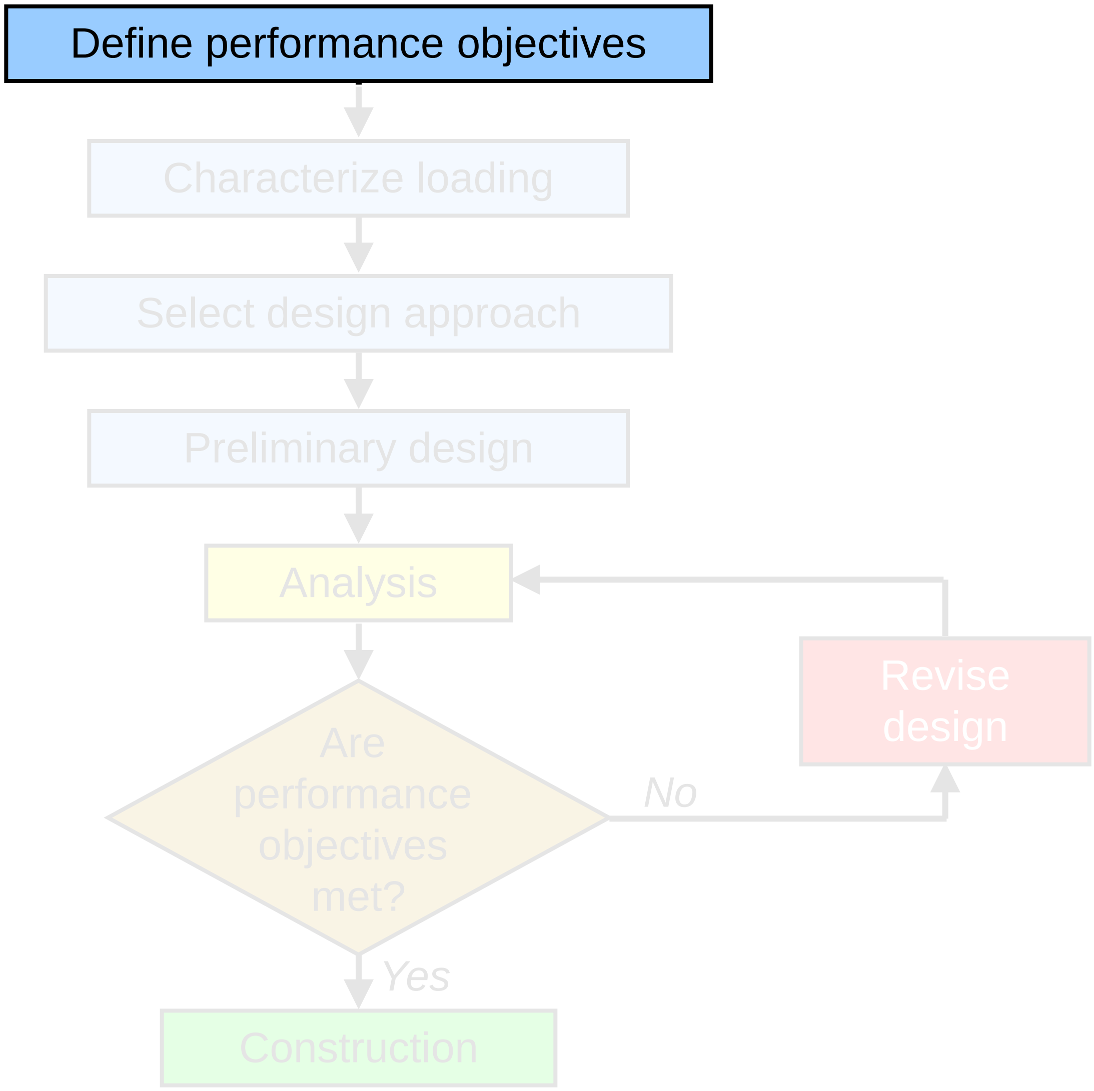
Geotechnical Design

The design process



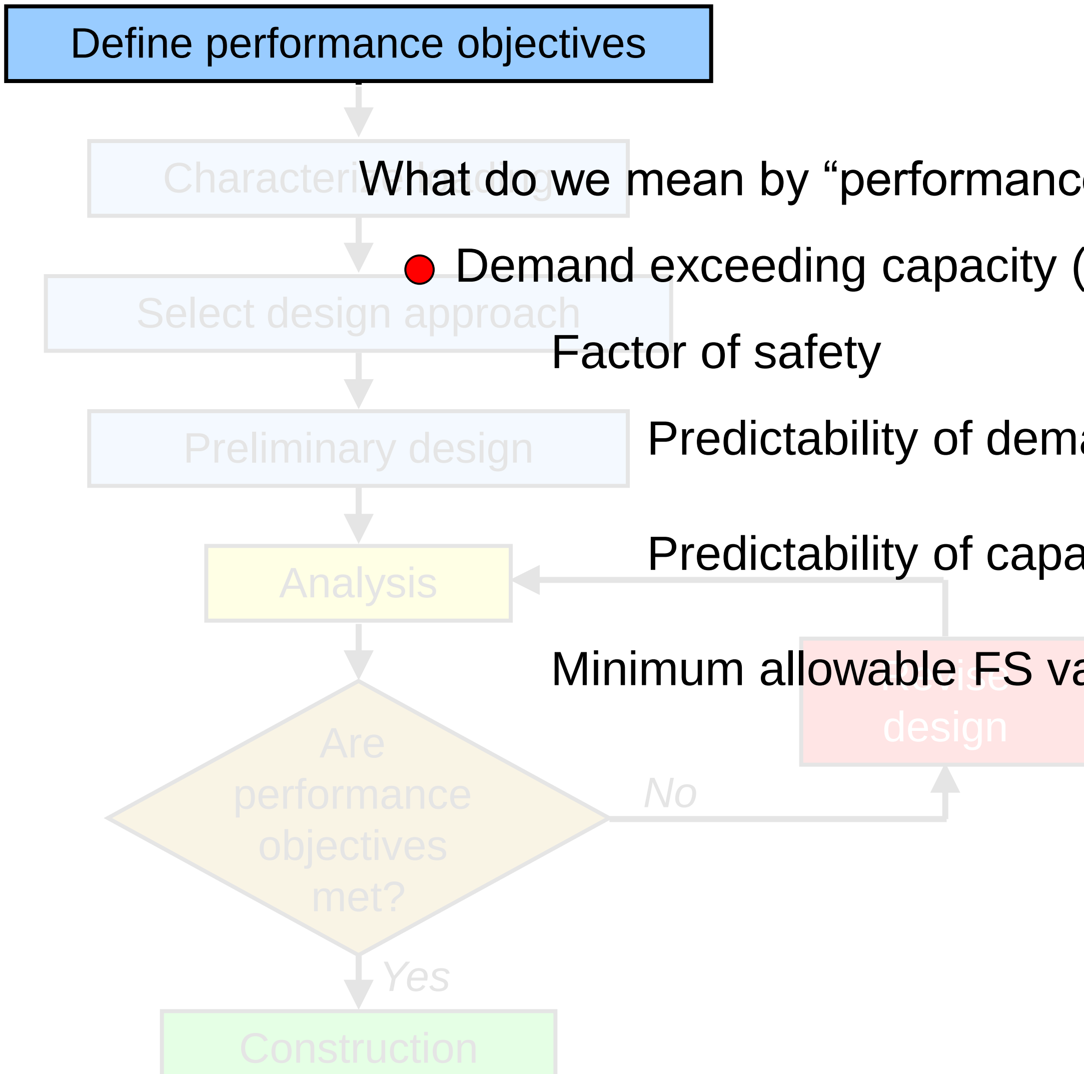
Geotechnical Design

The design process



Geotechnical Design

The design process



What do we mean by "performance?"

- Demand exceeding capacity (force, stress-based)?

Factor of safety

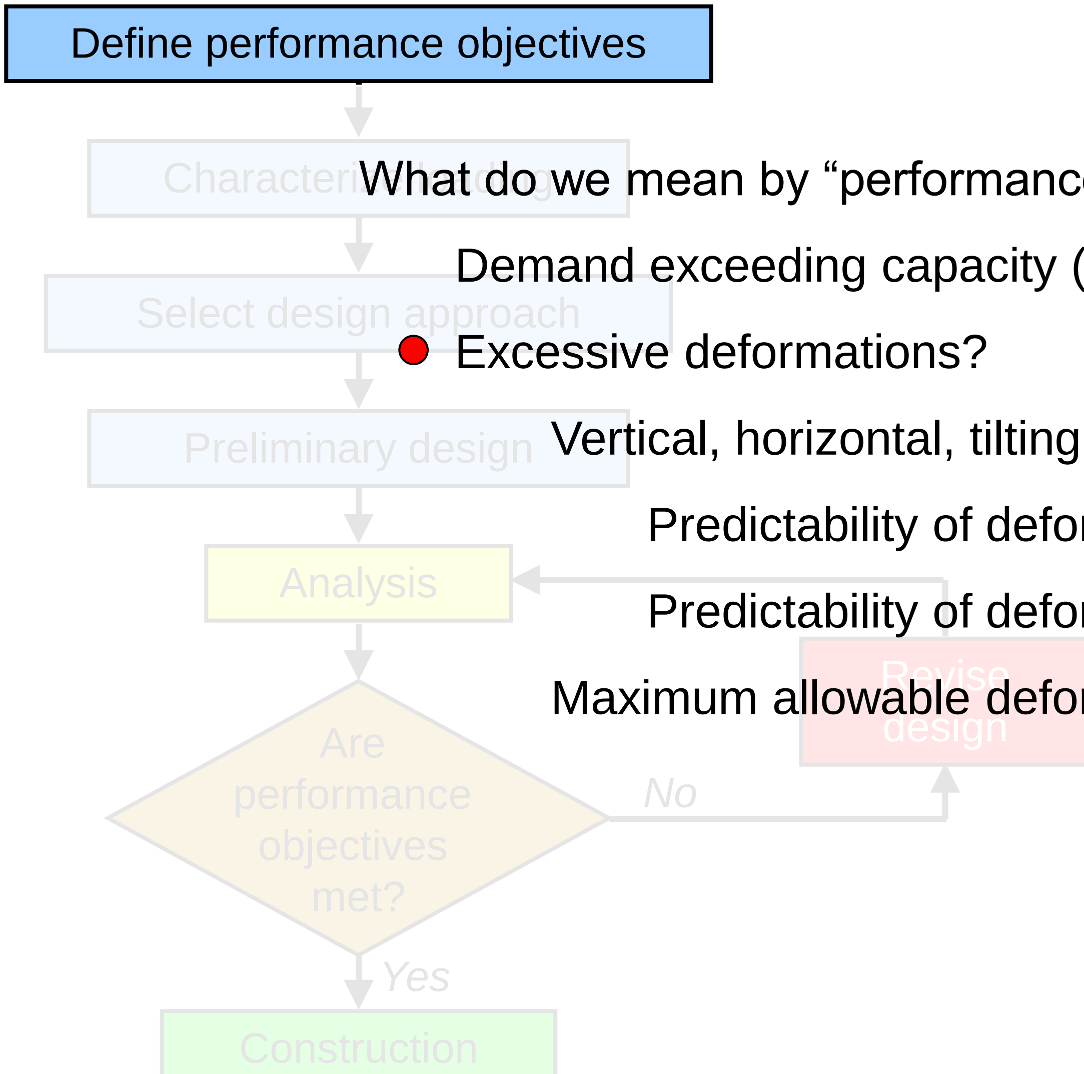
Predictability of demands?

Predictability of capacities?

Minimum allowable FS value?

Geotechnical Design

The design process

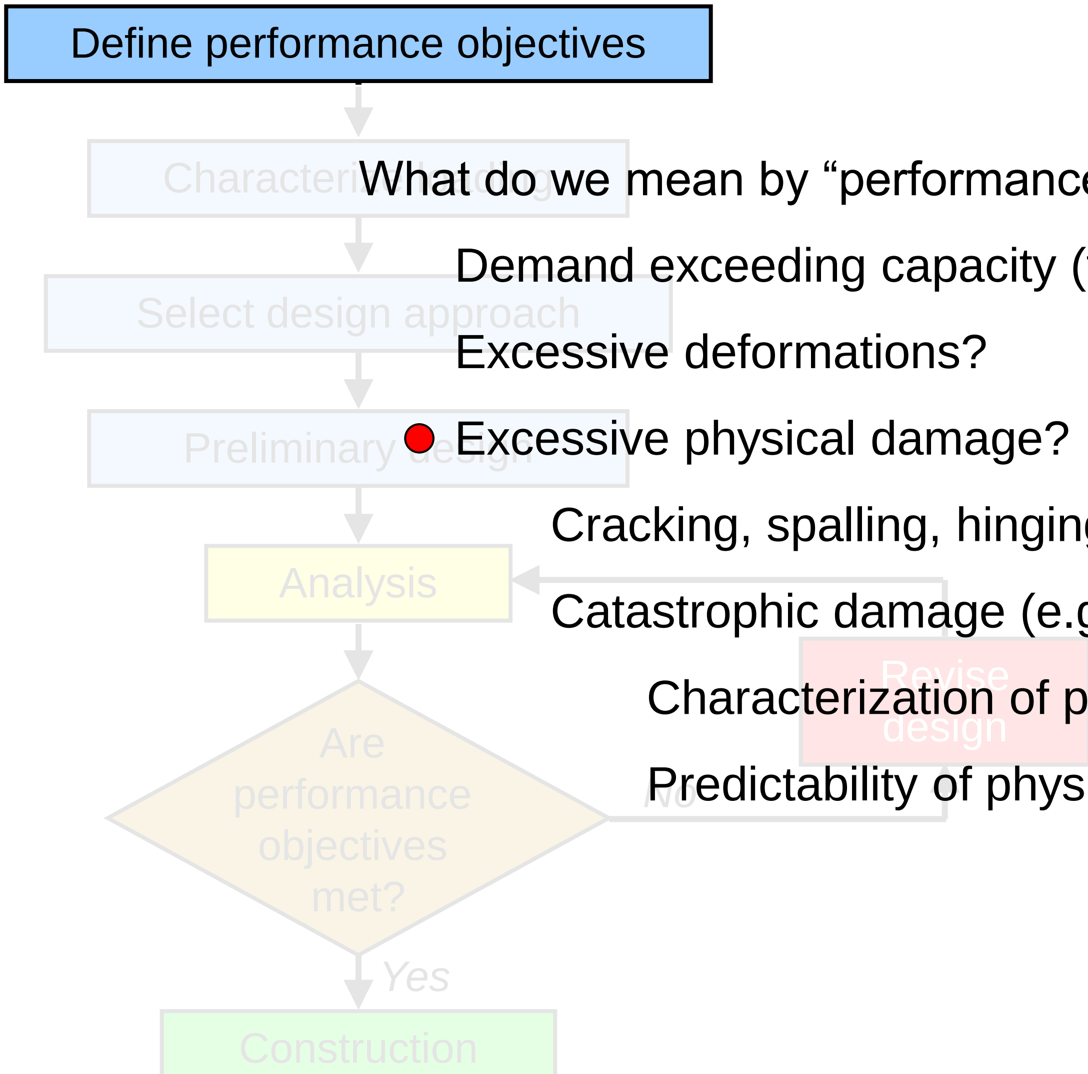


What do we mean by “performance?”

- Demand exceeding capacity (force, stress-based)?
- Excessive deformations?
  - Vertical, horizontal, tilting, rotation
    - Predictability of deformation demands?
    - Predictability of deformation capacities?
  - Maximum allowable deformations?

Geotechnical Design

The design process

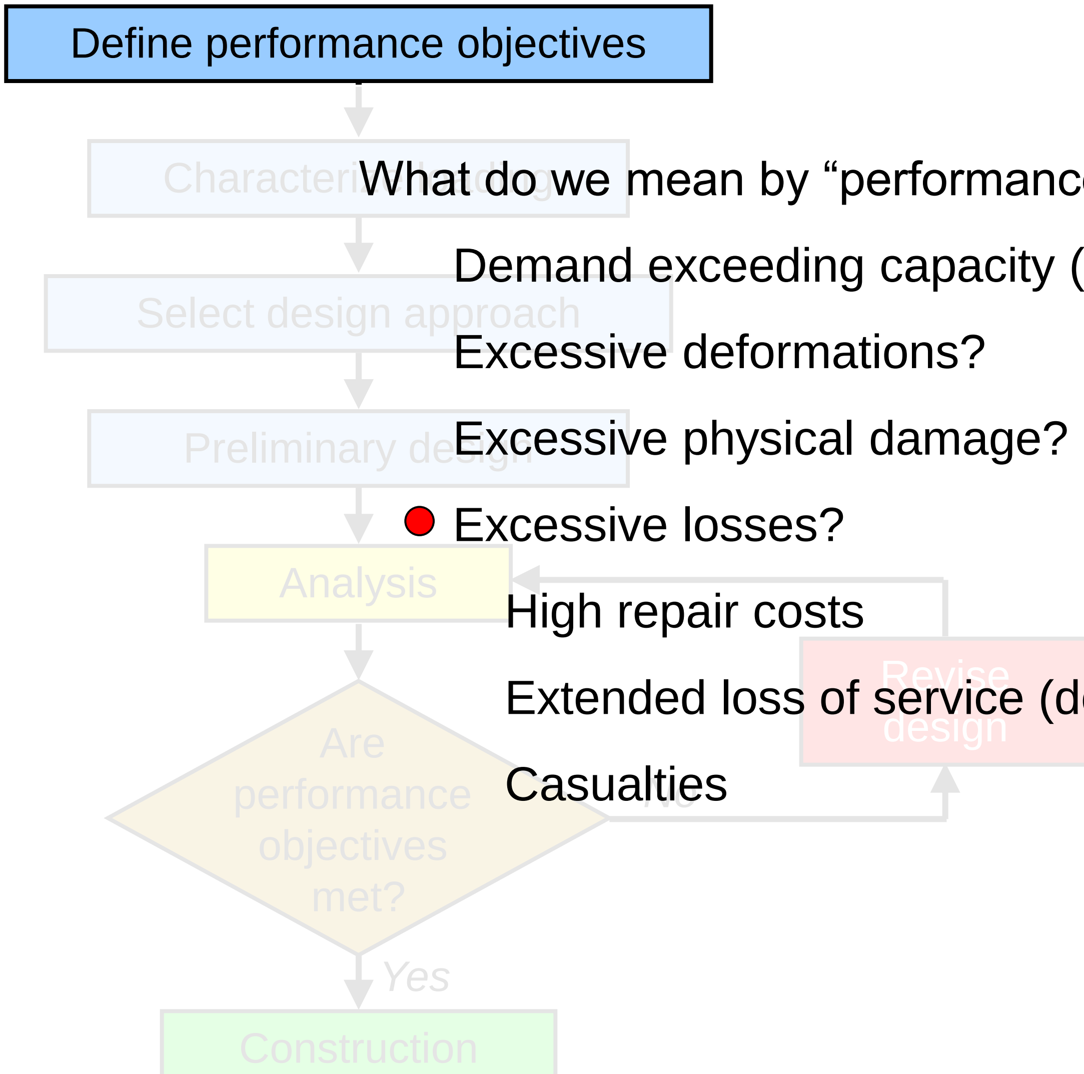


What do we mean by “performance?”

- Demand exceeding capacity (force, stress-based)?
- Excessive deformations?
- Excessive physical damage?
  - Cracking, spalling, hinging, etc.?
  - Catastrophic damage (e.g., collapse)?
    - Characterization of physical damage
    - Predictability of physical damage?

Geotechnical Design

The design process



What do we mean by "performance?"

- Demand exceeding capacity (force, stress-based)?
- Excessive deformations?
- Excessive physical damage?
- Excessive losses?
  - High repair costs
  - Extended loss of service (downtime)
  - Casualties

Historical Approaches to Seismic Design

Pseudo-Static

Retaining walls

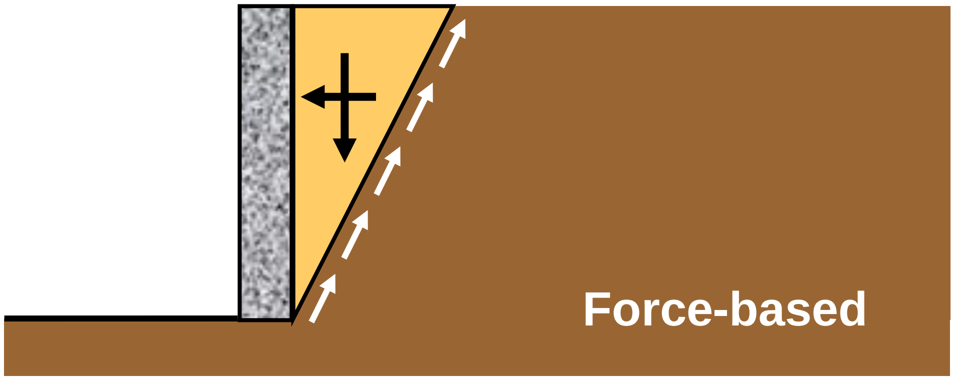
Mononobe and Matsuo (1926)

Okabe (1926)

Historical Approaches to Seismic Design

Pseudo-Static

Retaining walls



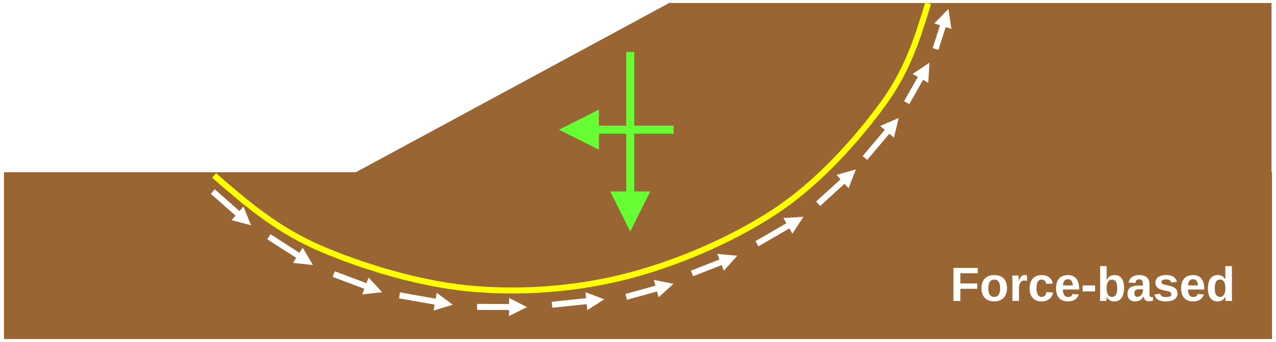
Okabe (1926)

Mononobe and Matsuo (1929)

Historical Approaches to Seismic Design

Pseudo-Static

- Retaining walls
- Slopes

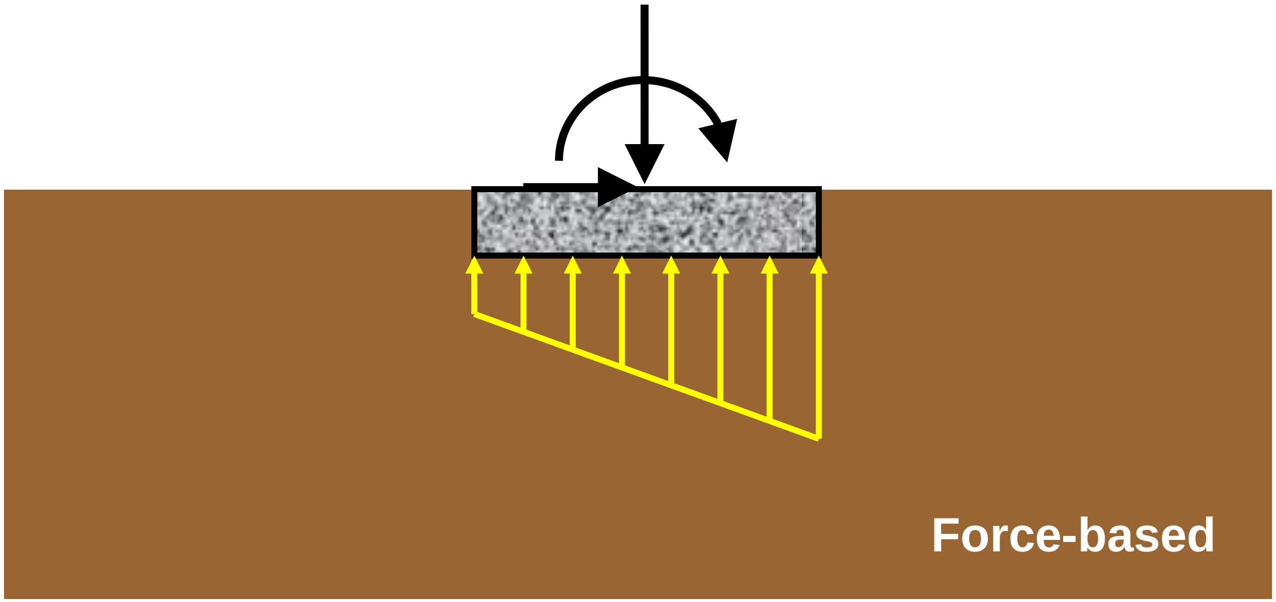


Historical Approaches to Seismic Design

Pseudo-Static

- Retaining walls
- Slopes
- Foundations

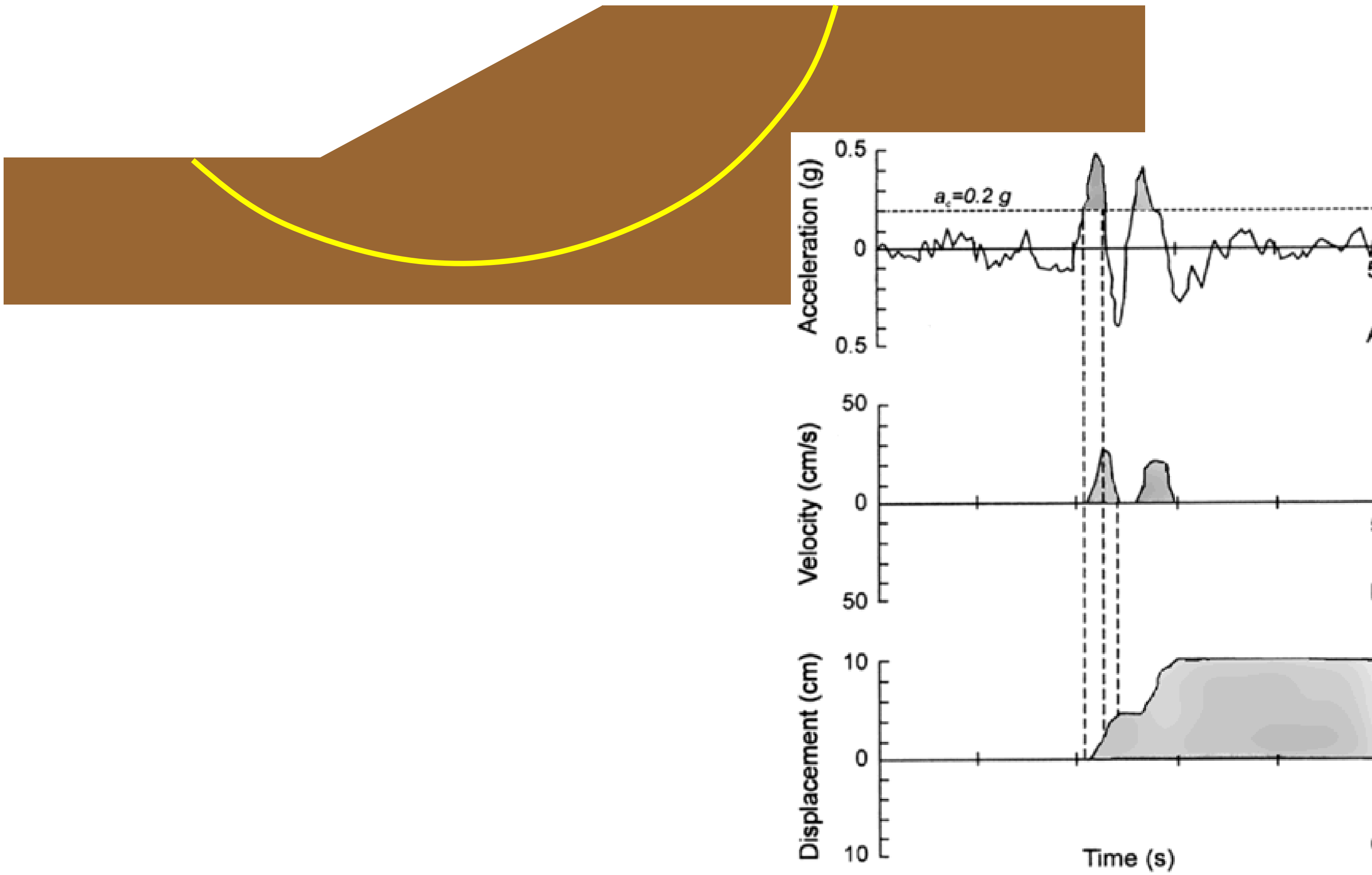
Results expressed in terms of factor of safety



Historical Approaches to Seismic Design

Displacement-based

Newmark analysis

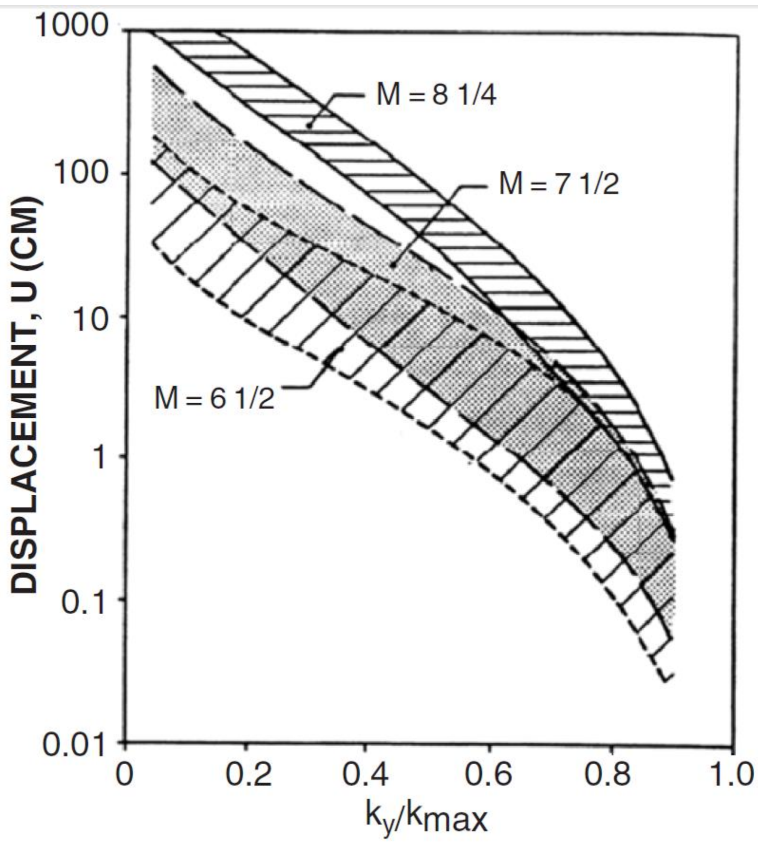


Historical Approaches to Seismic Design

Displacement-based

Newmark analysis

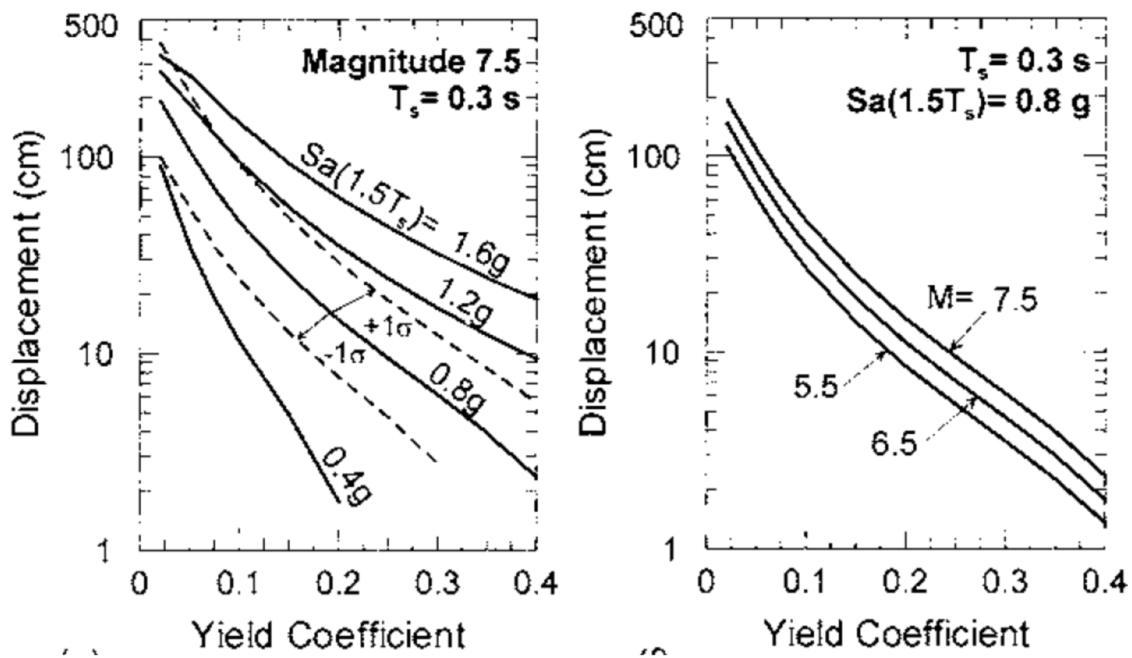
Makdisi-Seed (1978)



Historical Approaches to Seismic Design

Displacement-based

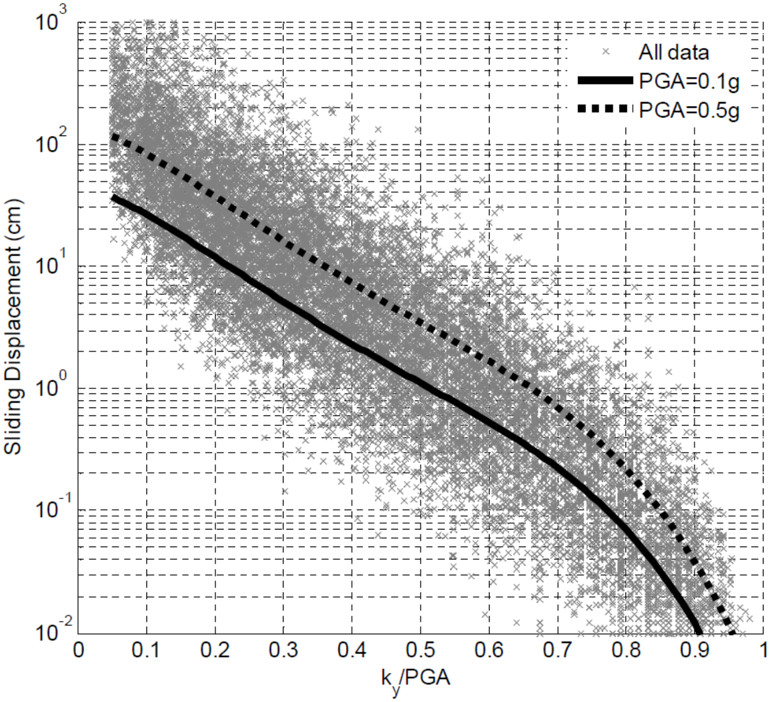
- Newmark analysis
  - Makdisi-Seed (1978)
  - Travasarou and Bray (2007)



Historical Approaches to Seismic Design

Displacement-based

- Newmark analysis
  - Makdisi-Seed (1978)
  - Bray and Travasarou (2007)
  - Rathje and Saygili (2009)

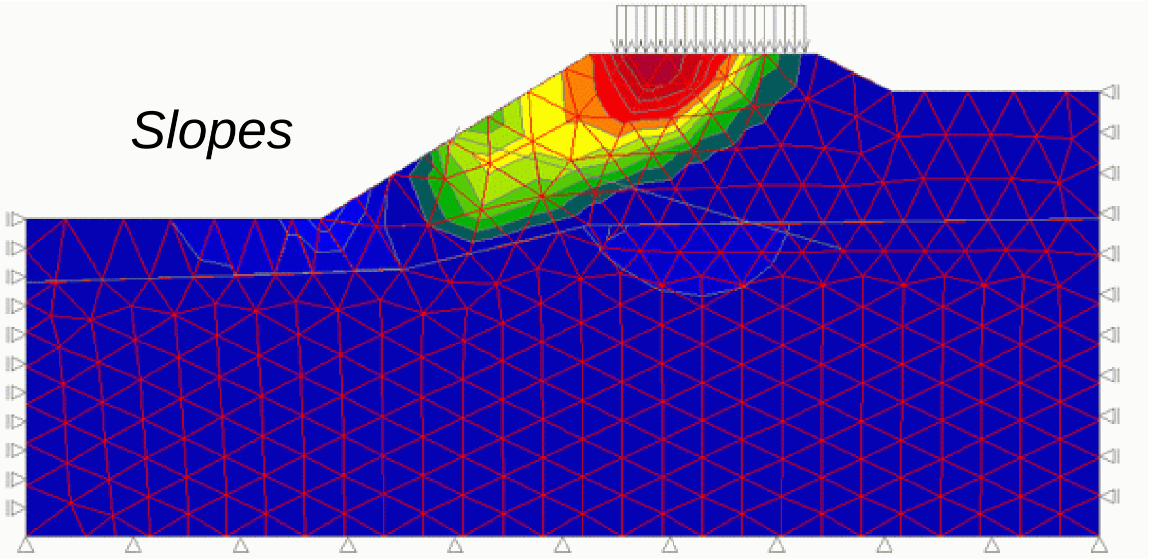


Historical Approaches to Seismic Design

Displacement-based

- Newmark analysis
  - Makdisi-Seed (1978)
  - Bray and Travasarou (2007)
  - Rathje and Saygili (2009)

- Stress-deformation analysis



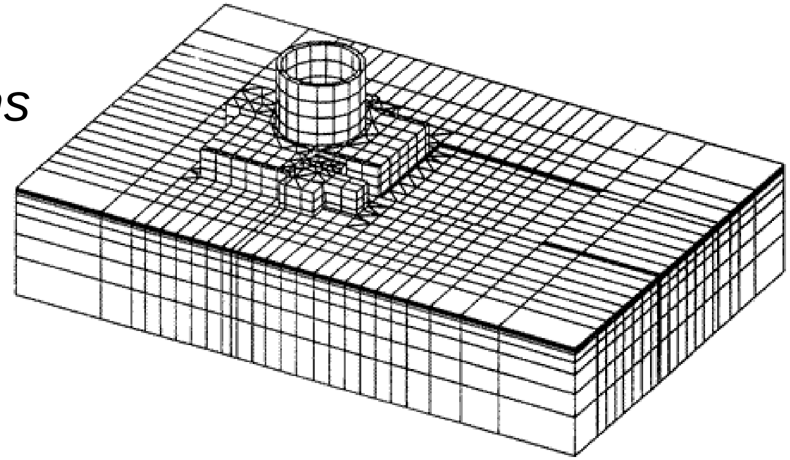
Historical Approaches to Seismic Design

Displacement-based

- Newmark analysis
  - Makdisi-Seed (1978)
  - Bray and Travasarou (2007)
  - Rathje and Saygili (2009)

- Stress-deformation analysis

Shallow foundations



Historical Approaches to Seismic Design

Displacement-based

Newmark analysis

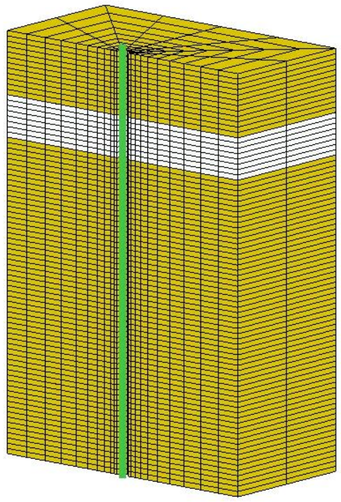
Makdisi-Seed (1978)

Bray and Travasarou (2007)

Rathje and Saygili (2009)

Stress-deformation analysis

Deep foundations

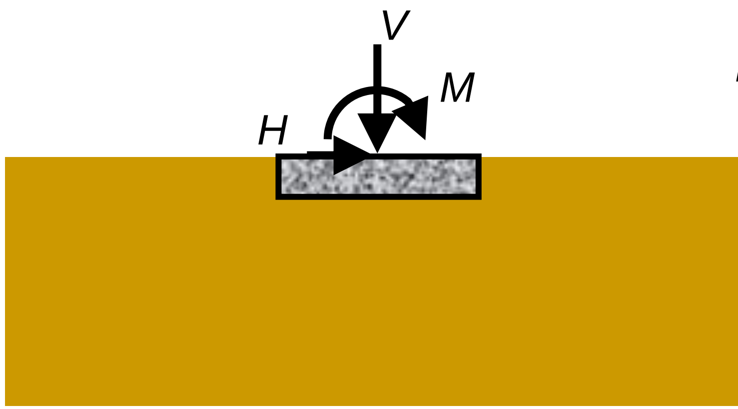


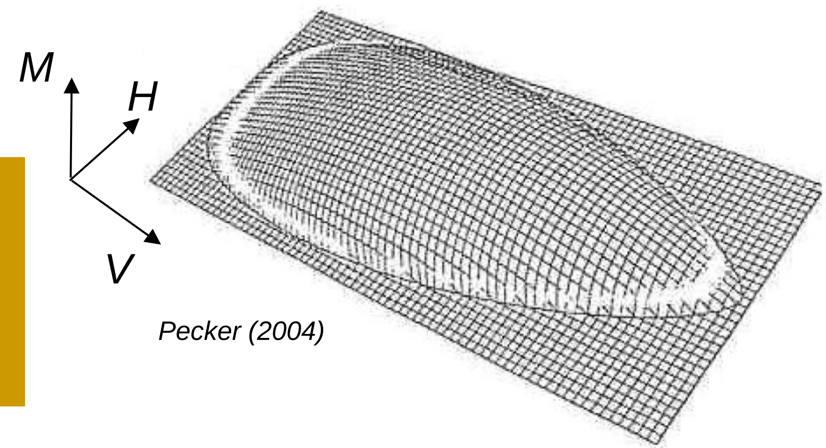
Historical Approaches to Seismic Design

Displacement-based

- Newmark analysis
  - Makdisi-Seed (1978)
  - Bray and Travasarou (2007)
  - Rathje and Saygili (2009)

- Stress-deformation analysis
- Macro-elements





Pecker (2004)

Historical Approaches to Seismic Design

Displacement-based

Newmark analysis

Makdisi-Seed (1978)

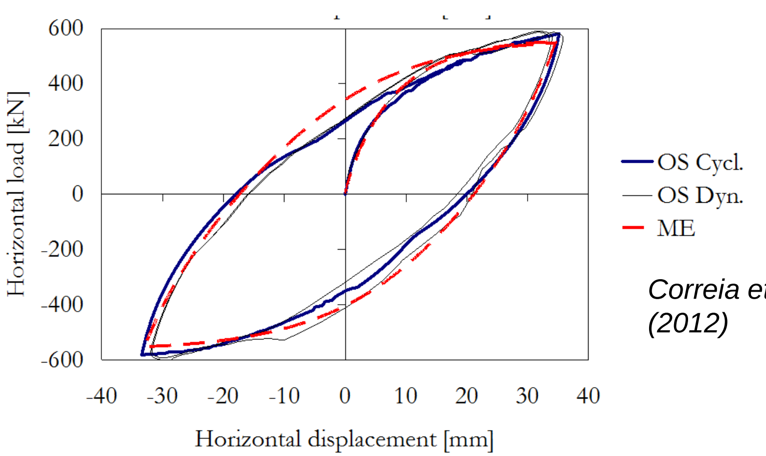
Bray and Travasarou (2007)

Rathje and Saygili (2009)

Stress-deformation analysis

Macro-elements

After Hutchinson et al. (2002)



Correia et al. (2012)

Code-Based Seismic Design

Early building codes – first edition of SEAOC Blue Book:

Intended that structure be able to resist:

- a minor level of shaking without damage (non-structural or structural),
- a moderate level of shaking without structural damage (but possibly with some non-structural damage), and
- a strong level of shaking without collapse (but possibly with both non-structural and structural damage).

Code-Based Seismic Design

Early building codes – first edition of SEAOC Blue Book:

Intended that structure be able to resist:

- a minor level of shaking without damage (non-structural or structural),
- a moderate level of shaking without structural damage (but possibly with some non-structural damage), and
- a strong level of shaking without collapse (but possibly with both non-structural and structural damage).

Multiple levels of seismic loading

Code-Based Seismic Design

Early building codes – first edition of SEAOC Blue Book:

Intended that structure be able to resist:

- a minor level of shaking without damage (non-structural or structural),
- a moderate level of shaking without structural damage (but possibly with some non-structural damage), and
- a strong level of shaking without collapse (but possibly with both non-structural and structural damage).

Multiple levels of seismic loading

Multiple performance objectives

Code-Based Seismic Design

Discrete hazard level approach

Vision 2000 – mid-1990s

- Multiple ground motion return periods
- Different performance objectives for each return period

Vision 2000		**Earthquake Performance Level**			
		Fully Operational	Operational	Life Safe	Near Collapse
Earthquake Design Level	Frequent (43 yrs)				
	Occasional (72 yrs)				
	Rare (475 yrs)				
	Very Rare (975 yrs)				

Basic

Essential /Hazardous

Safety Critical

Earthquake Losses

Process leading to losses

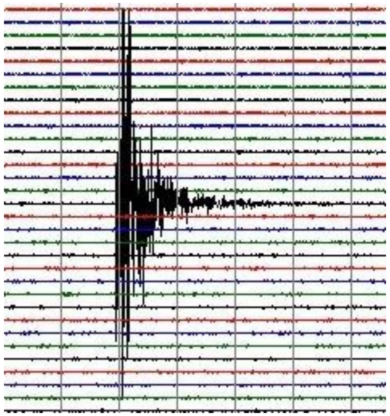
Ground motion → *System response* → *Physical damage* → *Loss*

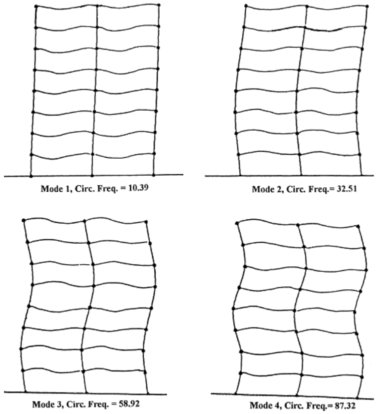
PGA, $S_a(T_o)$, I_a, *CAV*

δ_h, δ_v, ϕ

Crack width, spacing

Deaths, dollars, downtime





Performance-Based Design

Ultimately, we are interested in …

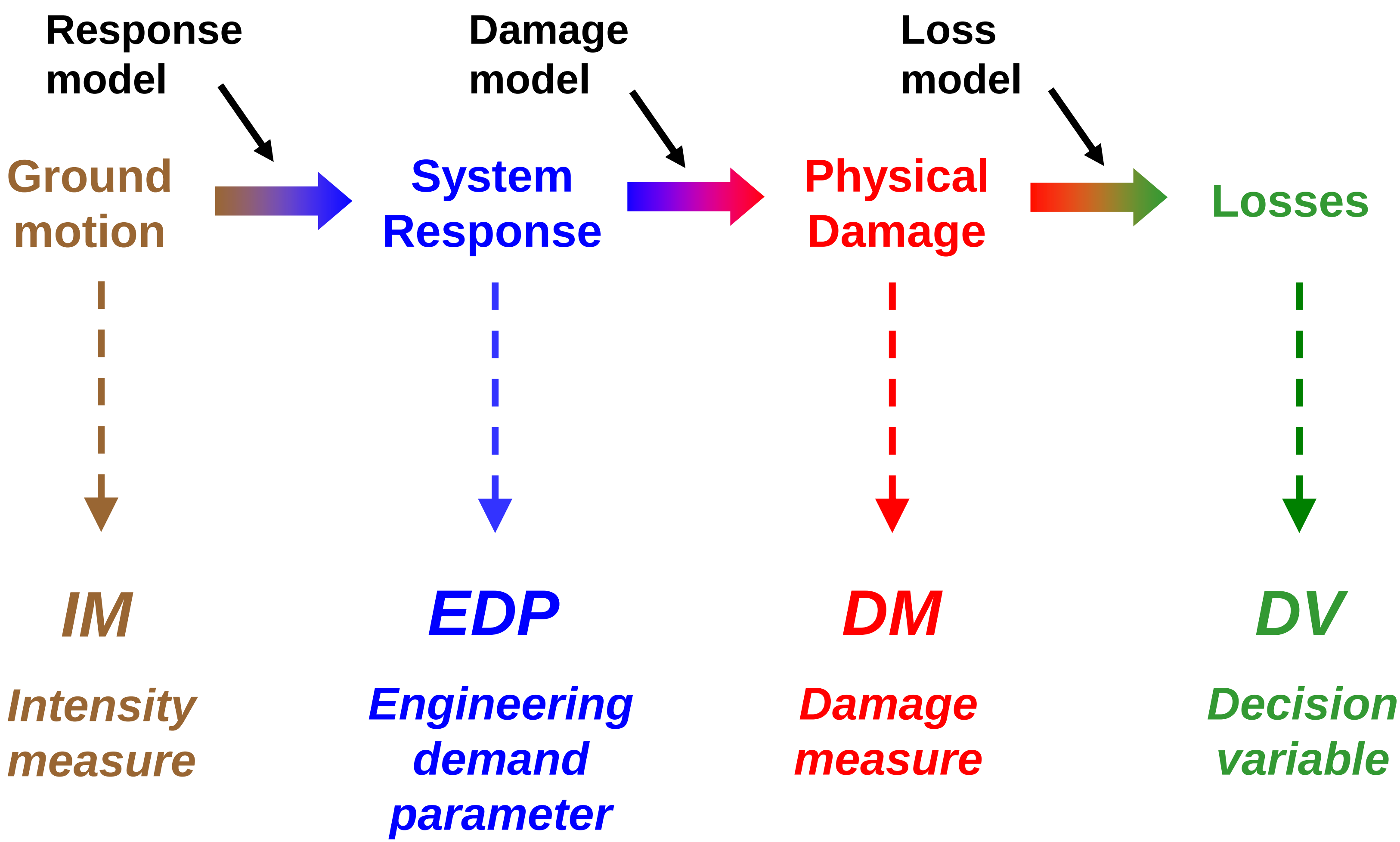
Response model → **Damage model** → **Loss model**

Ground motion → **System Response** → **Physical Damage** → **Losses**

Ground motion	System Response	Physical Damage	Losses
Peak acceleration, Spectral acceleration, Arias intensity, etc.	Interstory drift, Plastic rotation, Ground deformation, etc.	Concrete spalling, Column cracking, etc.	Deaths, Injuries, Repair cost, Downtime, etc.

Performance-Based Design

Ultimately, we are interested in …



Performance-Based Design

Ultimately, we are interested in …

Response model

Damage model

Loss model

Ground motion

Physical Damage

Losses

All are uncertain !!!

Response given ground motion	Damage given response	Loss given damage	
EDP* | *IM	***DM* | *EDP***	***DV* | *DM***	
IM	***EDP***	***DM***	***DV***
Intensity measure	***Engineering demand parameter***	***Damage measure***	***Decision variable***

Performance-Based Design

Uncertainty exists – can't ignore it

- Uncertainty in ground motions varies from location to location
- Uncertainty in response varies from site to site
- Uncertainty in damage varies from structure to structure
- Uncertainty in loss varies with location (material costs, labor costs, …) and time (inflation, interest rates, etc.)

Ignoring uncertainty, or assuming it is uniform, leads to:

Performance-Based Design

Uncertainty exists – can't ignore it

- Uncertainty in ground motions varies from location to location
- Uncertainty in response varies from site to site
- Uncertainty in damage varies from structure to structure
- Uncertainty in loss varies with location (material costs, labor costs, …) and time (inflation, interest rates, tweets, …)

Ignoring uncertainty, or assuming it is uniform, leads to:

- Inaccurate performance predictions

Performance-Based Design

Uncertainty exists – can't ignore it

- Uncertainty in ground motions varies from location to location
- Uncertainty in response varies from site to site
- Uncertainty in damage varies from structure to structure
- Uncertainty in loss varies with location (material costs, labor costs, …) and time (inflation, interest rates, tweets, …)

Ignoring uncertainty, or assuming it is uniform, leads to:

- Inaccurate performance predictions
- Inconsistent levels of safety from one project to another

Performance-Based Design

Uncertainty exists – can't ignore it

- Uncertainty in ground motions varies from location to location
- Uncertainty in response varies from site to site
- Uncertainty in damage varies from structure to structure
- Uncertainty in loss varies with location (material costs, labor costs, …) and time (inflation, interest rates, tweets, …)

Ignoring uncertainty, or assuming it is uniform, leads to:

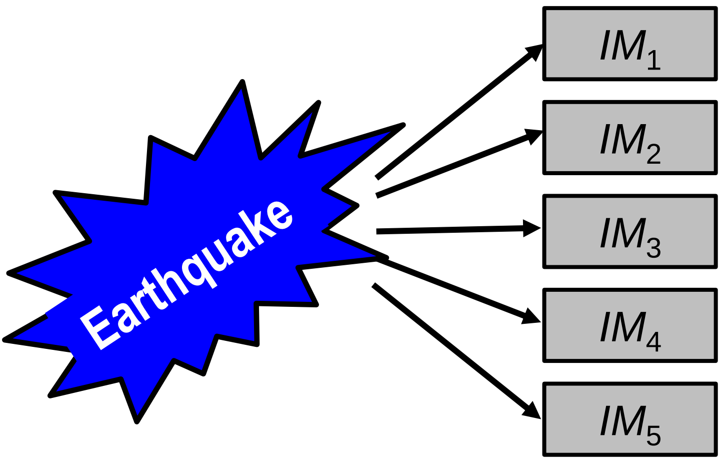
- Inaccurate performance predictions
- Inconsistent levels of safety from one project to another
- Inefficient use of resources for seismic retrofit/design

Discrete Hazard Level Approach

Divide *IMs*, *EDPs*, *DMs*, and *DVs* into finite number of ranges

Consider all combinations

Account for conditional probabilities

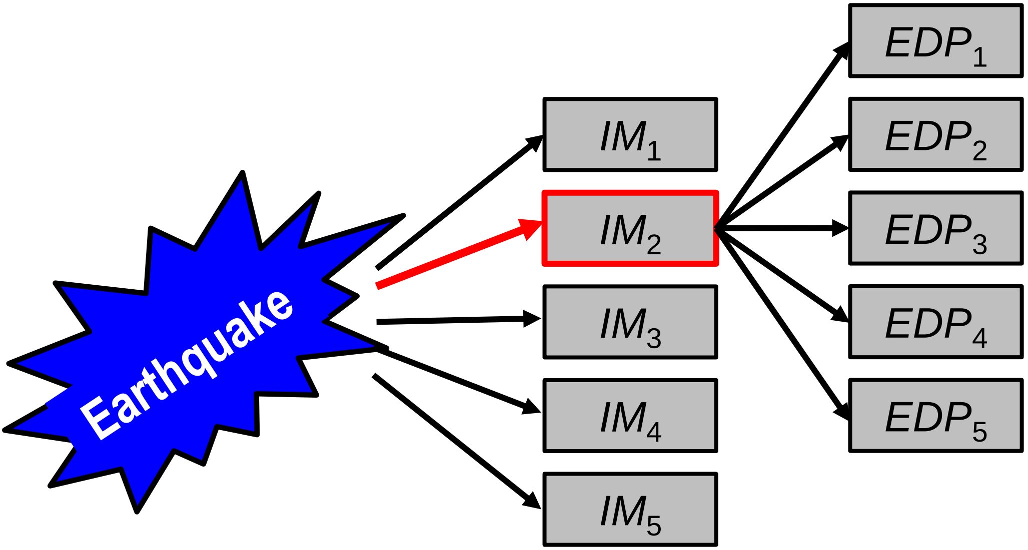


Discrete Hazard Level Approach

Divide *IMs*, *EDPs*, *DMs*, and *DVs* into finite number of ranges

Consider all combinations

Account for conditional probabilities

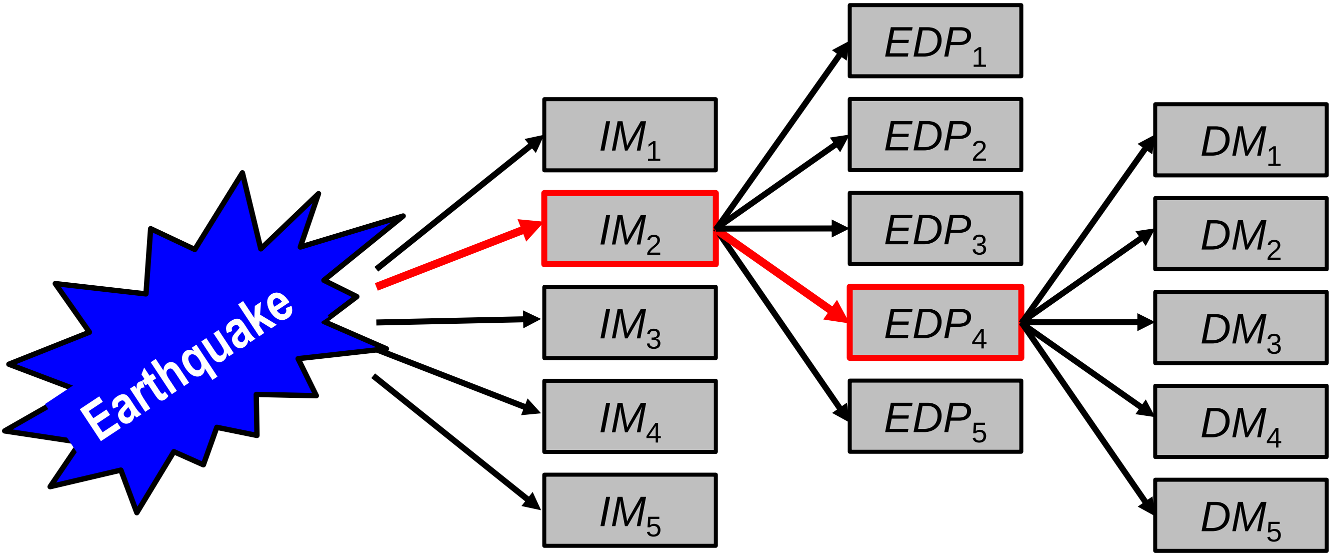


Discrete Hazard Level Approach

Divide *IMs*, *EDPs*, *DMs*, and *DVs* into finite number of ranges

Consider all combinations

Account for conditional probabilities

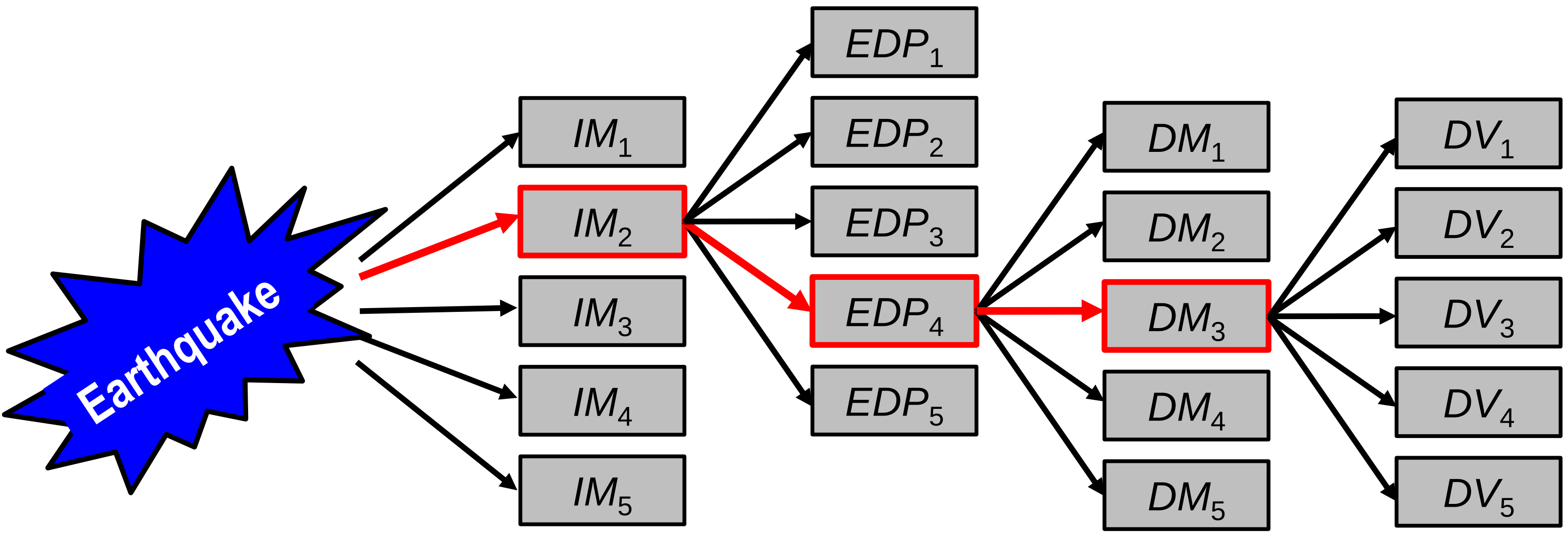


Discrete Hazard Level Approach

Divide *IMs*, *EDPs*, *DMs*, and *DVs* into finite number of ranges

Consider all combinations

Account for conditional probabilities

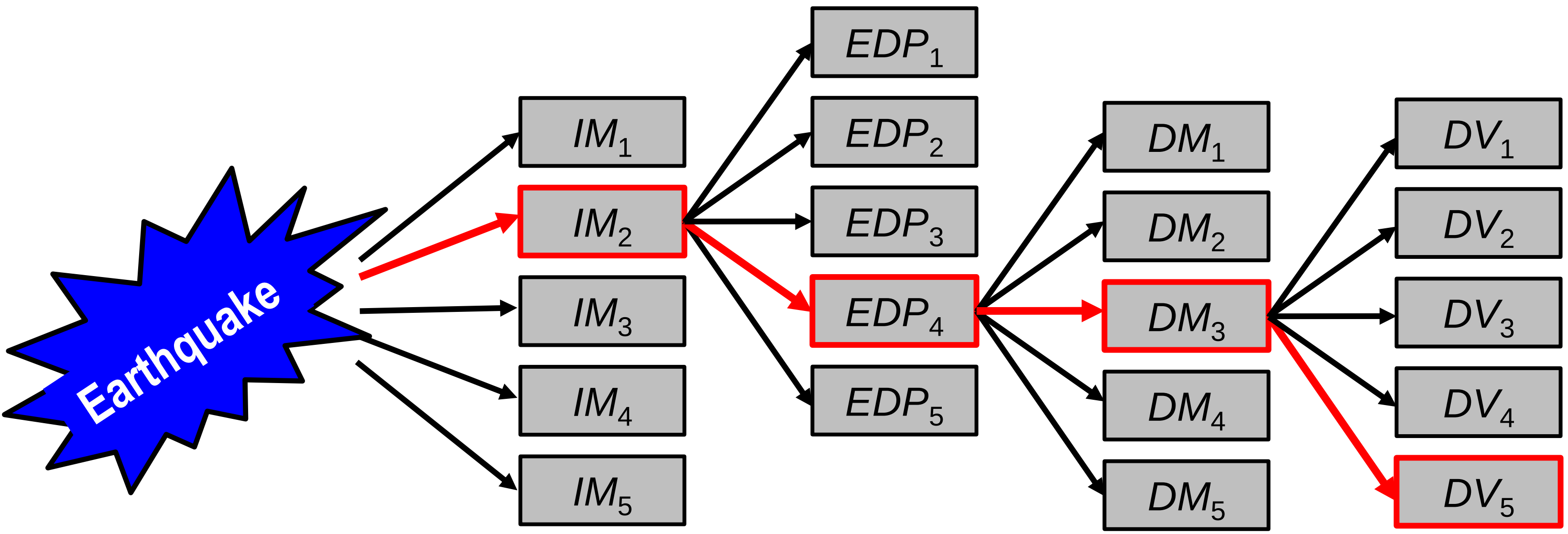


Discrete Hazard Level Approach

Divide *IMs*, *EDPs*, *DMs*, and *DVs* into finite number of ranges

Consider all combinations

Account for conditional probabilities

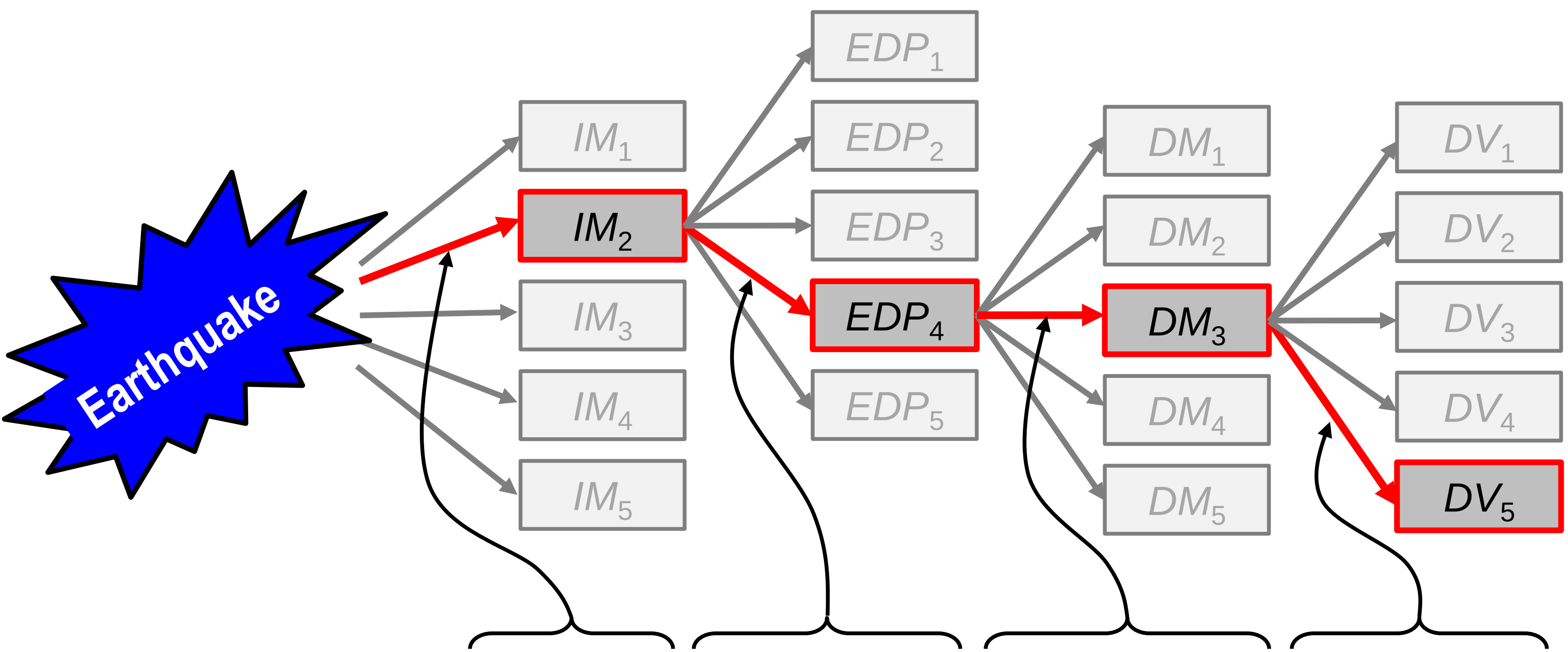


Discrete Hazard Level Approach

Divide *IM*s, *EDP*s, *DM*s, and *DV*s into finite number of ranges

Consider all combinations

Account for conditional probabilities



$$DV_{2\text{-}4\text{-}3\text{-}5} = P[IM_2|eq]\; P[EDP_4|IM_2]\; P[DM_3|EDP_4]\; P[DV_5|DM_3]\;\; DV_5$$

Summing over all paths

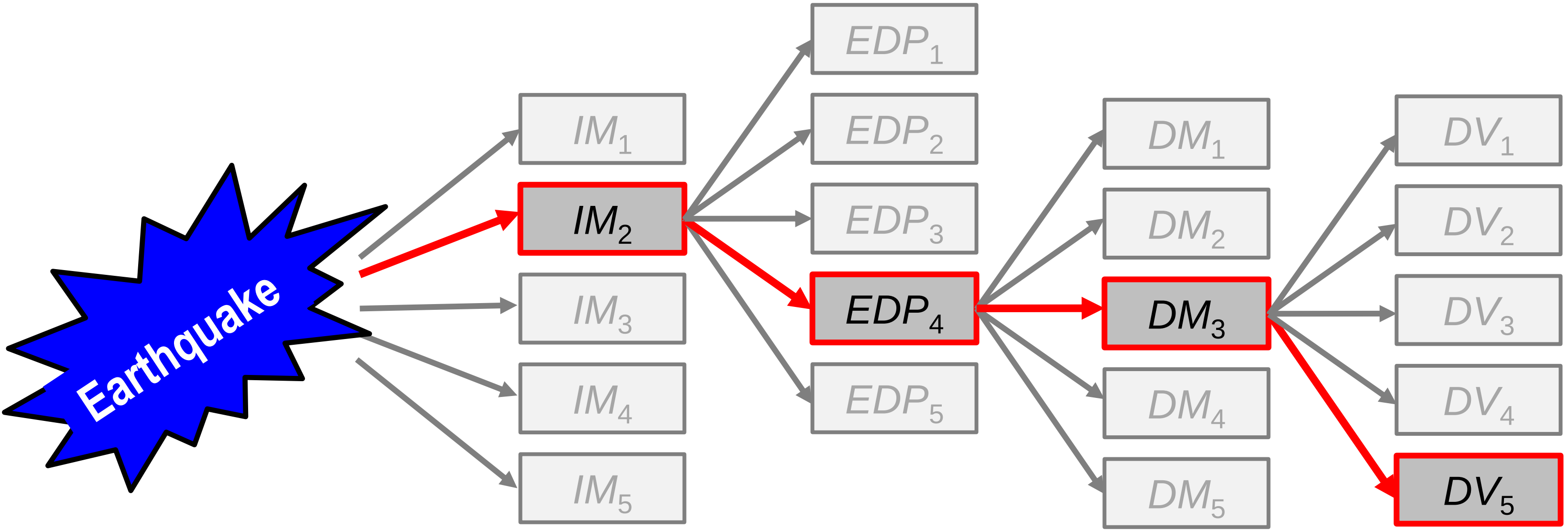
$$DV = \Sigma\, DV_{i\text{-}j\text{-}k\text{-}l}$$

Discrete Hazard Level Approach

Divide *IMs*, *EDPs*, *DMs*, and *DVs* into finite number of ranges

Consider all combinations

Account for conditional probabilities



For this case, 5 x 5 x 5 x 5 = 625 paths

With 100 values for each . . . 100 million paths

Integral Hazard Level Approach

Covers entire range of hazard (ground motion) levels

Accounts for uncertainty in parameters, relationships

PEER framework

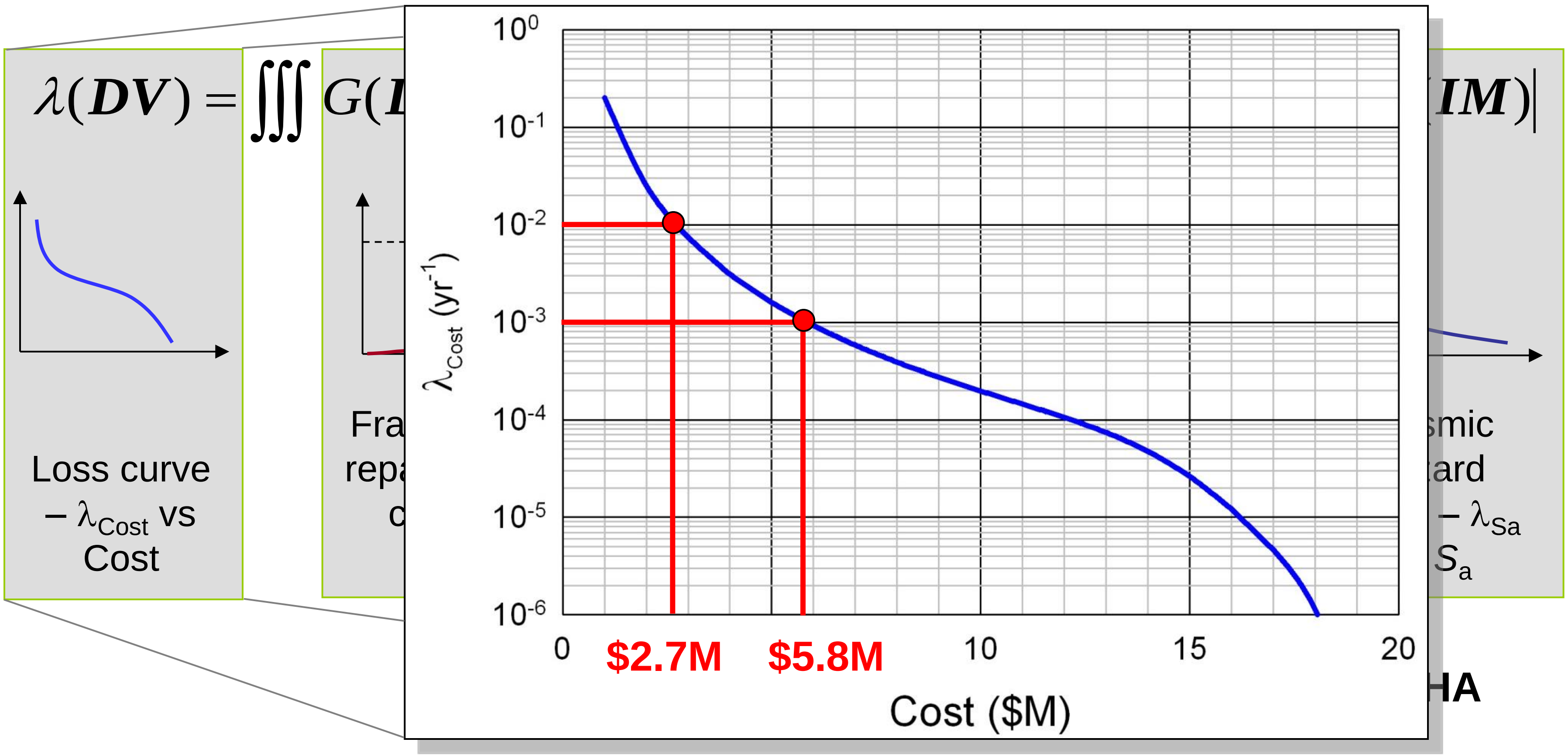
$$\lambda(\boldsymbol{DV}) = \iiint G(\boldsymbol{DV} \mid \boldsymbol{DM}) \left| dG(\boldsymbol{DM} \mid \boldsymbol{EDP}) \right| \left| dG(\boldsymbol{EDP} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

Integral Hazard Level Approach

Covers entire range of hazard (ground motion) levels

Accounts for uncertainty in parameters, relationships

PEER framework

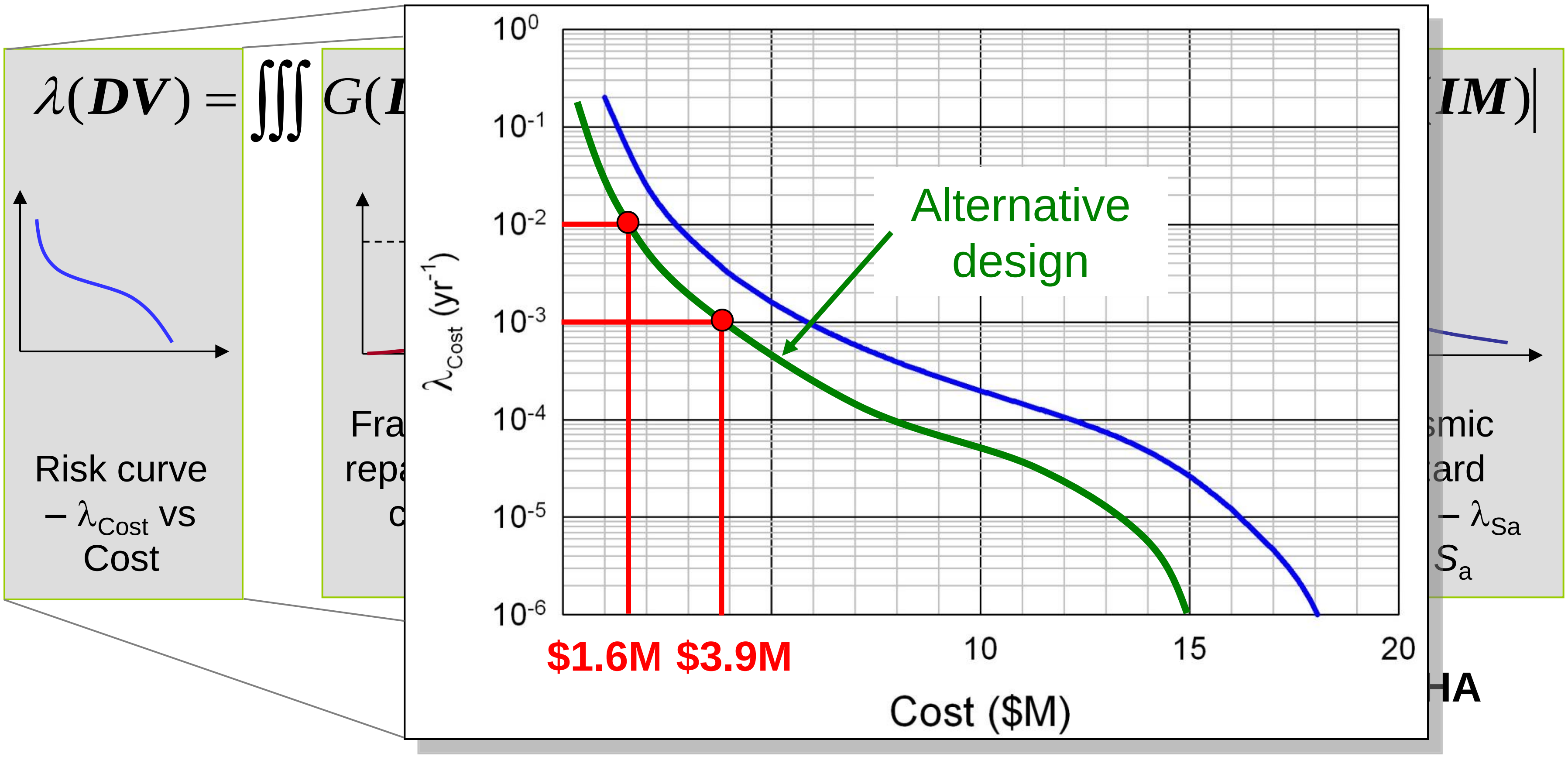


PEER Performance-Based Framework

Covers entire range of hazard (ground motion) levels

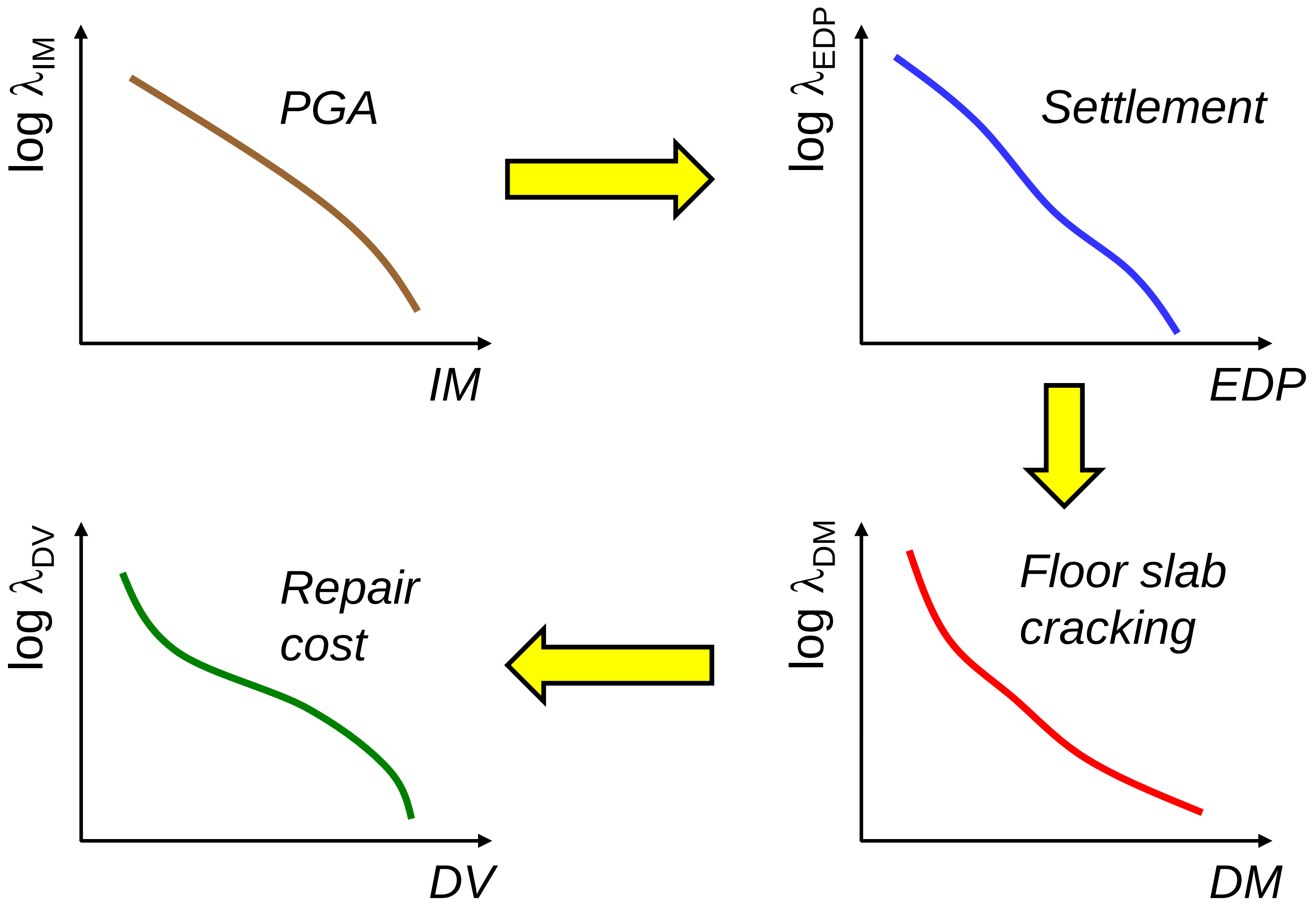
Accounts for uncertainty in parameters, relationships

PEER framework



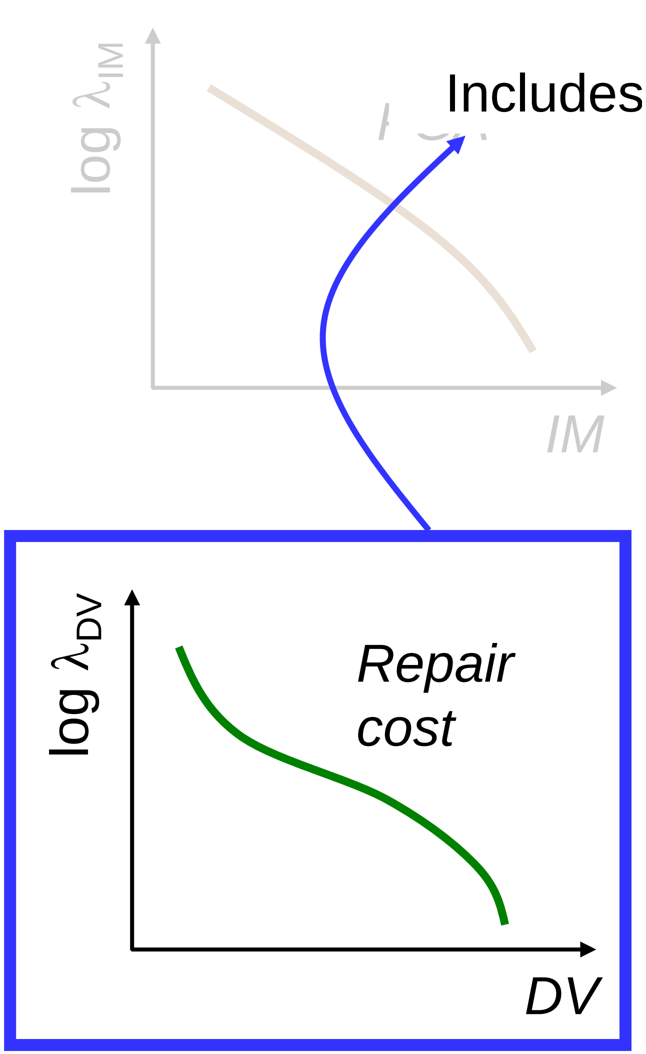
PEER Performance-Based Framework

Modular – response, damage, loss components



PEER Performance-Based Framework

Modular – response, damage, loss components

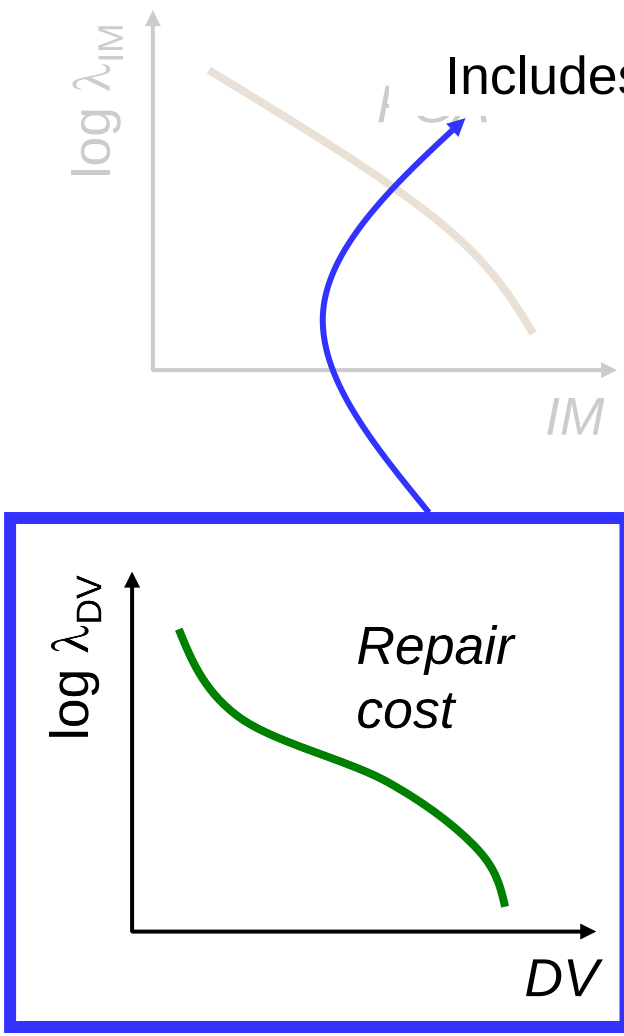


Includes - all earthquake magnitudes
- all source-to-site distances
- uncertainty in ground motion
- uncertainty in response given ground motion
- uncertainty in damage given response
- uncertainty in loss given damage

All levels of shaking are cosidered and accounted for, not just shaking at one return period.

PEER Performance-Based Framework

Modular – response, damage, loss components



Includes - all earthquake magnitudes
- all source-to-site distances
- uncertainty in ground motion
- uncertainty in response given ground motion
- uncertainty in damage given response
- uncertainty in loss given damage

Response, damage, and loss are all explicitly computed – with explicit consideration of uncertainty in each

Performance-Based Response Evaluation

Closed-form solution

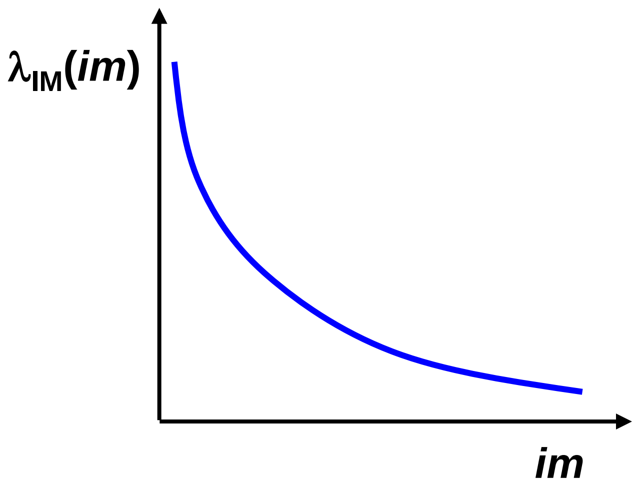
Assume hazard curve is of power law form

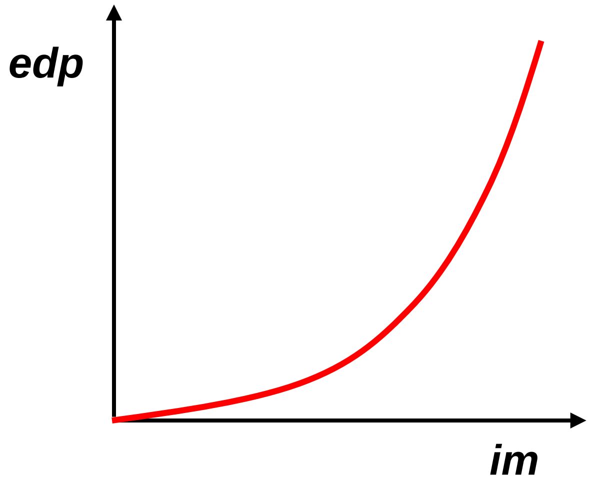
$$\lambda_{IM}(im) = k_o(im)^{-k}$$

and response is related to intensity as

$$edp = a(im)^b$$

with lognormal conditional uncertainty (ln *edp* is normally distributed with standard deviation $\sigma_{\ln edp|im}$)



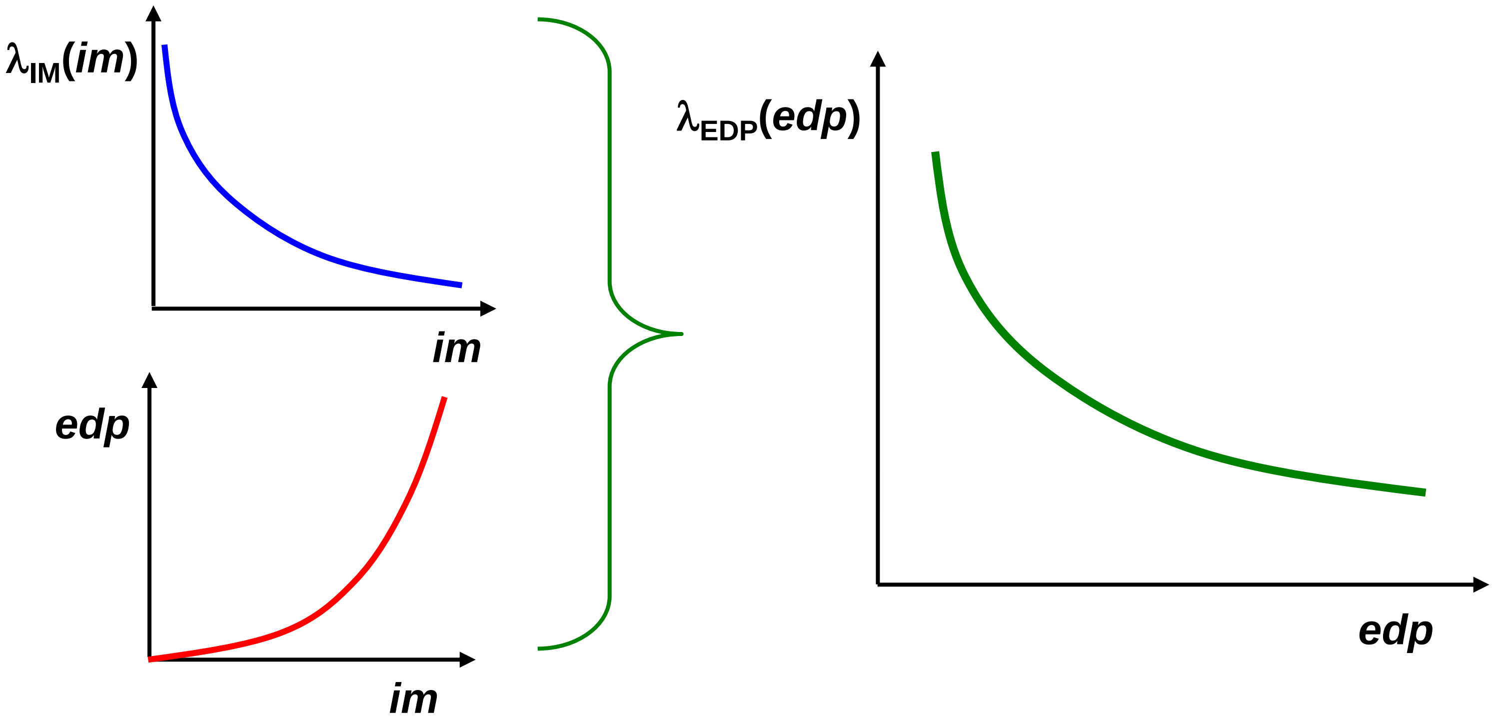


Performance-Based Response Evaluation

Closed-form solution

Then median *EDP* hazard curve can be expressed in closed form as

$$\lambda_{EDP}(edp) = k_o \left[\left(\frac{edp}{a} \right)^{1/b} \right]^{-k} \exp\left(\frac{k^2}{2b^2} \sigma^2_{\ln edp|im} \right)$$



Performance-Based Response Evaluation

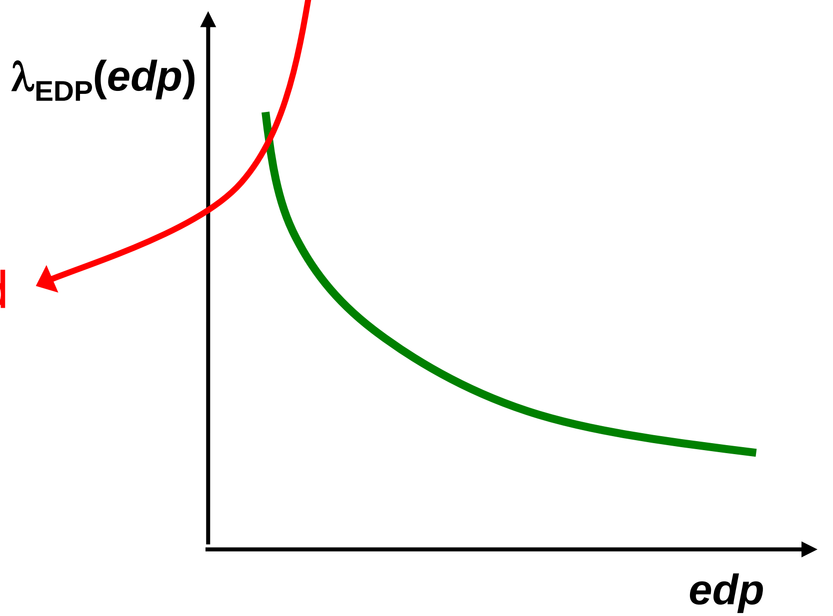
Closed-form solution

Then median *EDP* hazard curve can be expressed in closed form as

$$\lambda_{EDP}(edp) = k_o \left[\left(\frac{edp}{a} \right)^{1/b} \right]^{-k} \exp\left(\frac{k^2}{2b^2} \sigma^2_{\ln edp|im} \right)$$

Based on median *IM* and *EDP-IM* relationship

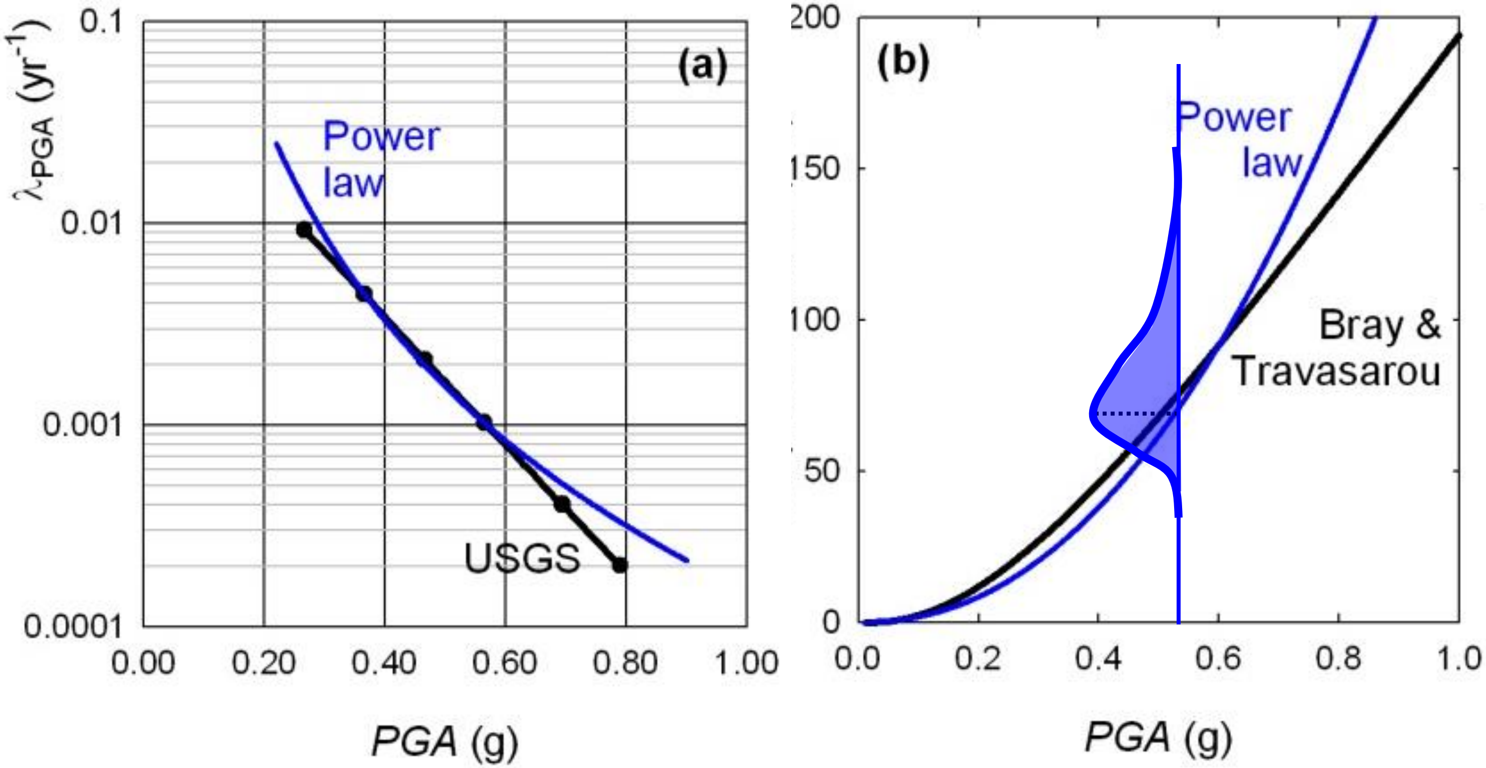
EDP “amplifier” based on uncertainty in *EDP*|*IM* relationship



Performance-Based Response Evaluation

Closed-form solution

Example: Slope displacement

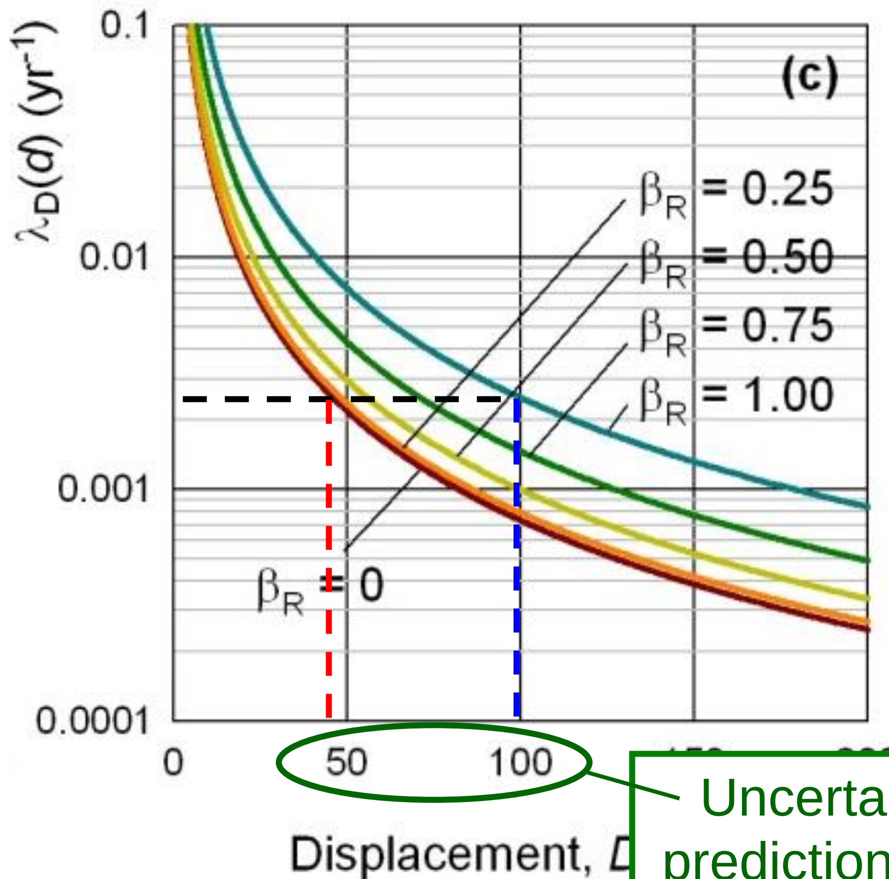


Combining, with different levels of response model uncertainty

Performance-Based Response Evaluation

Closed-form solution

Example: Slope displacement



Uncertainty in response prediction accounts for half

Performance-Based Loss Evaluation

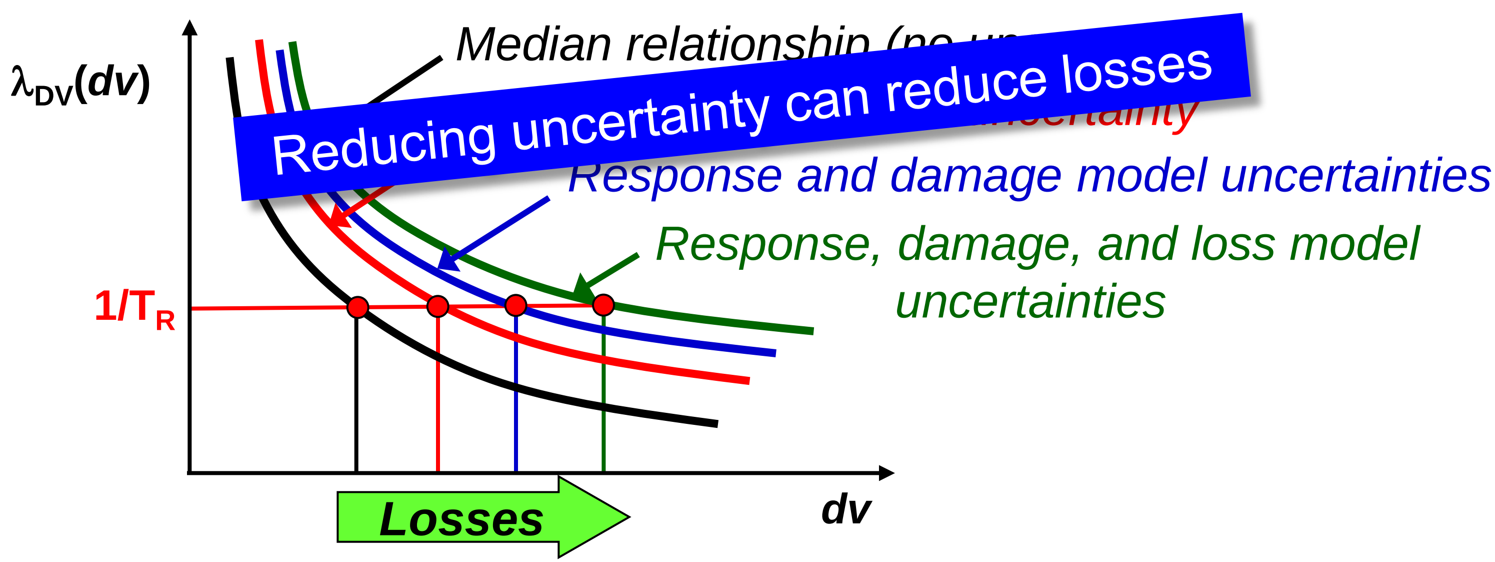
Closed-form solution

Extending to *DM* and *DV*, with same assu

Response model **Damage model** **Loss model**

$$\lambda_{DV}(dv) = k_0\left[\frac{1}{a}\left\{\frac{1}{c}\left(\frac{dv}{e}\right)^{1/f}\right\}^{1/d}\right]^{-k/b}\exp\left[\frac{k^2}{2b^2d^2f^2}\left(d^2f^2\beta_R^2+f^2\beta_D^2+\beta_L^2\right)\right]$$

Median relationships **Uncertainty amplifier**



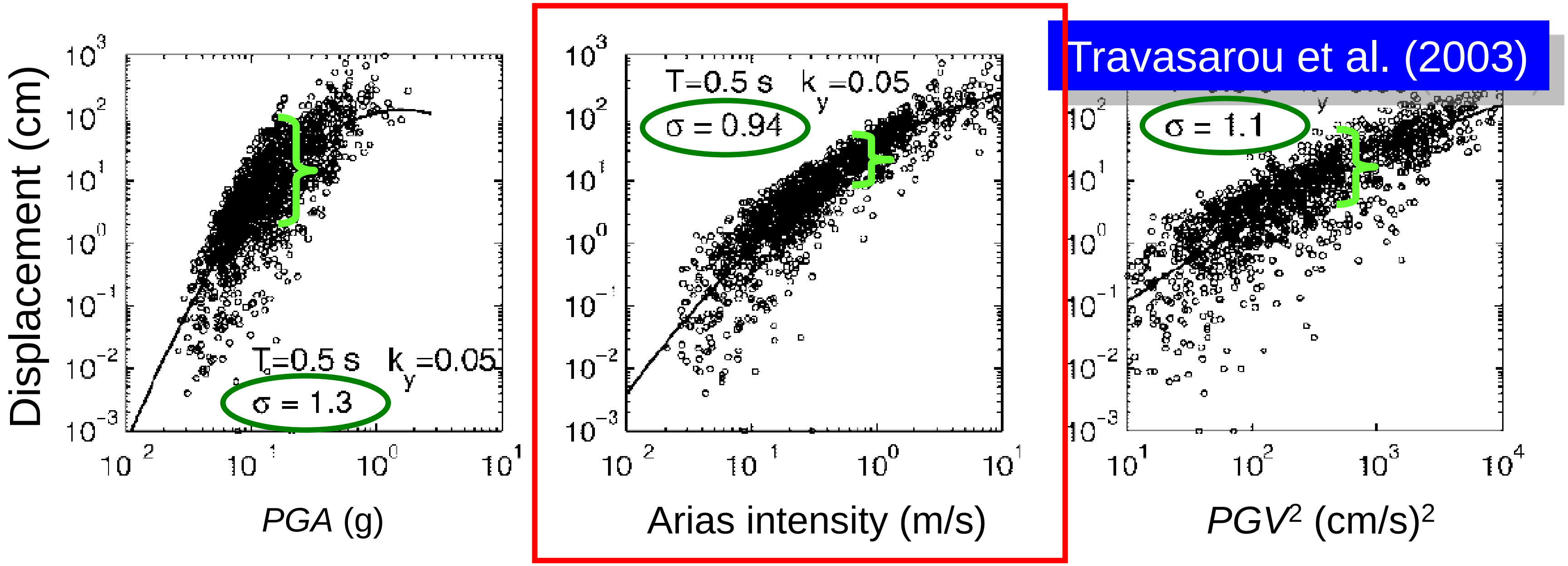
Implementation of Performance-Based Design

Characterization of loading

Select *IMs* – important considerations include:

Efficiency – how well does *IM* predict response?

Permanent displacement of shallow slides



Implementation of Performance-Based Design

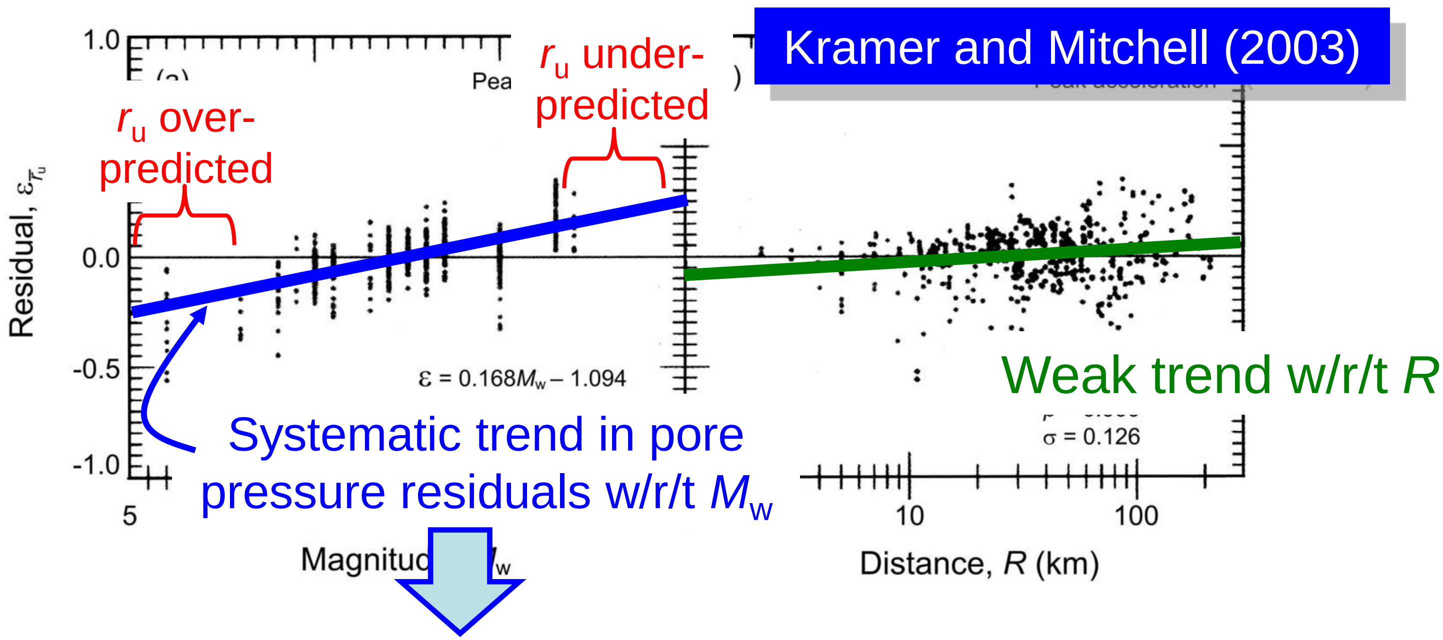
Characterization of loading

Select *IMs*

Efficiency – how well does *IM* predict response?

Sufficiency – how completely does *IM* predict response?

Deviations from mean excess pore pressure ratio correlation to PGA



Magnitude scaling factor

Implementation of Performance-Based Design

Characterization of loading

Select *IM*s

Efficiency – how well does *IM* predict response?

Sufficiency – how completely does *IM* predict response?

Predictability – how well can we predict *IM*?

Intensity Measure, *IM*	**Standard error, $\sigma_{\ln IM}$**	**Reference**
PGA	0.53 – 0.55	Campbell and Bozorgnia, 2008
PGV	0.53 – 0.56	Campbell and Bozorgnia, 2008
S_a (0.2 sec)	0.59 – 0.61	Campbell and Bozorgnia, 2008
S_a (1.0 sec)	0.62 – 0.66	Campbell and Bozorgnia, 2008
Arias intensity, I_a	1.0 – 1.3	Travasarou et al. (2003)
CAV	0.40 – 0.44	Campbell and Bozorgnia, 2010

Implementation of Performance-Based Design

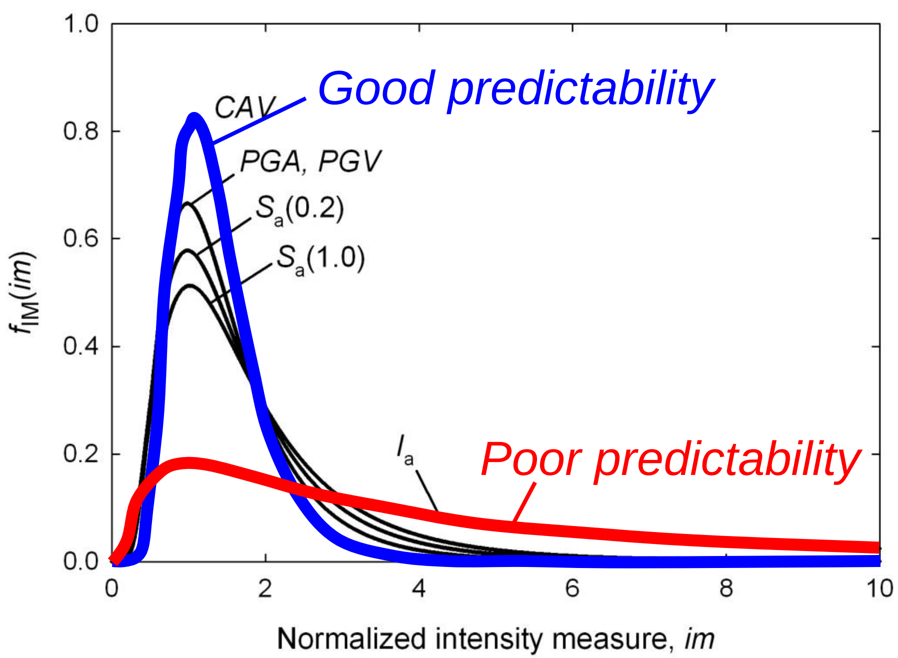
Characterization of loading

Select *IMs*

Efficiency – how well does *IM* predict response?

Sufficiency – how completely does *IM* predict response?

Predictability – how well can we predict *IM*?



Implementation of Performance-Based Design

Characterization of loading

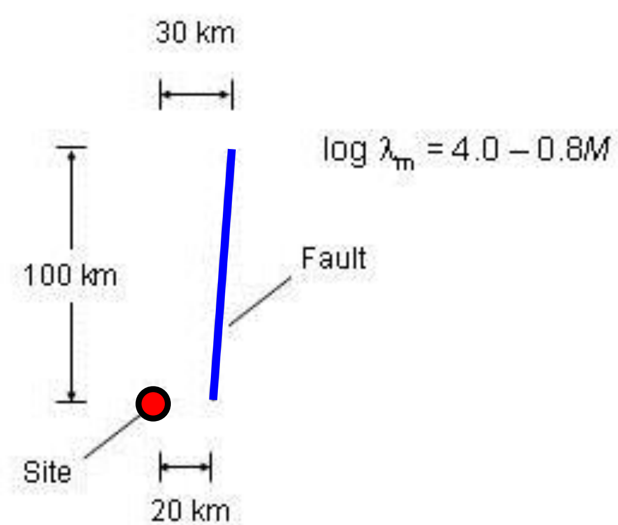
Select *IMs*

Efficiency – how well does *IM* predict response?

Sufficiency – how completely does *IM* predict response?

Predictability – how well can we predict *IM*?

Example:



Implementation of Performance-Based Design

Characterization of loading

Select *IMs*

Efficiency – how well does *IM* predict response?

Sufficiency – how completely does *IM* predict response?

Predictability – how well can we predict *IM*?

Example:

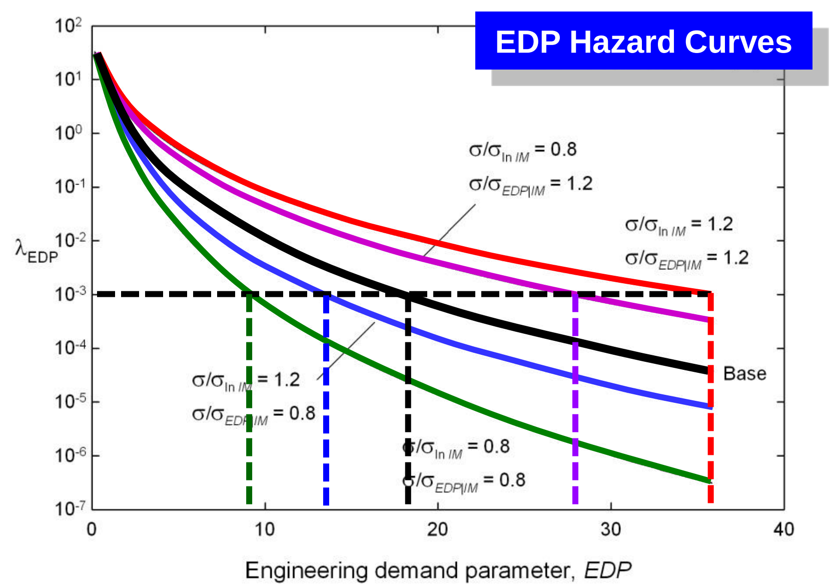
Typical predictability, typical efficiency

Worse predictability, worse efficiency

Better predictability, worse efficiency

Worse predictability, better efficiency

Better predictability, better efficiency



Implementation of Performance-Based Design

Characterization of loading

Select *IMs*

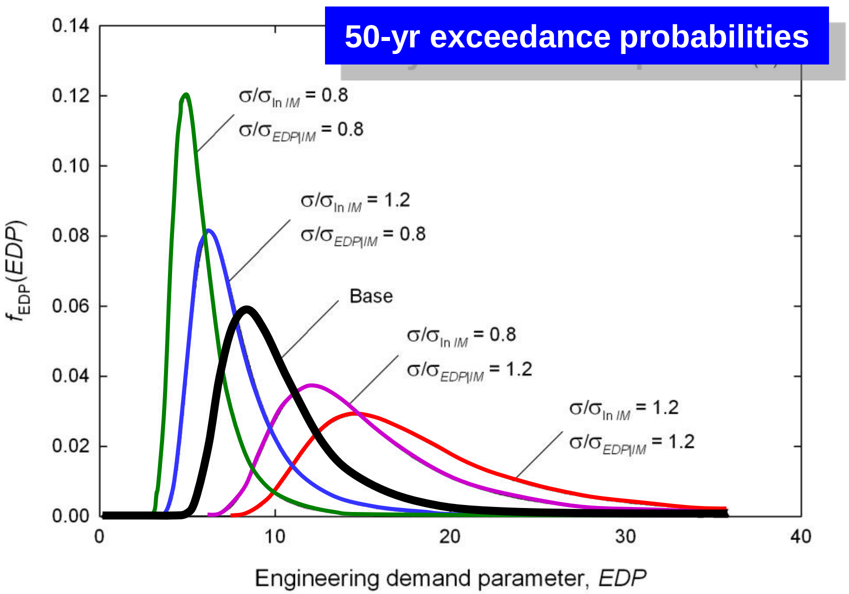
Efficiency – how well does *IM* predict response?

Sufficiency – how completely does *IM* predict response?

Predictability – how well can we predict *IM*?

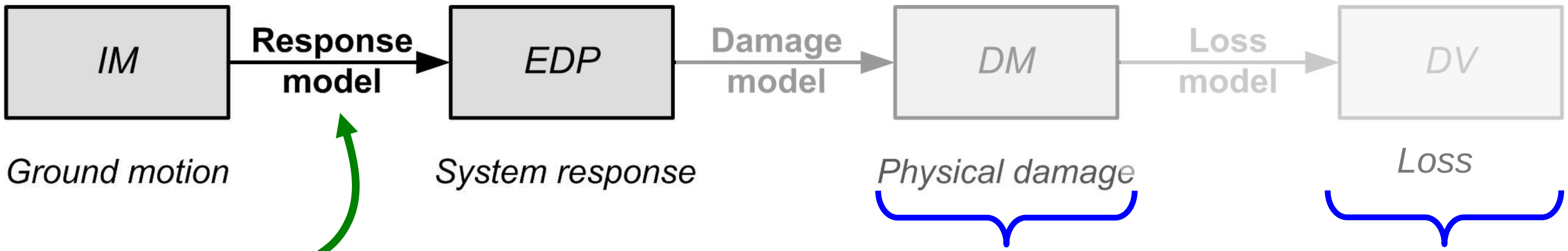
Example:

Predictability and efficiency both affect response for a given return period



Response-Level Implementation

Performance characterized in terms of response variables



Probabilistic response model needed – must account for uncertainty in *EDP|IM*

Inferred from computed response

Inferred from inferred damage

Response-Level Implementation

Performance characterized in terms of response variables

Site response

Soil hazard curve

$$\lambda_{IM_S}(im_s) = \int_0^\infty P[IM_S > im_s \mid im_r] \left| d\lambda_{IM_R}(im_r) \right|$$

Rock hazard curve

$$\lambda_{IM_S}(im_s) = \int_0^\infty P\left[AF > \frac{im_s}{im_r} \mid im_r\right] \left| d\lambda_{IM_R}(im_r) \right|$$

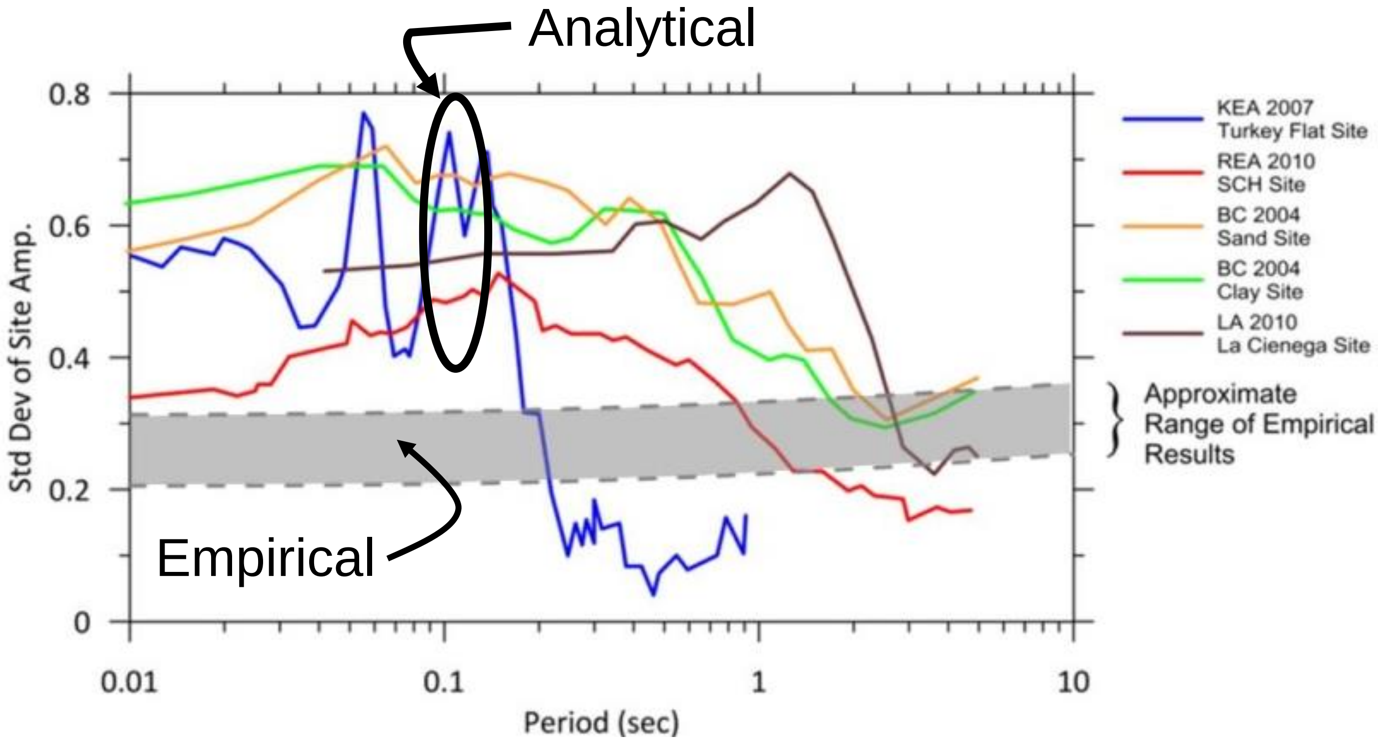
Integrating over all rock motion levels

Uncertainty in amplification behavior

Response-Level Implementation

Performance characterized in terms of response variables

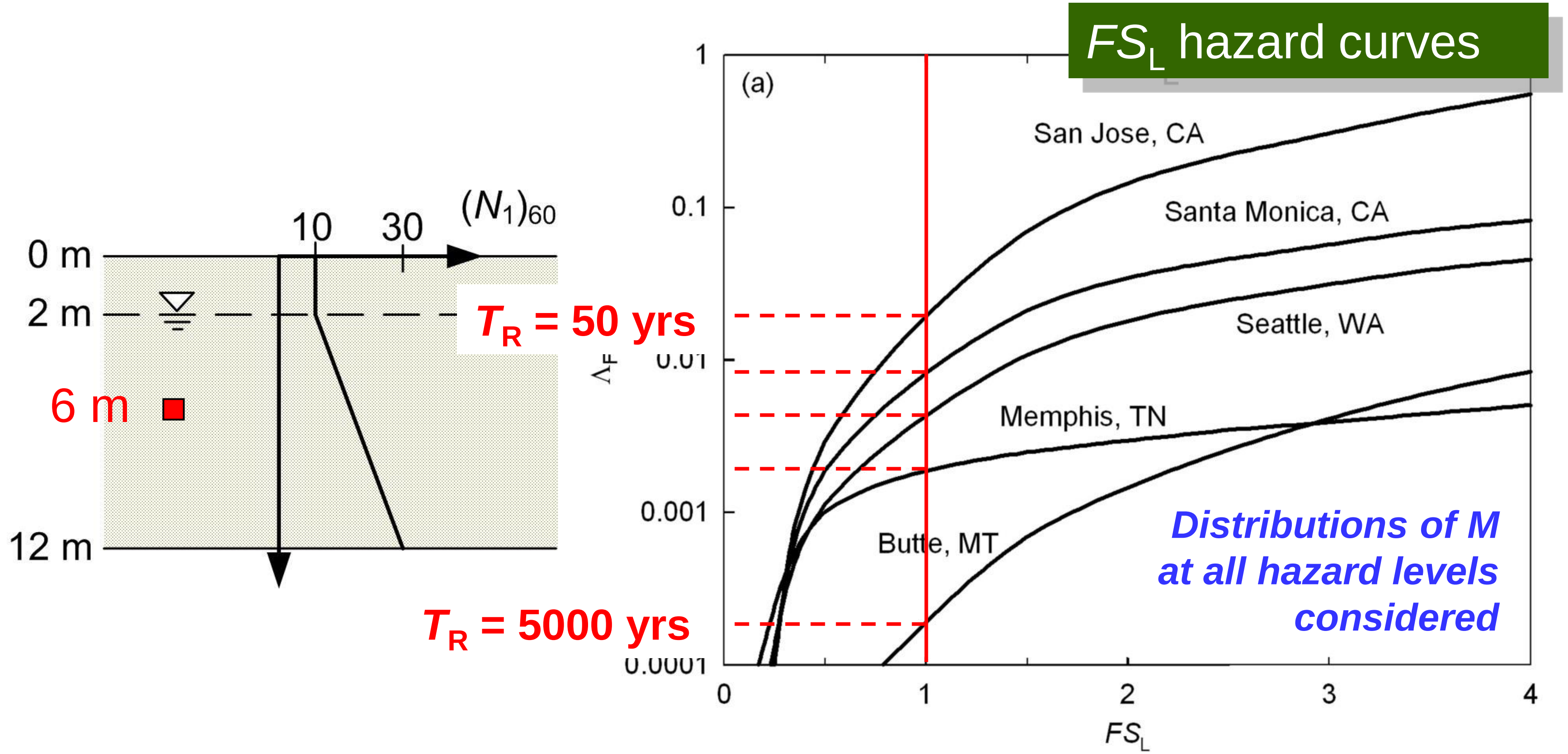
Site response



Response-Level Implementation

Performance characterized in terms of response variables

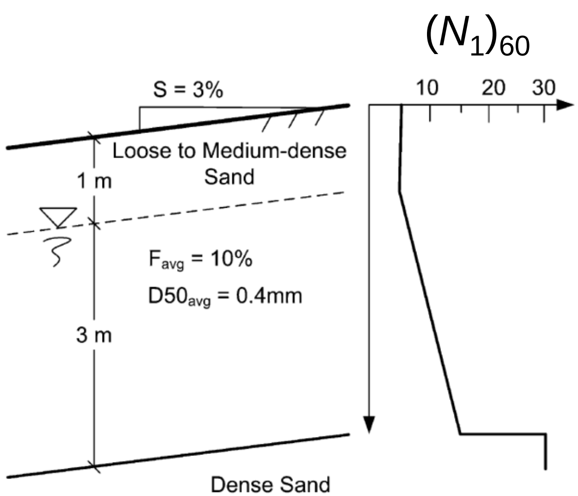
Liquefaction (Kramer and Mayfield, 2007)

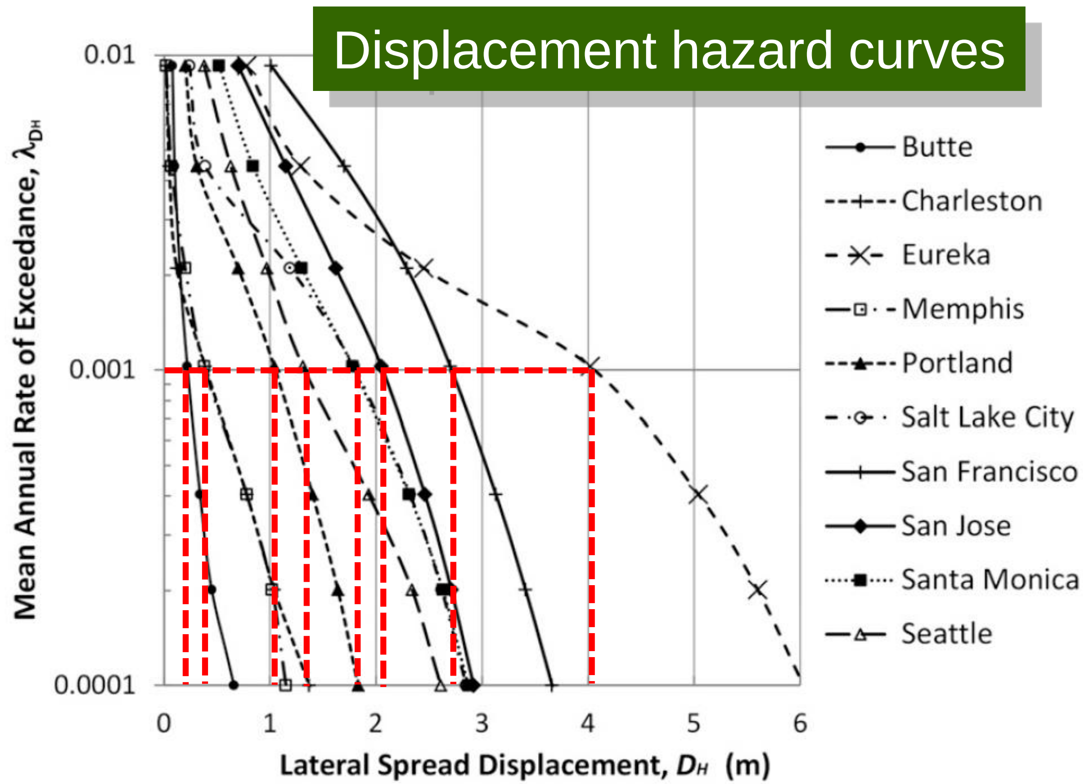


Response-Level Implementation

Lateral Spreading – Franke and Kramer (2014)

Reference soil profile



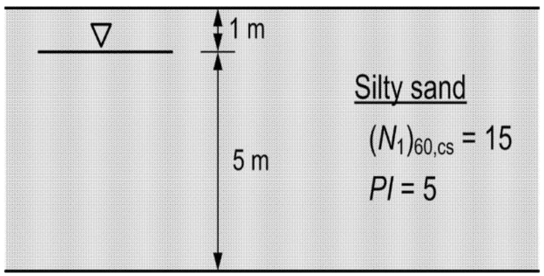


Response-Level Implementation

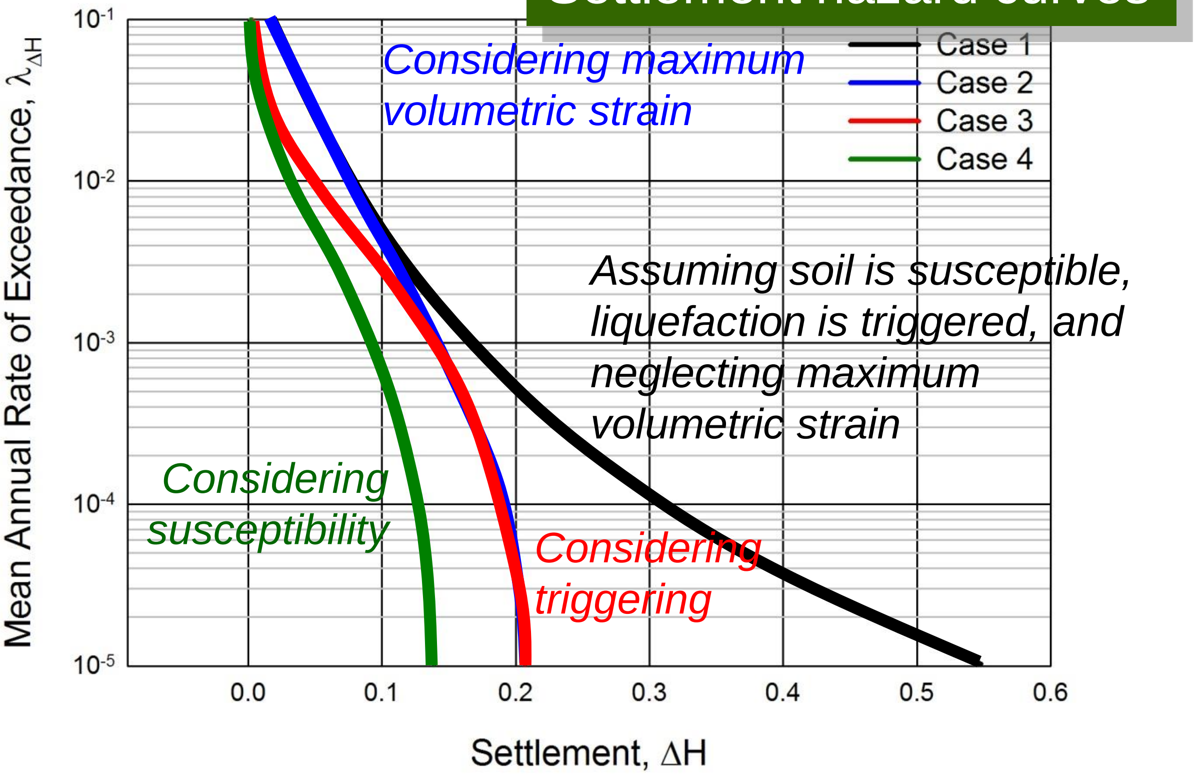
Performance characterized in terms of response variables

Post-liquefaction settlement (Kramer and Huang, 2010)

Hypothetical site in Seattle, Washington



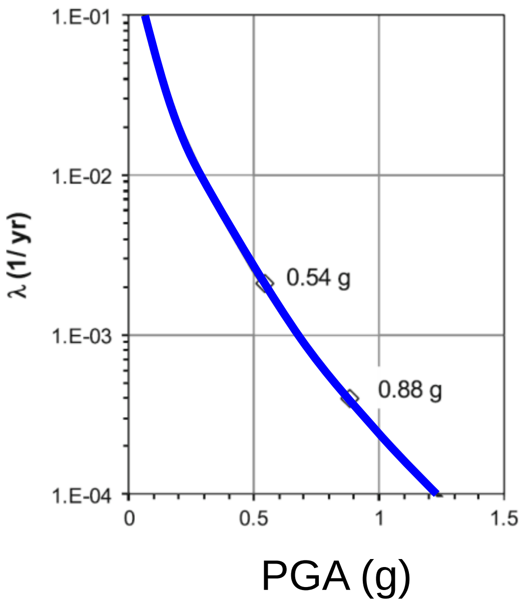
Settlement hazard curves



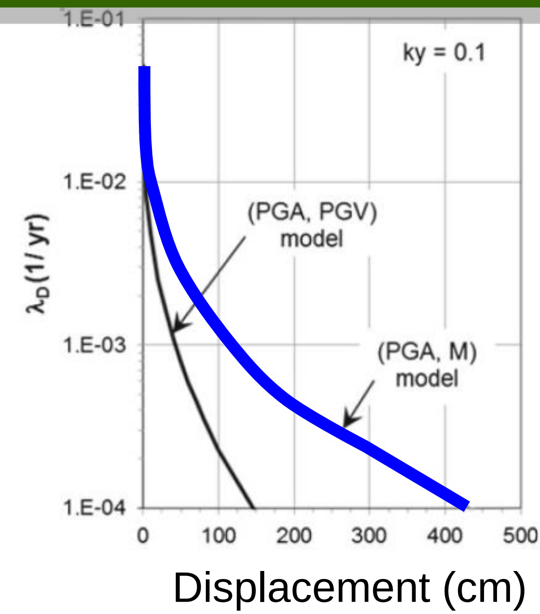
Response-Level Implementation

Performance characterized in terms of response variables

Slope instability (Rathje et al., 2013)



Displacement hazard curves

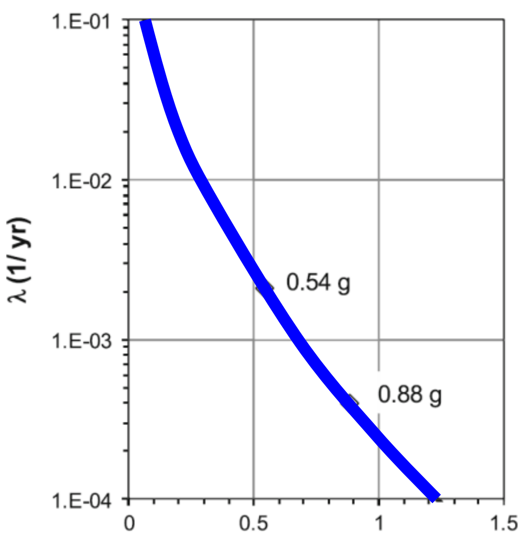


Response-Level Implementation

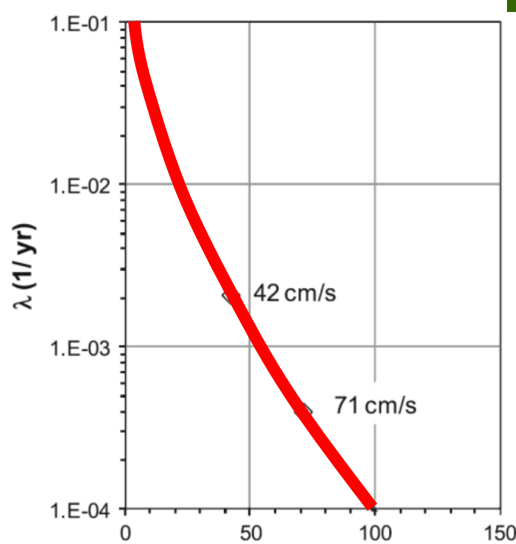
Performance characterized in terms of response variables

Slope instability (Rathje et al., 2013)

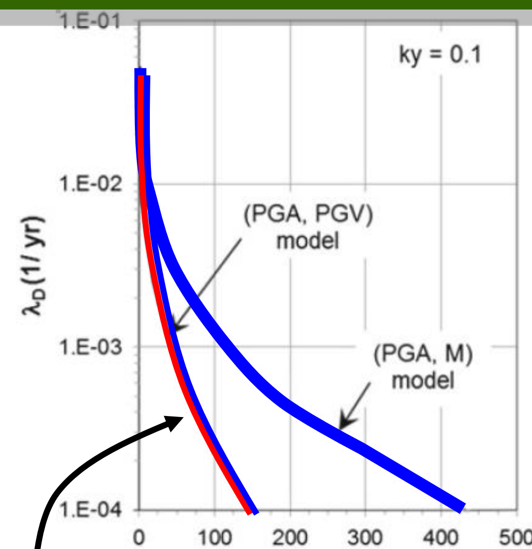
Displacement hazard curves



PGA (g)



PGV (cm/sec)



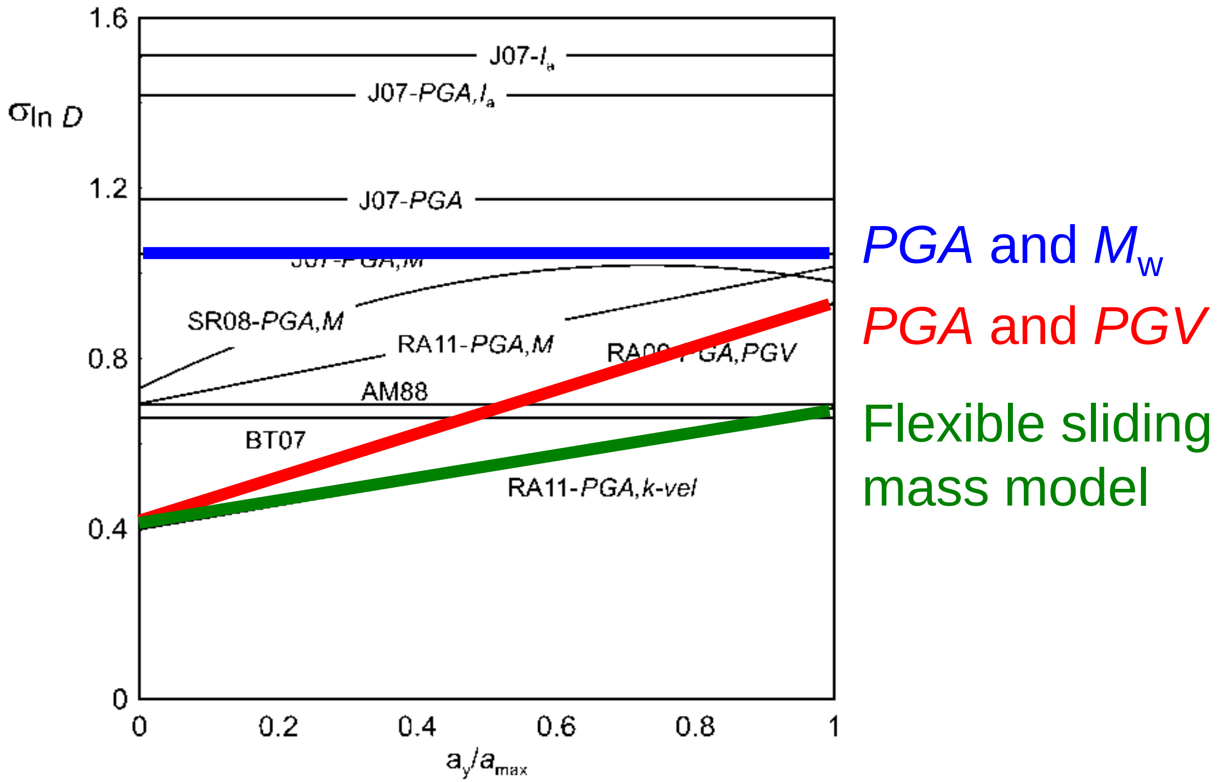
Displacement (cm)

Vector *IM* cuts displacement in half

Response-Level Implementation

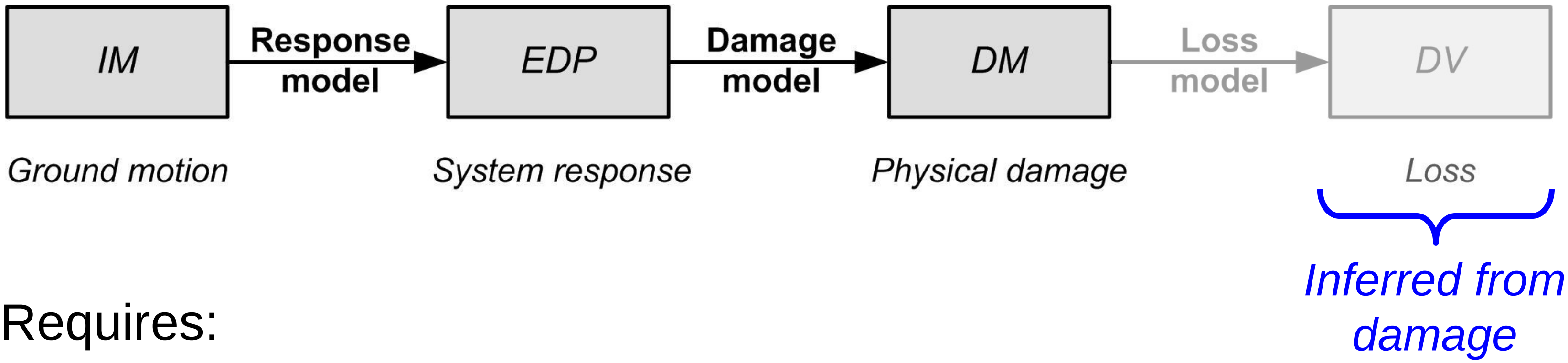
Performance characterized in terms of response variables

Uncertainties from different sliding block models



Damage-Level Implementation

Performance characterized in terms of damage measures



Requires:

Characterization of allowable levels of physical damage

Damage model

How much settlement is required to crack a slab?

How much lateral displacement is required to produce hinging in a concrete pile? in a steel pile?

Damage-Level Implementation

- Performance characterized in terms of damage measures
  - Continuous *DM* scales
    - Fragility curve approach
    - Some damage states (e.g., collapse) are binary
    - Insufficient data available for others
  - Discrete *DM* scales
    - Damage probability matrix approach

Damage State, *DM*	Description	*EDP* interval				
		edp_1	edp_2	edp_3	edp_4	edp_5
dm_1	Negligible	X_{11}	X_{12}	X		
dm_2	Slight	X_{21}	X_{22}	X		
dm_3	Moderate	X_{31}	X_{32}	X		
dm_4	Severe	X_{41}	X_{42}	X_{43}	X_{44}	X_{45}
dm_5	Catastrophic	X_{51}	X_{52}	X_{53}	X_{54}	X_{55}

Probability that response in EDP interval 2 produces severe damage

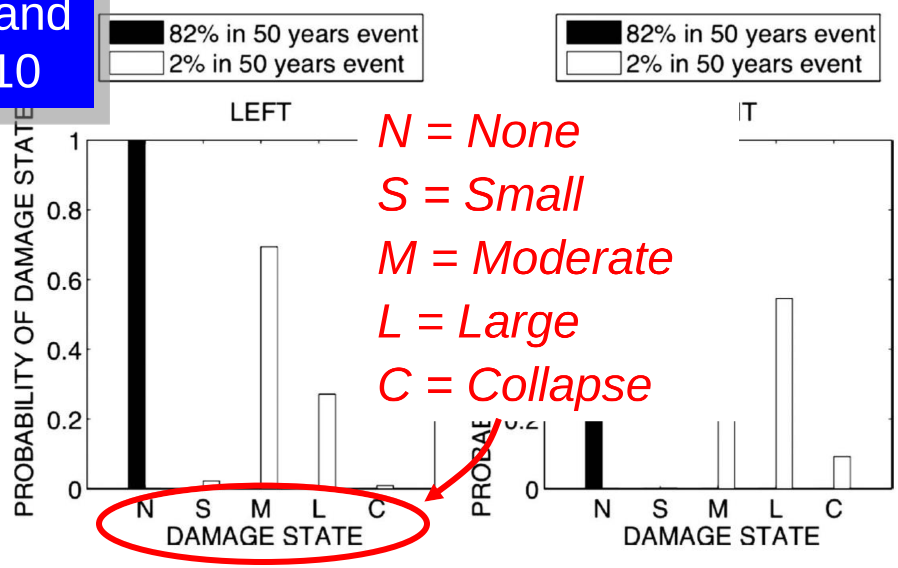
Damage-Level Implementation

Performance characterized in terms of damage measures

- Fragility curve approach
  - Continuous DM scales difficult to quantify
    - Some damage states (e.g., collapse) are binary
    - Insufficient data available for others
- Damage probability matrix approach

Ledezma and Bray, 2010

Pile-supported bridge founded on liquefiable soils



Damage-Level Implementation

Performance characterized in terms of damage measures

Fragility curve approach

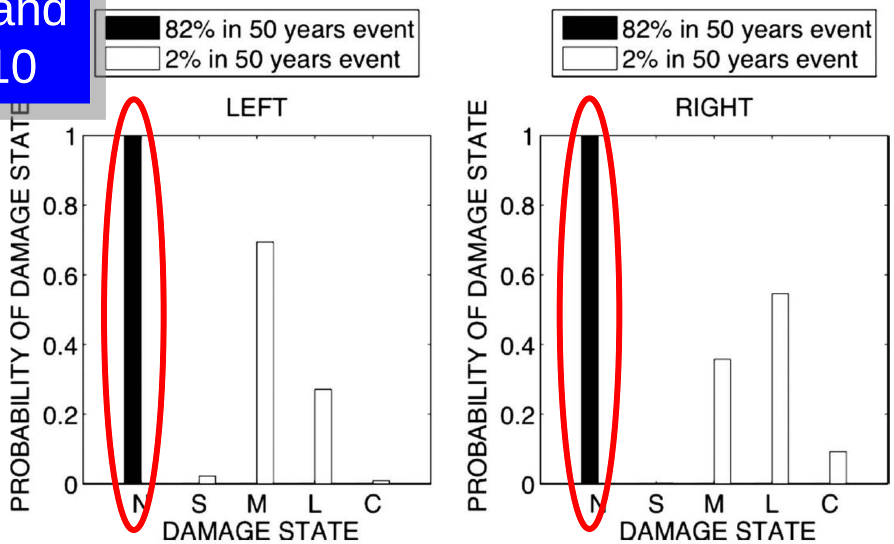
Continuous DM scales difficult to quantify

Some damage states (e.g., collapse) are binary

Insufficient data available for others

Damage probability matrix approach

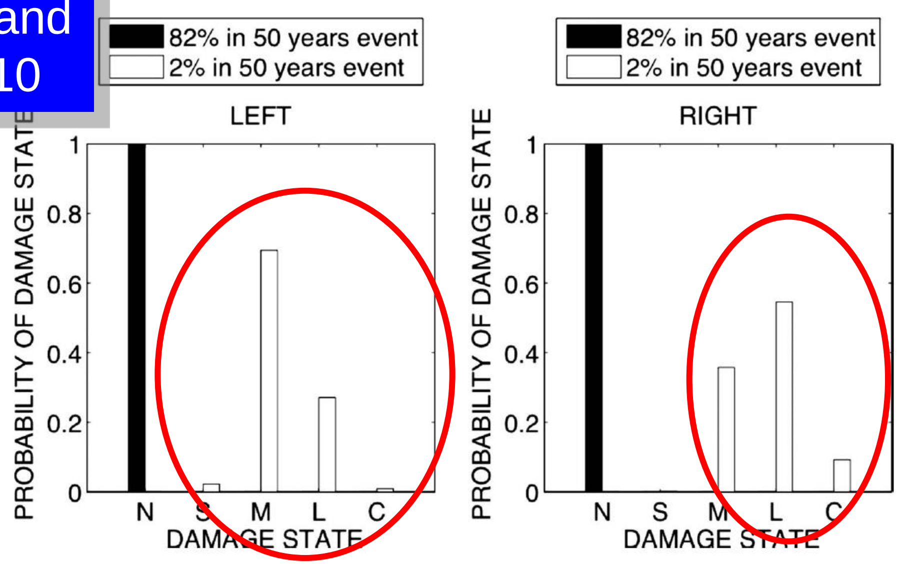
Ledezma and Bray, 2010



Damage-Level Implementation

- Performance characterized in terms of damage measures
  - Fragility curve approach
    - Continuous *DM* scales difficult to quantify
      - Some damage states (e.g., collapse) are binary
      - Insufficient data available for others
  - Damage probability matrix approach

Ledezma and Bray, 2010

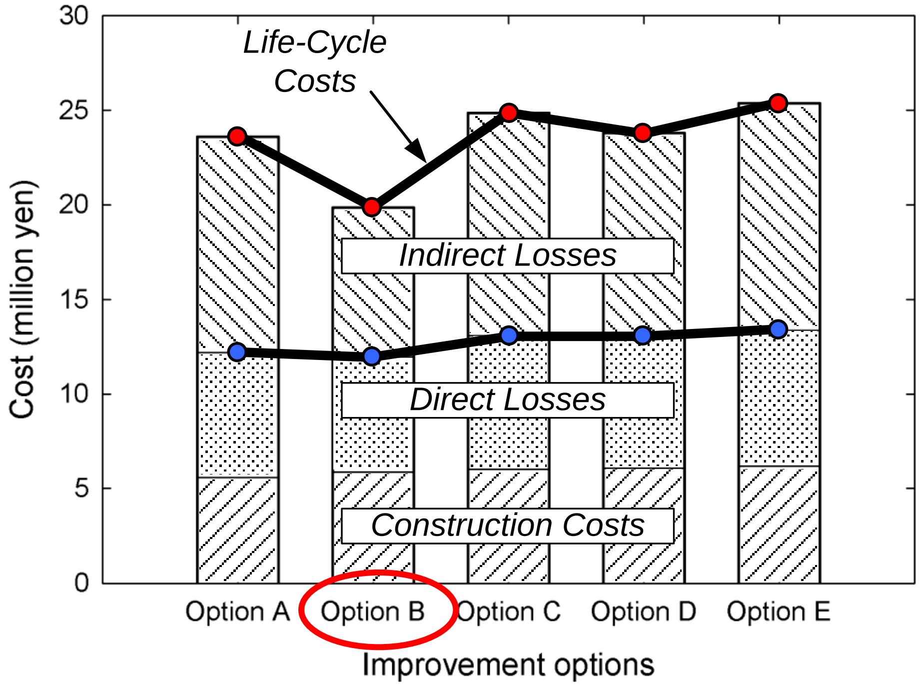


Loss-Level Implementation

Performance characterized in terms of decision variables

Example: Caisson quay wall (Iai, 2008)

Life cycle cost as decision variable, *DV*



Options:

A: Foundation compaction only

B: Foundation cementation

C: Foundation and backfill compaction (1.8 m spacing)

D: Foundation and backfill compaction (1.6 m spacing)

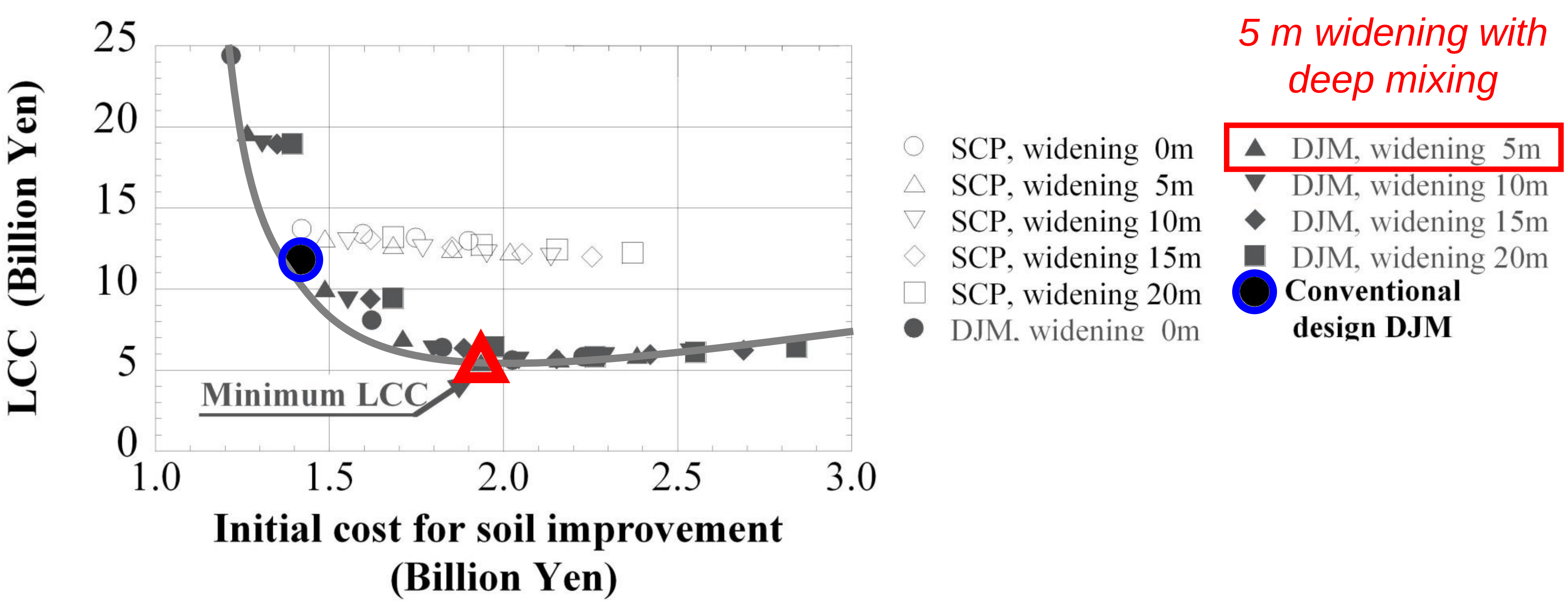
E: Foundation compaction and structural modification

Loss-Level Implementation

Performance characterized in terms of decision variables

Example: Expressway embankment widening (Towhata, 2008)

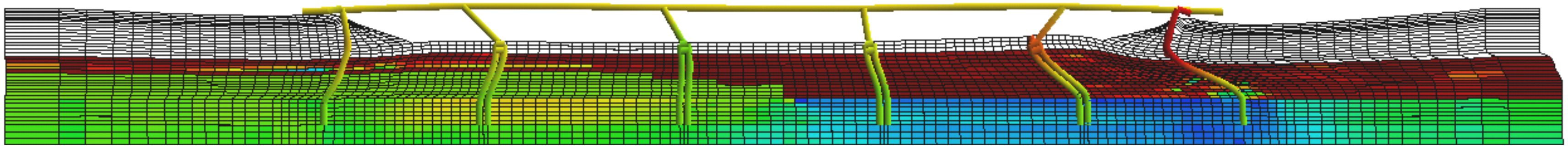
Life cycle cost as decision variable, *DV*



Loss-Level Implementation

Performance characterized in terms of decision variables

- Fragility curve approach – Kramer et al. (2009)
- Pile-supported bridge on liquefiable soils

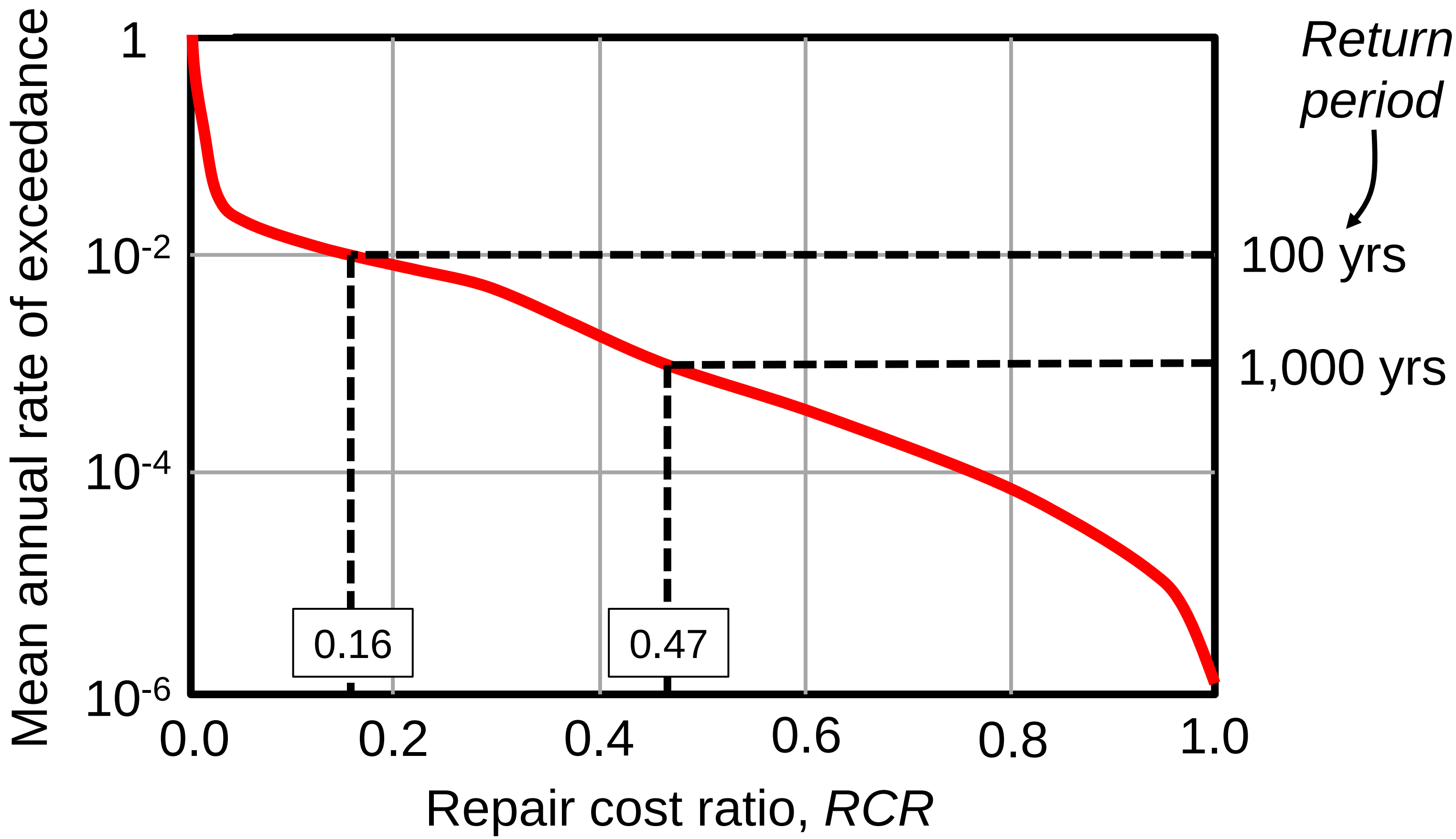


Loss-Level Implementation

Repair cost losses only

Doesn't include losses due to downtime

Doesn't include losses due to casualties

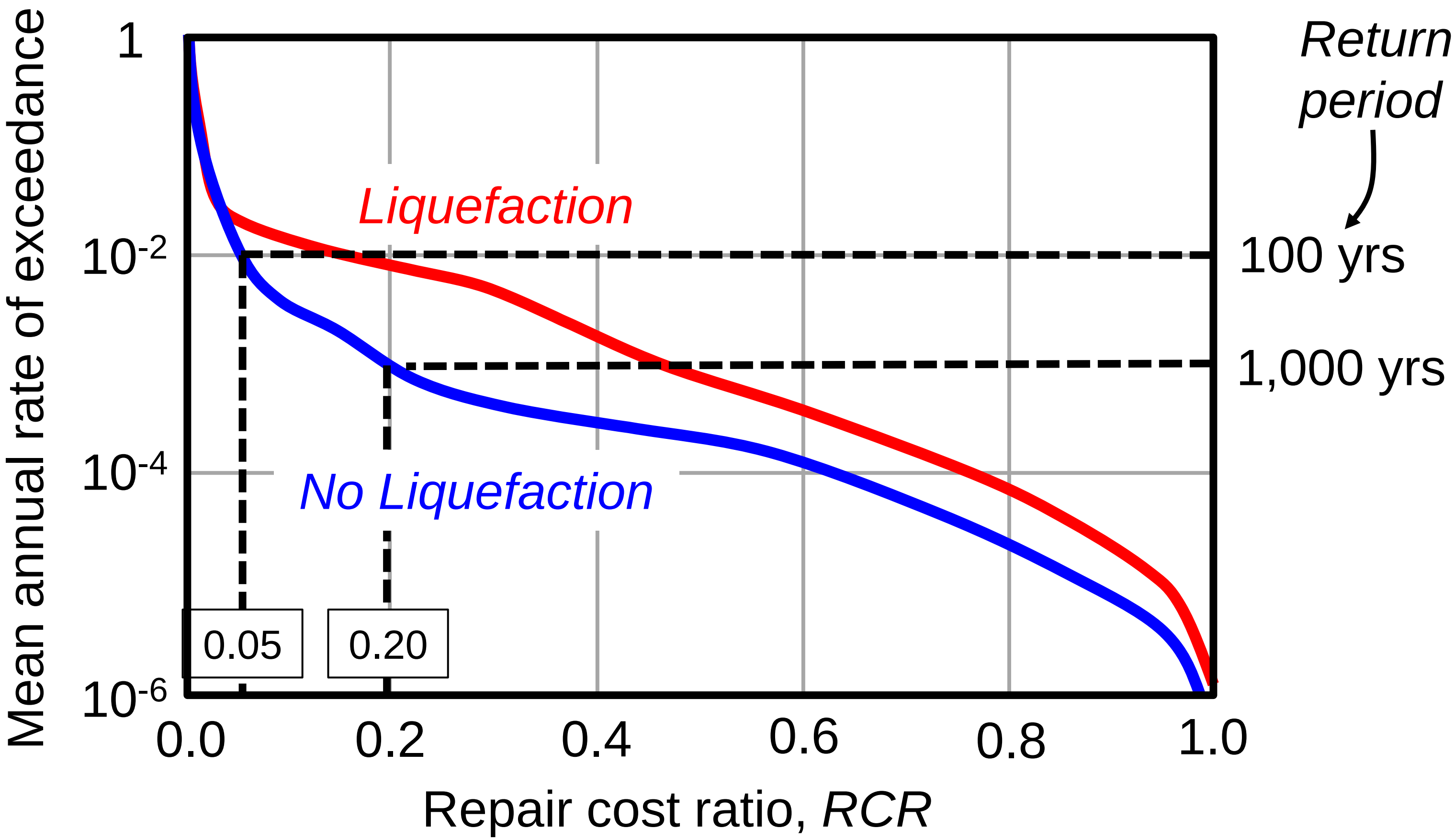


Loss-Level Implementation

Repair cost losses only

Doesn't include losses due to downtime

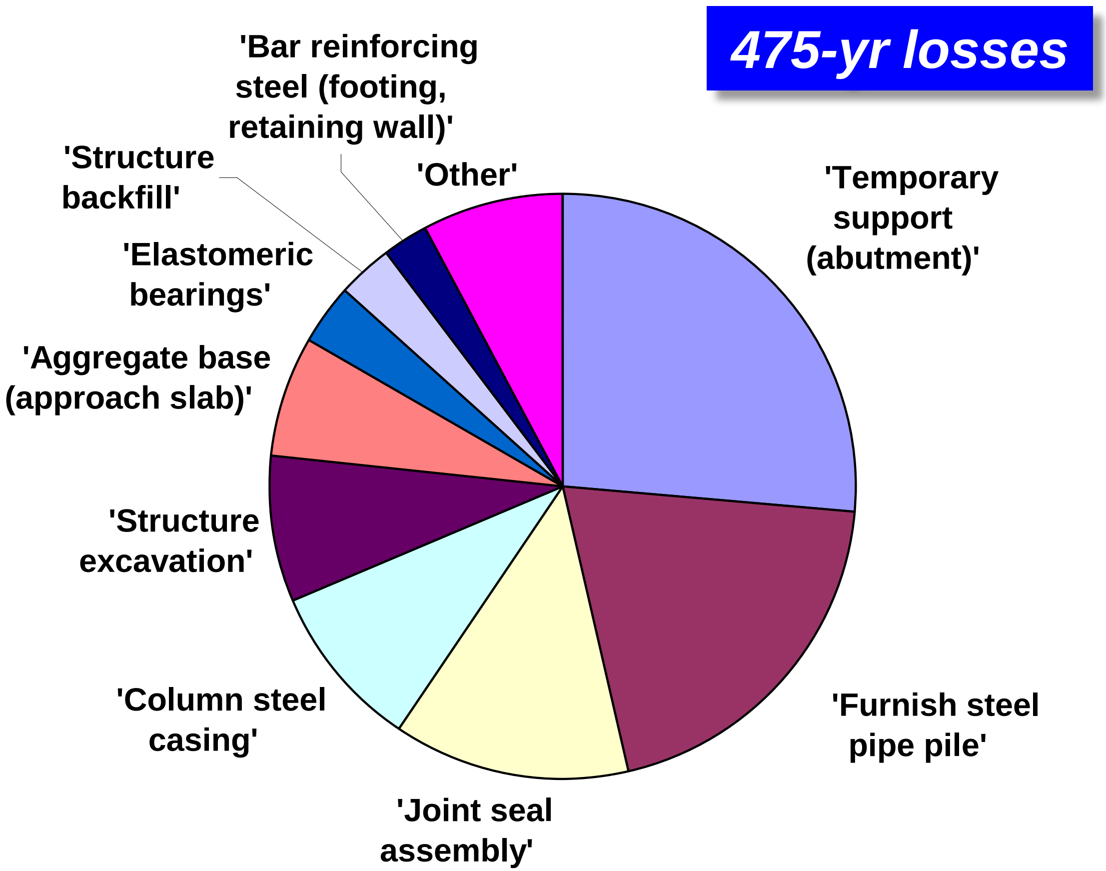
Doesn't include losses due to casualties



Loss-Level Implementation

Impacts on bridge structure

PBEE framework allows deaggregation of costs



Advancing Performance-Based Design

Improved Characterization of Capacity

How should we characterize physical damage?

How much ground movement can structures tolerate?

Bird et al. (2005; 2006)

Analyses of RC frame buildings subjected to ground deformation

Four damage states:

None to slight – linear elastic response, flexural or shear-type hairline cracks (<1 mm) in some members, no yielding in any critical section

LS1

Moderate – member flexural strengths achieved, limited ductility developed, crack widths reach 1 mm, initiation of concrete spalling

LS2

Extensive – significant repair required to building, wide flexural or shear cracks, buckling of longitudinal reinforcement may occur

LS3

Complete – repair of building not feasible either physically or economically, demolition after earthquake required, could be due to shear failure of vertical elements or excess displacement

Advancing Performance-Based Design

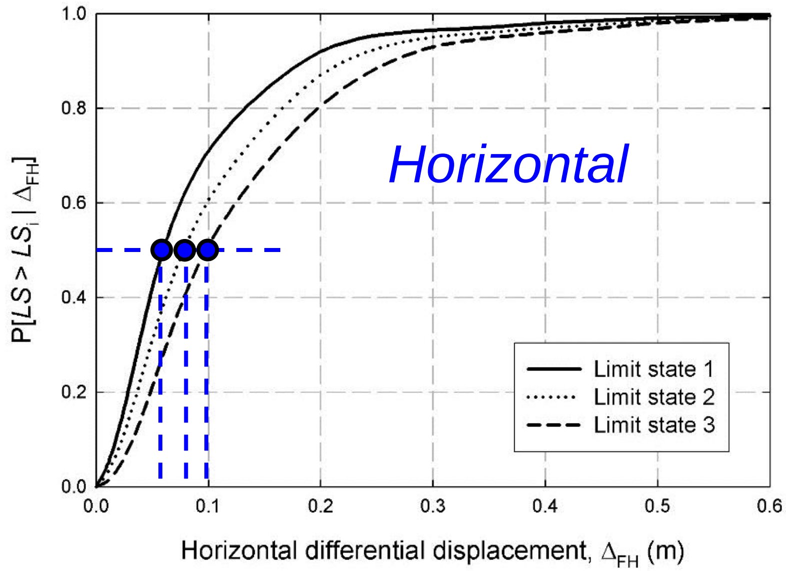
Improved Characterization of Capacity

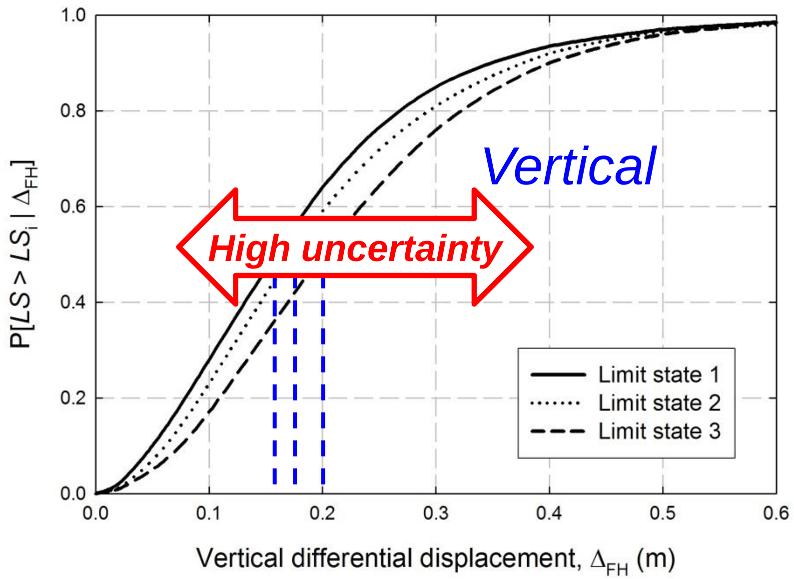
How should we characterize physical damage

How much ground movement can structures tolerate?

Bird et al. (2005)

Analyses of structures subjected to ground deformation





Rational, quantified fragility curves for R/C frame buildings

Advancing Performance-Based Design

Improved Characterization of Capacity

Effects of uncertainty in capacity

Response hazard curve

$$\lambda_{EDP}(edp_j) = \nu \sum_{i=1}^{N_{IM}} P\left[EDP > edp_j \mid IM = im_i\right] P\left[IM = im_i\right]$$

Let C = capacity (response corresponding to given damage state)

$$\lambda_{EDP|C}(c) = k_o \left(\frac{c}{a}\right)^{-k/b} \exp\left[\frac{1}{2}\frac{k^2}{b^2}\sigma^2_{\ln EDP|IM}\right]$$

Integrating over distribution of capacity

$$\lambda_{EDP}(edp) = \int_0^\infty \lambda_{EDP|C}(c) f_C(c) dc$$

Assuming lognormal capacity distribution

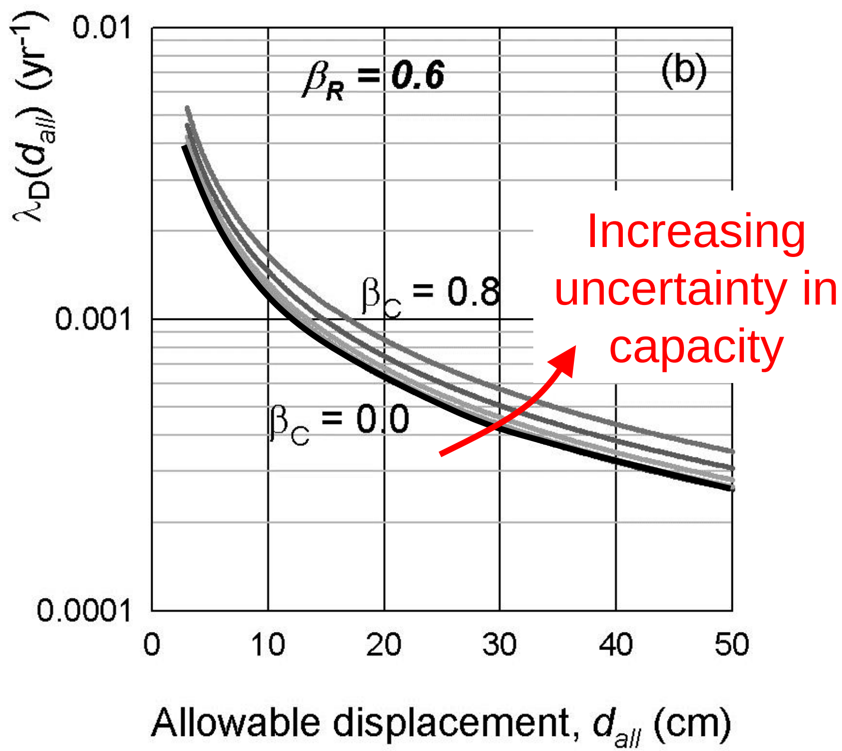
$$\lambda_{EDP}(c) = \lambda_{IM}(im^{\mu_{\ln C}}) \exp\left[\frac{1}{2}\frac{k^2}{b^2}\sigma^2_{\ln EDP|IM}\right] \exp\left[\frac{1}{2}\frac{k^2}{b^2}\sigma^2_{\ln C}\right]$$

Capacity uncertainty amplifier

Advancing Performance-Based Design

Improved Characterization of Capacity

Effects of uncertainty in capacity



Accurate characterization of uncertainty in capacity nearly as important as uncertainty in response

Advancing Performance-Based Design

Can PBEE concepts be used to develop load and resistance factors associated with predictable rate of limit state exceedance, λ_{LS}?

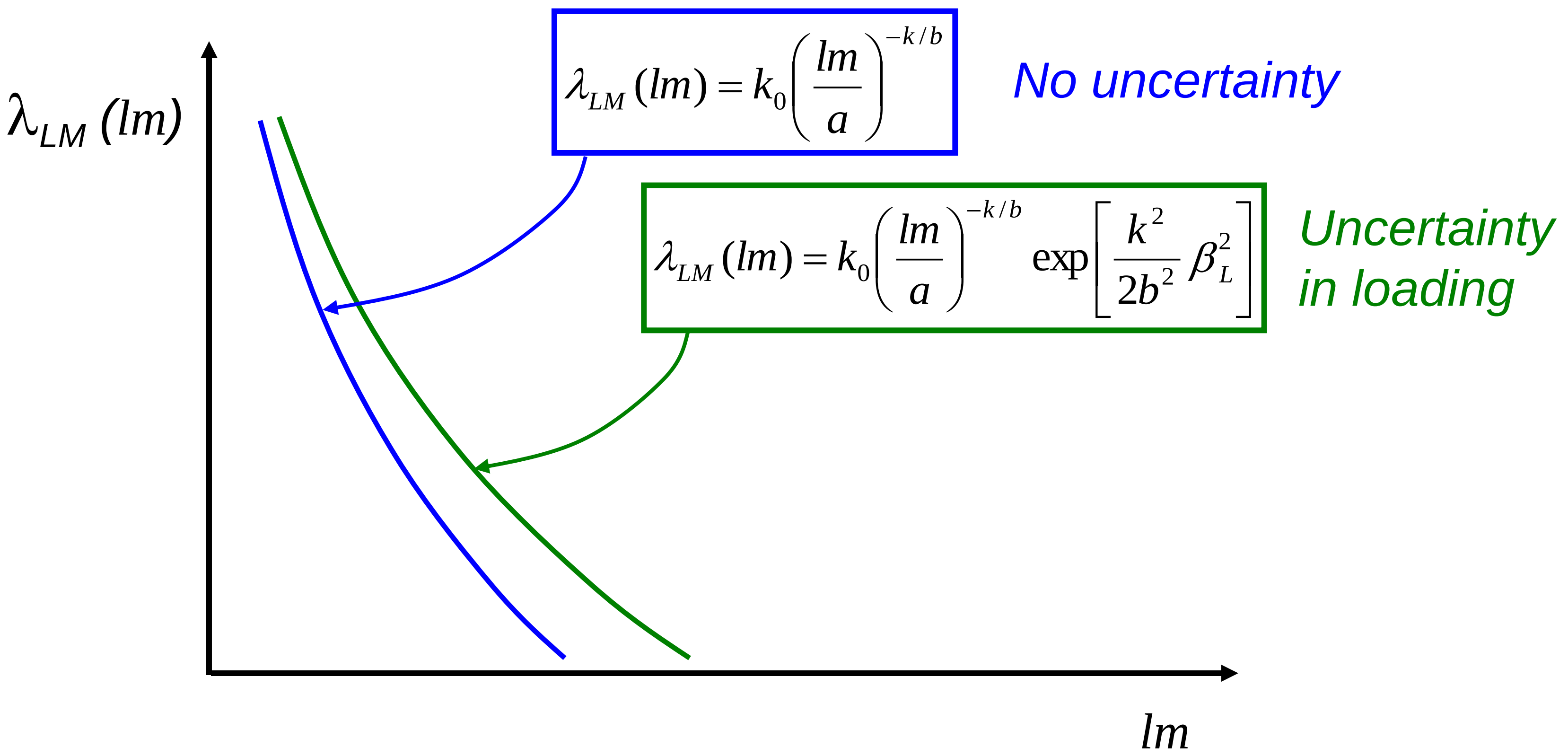
Capacity

Advancing Performance-Based Design

Can PBEE concepts be used to develop load and resistance factors associated with predictable rate of limit state exceedance, λ_{LS}?

Let LM = load measure = aIM^b

Capacity

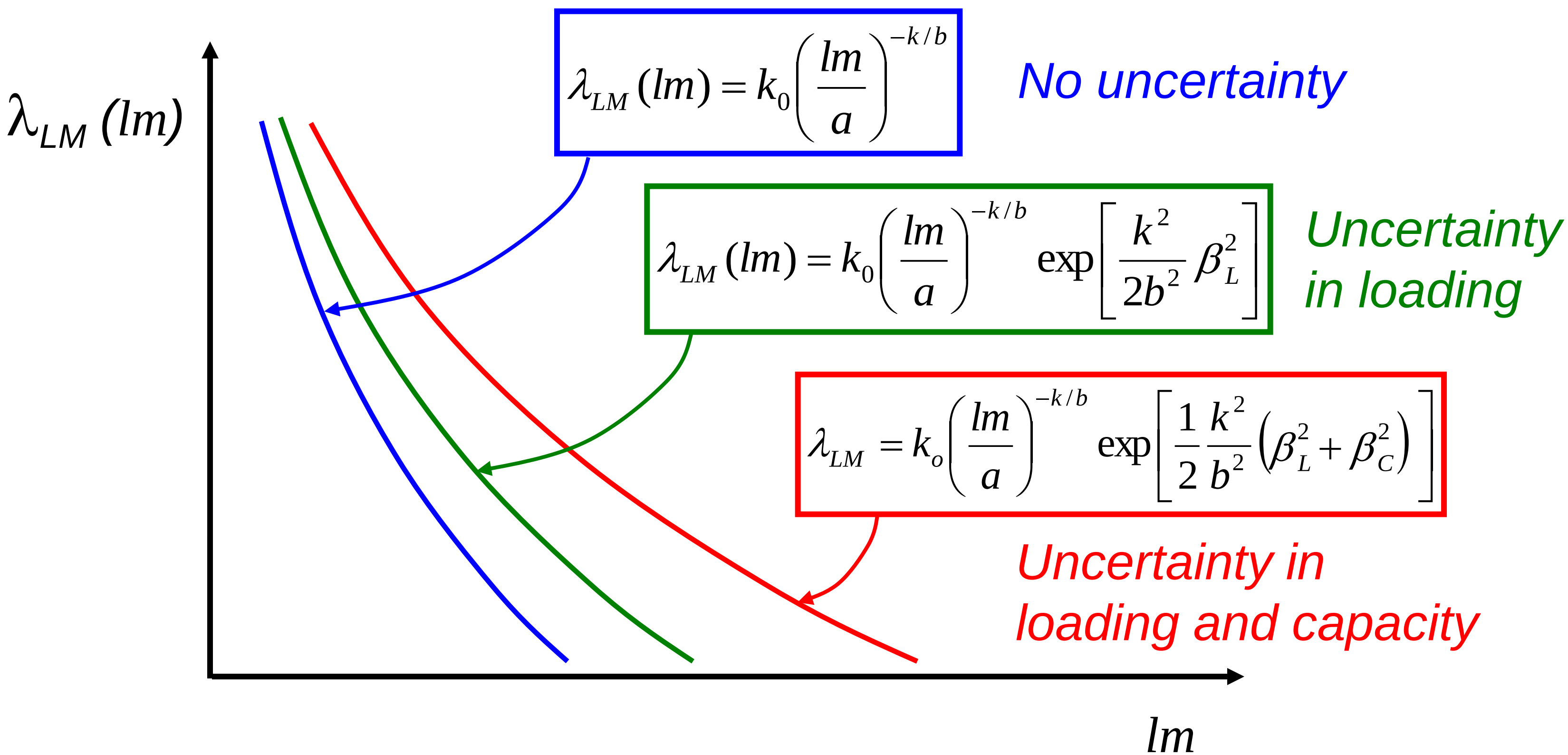


Advancing Performance-Based Design

Can PBEE concepts be used to develop load and resistance factors associated with predictable rate of limit state exceedance, λ_{LS}?

Capacity

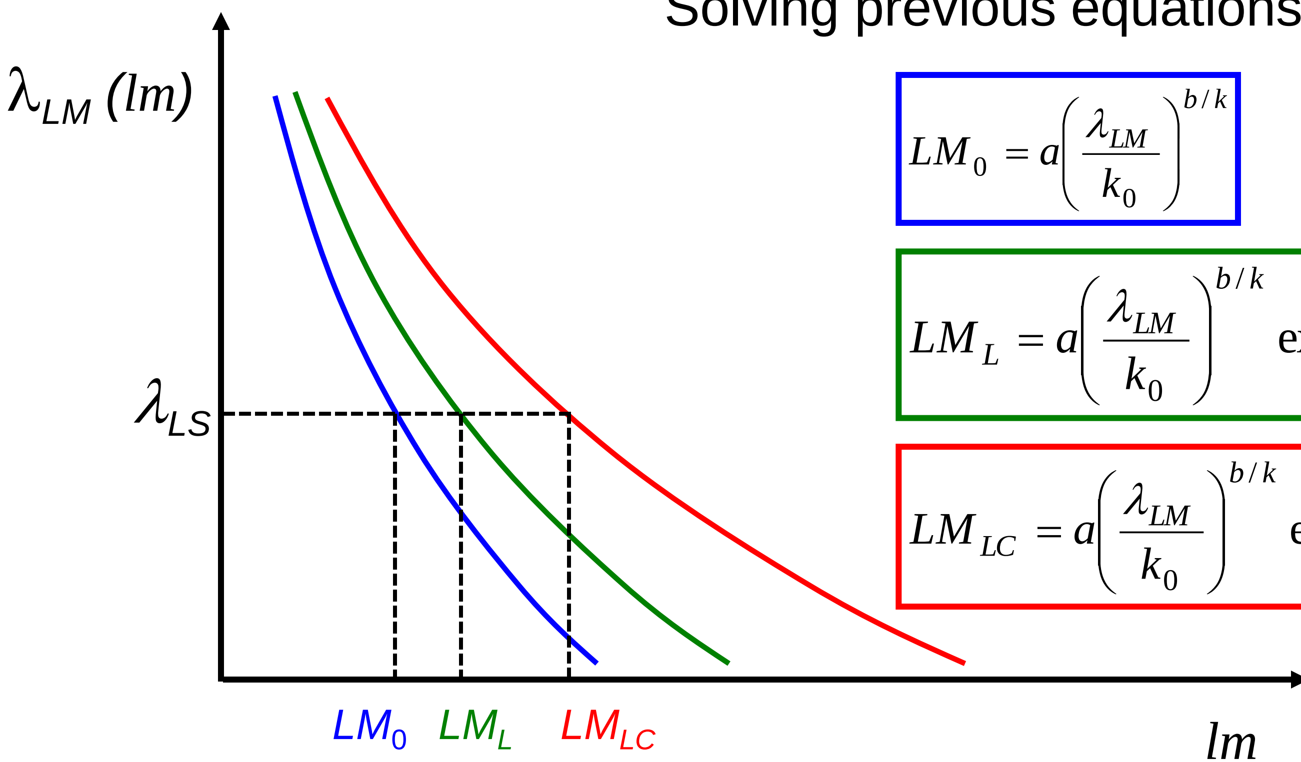
Let LM = load measure = aIM^b



Advancing Performance-Based Design

Can PBEE concepts be used to develop load and resistance factors associated with predictable rate of limit state exceedance, λ_{LS}?

Let LM = load measure



Solving previous equations for LM,

$$LM_0 = a\left(\frac{\lambda_{LM}}{k_0}\right)^{b/k}$$

$$LM_L = a\left(\frac{\lambda_{LM}}{k_0}\right)^{b/k} \exp\left[\frac{k}{2b}\beta_L^2\right]$$

$$LM_{LC} = a\left(\frac{\lambda_{LM}}{k_0}\right)^{b/k} \exp\left[\frac{k}{2b}\left(\beta_L^2 + \beta_C^2\right)\right]$$

Advancing Performance-Based Design

Can PBEE concepts be used to develop load and resistance factors associated with predictable rate of limit state exceedance, λ_{LS}?

Let *LM* = load measure

LM_{LC} can be interpreted as median capacity that will be exceeded every T_R years, on average, and LM_0 as the median load. Then

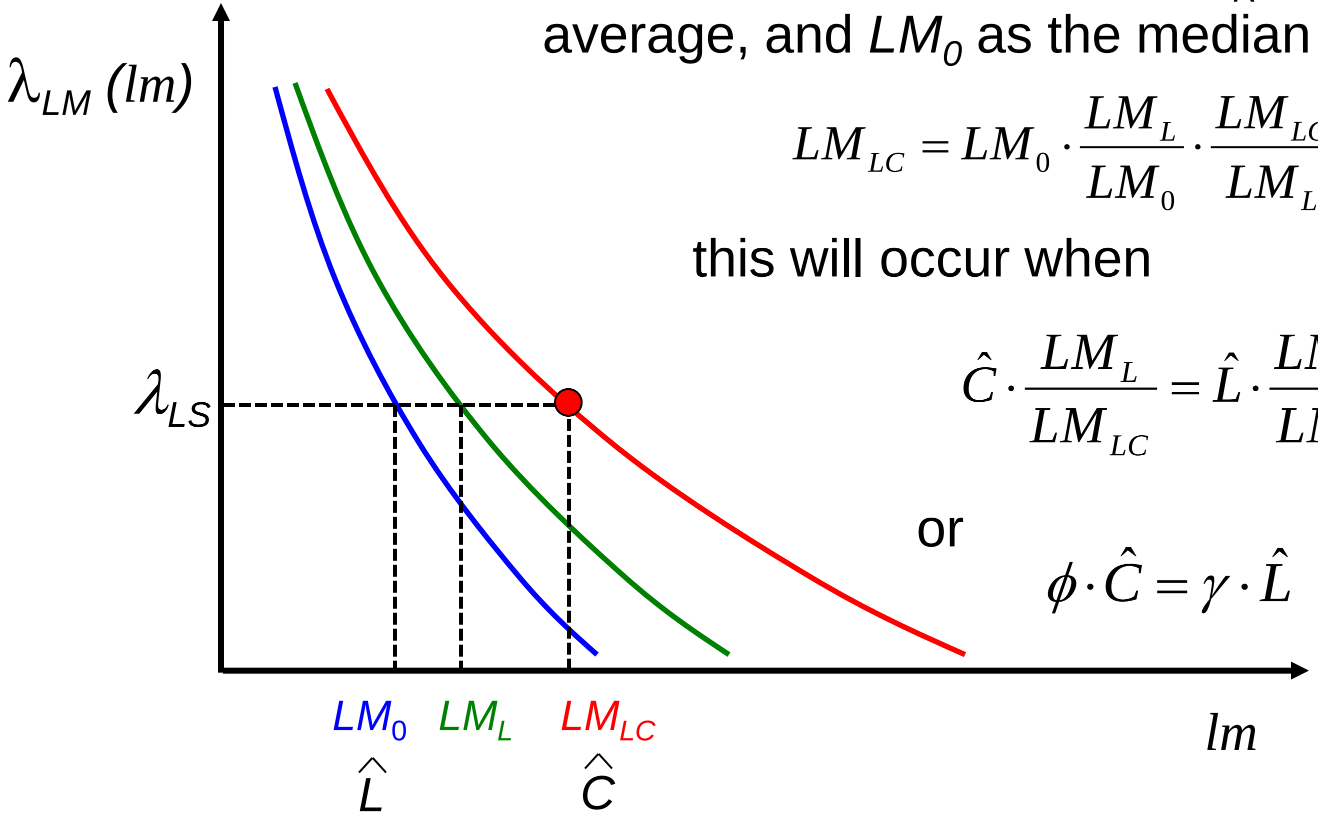
$$LM_{LC} = LM_0 \cdot \frac{LM_L}{LM_0} \cdot \frac{LM_{LC}}{LM_L}$$

this will occur when

$$\hat{C} \cdot \frac{LM_L}{LM_{LC}} = \hat{L} \cdot \frac{LM_L}{LM_0}$$

or

$$\phi \cdot \hat{C} = \gamma \cdot \hat{L}$$



Advancing Performance-Based Design

Can PBEE concepts be used to develop load and resistance factors associated with predictable rate of limit state exceedance, λ_{LS}?

Let *LM* = load measure

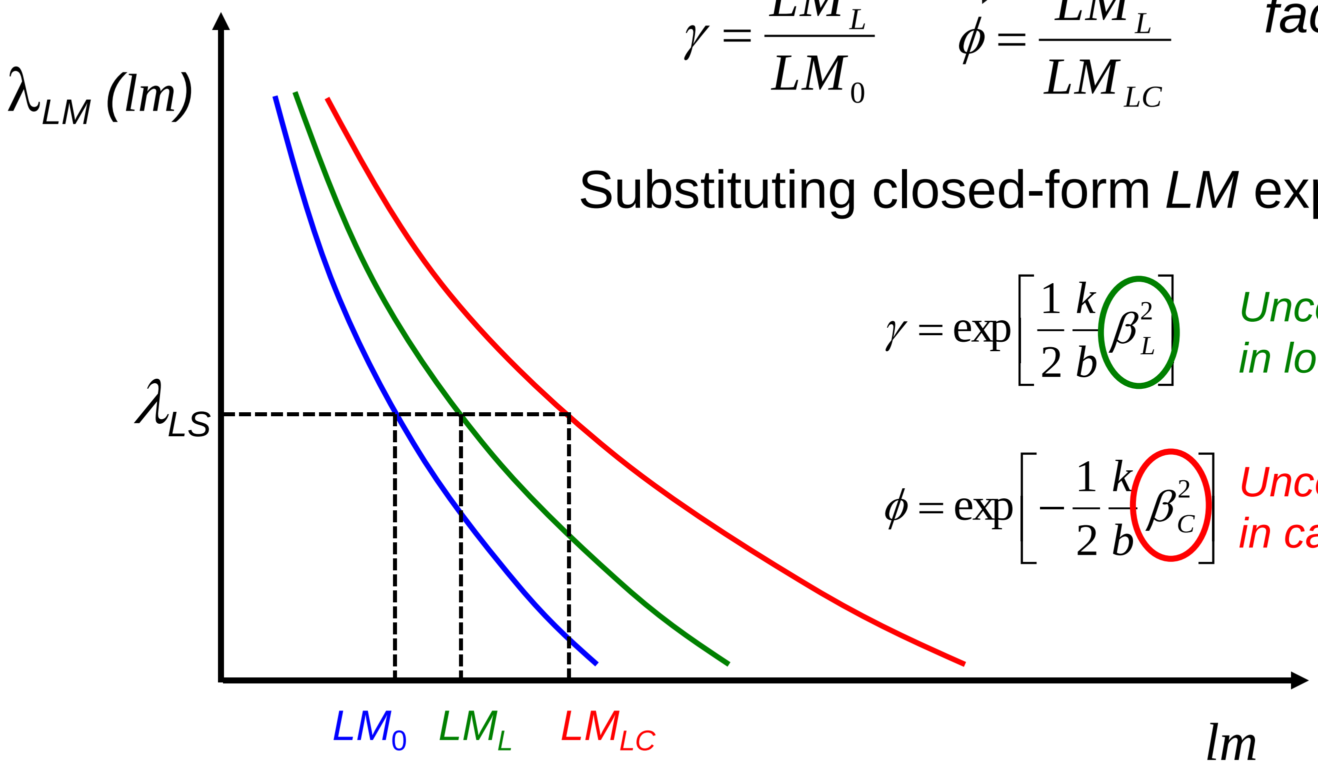
So,

Load factor

$$\gamma = \frac{LM_L}{LM_0}$$

Resistance factor

$$\phi = \frac{LM_L}{LM_{LC}}$$



Substituting closed-form *LM* expressions,

$$\gamma = \exp\left[\frac{1}{2}\frac{k}{b}\beta_L^2\right]$$

Uncertainty in loading

$$\phi = \exp\left[-\frac{1}{2}\frac{k}{b}\beta_C^2\right]$$

Uncertainty in capacity

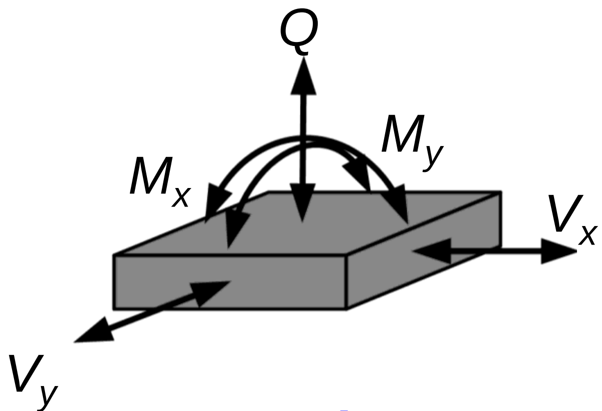
Application to Foundation Design

Extension to foundation displacements

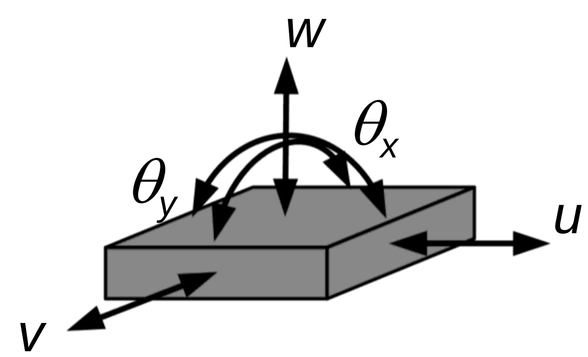
Let *LM* = load measure, *EDP* = response measure

Note that $LM = \{Q, V_x, V_y, M_x, M_y\}$

$EDP = \{w, u, v, \theta_x, \theta_y\}$



Loads
(*LM*s)



Deformations
(*EDP*s)

Application to Foundation Design

Extension to foundation displacements

Let *LM* = load measure, *EDP* = response measure

Note that $LM = \{Q, V_x, V_y, M_x, M_y\}$

$EDP = \{w, u, v, \theta_x, \theta_y\}$

$$\lambda_{EDP}(\boldsymbol{edp}) = \iint G(\boldsymbol{EDP} \mid \boldsymbol{LM}) \left| dG(\boldsymbol{LM} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

Closed-form assumptions:

Loads and moments

$$\lambda_{IM}(im) = k_0 (IM)^{-k}$$

$$LM = aIM^b$$

$$EDP = dLM^e$$

Displacements and rotations

Application to Foundation Design

$$\lambda_{EDP}(\boldsymbol{edp}) = \iint G(\boldsymbol{EDP} \mid \boldsymbol{LM}) \left| dG(\boldsymbol{LM} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

Closed-form assumptions:

$$\lambda_{IM}(im) = k_0 (IM)^{-k} \qquad LM = aIM^b \qquad EDP = dLM^e$$

Solution:

Uncertainty in *LM|IM* — Uncertainty in *EDP|LM*

$$\lambda_{EDP}(edp) = k_0 \left[\frac{1}{a} \left(\frac{edp}{d} \right)^{1/e} \right]^{-k/b} \exp\left[\frac{k^2}{2b^2e^2} \left(e\beta_L^2 + \beta_R^2 \right) \right]$$

Considering capacity:

Uncertainty in capacity

$$\lambda_{EDP}(edp) = k_0 \left[\frac{1}{a} \left(\frac{edp}{d} \right)^{1/e} \right]^{-k/b} \exp\left[\frac{k^2}{2b^2e^2} \left(e\beta_L^2 + \beta_R^2 + \beta_C^2 \right) \right]$$

Application to Foundation Design

$$\lambda_{EDP}(\boldsymbol{edp}) = \iint G(\boldsymbol{EDP} \mid \boldsymbol{LM}) \left| dG(\boldsymbol{LM} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

$$\lambda_{EDP}(edp) = k_0 \left[\frac{1}{a} \left(\frac{\hat{C}}{d} \right)^{1/e} \right]^{-k/b}$$

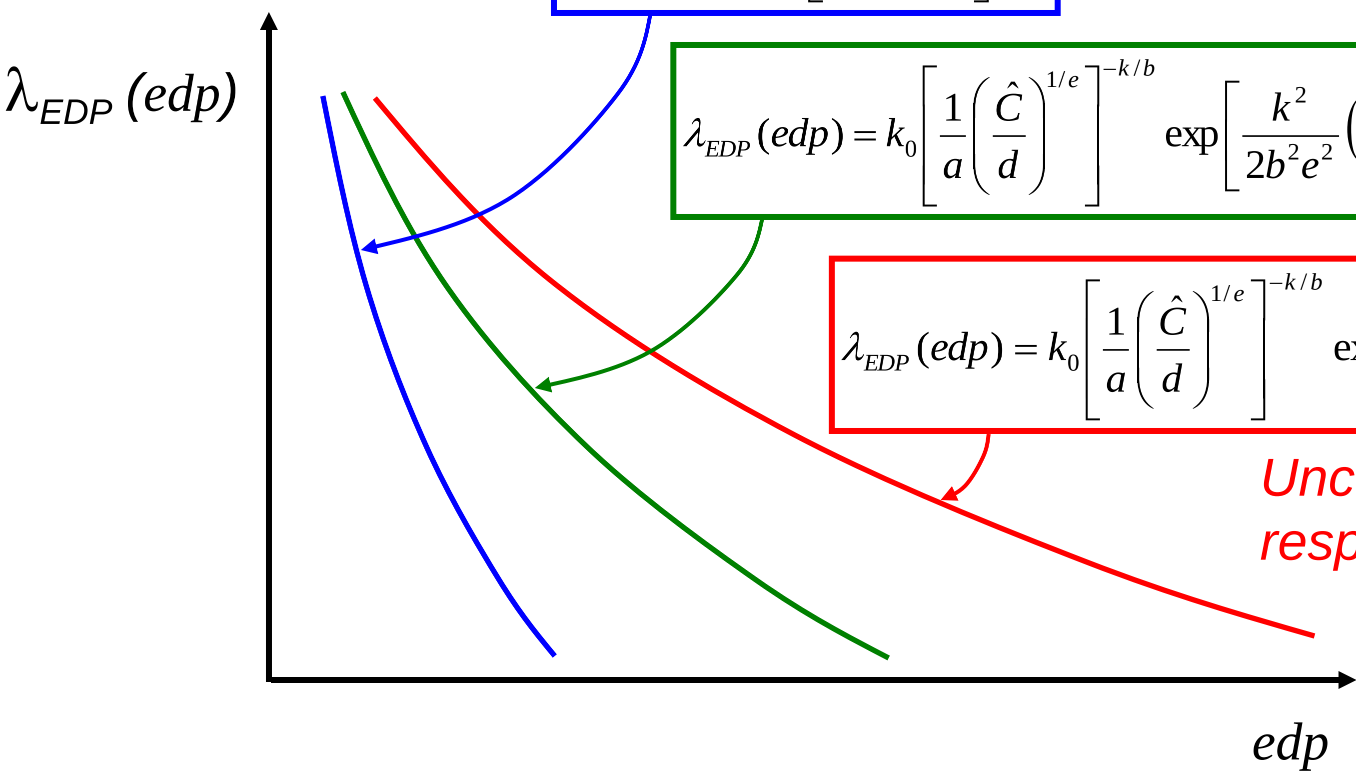
No uncertainty

$$\lambda_{EDP}(edp) = k_0 \left[\frac{1}{a} \left(\frac{\hat{C}}{d} \right)^{1/e} \right]^{-k/b} \exp\left[\frac{k^2}{2b^2 e^2} \left(e\beta_L^2 + \beta_R^2 \right) \right]$$

Uncertainty in loading and response

$$\lambda_{EDP}(edp) = k_0 \left[\frac{1}{a} \left(\frac{\hat{C}}{d} \right)^{1/e} \right]^{-k/b} \exp\left[\frac{k^2}{2b^2 e^2} \left(e\beta_L^2 + \beta_R^2 + \beta_C^2 \right) \right]$$

Uncertainty in loading, response, and capacity



Application to Foundation Design

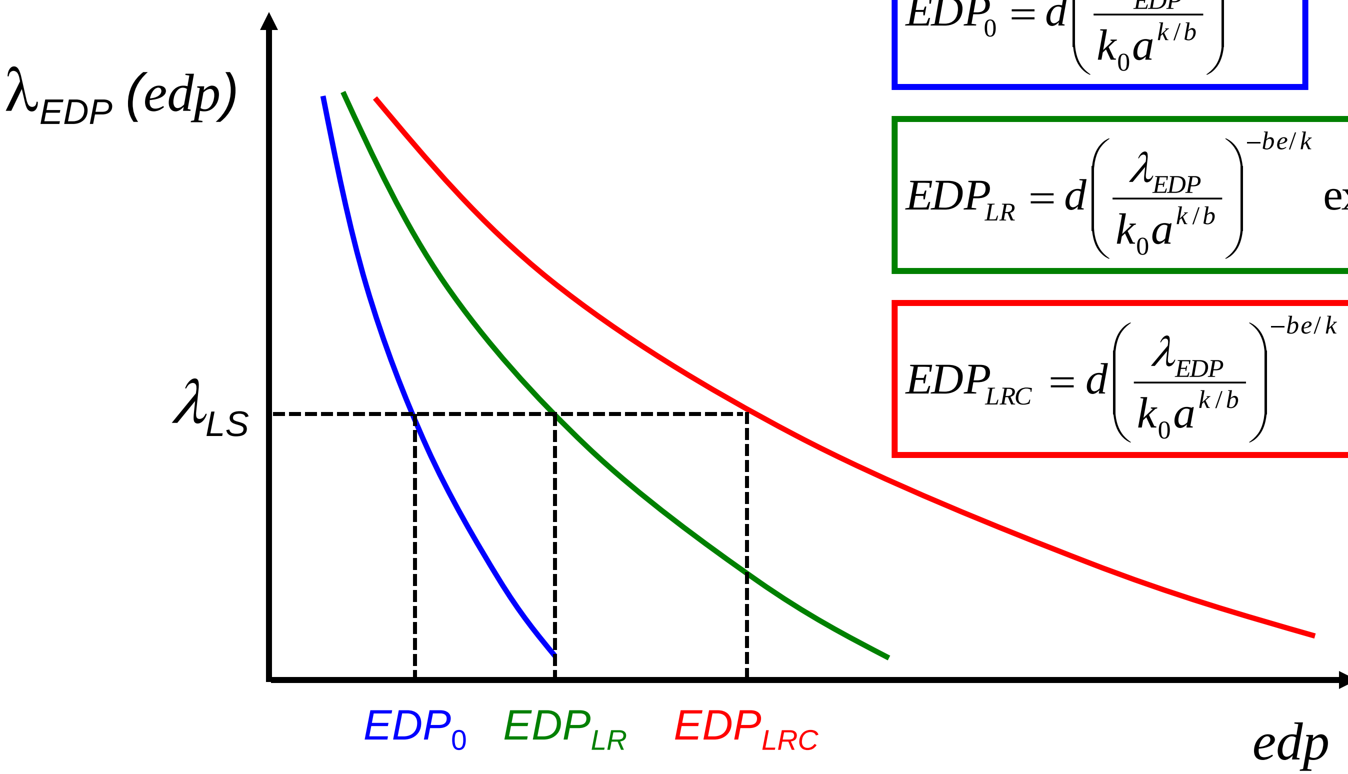
$$\lambda_{EDP}(\boldsymbol{edp}) = \iint G(\boldsymbol{EDP} \mid \boldsymbol{LM}) \left| dG(\boldsymbol{LM} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

Solving previous equations for *EDP*,

$$EDP_0 = d\left(\frac{\lambda_{EDP}}{k_0 a^{k/b}}\right)^{-be/k}$$

$$EDP_{LR} = d\left(\frac{\lambda_{EDP}}{k_0 a^{k/b}}\right)^{-be/k} \exp\left[\frac{k}{2be}\left(e\beta_L^2 + \beta_R^2\right)\right]$$

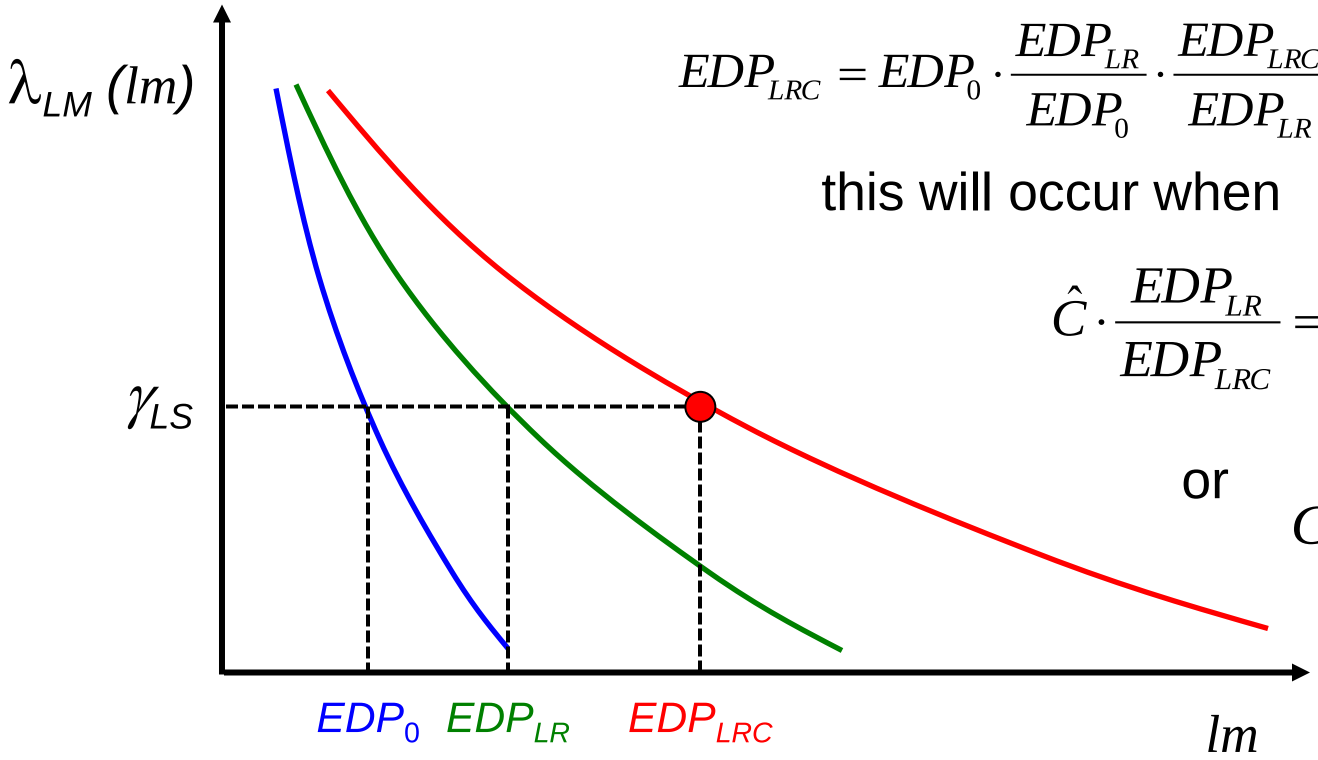
$$EDP_{LRC} = d\left(\frac{\lambda_{EDP}}{k_0 a^{k/b}}\right)^{-be/k} \exp\left[\frac{k}{2be}\left(e\beta_L^2 + \beta_R^2 + \beta_C^2\right)\right]$$



Application to Foundation Design

$$\lambda_{EDP}(\boldsymbol{edp}) = \iint G(\boldsymbol{EDP} \mid \boldsymbol{LM}) \left| dG(\boldsymbol{LM} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

EDP_{LRC} can be interpreted as median displacement capacity that will be exceeded every T_R years, on average, and EDP_0 as the median displacement demand. Then



$$EDP_{LRC} = EDP_0 \cdot \frac{EDP_{LR}}{EDP_0} \cdot \frac{EDP_{LRC}}{EDP_{LR}}$$

this will occur when

$$\hat{C} \cdot \frac{EDP_{LR}}{EDP_{LRC}} = \hat{D} \cdot \frac{EDP_{LR}}{EDP_0}$$

or

$$CF \cdot \hat{C} = DF \cdot \hat{L}$$

Application to Foundation Design

$$\lambda_{EDP}(\boldsymbol{edp}) = \iint G(\boldsymbol{EDP} \mid \boldsymbol{LM}) \left| dG(\boldsymbol{LM} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

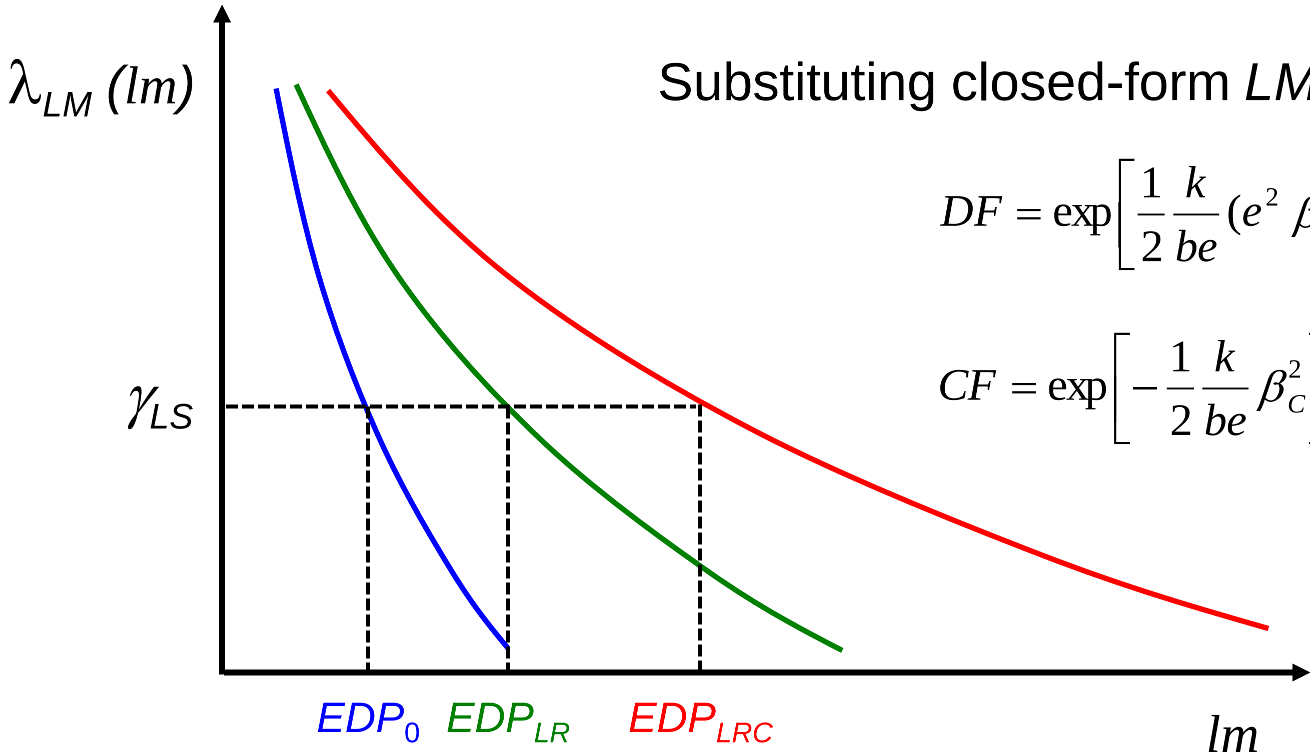
So,

Demand factor

$$DF = \frac{EDP_{LR}}{EDP_0}$$

Capacity factor

$$CF = \frac{EDP_{LR}}{EDP_{LRC}}$$



Substituting closed-form *LM* expressions,

$$DF = \exp\left[\frac{1}{2}\frac{k}{be}(e^2\,\beta_L^2 + \beta_R^2)\right]$$

$$CF = \exp\left[-\frac{1}{2}\frac{k}{be}\beta_C^2\right]$$

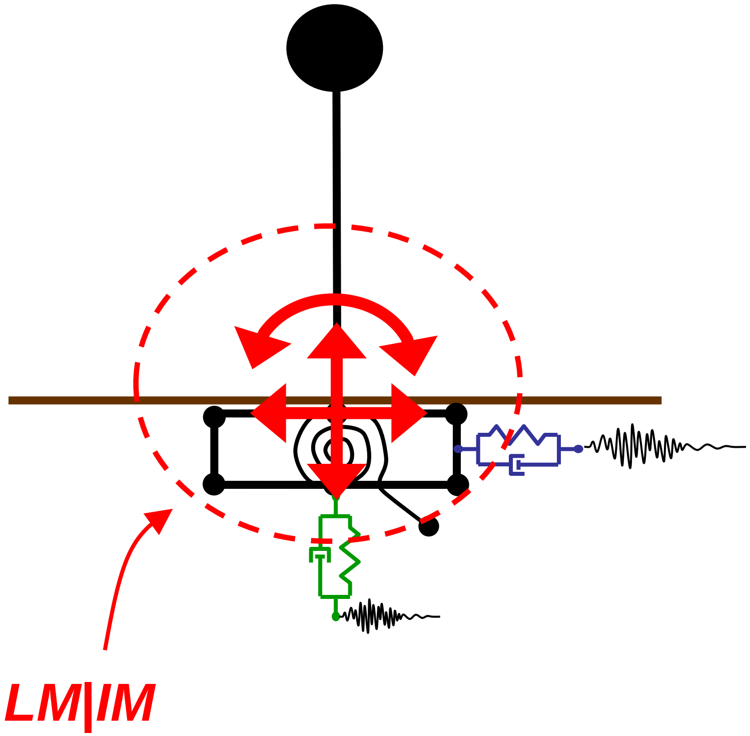
Application to Foundation Design

Example: 5x5 pile group in sand

- Closed-form expression helps in understanding
- Actual problem more complicated
  - Five components of load
  - Five components of displacement
  - Components of both may be correlated
  - Relationships not described by power laws
  - Uncertainty may not be lognormal
- Numerical integration required – in five dimensions

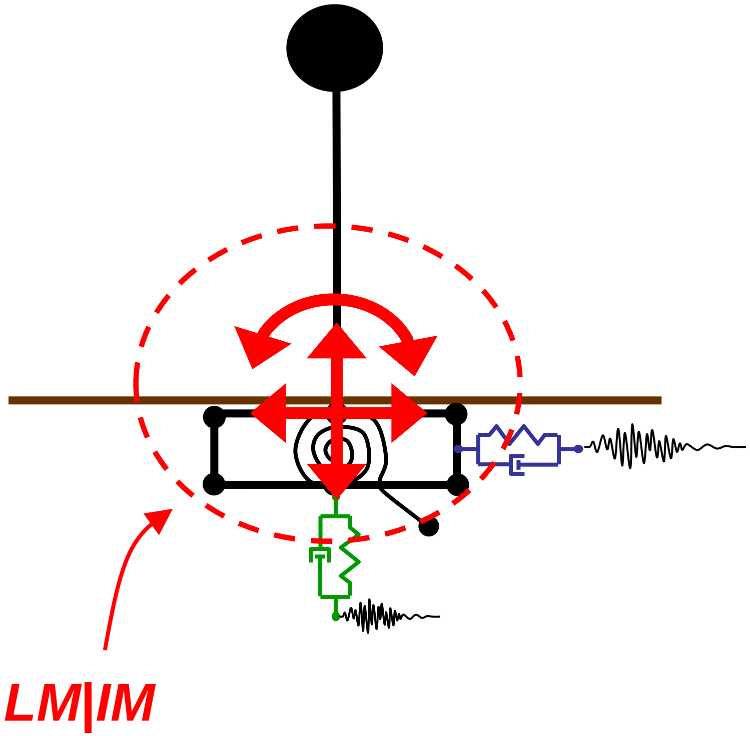
Application to Foundation Design

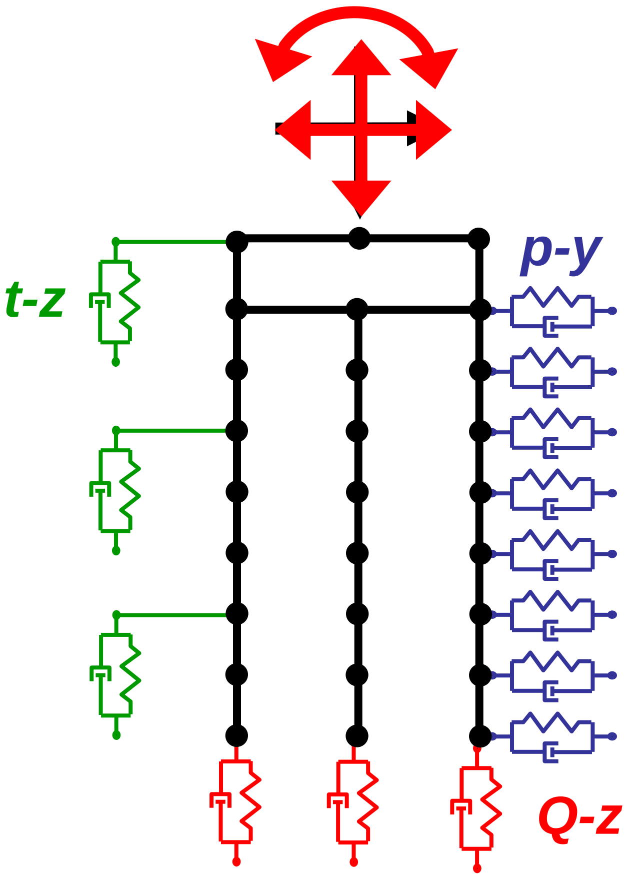
Computational approach: Decoupled analyses



Application to Foundation Design

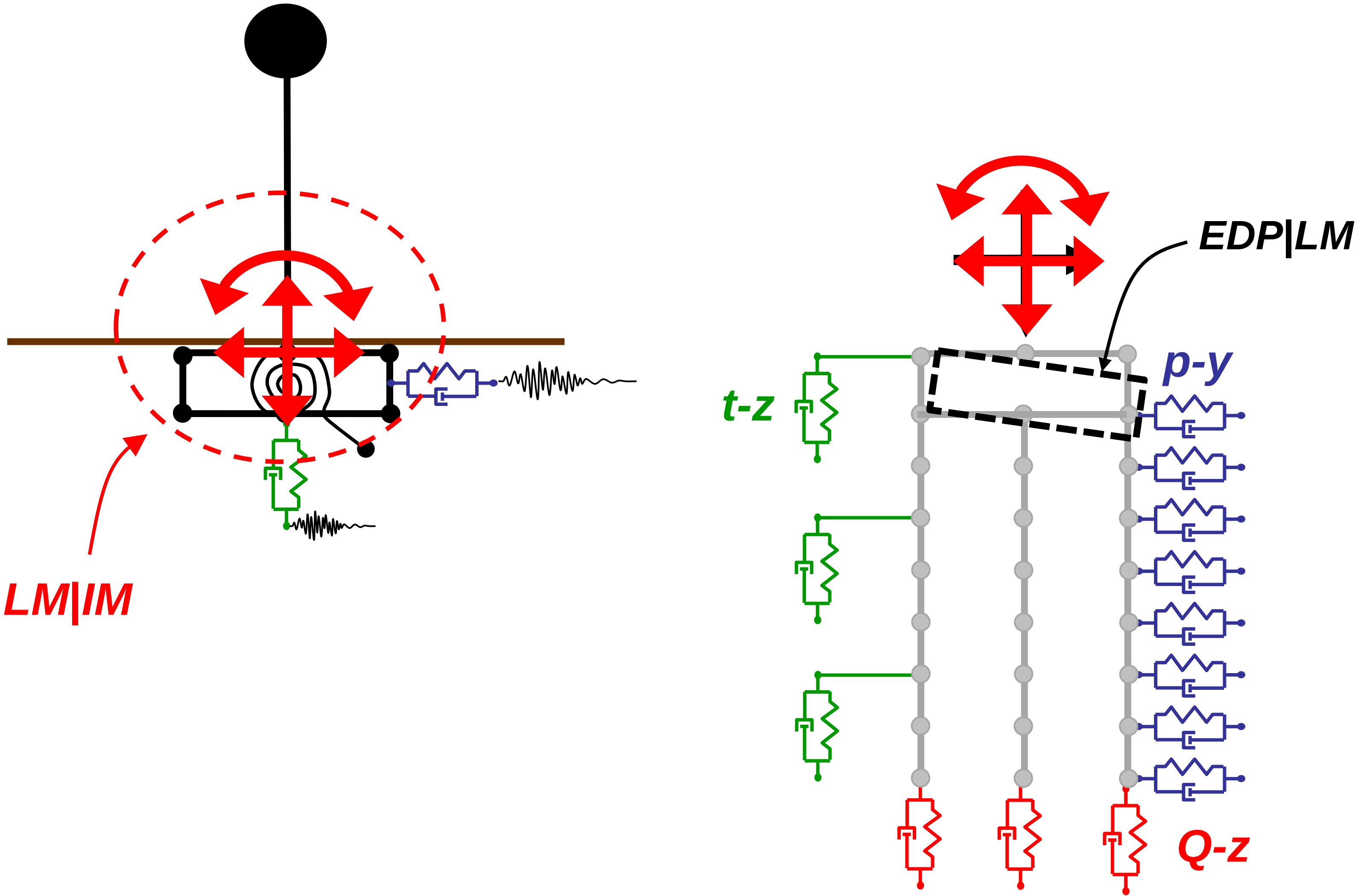
<u>Computational approach</u>: Decoupled analyses





Application to Foundation Design

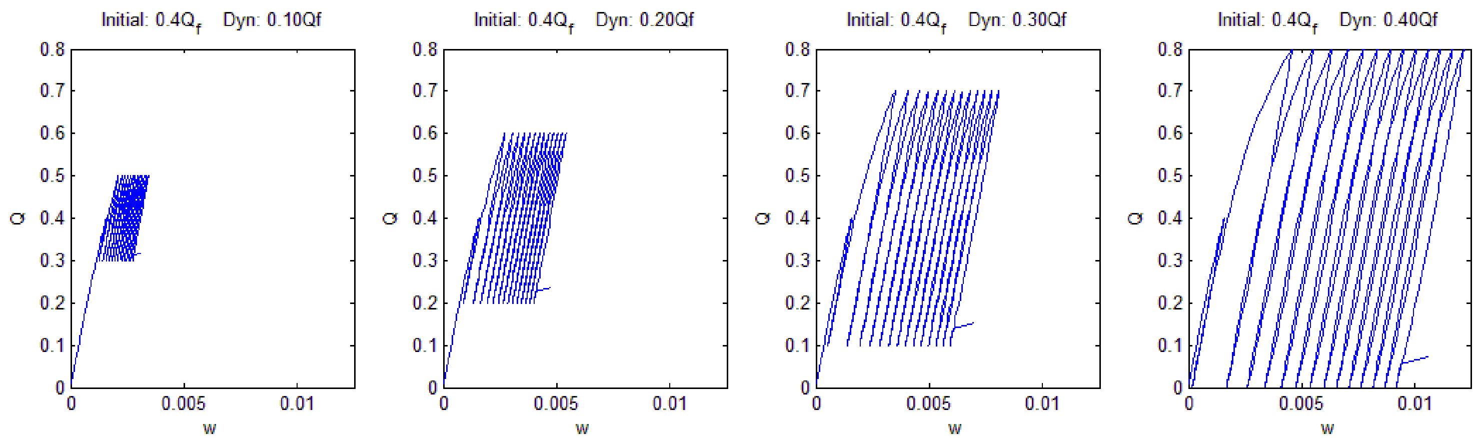
Computational approach: Decoupled analyses



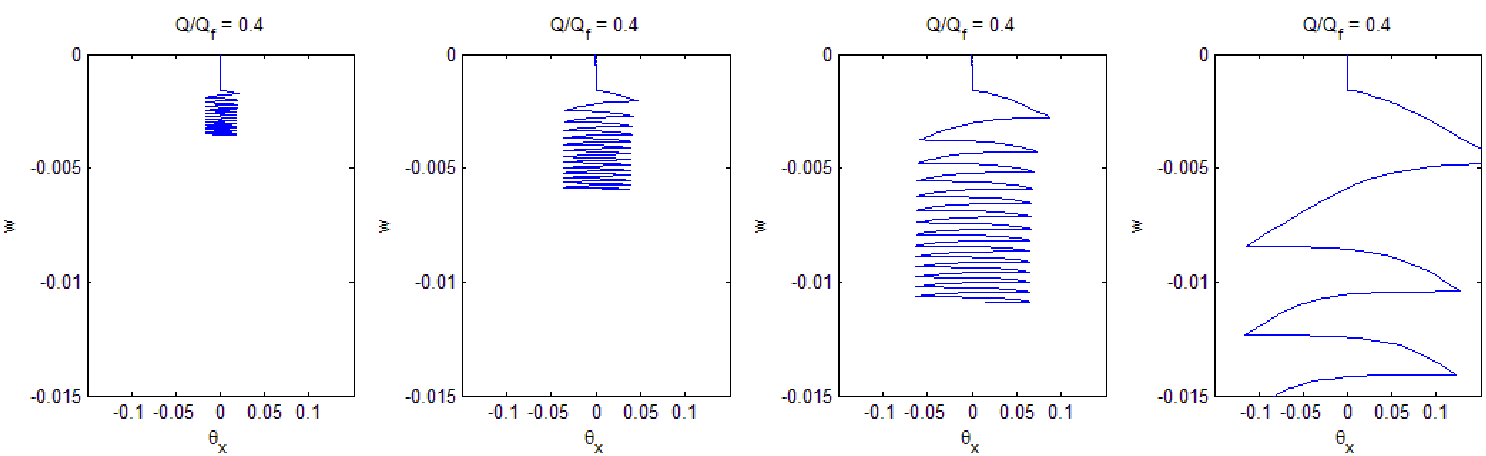
Application to Foundation Design

OpenSees pile group model

Vertical settlement due to static plus cyclic vertical load



Vertical settlement due to static vertical load plus cyclic moment



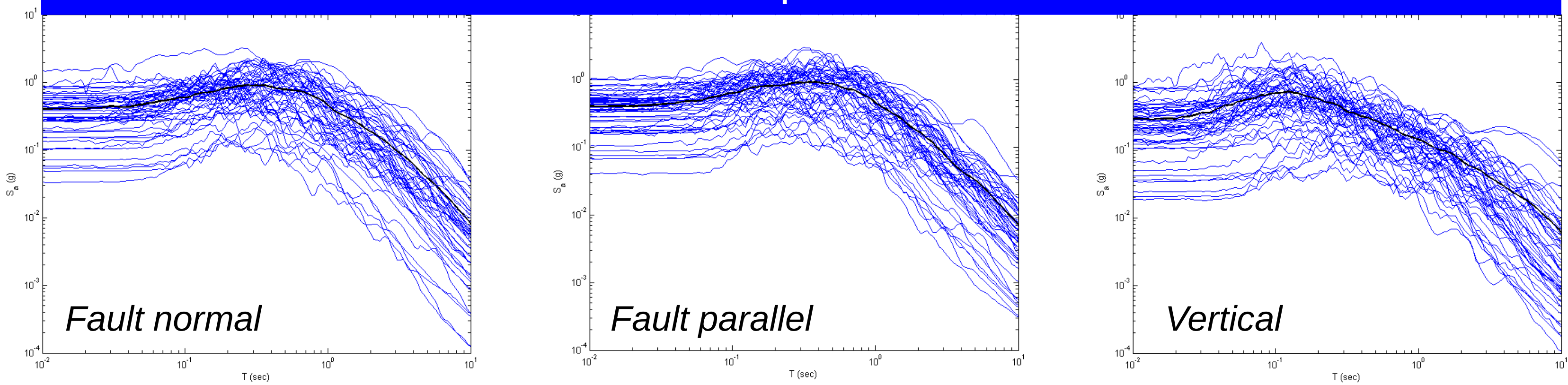
Application to Foundation Design

OpenSees pile group model

Analyzed multiple cases:

3 x 3	Sand profile	Linear structure, T_o = 0.5 sec
5 x 5	Clay profile	Linear structure, T_o = 1.0 sec
7 x 7		Nonlinear structure, T_o = 0.5 sec
3 x 5		Nonlinear structure, T_o = 1.0 sec
3 x 7 groups		

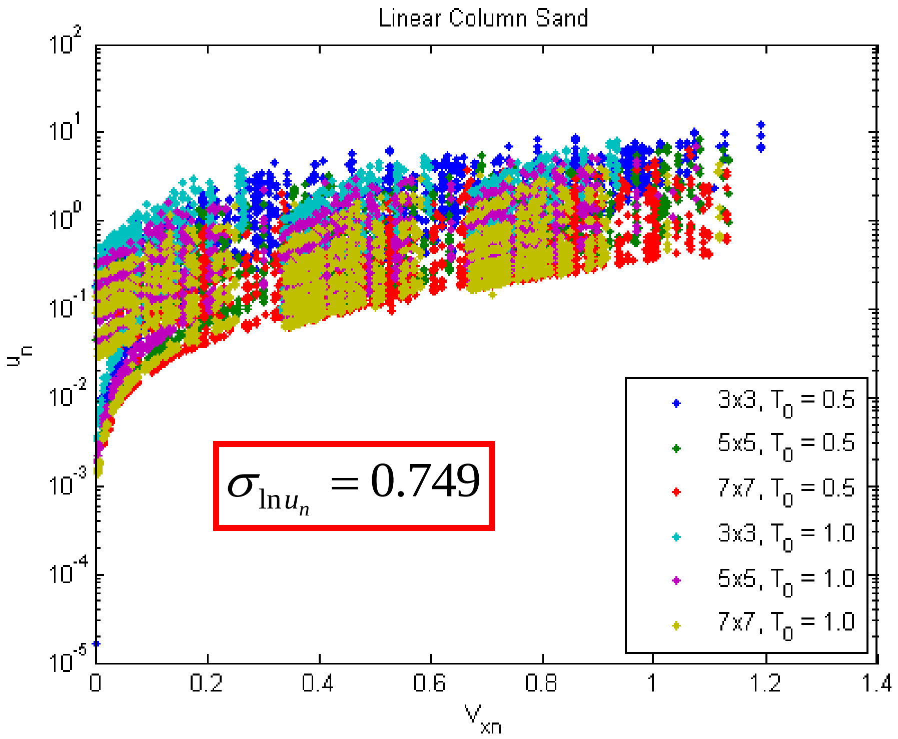
50 three-component motions



Application to Foundation Design

OpenSees pile group model

Analyzed multiple cases:



Normalized displacement vs. normalized load

$$\ln u_n = 0.191 + 0.364 \ln Q_n + 0.990 V_{xn} - 0.320 V_{yn} + 0.796 \ln(M_{xn} + M_{yn})$$

Application to Foundation Design

Example: 5x5 group of 60 cm, 20-m-long pipe piles in m. dense sand

Static loads

Q = 40,000 kN

V_x = 10,000 kN

V_y = 15,000 kN

M_x = 30,000 kN-m

M_y = 20,000 kN-m

β_s = 0.1

β_{ref} = 0.3

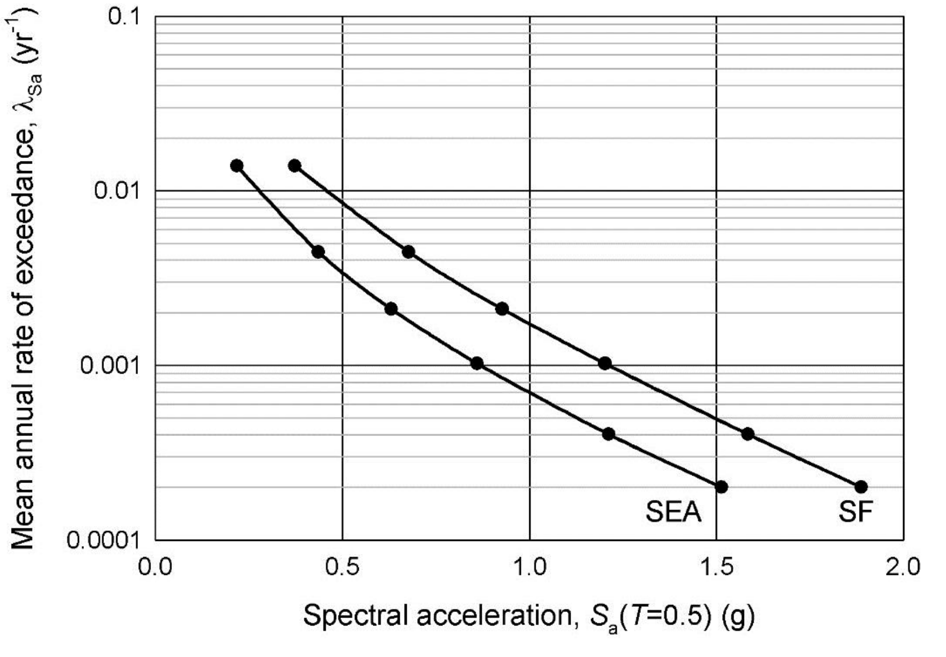
β_L = 0.2

β_C = 0.3

Assumed to be located in:

San Francisco

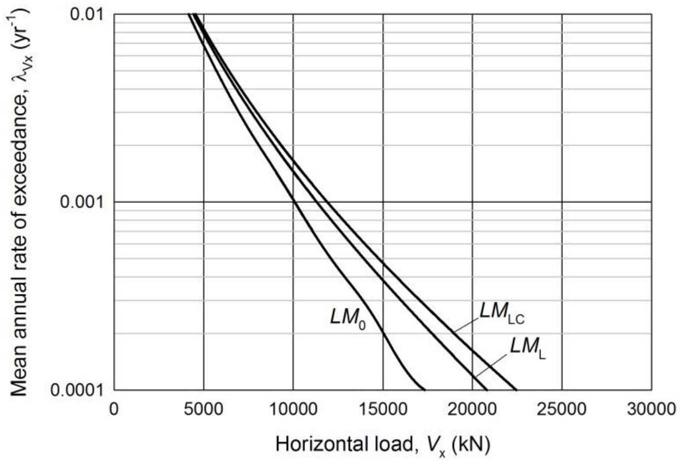
Seattle

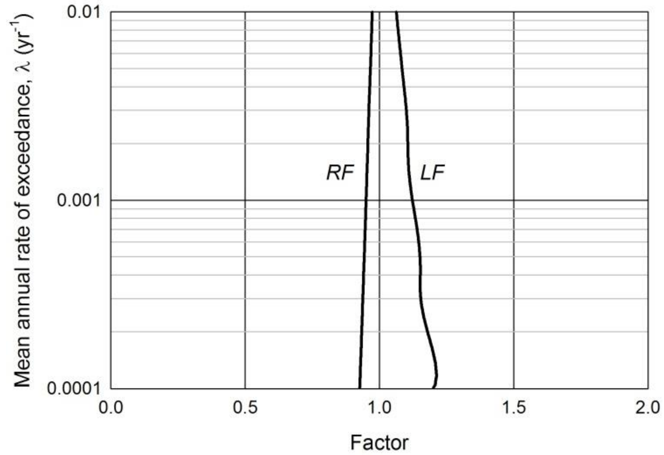


Application to Foundation Design

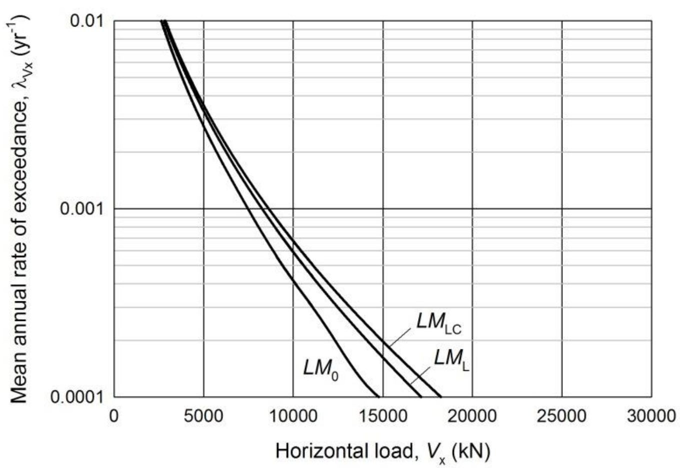
Example: 5x5 group of 60 cm, 20-m-long pipe piles in m. dense sand

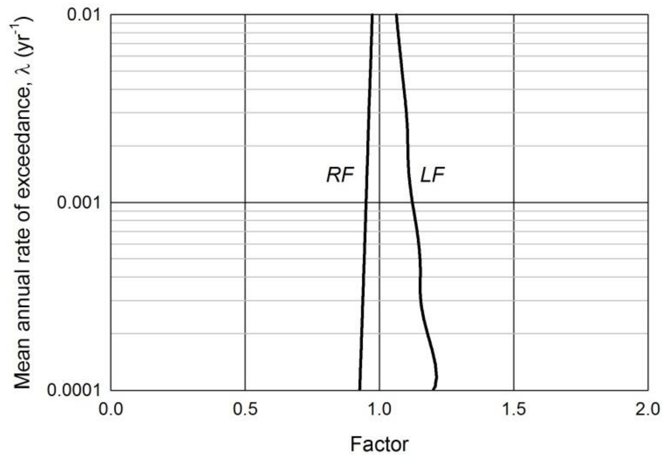
San Francisco





Seattle

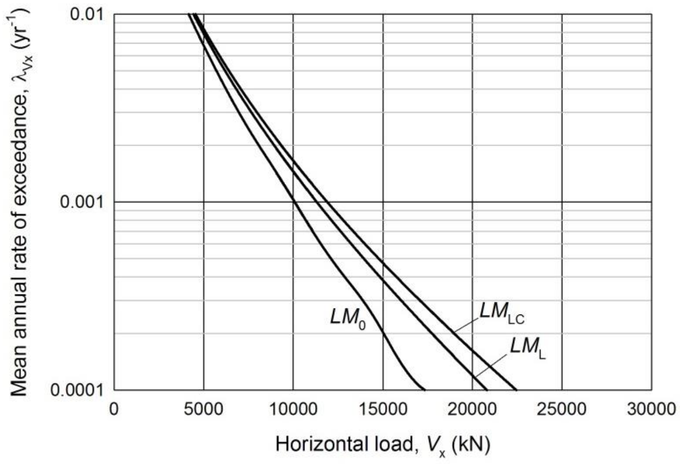


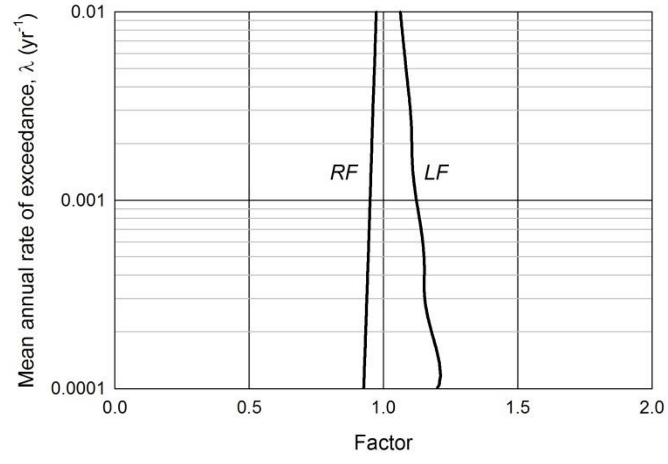


Application to Foundation Design

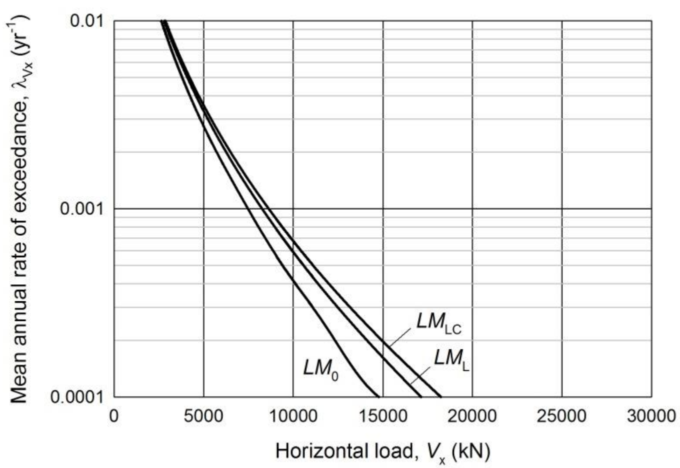
Example: 5x5 group of 60 cm, 20-m-long pipe piles in m. dense sand

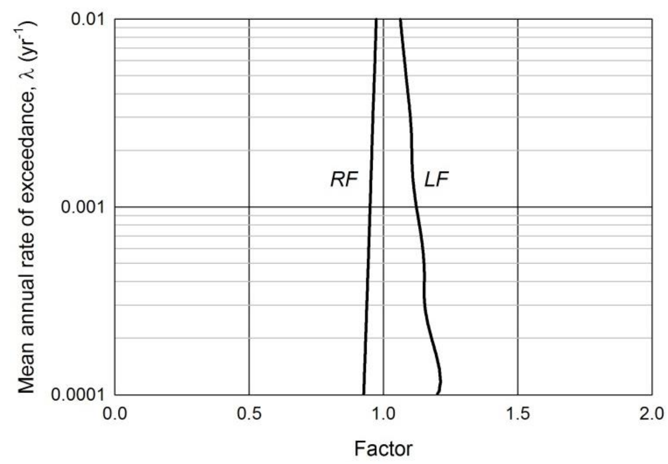
San Francisco





Seattle

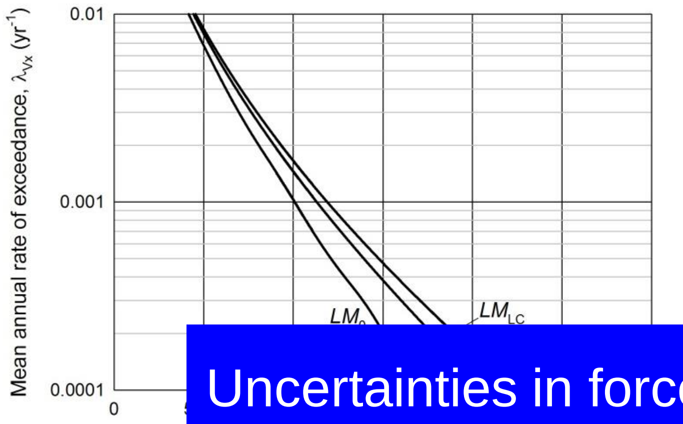


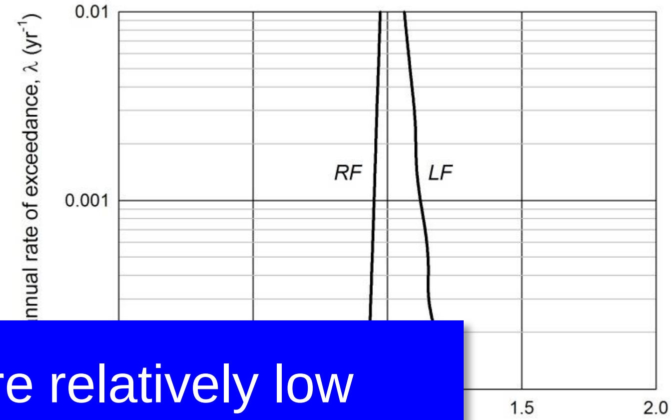


Application to Foundation Design

Example: 5x5 group of 60 cm, 20-m-long pipe piles in m. dense sand

San Francisco





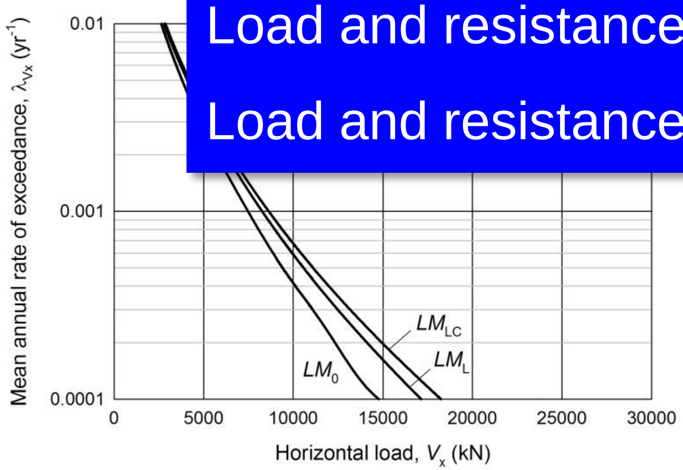
Uncertainties in forces are relatively low

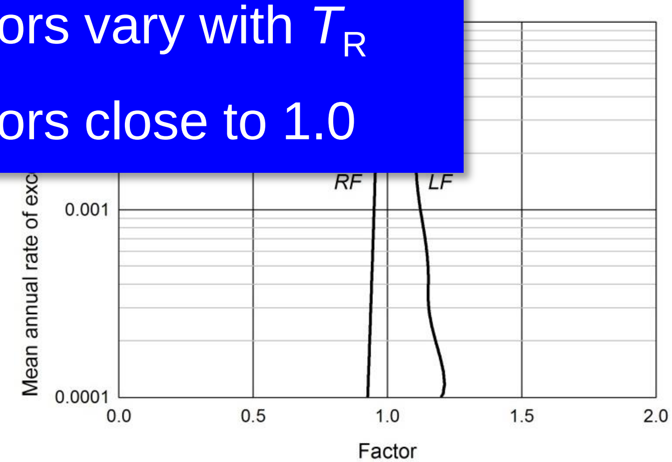
LM hazard curves are close to each other

Load and resistance factors vary with T_R

Load and resistance factors close to 1.0

Seattle

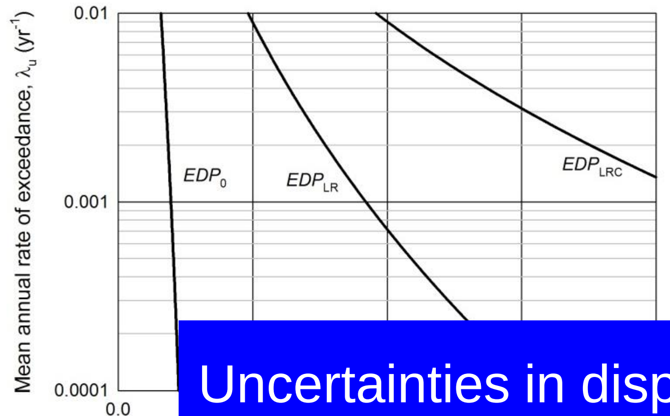


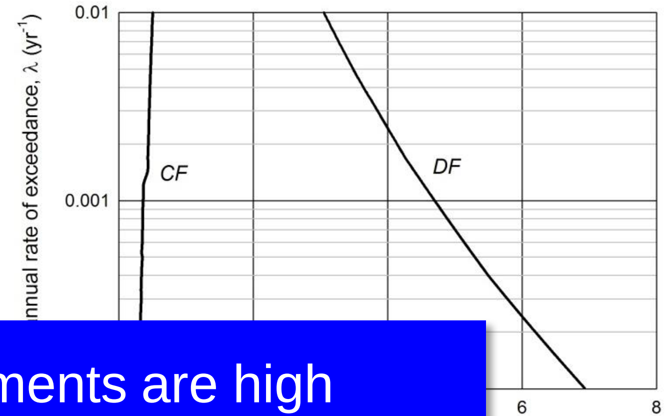


Application to Foundation Design

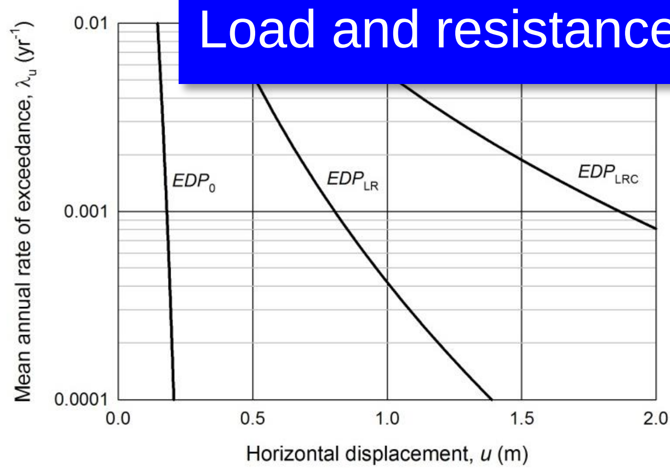
Example: 5x5 group of 60 cm, 20-m-long pipe piles in m. dense sand

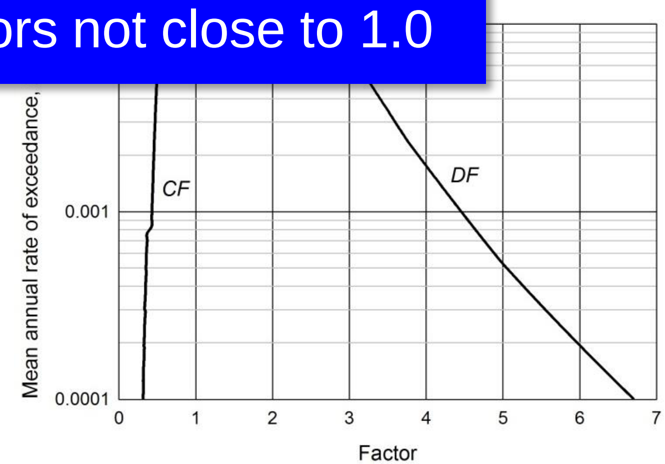
San Francisco





Seattle





Uncertainties in displacements are high

EDP hazard curves are far from each other

Load and resistance factors not close to 1.0

Summary and Conclusions

- Seismic design has always considered performance, but not always in rigorous manner
- Performance can be characterized in different ways – response, damage, loss
- It is important to define performance objectives in clear, quantitative way
- Design for specified performance level requires consideration of uncertainties
- For a given return period, response, damage, and loss all increase with increasing uncertainty
- Geotechnical engineers are able to reduce expected losses by reducing uncertainty through more extensive subsurface investigation, improved field and laboratory testing, and more rigorous analyses

Summary and Conclusions

- Application of performance-based concepts has increased – usually implemented in terms of response measures (displacement, rotation, curvature, etc.)
- Performance-based concepts can be implemented for such structures in LRFD-type format
- Force-based load and resistance factors reflect relatively low uncertainty in ability to predict forces
- Displacement-based demand and capacity factors reflect high uncertainty in displacements
- Performance-based earthquake engineering offers a framework for more complete and consistent seismic designs and seismic evaluations

Thank you