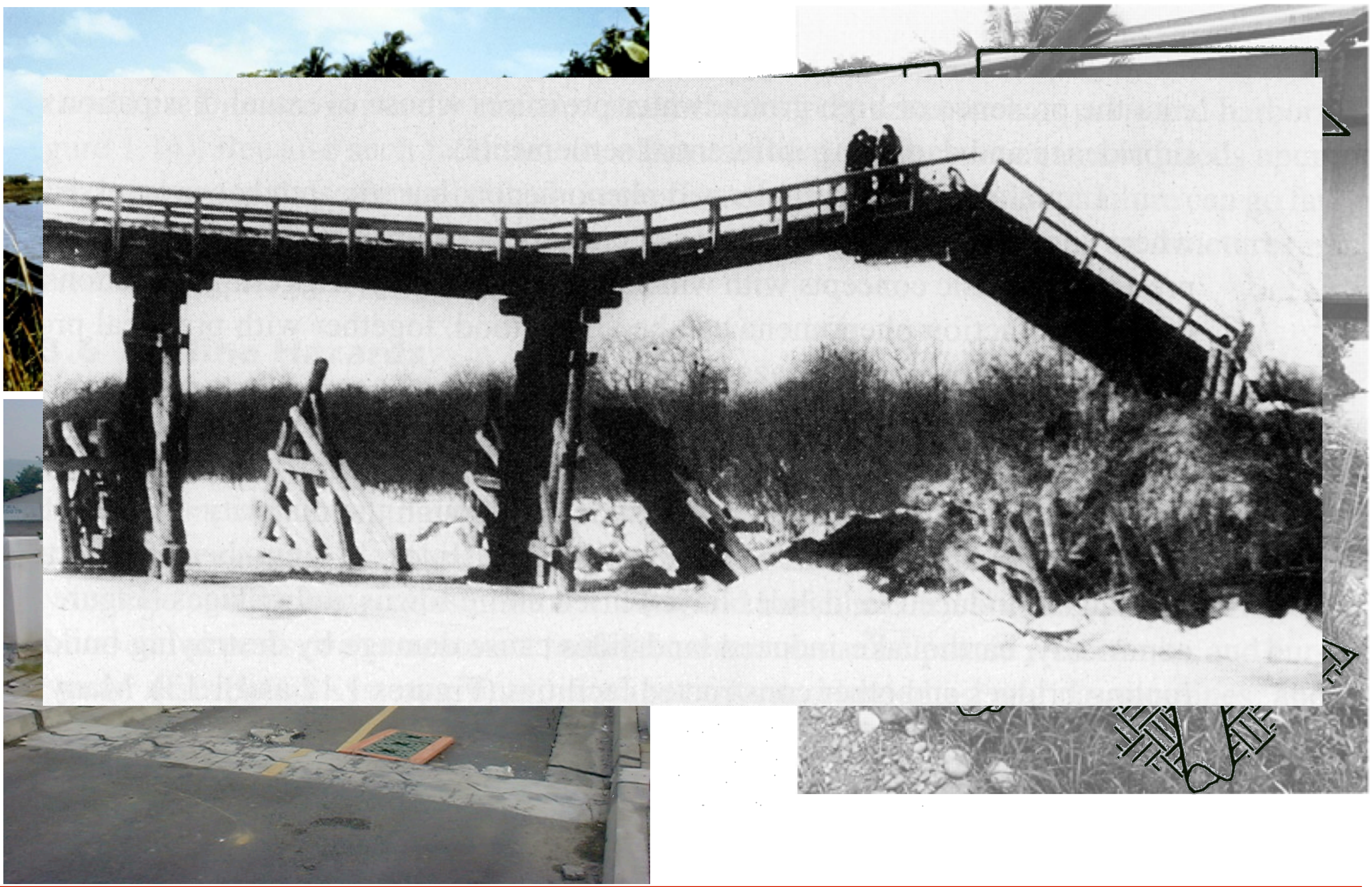
PBEE evaluation of a bridge with liquefaction hazards

Pedro Arduino
Steven Kramer
HyungSuk Shin

University of Washington

Introduction (earthquake bridge damage)

Introduction (earthquake bridge damage)



Objective

- Estimate bridge performance hazards considering several sources of uncertainties using the PEER PBEE framework

Outline

- PEER PBEE framework
- Target bridge structure and modeling
- Input Motions
- Bridge response
- Uncertainty in EDP
- Foundation Damage and loss
- Bridge damage and loss

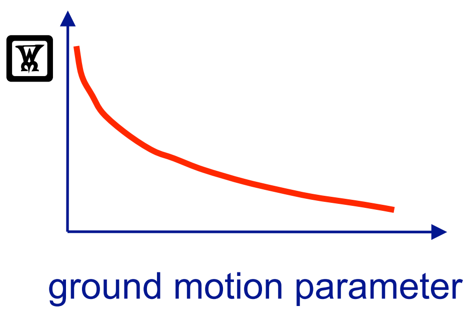
Outline

- **PEER PBEE framework**
- Target bridge structure and modeling
- Input Motions
- Bridge response
- Uncertainty in EDP
- Foundation Damage and loss
- Bridge damage and loss

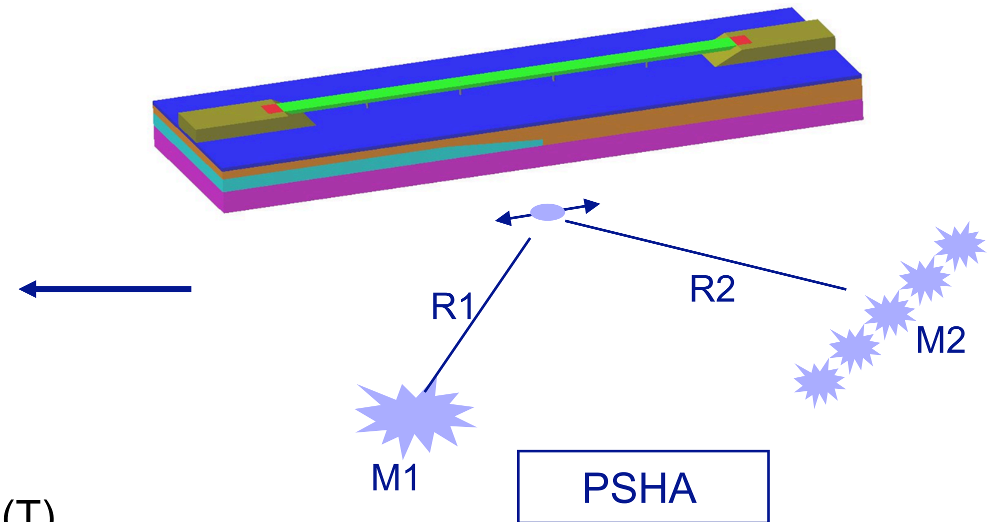
PEER Performance-Based Earthquake Engineering

Intensity Measure (IM)	→	Engineering Demand Parameter (EDP)	→	Damage Measure (DM)	→	Decision Variable (DV)
Peak accel = 0.4g		Column drift = 3 %		Damage = spalling		Repair cost = $3k

Probabilistic Seismic Hazard Analysis (PSHA)

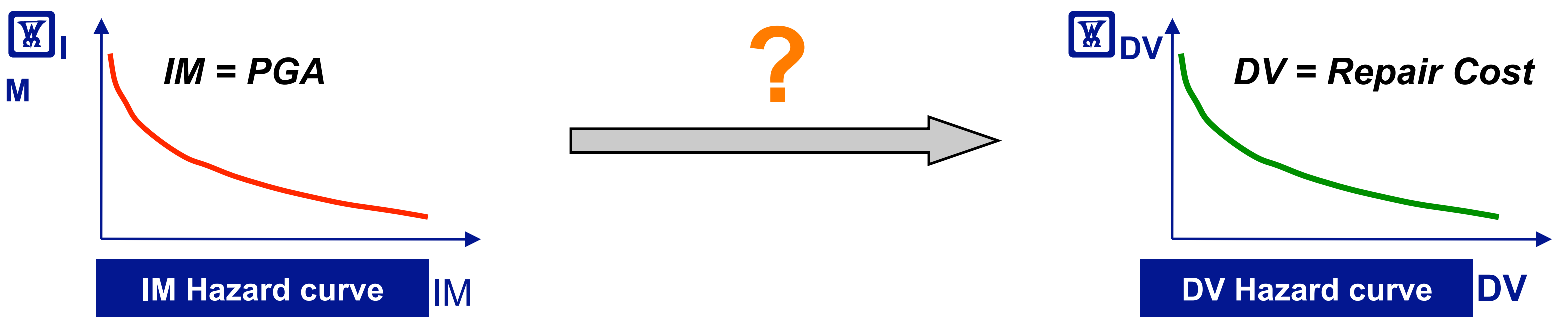


PGA, PGV, Ia, CAV5, Sa(T)



PEER Performance-Based Earthquake Engineering

Intensity Measure (IM)	→	Engineering Demand Parameter (EDP)	→	Damage Measure (DM)	→	Decision Variable (DV)
Peak accel = 0.4g		Column drift = 3 %		Damage = spalling		Repair cost = $3k

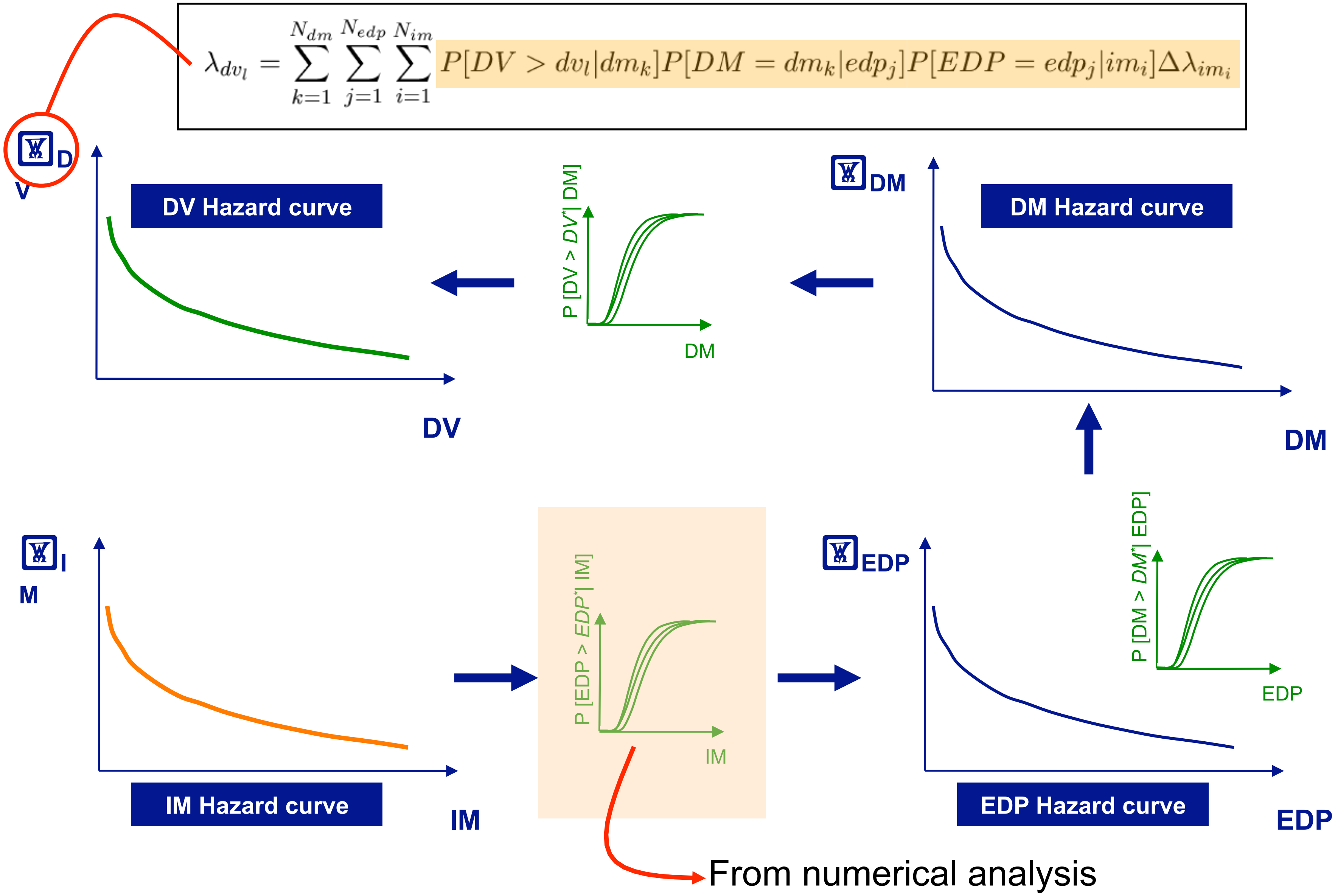


total probability theorem

$$\lambda_{dv_l} = \sum_{k=1}^{N_{dm}} \sum_{j=1}^{N_{edp}} \sum_{i=1}^{N_{im}} P[DV > dv_l | dm_k] P[DM = dm_k | edp_j] P[EDP = edp_j | im_i] \Delta\lambda_{im_i}$$

PEER Performance-Based Earthquake Engineering

$$\lambda_{dv_l} = \sum_{k=1}^{N_{dm}} \sum_{j=1}^{N_{edp}} \sum_{i=1}^{N_{im}} P[DV > dv_l | dm_k] P[DM = dm_k | edp_j] P[EDP = edp_j | im_i] \Delta\lambda_{im_i}$$

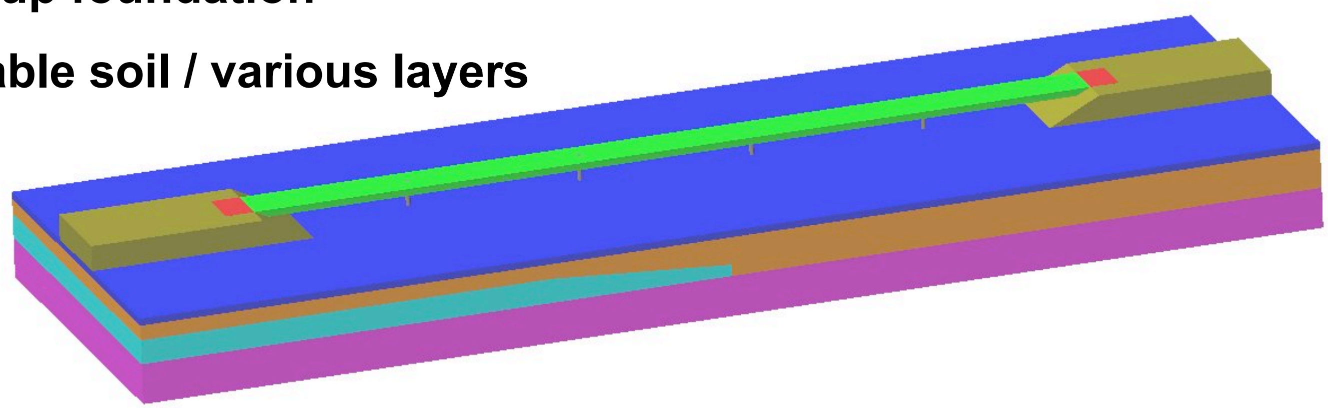


Outline

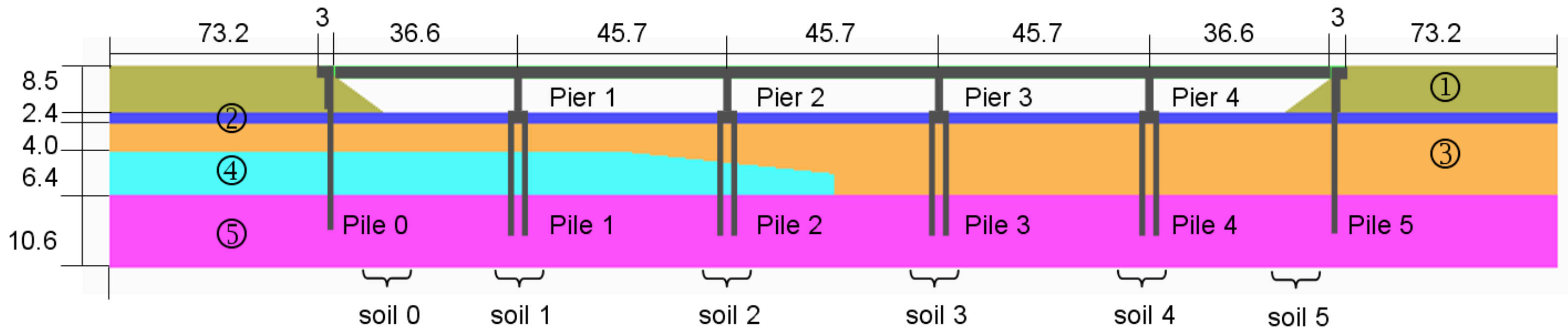
- **PEER PBEE framework**
- **Target bridge structure and modeling**
- Input Motions
- Bridge response
- Uncertainty in EDP
- Foundation Damage and loss
- Bridge damage and loss

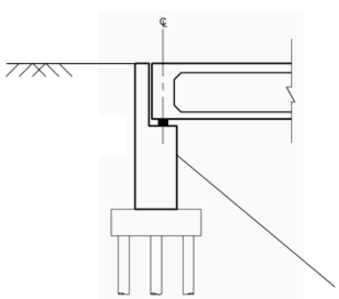
Target Structure = Bridge system on liquefiable soil

- Five-span bridge
- Pile group foundation
- Liquefiable soil / various layers

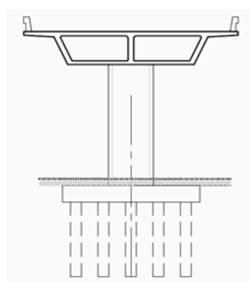


Target Bridge System

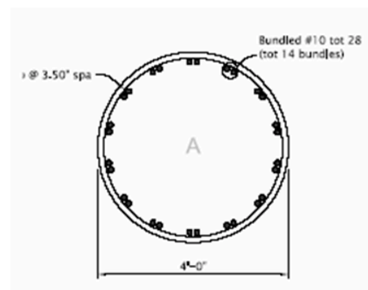




Seat wall abutment



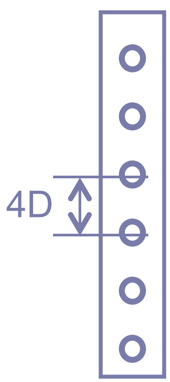
Bridge structure



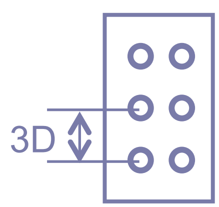
Pier section

- ① embankment
- ② med. stiff clay
- ③ loose-med sand
- ④ stiff clay
- ⑤ dense sand

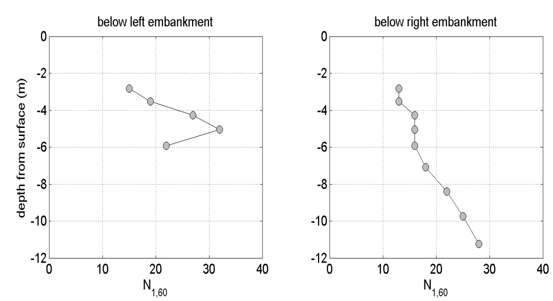
Soil type



6×1 pile group

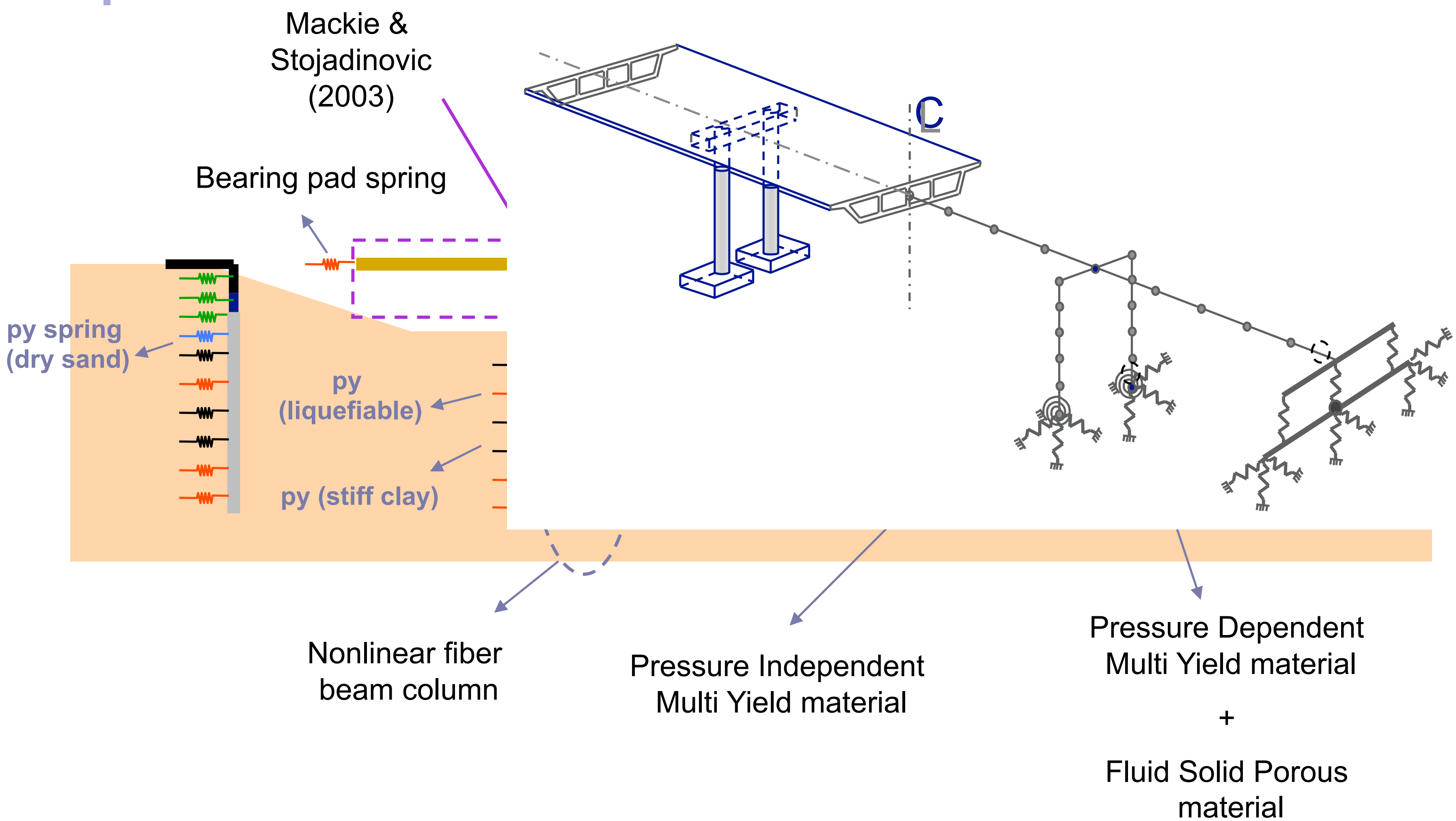


3×2 pile group



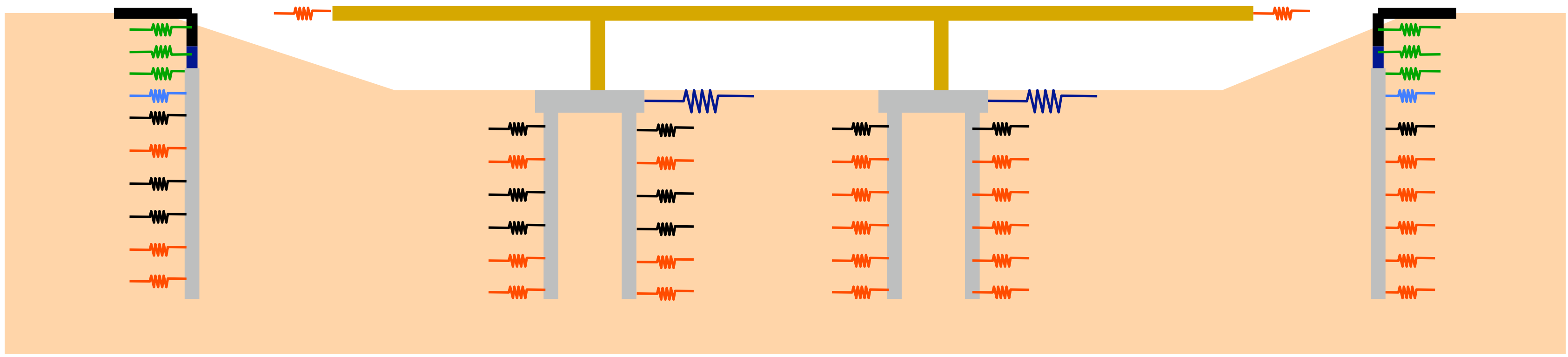
$N_{1,60}$ below embankments

Numerical modeling of target bridge system in OpenSees

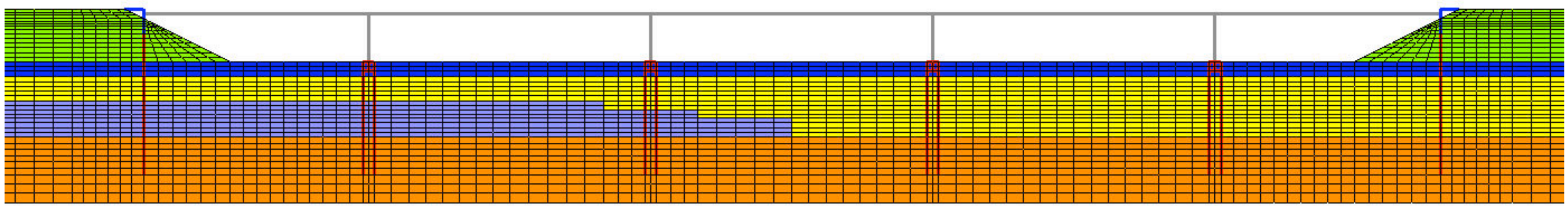


Numerical modeling of target bridge system in OpenSees

Bridge Idealization



OpenSees model

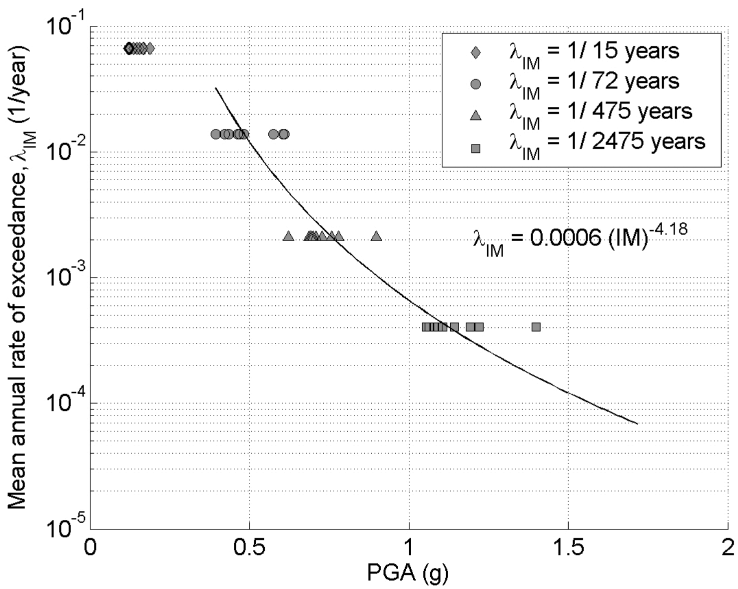


Outline

- **PEER PBEE framework**
- **Target bridge structure and modeling**
- **Input Motions**
- **Bridge response**
- Uncertainty in EDP
- Foundation Damage and loss
- Bridge damage and loss

Input Motions and Intensity Measures (IMs)

- 4 hazards of input motions (I-880 bridge site, near-fault)
- Return periods (15, 72,475, 2475 years)
- 10 motions for each hazard



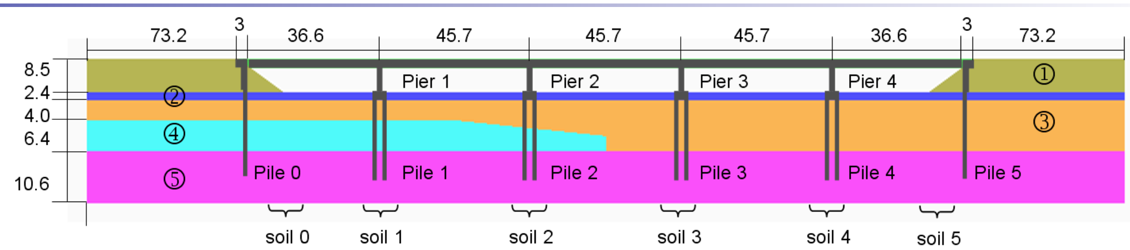
IM	Definition	Unit
Peak Ground Acceleration (PGA)	$max\ \lvert a(t) \rvert$	g
Peak Ground Velocity (PGV)	$max\ \lvert v(t) \rvert$	m/s
Arias Intensity (I_a)	$\frac{\pi}{2g}\int_0^{T_d}[a(t)]^2\,dt$	cm/s
Cumulative Absolute Velocity (CAV_5)	$\int_0^{T_d}\langle\chi\rangle\,\lvert a(t)\rvert\,dt$	cm/s
Spectral Acceleration (Sa(T))	$Sa(T_1)$	g
Cordova Predictor	$Sa(T_1)\sqrt{\frac{Sa(2T_1)}{Sa(T_1)}}$	g

T_d = duration of earthquake motion
$\langle\chi\rangle = 0$, if $\lvert a(t)\rvert < 5\ cm/s^2$ and $\langle\chi\rangle = 1$, if $\lvert a(t)\rvert \geq 5\ cm/s^2$

- Motions scaled to a constant value of a target magnitude corrected PGA
- Remove free-surface effect (Proshake)

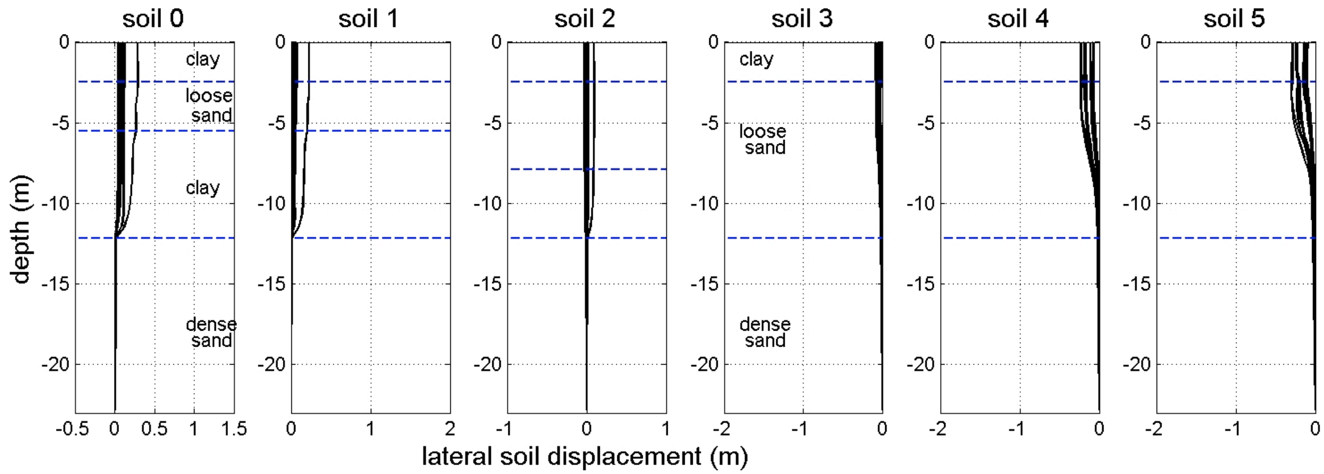
System Response

Lateral Spreading



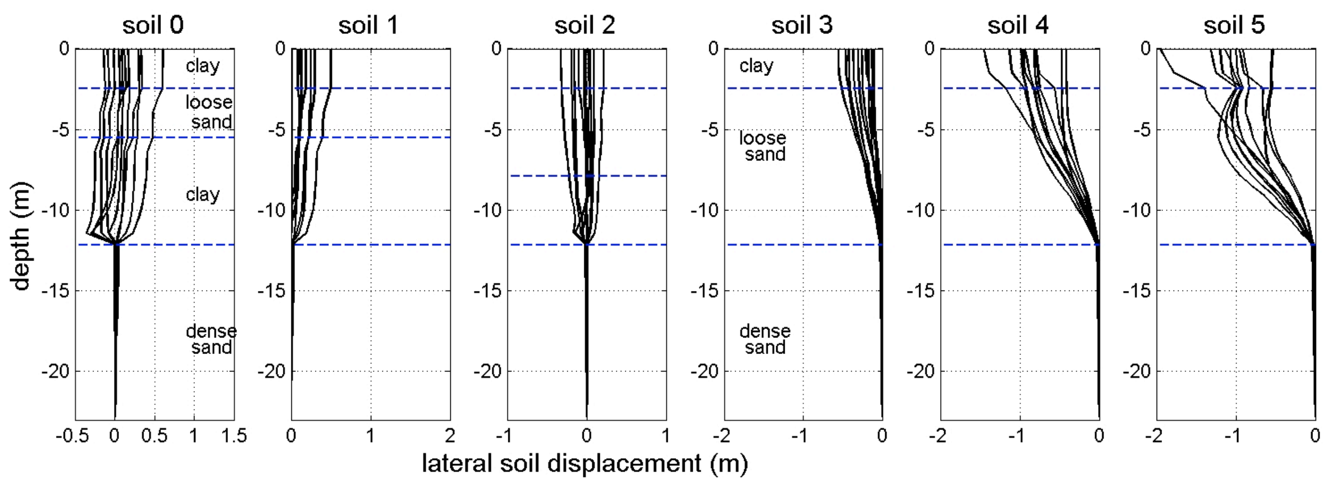
T_R = 72 yrs

(50% in 50 yrs)



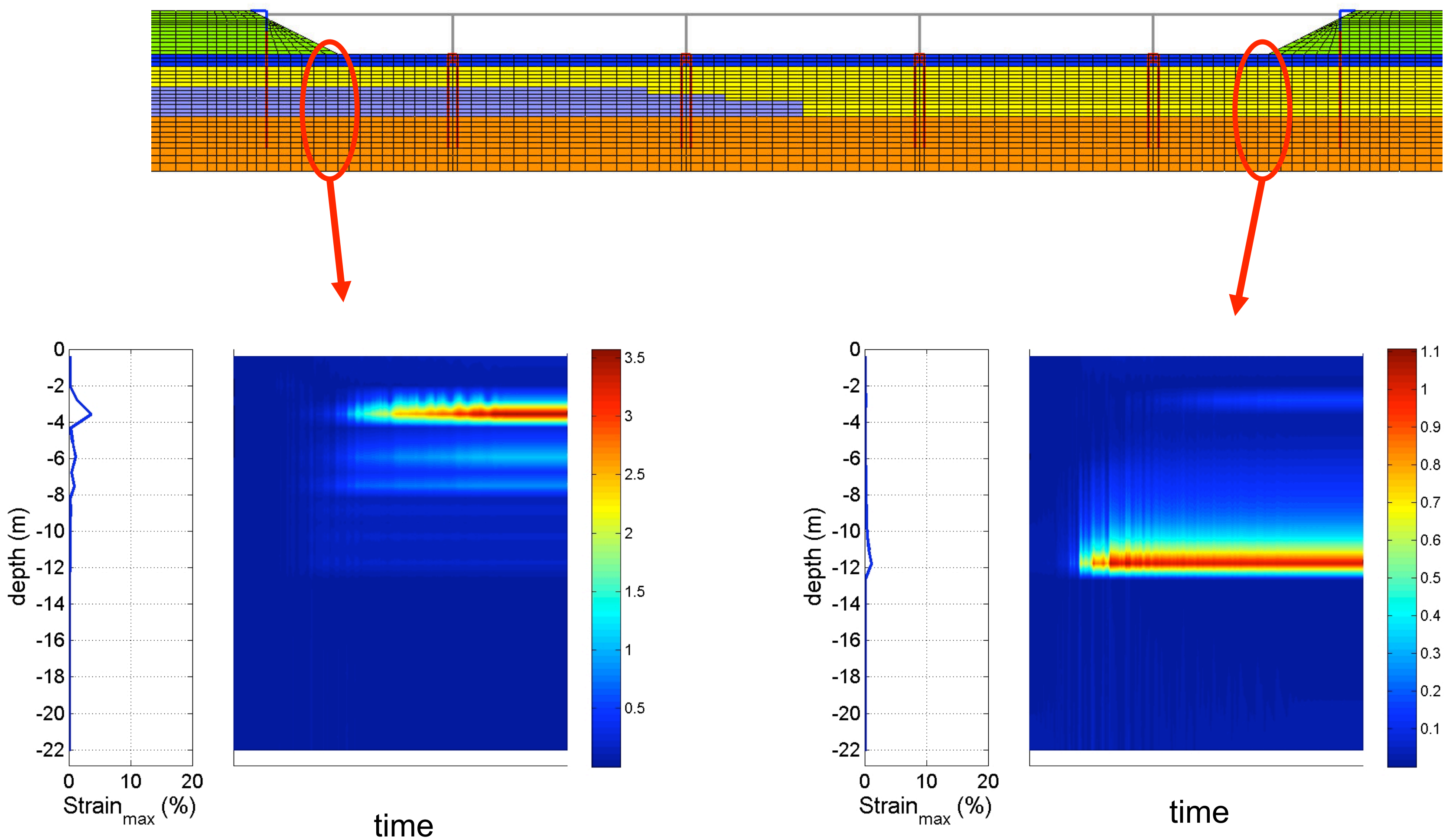
T_R = 2475 yrs

(2% in 50 yrs)



System Response

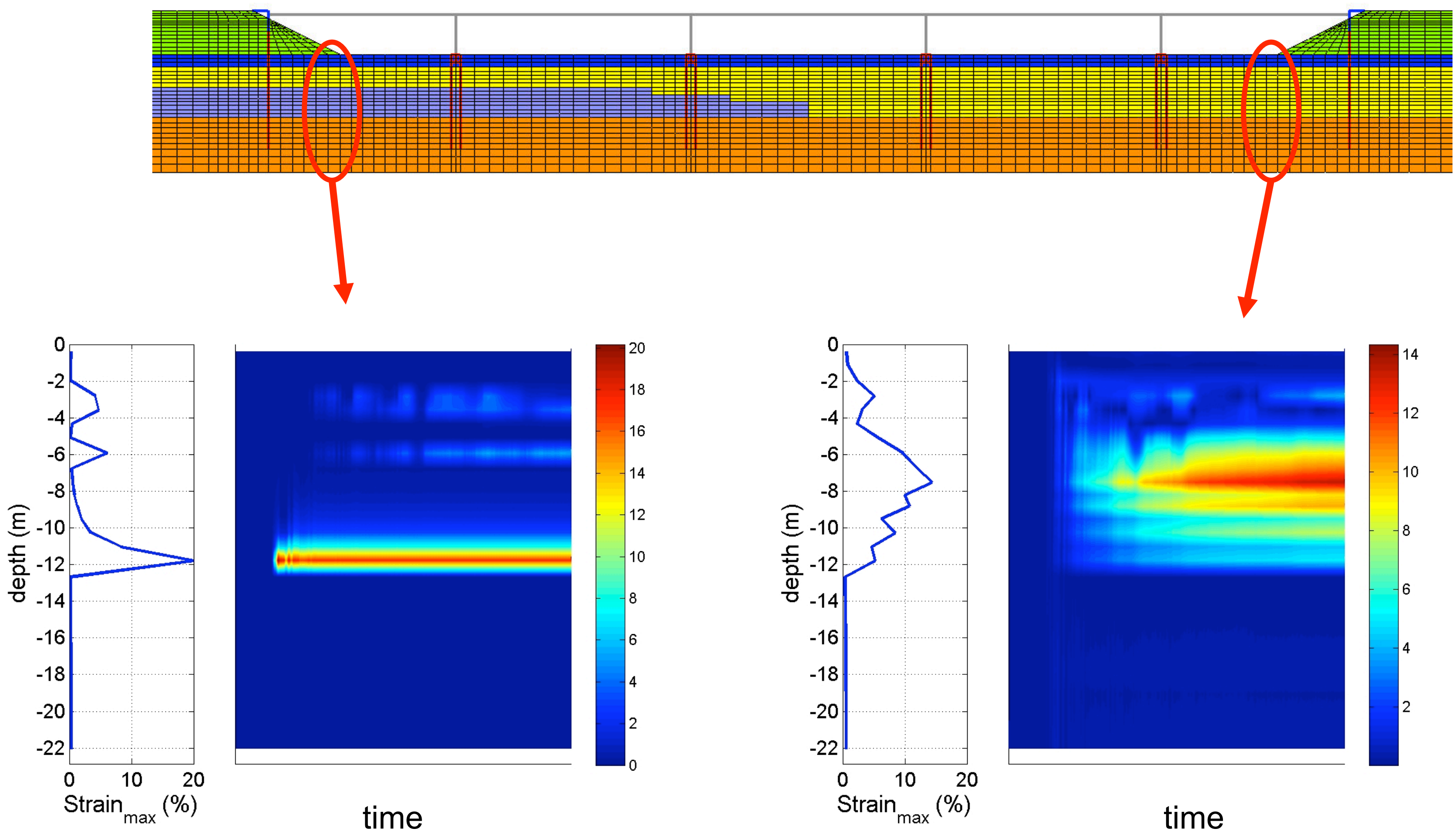
Soil Strain Profile during shaking



Northridge motion (0.25g)

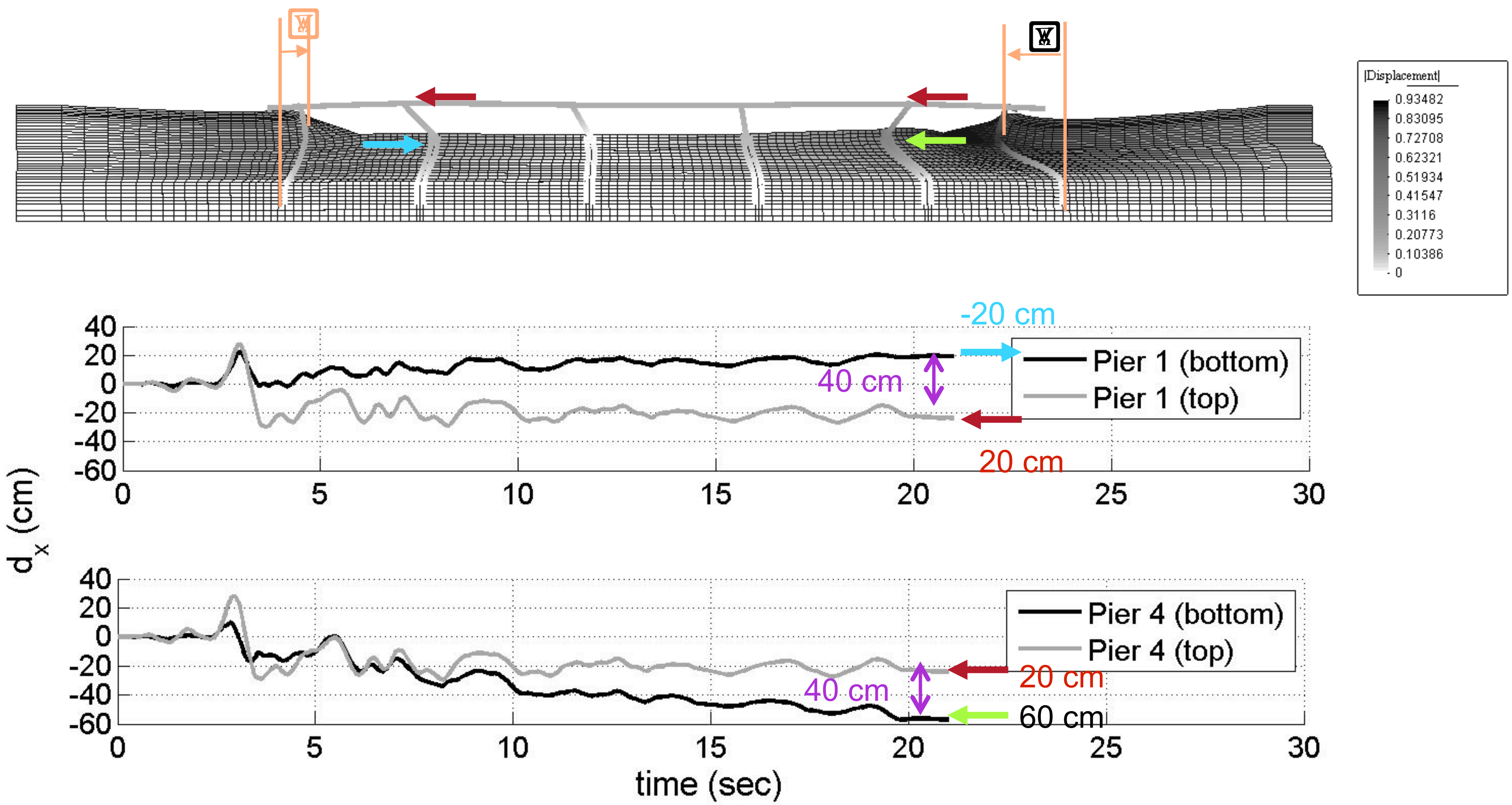
System Response

Soil Strain Profile during shaking

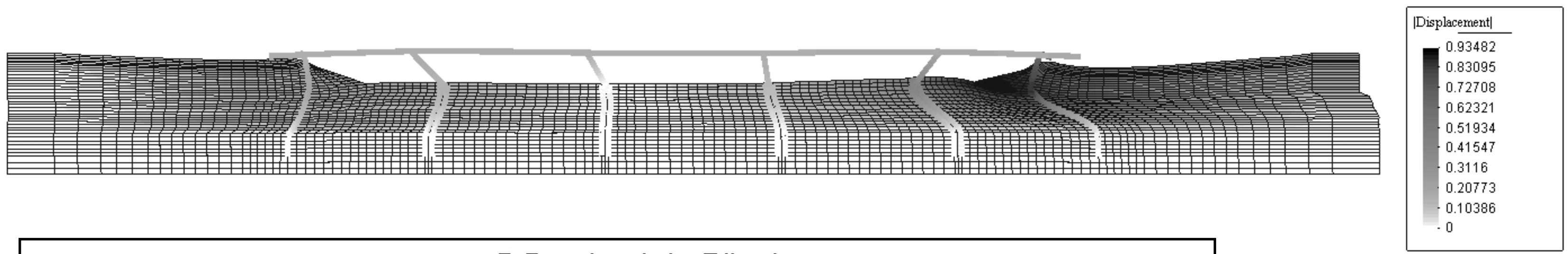


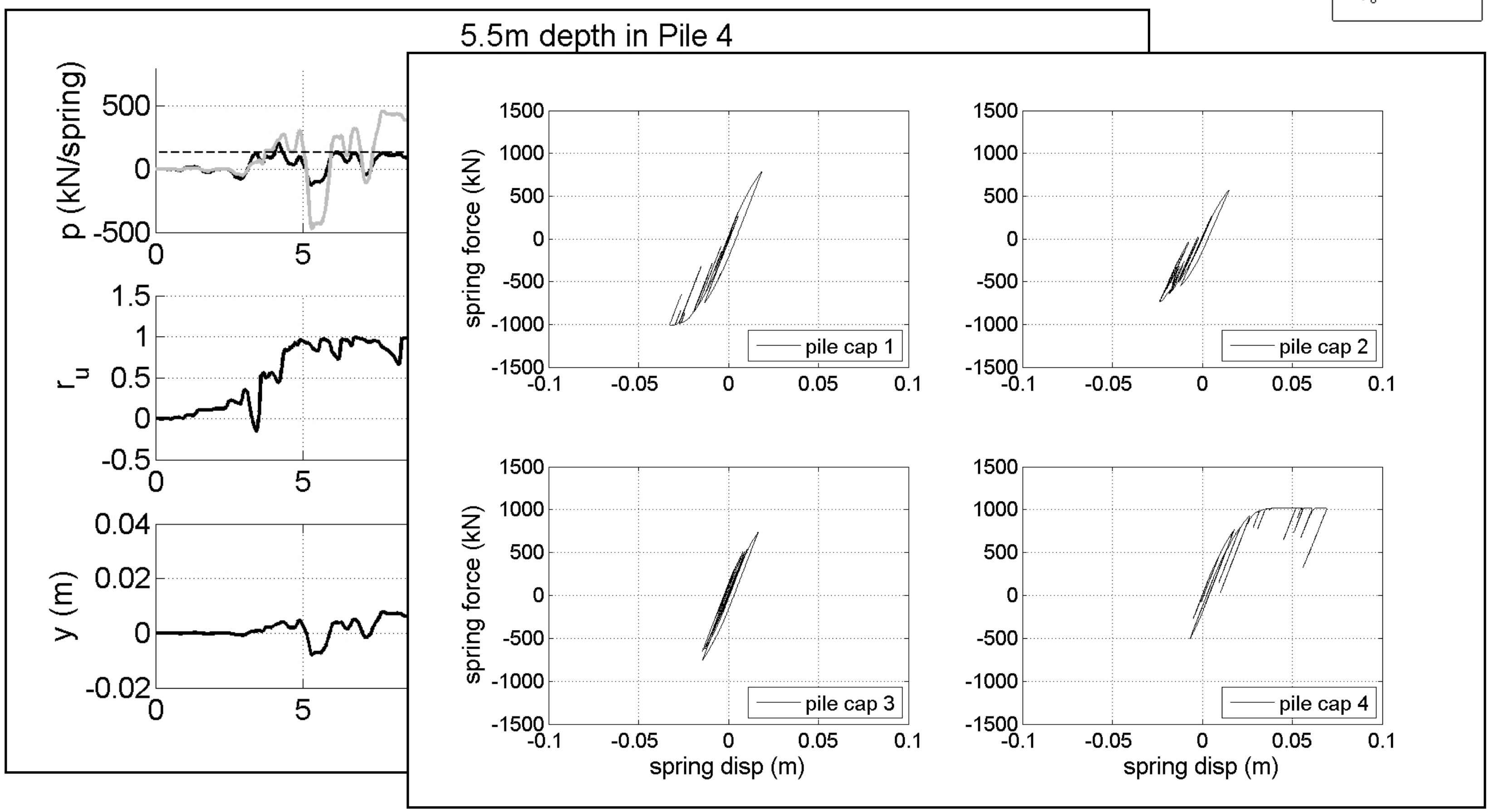
Loma Prieta (1.19g)

System Response

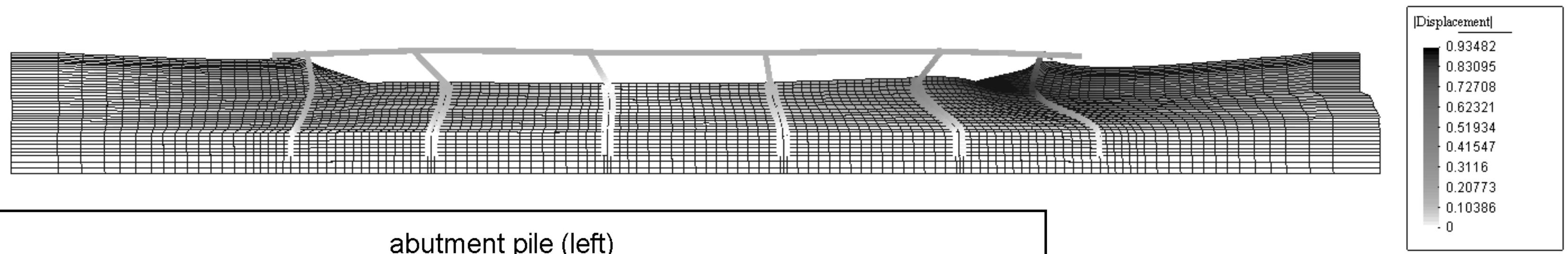


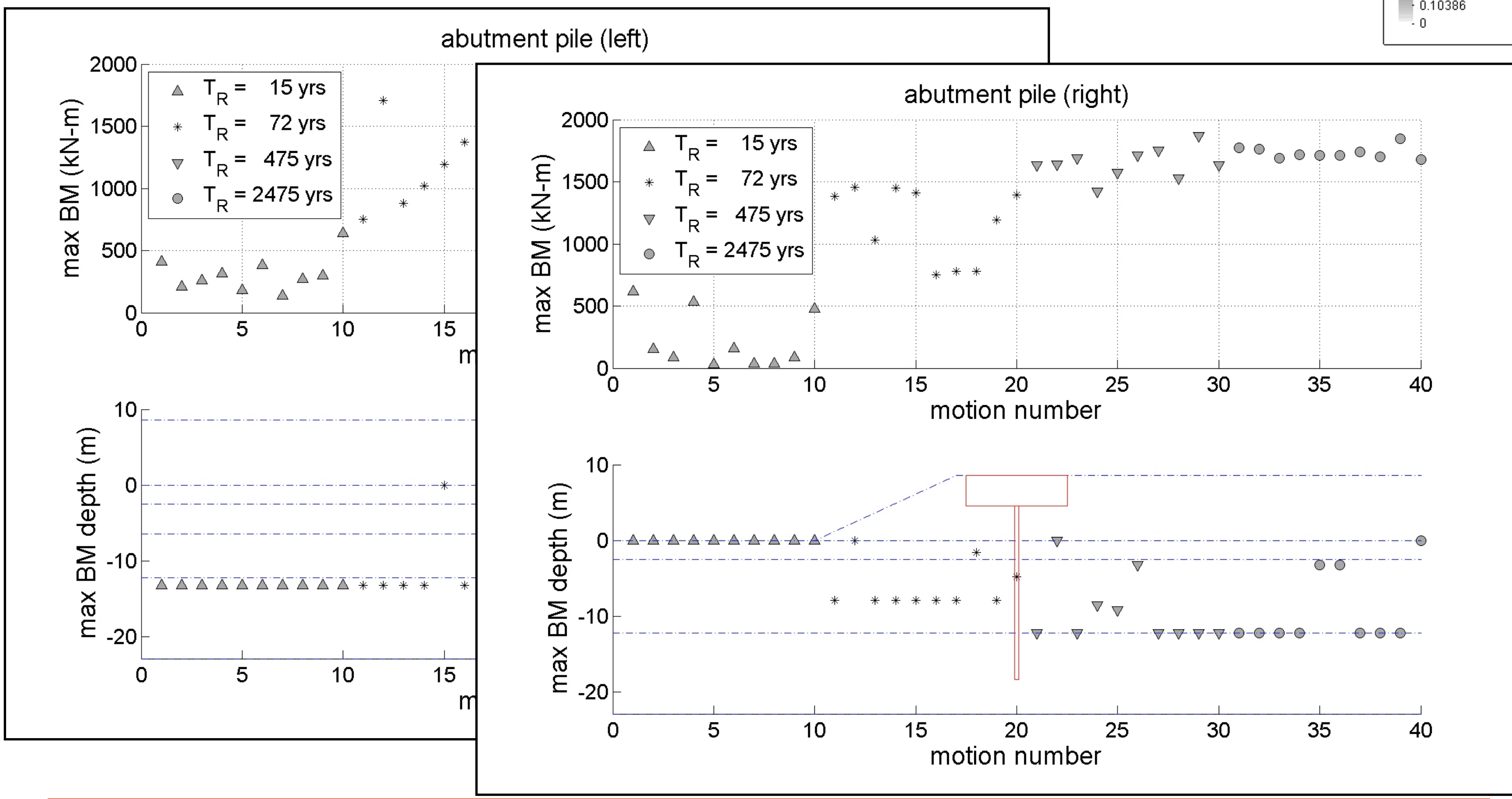
System response



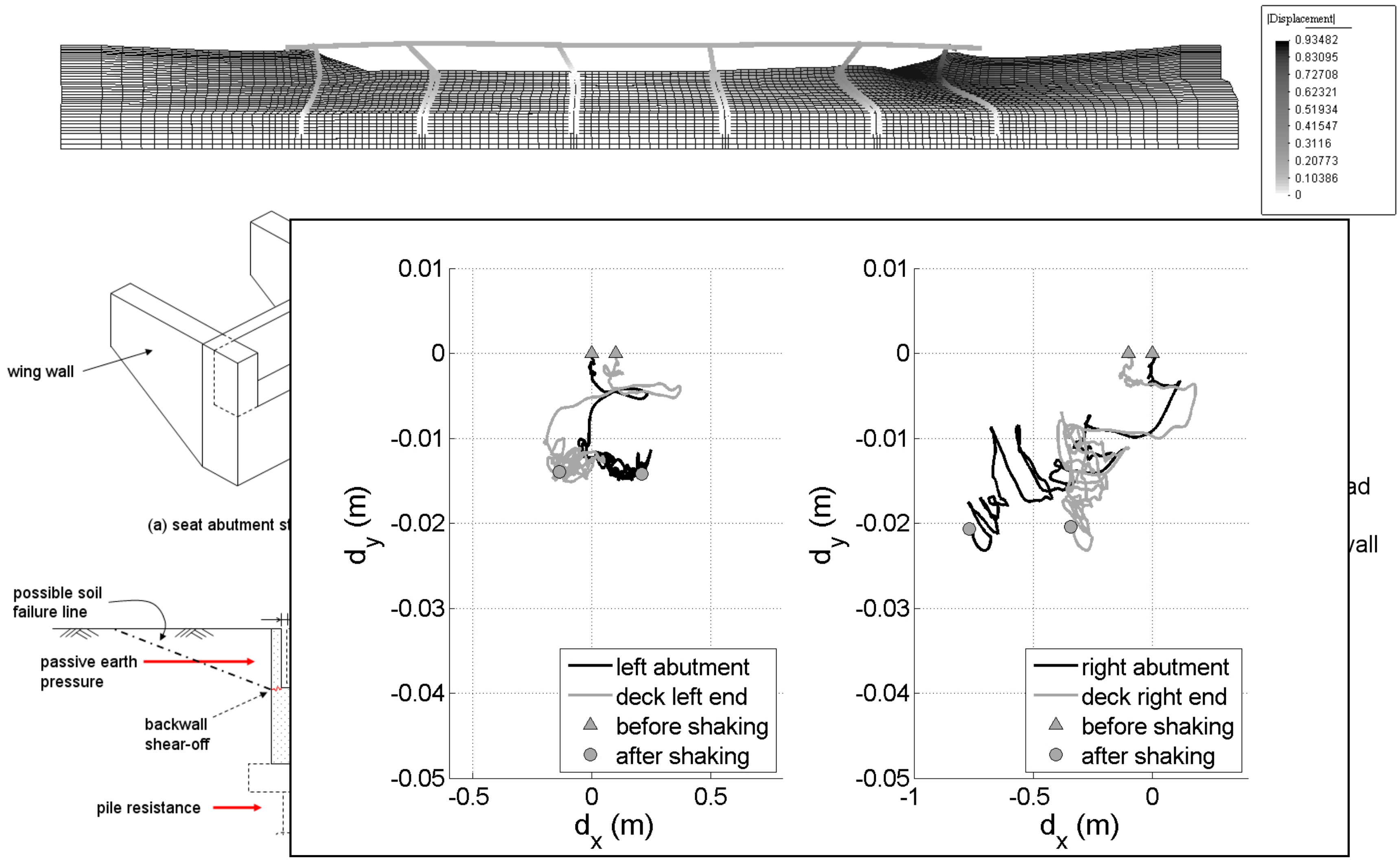


System response





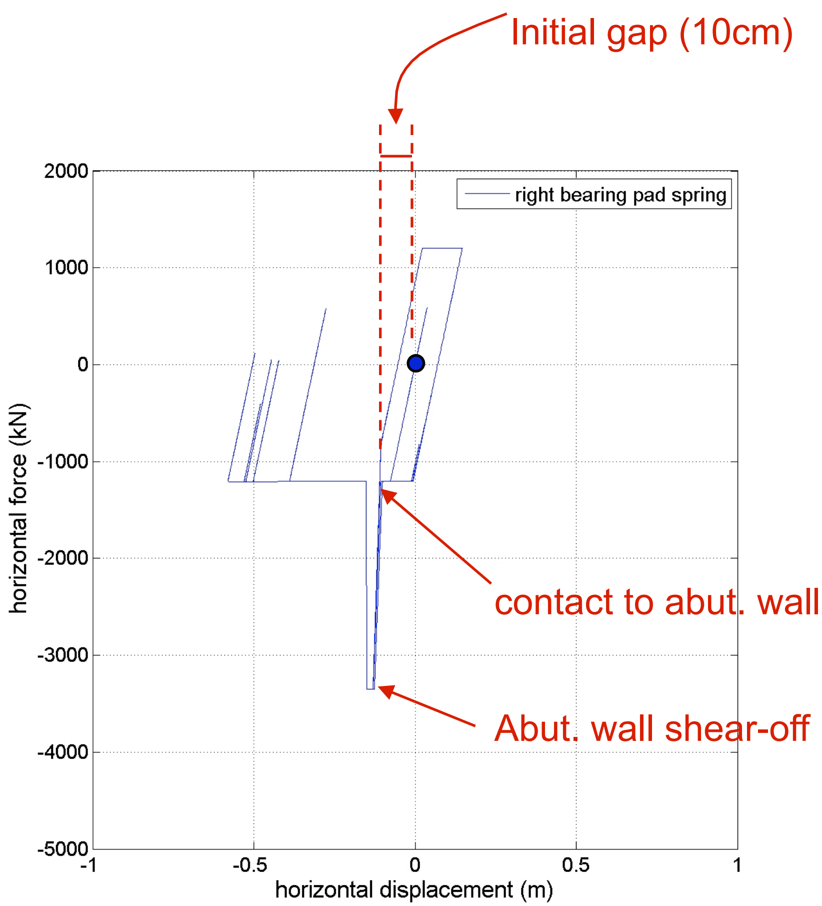
System response



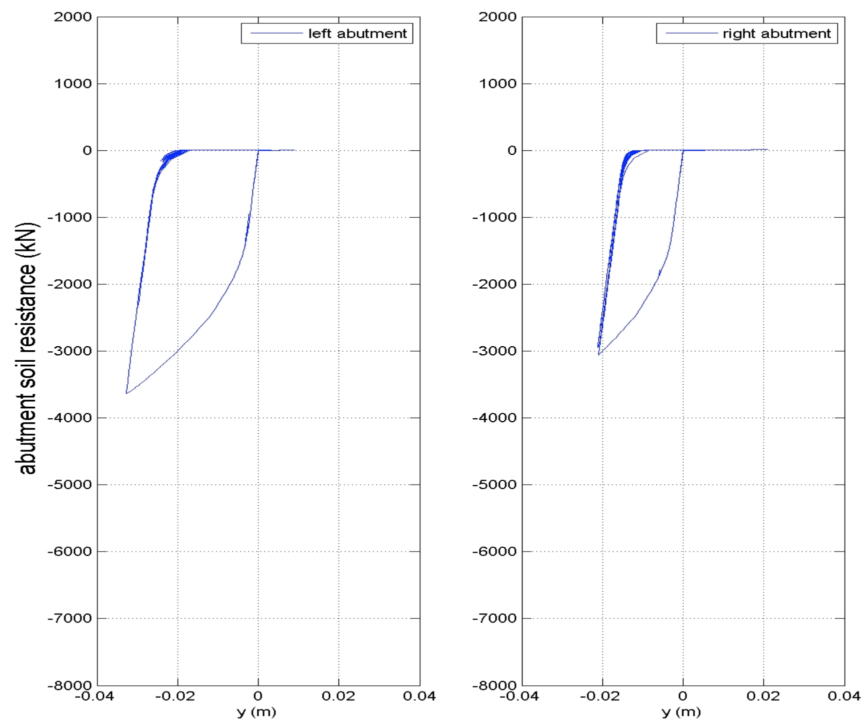
(b) bridge deck-abutment-soil

System Response

Abutment spring
(bearing pad + break-off wall)

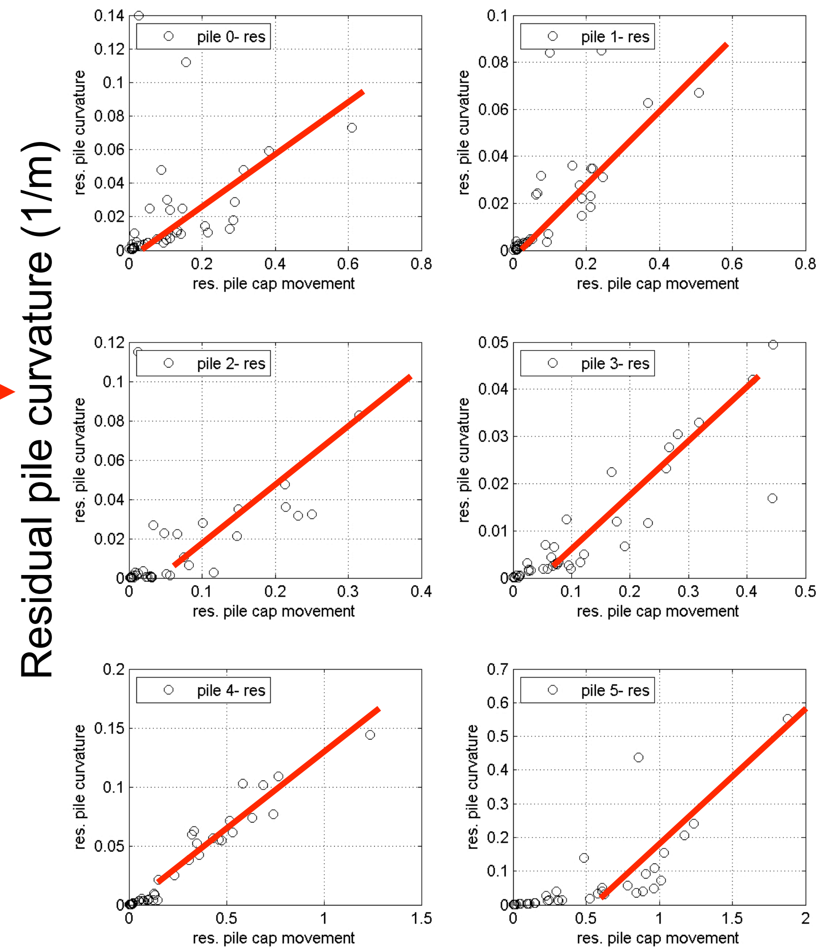


Passive earth pressure spring



EDP groups in bridge system

EDP group	EDP description	EDP symbol
column	drift ratio	$C1_{[\text{drift,max}]}$ $C2_{[\text{drift,max}]}$ $C3_{[\text{drift,max}]}$ $C4_{[\text{drift,max}]}$
pile cap	pile cap drift (displacement)	$P0_{[\text{drift,res}]}$ $P1_{[\text{drift,res}]}$ $P2_{[\text{drift,res}]}$ $P3_{[\text{drift,res}]}$ $P4_{[\text{drift,res}]}$ $P5_{[\text{drift,res}]}$
abutment exp. joint	gap between deck and abutment	$EJ1_{[\text{gap,res}]}$ $EJ2_{[\text{gap,res}]}$
abutment backwall	backwall displacement	$BW1_{[\text{dx,max}]}$ $BW2_{[\text{dx,max}]}$
abutment approach	bridge approach vert. off-set	$BA1_{[\text{dy,res}]}$ $BA2_{[\text{dy,res}]}$
bearing pad	bearing pad displacement	$BP1_{[\text{dx,max}]}$ $BP2_{[\text{dx,max}]}$
embankment slope	lateral disp.	$E1_{[\text{dx,res}]}$ $E2_{[\text{dx,res}]}$



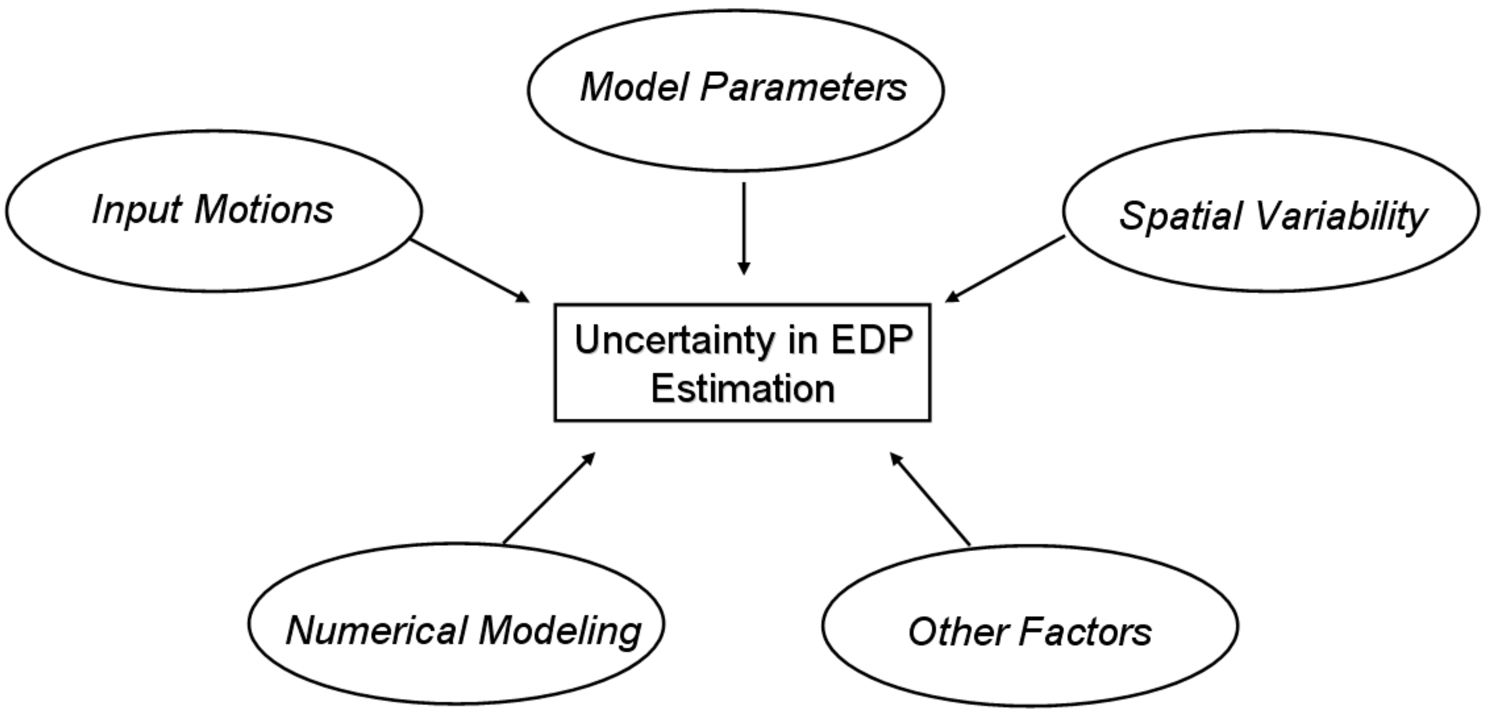
Residual pile cap disp. (m)

Numerical modeling allows evaluation of median values for each EDP and corresponding uncertainties.

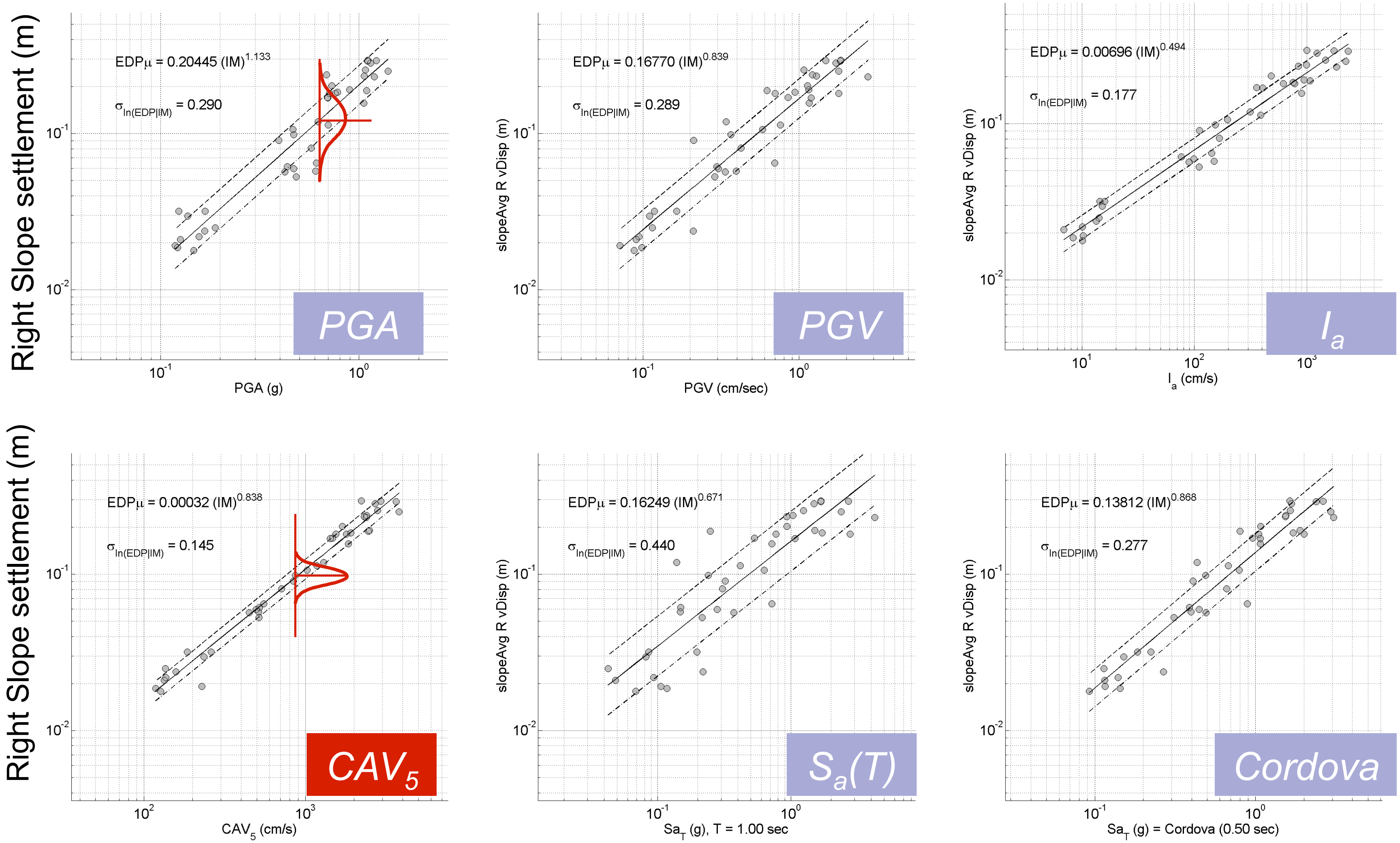
Outline

- PEER PBEE framework
- Target bridge structure and modeling
- Input Motions
- Bridge response
- **Uncertainty in EDP**
- Foundation Damage and loss
- Bridge damage and loss

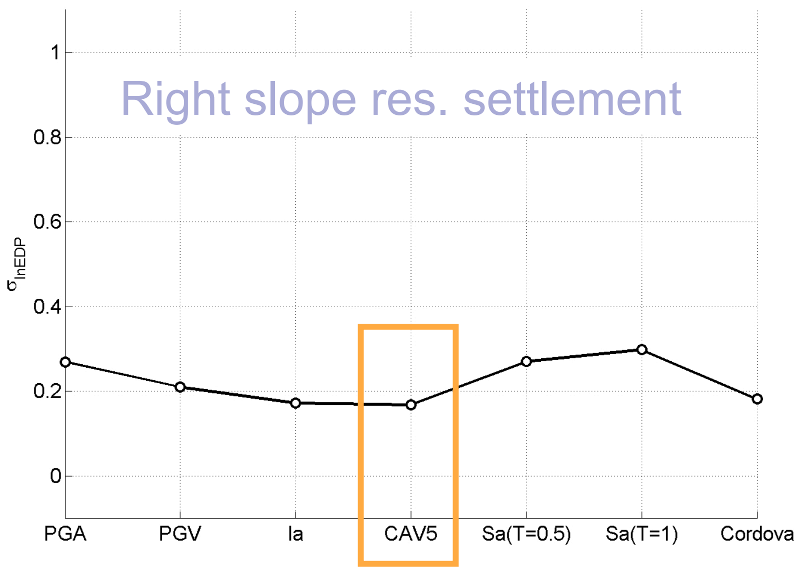
Uncertainties in EDP estimation

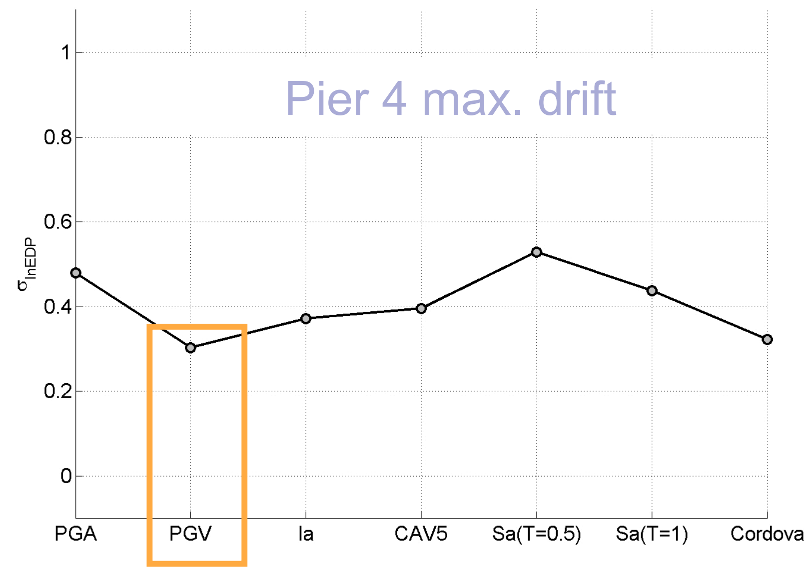


Record-to-record uncertainty (EDP-IM relationship)



Record-to-record uncertainty (IM efficiency)





Why is the IM efficiency important?

Parametric uncertainty

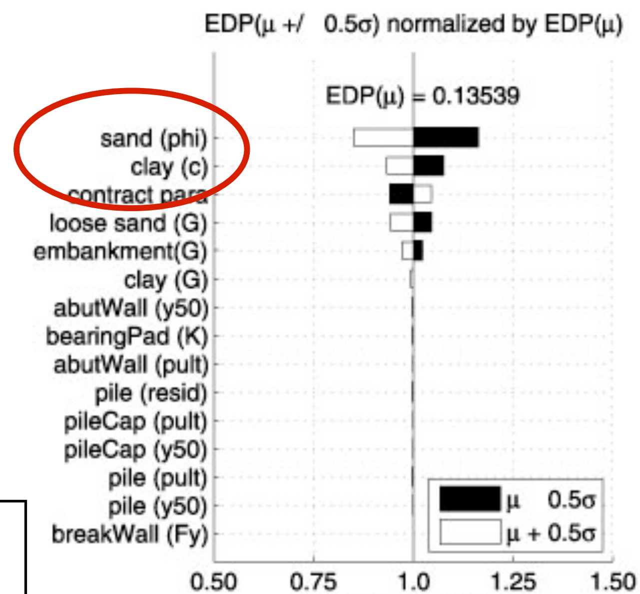
Sensitivity analysis

Parameters	used COV
Shear modulus, G	0.4
undrained shear strength, c	0.3
friction angle, ϕ	0.1
contraction parameter, contrac1	0.2
py spring (stiffness, K_1)	0.4
py spring (pult): clay	0.3
py spring (pult): sand	0.1
abutment earth spring (stiffness, K_2)	0.4
break-off wall capacity	0.1
bearing pad (stiffness, K_3)	0.05
Shear wave velocity, V_s	0.2
SPT resistance	0.3
density	0.08

$$\begin{cases} \mathbf{x_i}^{+} = x_{\boxtimes}\,(1+COV/2) \\ \mathbf{x}_{\boxtimes} = x_{\boxtimes} \\ \mathbf{x}_{\boxtimes}^{-} = x_{\boxtimes}\,(1+COV/2) \end{cases}$$

→ simulations

Tornado diagram

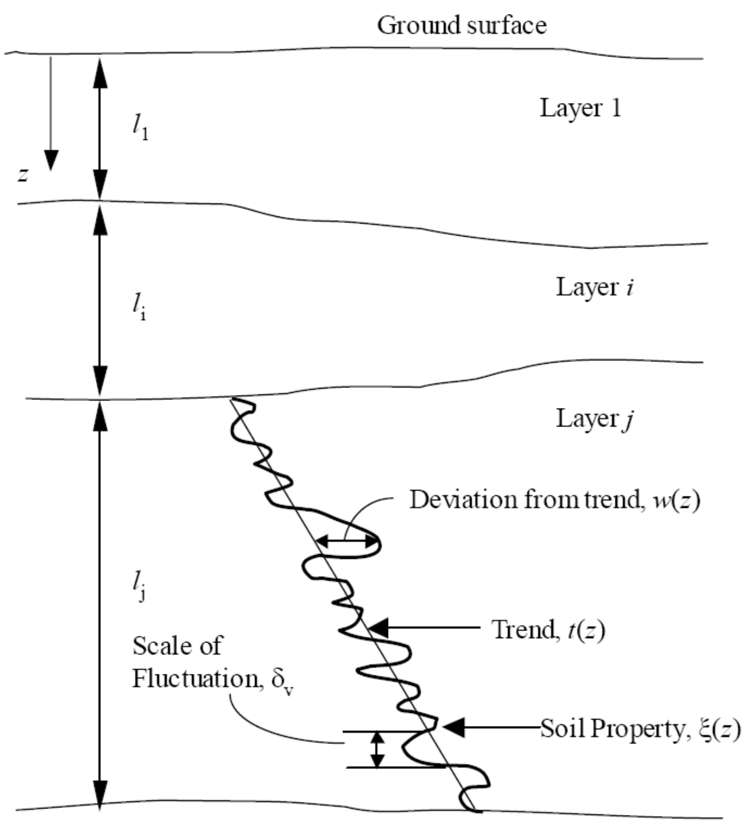


Slope res. lateral disp.

FOSM analysis

$$\sigma_Y^2 \approx \sum_{i=1}^{N} \sigma_{X_i}^2 \left(\frac{\partial g}{\partial X_i}\right)^2 + \sum_{i=1}^{N} \sum_{j\neq i}^{N} \rho_{X_i,X_j}\, \sigma_{X_i}\, \sigma_{X_j} \frac{\partial g}{\partial X_i} \frac{\partial g}{\partial X_j}$$

Spatial variability uncertainty



After Phoon and Kulhawy (1999)

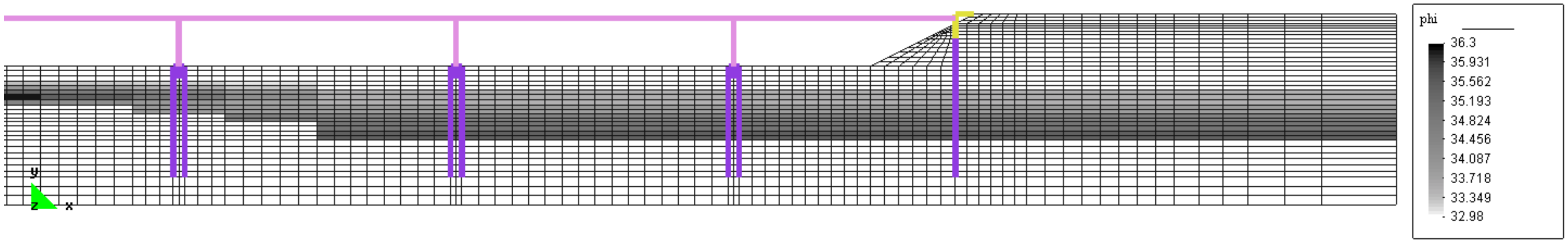
Gaussian random field

(Yamazaki and Shinozuka 1988)

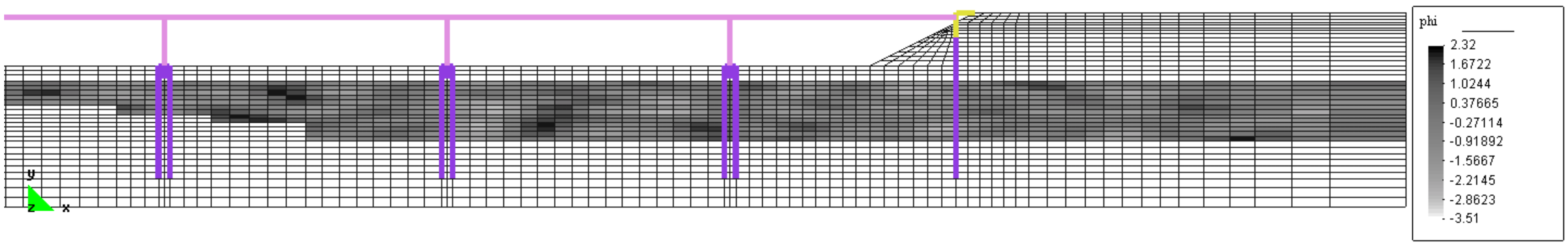
$$F_{stochastic} = (1+COV)\ F_{trend}\ F_{Gaussian}$$

mean (trend) field

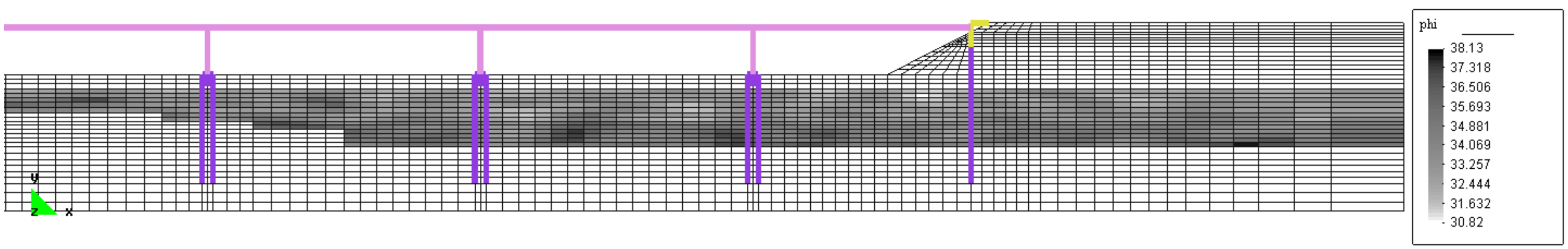
Spatial variability uncertainty



Original field (mean) -



Gaussian field (residual) -



Gaussian stochastic field (mean + residual) -

Total uncertainty in EDP estimation

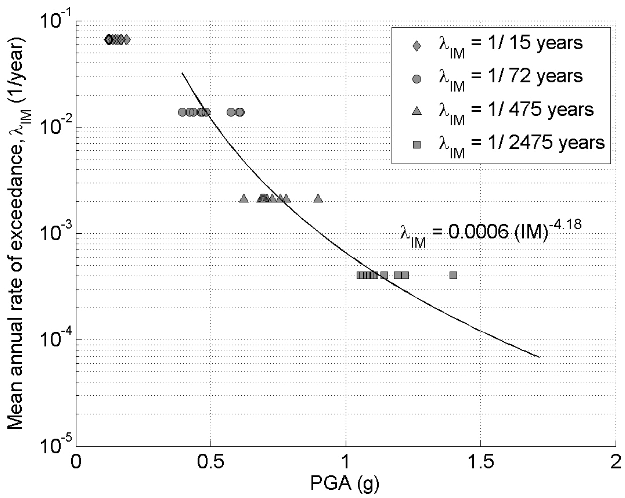
$$\sigma_{\ln EDP|IM,total} = \sqrt{\sigma^2_{\ln EDP|IM,record} + \sigma^2_{\ln EDP|IM,parameter} + \sigma^2_{\ln EDP|IM,spatial}}$$

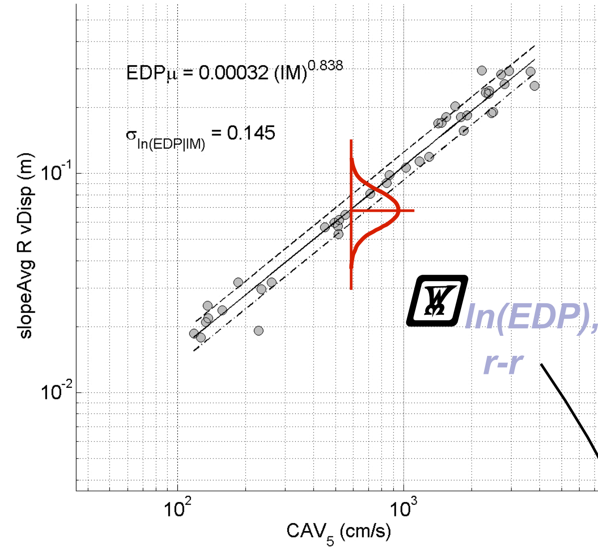
EDP symbol	efficient IM	record-to-record uncertainty	parametric uncertainty	spatial uncertainty	total EDP uncertainty
$C1_{[\text{drift,max}]}$	Cordova(T=0.5)	0.327 (84%)	0.134 (14%)	0.048 (2%)	0.356
$C2_{[\text{drift,max}]}$	PGV	0.401 (98%)	0.031 (1%)	0.044 (1%)	0.404
$C3_{[\text{drift,max}]}$	Sa(T=1.0)	0.432 (99%)	0.123 (1%)	0.018 (0%)	0.434
$C4_{[\text{drift,max}]}$	PGV	0.311 (95%)	0.104 (2%)	0.050 (3%)	0.311
$P0_{[\text{dx,res}]}$	CAV_5	1.275 (99%)	0.068 (1%)	0.062 (0%)	1.278
$P1_{[\text{dx,res}]}$	I_a	1.026 (91%)	0.283 (7%)	0.141 (8%)	1.073
$P2_{[\text{dx,res}]}$	Sa(T=0.5)	1.266 (89%)	0.384 (8%)	0.213 (3%)	1.340
$P3_{[\text{dx,res}]}$	CAV_5	0.673 (95%)	0.119 (4%)	0.087 (1%)	0.689
$P4_{[\text{dx,res}]}$	I_a	0.761 (98%)	0.087 (1%)	0.064 (1%)	0.769
$P5_{[\text{dx,res}]}$	CAV_5	0.687 (97%)	0.105 (2%)	0.056 (1%)	0.697

90-95%

5-10%

EDP hazard





+ ln(EDP), para

+ ln(EDP), spat

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

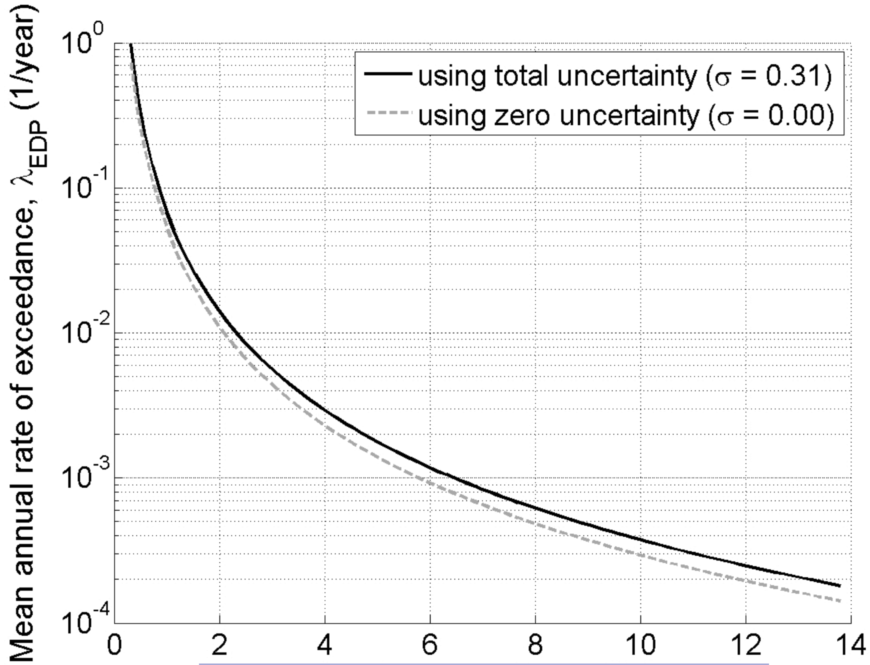
$EDP = a\ (IM)^b$

$$\lambda_{EDP} = k_0\ [\frac{EDP}{a}]^{-k/b}\ \exp[\frac{1}{2}\frac{k^2}{b^2}\sigma^2_{\ln EDP|IM,total}]$$

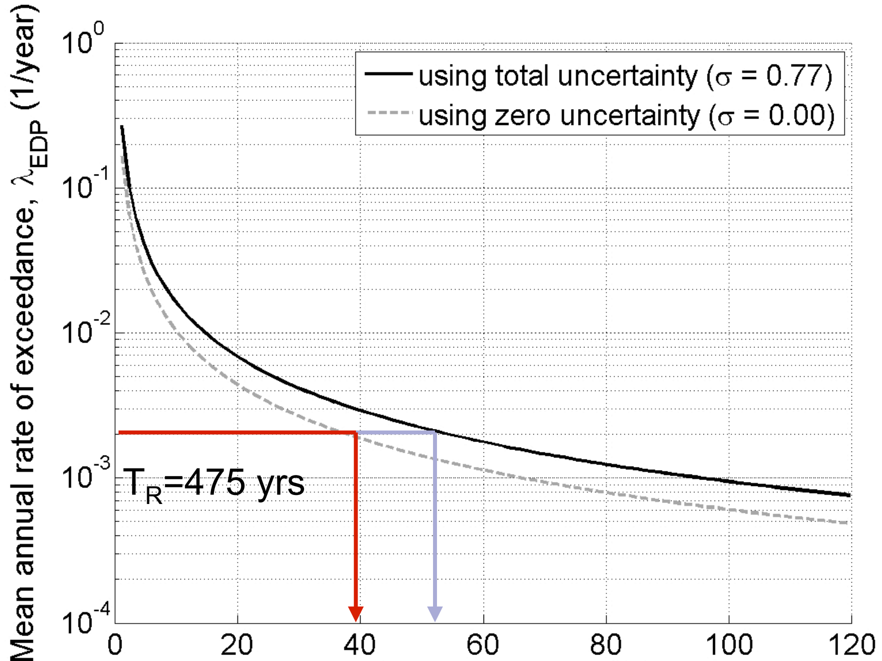
Jalayer (2003)

Uncertainty-based amplification

EDP hazard

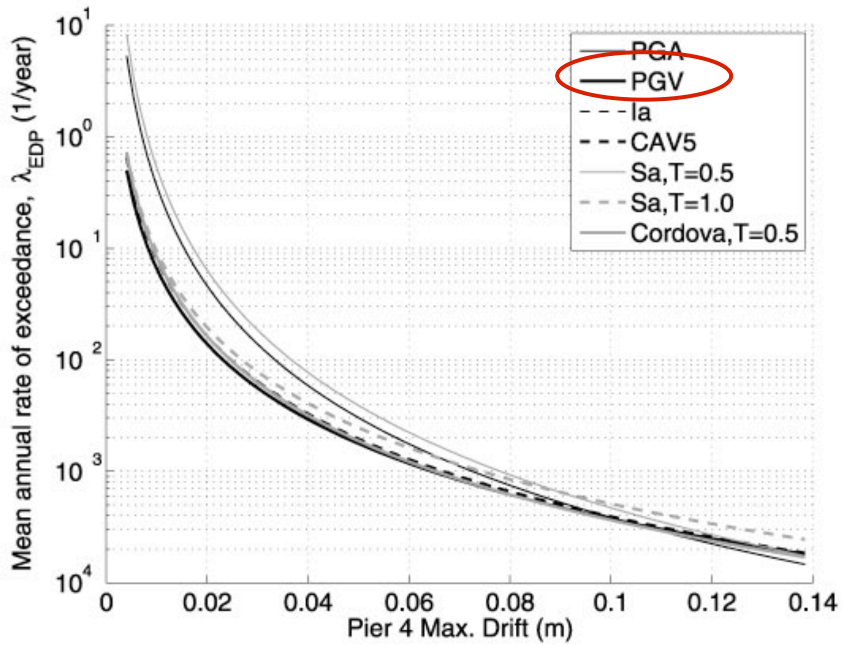


Pier 4 max. drift ratio (%)

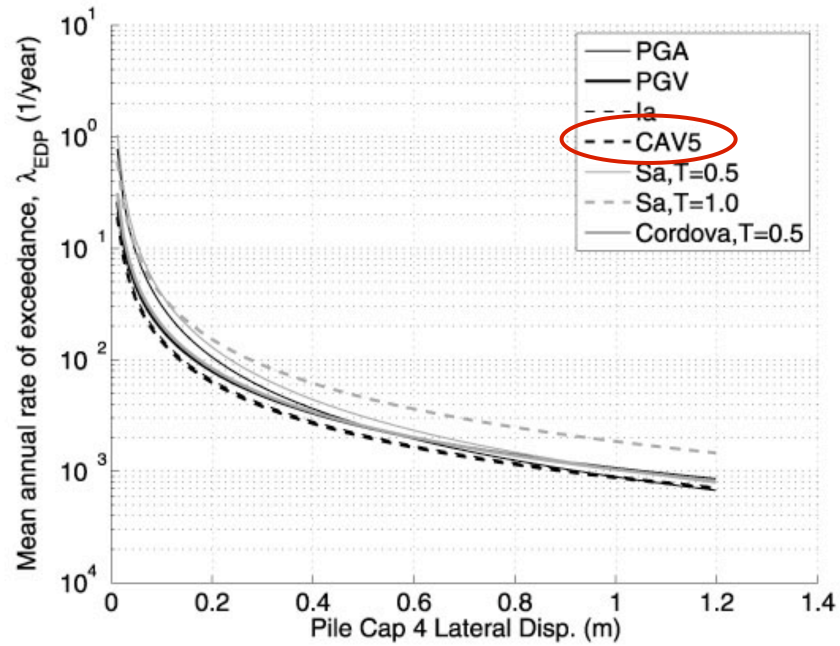


Pile cap 4 res. lateral disp (cm)

Importance of IM efficiency



Pier 4 max. drift



Pile cap 4 res. lateral disp

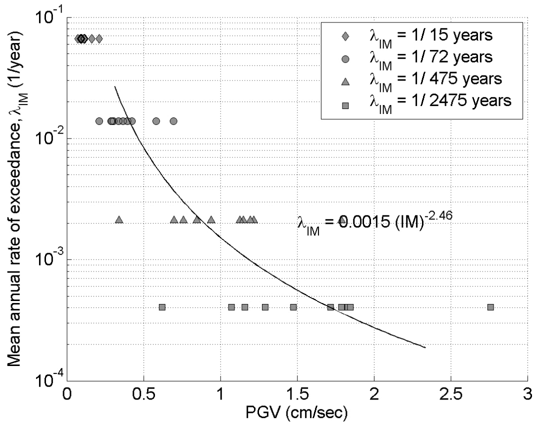
Outline

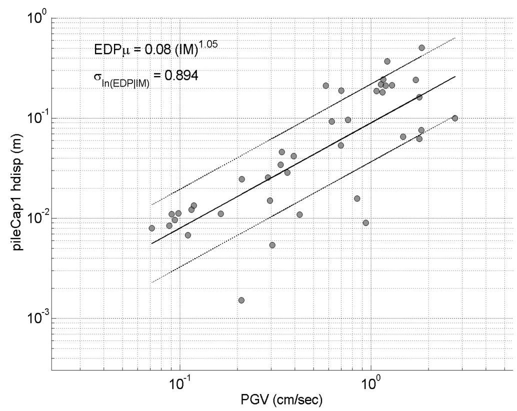
- PEER PBEE framework
- Target bridge structure and modeling
- Input Motions
- Bridge response
- Uncertainty in EDP
- **Foundation Damage and loss**
- Bridge damage and loss

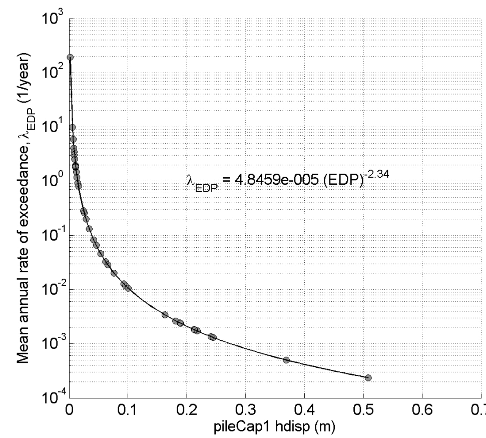
Integration of Uncertainties through PBEE Framework

EDP = Pile cap 1 horizontal displacement

IM hazard curve **EDP|IM relationship** **EDP hazard curve**







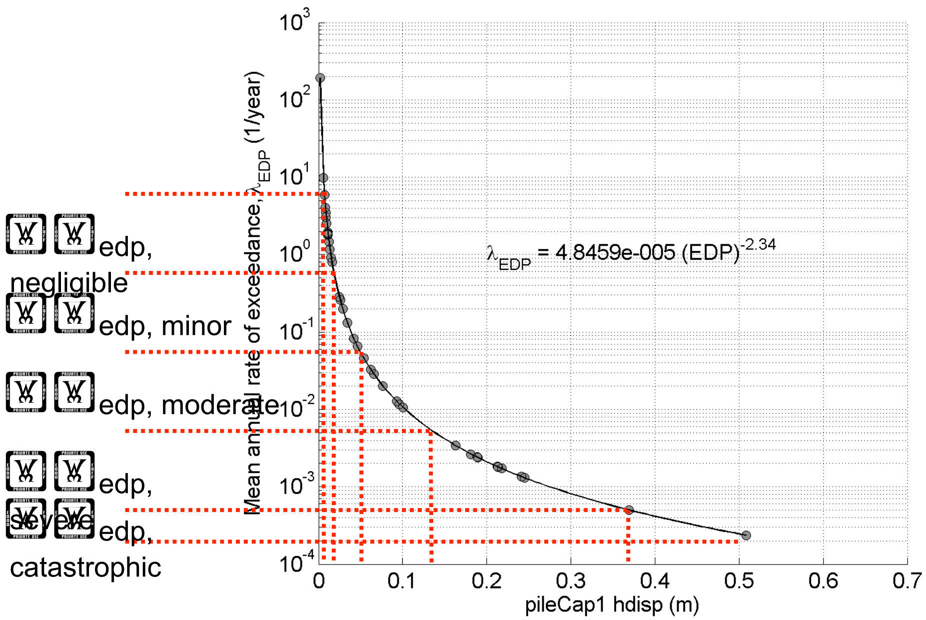
DM fragility curves **DM hazard curve** **DM fragility curve** **DV hazard curve**

?

EDP Hazard to DM/DV Hazard

$$\lambda_{dm(j)} = \sum_{i=1}^{N_{EDP}} P[DM > dm(j) \mid edp(i)] \Delta\lambda_{edp(i)}$$

$$\lambda_{dv(k)} = \sum_{k=1}^{N_{DM}} \sum_{j=1}^{N_{EDP}} P[DV > dv(k) \mid dm(j)] P[DM = dm(k) \mid edp(j)] \Delta\lambda_{edp(j)}$$



EDP Hazard to DM/DV Hazard

$$\lambda_{dm(j)} = \sum_{i=1}^{N_{EDP}} P[DM > dm(j) \mid edp(i)] \Delta\lambda_{edp(i)}$$

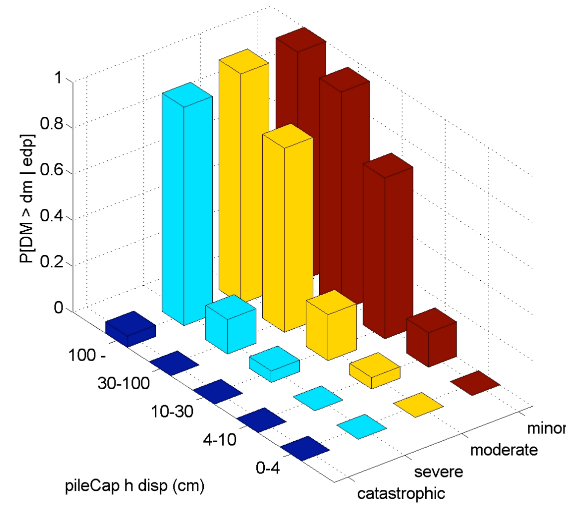
$$\lambda_{dv(k)} = \sum_{k=1}^{N_{DM}} \sum_{j=1}^{N_{EDP}} P[DV > dv(k) \mid dm(j)] P[DM = dm(k) \mid edp(j)] \Delta\lambda_{edp(j)}$$

EDP Hazard to DM/DV Hazard

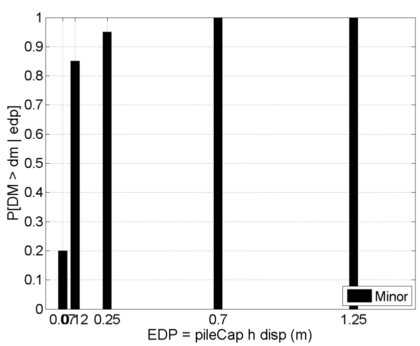
DM fragility matrix

damage state	~ 4 cm	4 ~ 10 cm	10 ~ 30 cm	30 ~ 100 cm	100 cm ~
Neglegible	0.95	0.05	0.00	0.00	0.00
Minor	0.05	0.80	0.20	0.05	0.00
Moderate	0.05	0.10	0.60	0.25	0.05
Severe	0.00	0.05	0.15	0.55	0.10
Catastophic	0.00	0.00	0.05	0.15	0.85

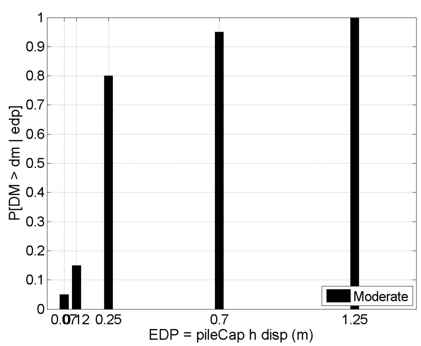
damage state	~ 4 cm	4 ~ 10 cm	10 ~ 30 cm	30 ~ 100 cm	100 cm ~
P[DM > Negligible | edp]	0.10	0.95	1.00	1.00	1.00
P[DM > Minor | edp]	0.05	0.15	0.80	0.95	1.00
P[DM > Moderate | edp]	0.00	0.05	0.20	0.70	0.95
P[DM > Severe | edp]	0.00	0.00	0.05	0.15	0.85
P[DM > Catastophic | edp]	0.00	0.00	0.00	0.00	0.00



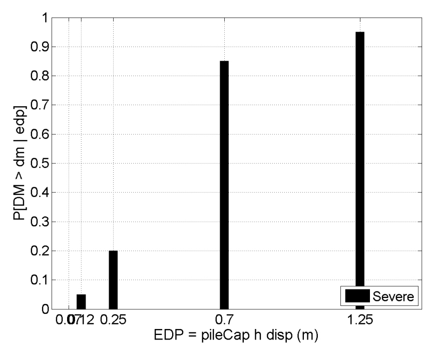
minor



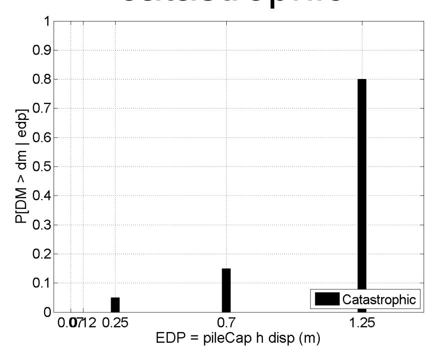
moderate



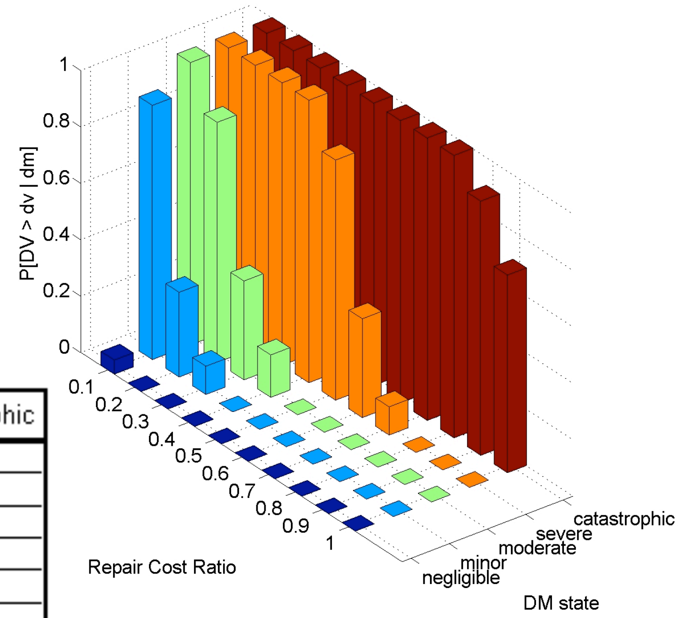
severe



catastrophic



EDP Hazard to DM/DV Hazard



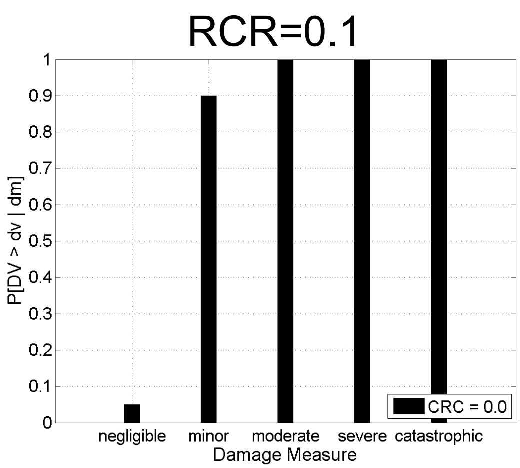
DV fragility matrix

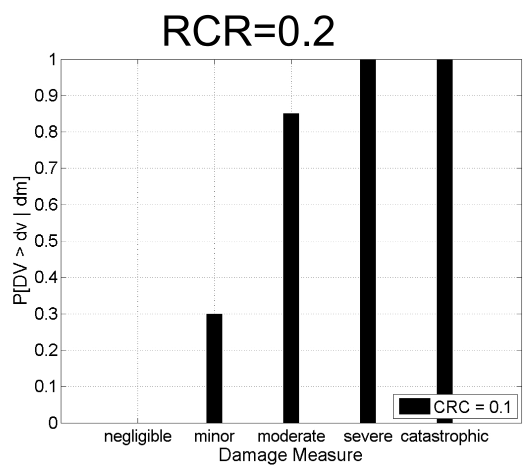
Rapair Cost Ratio	Neglegible	Minor	Moderate	Severe	Catastophic
0	0.95	0.10	0.00	0.00	0.00
0.1	0.05	0.60	0.15	0.00	0.00
0.2	0.00	0.20	0.50	0.00	0.00
0.3	0.00	0.10	0.20	0.00	0.00
0.4	0.00	0.00	0.15	0.15	0.00
0.5	0.00	0.00	0.00	0.50	0.00
0.6	0.00	0.00	0.00	0.25	0.00
0.7	0.00	0.00	0.00	0.10	0.00
0.8	0.00	0.00	0.00	0.00	0.10
0.9	0.00	0.00	0.00	0.00	0.20
1	0.00	0.00	0.00	0.00	0.70

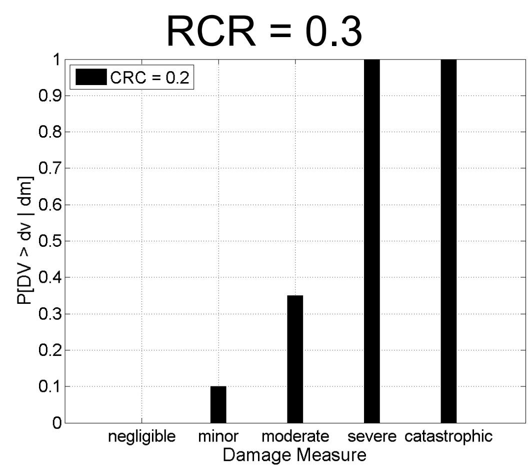
Rapair Cost Ratio	Neglegible	Minor	Moderate	Severe	Catastophic
P[DV > RCR=0.0 | DM]	0.05	0.90	1.00	1.00	1.00
P[DV > RCR=0.1 | DM]	0.00	0.30	0.85	1.00	1.00
P[DV > RCR=0.2 | DM]	0.00	0.10	0.35	1.00	1.00
P[DV > RCR=0.3 | DM]	0.00	0.00	0.15	1.00	1.00
P[DV > RCR=0.4 | DM]	0.00	0.00	0.00	0.85	1.00
P[DV > RCR=0.5 | DM]	0.00	0.00	0.00	0.35	1.00
P[DV > RCR=0.6 | DM]	0.00	0.00	0.00	0.10	1.00
P[DV > RCR=0.7 | DM]	0.00	0.00	0.00	0.00	1.00
P[DV > RCR=0.8 | DM]	0.00	0.00	0.00	0.00	0.90
P[DV > RCR=0.9 | DM]	0.00	0.00	0.00	0.00	0.70
P[DV > RCR=1.0 | DM]	0.00	0.00	0.00	0.00	0.00

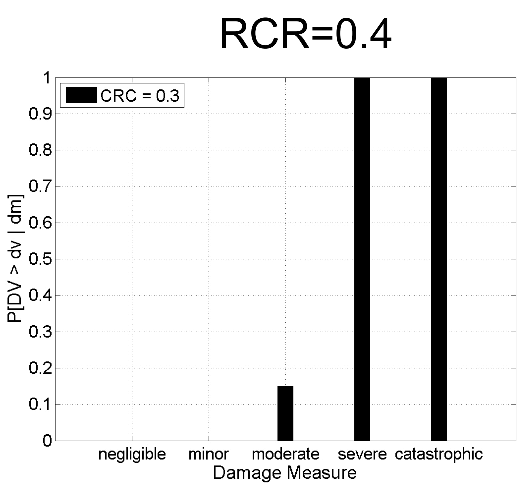
EDP Hazard to DM/DV Hazard

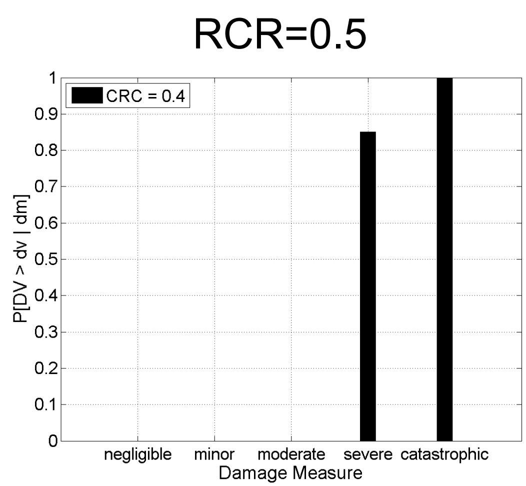
DV fragility curve

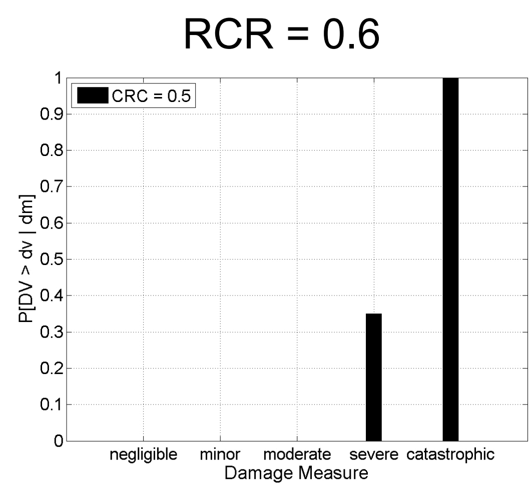








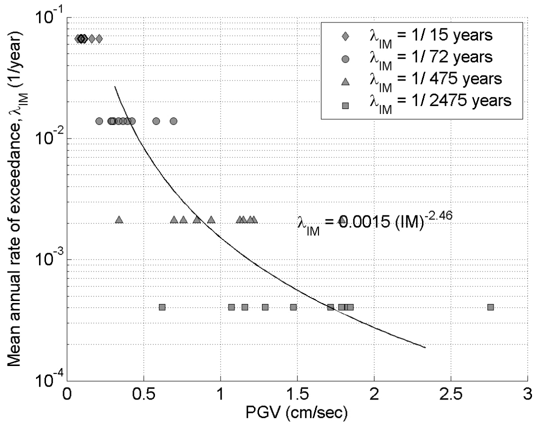




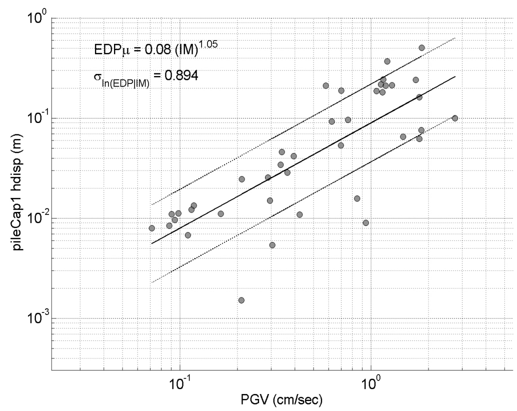
Integration of Uncertainties through PBEE Framework

EDP = Pile cap 1 horizontal displacement

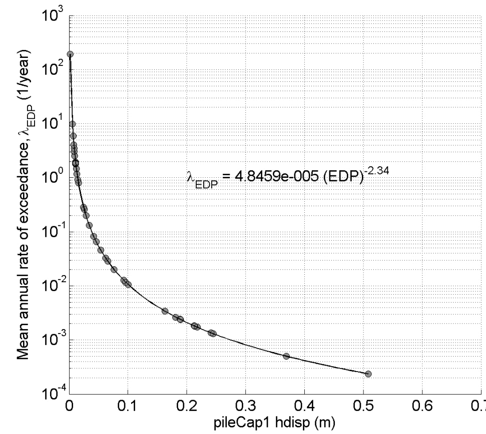
IM hazard curve



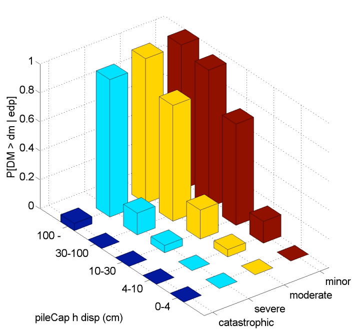
EDP|IM relationship



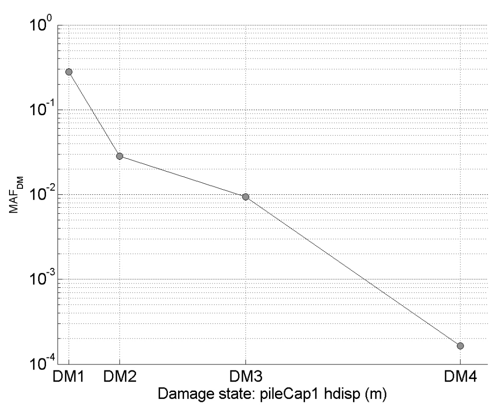
EDP hazard curve



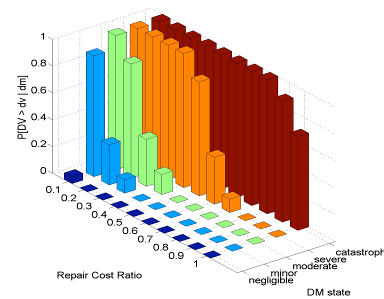
DM fragility



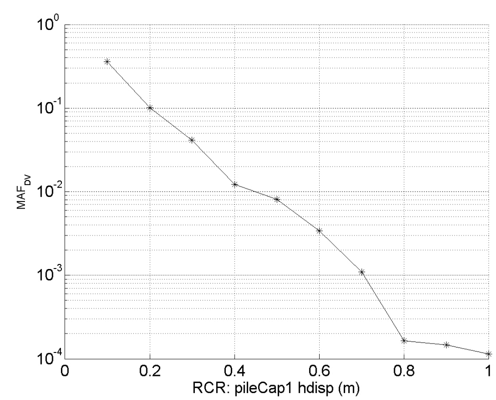
DM hazard curve



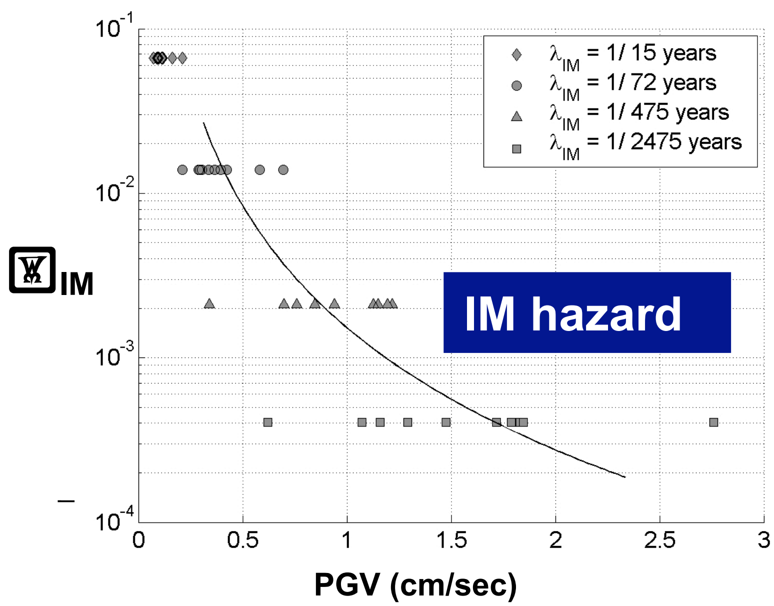
DM fragility

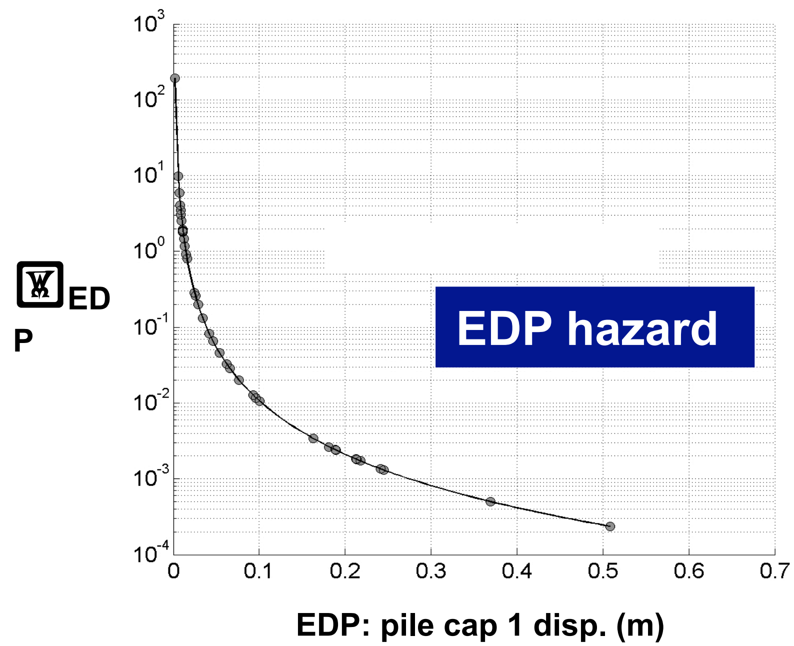


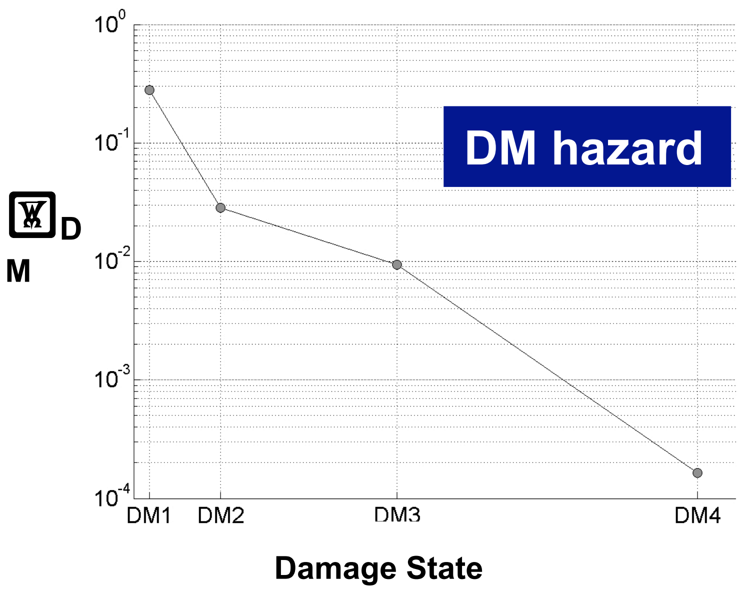
DV hazard curve

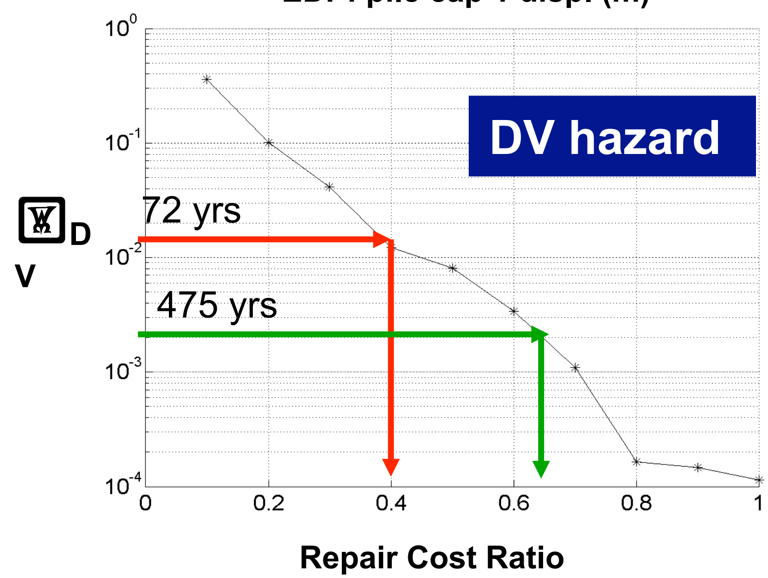


Integration of Uncertainties through PBEE Framework









Outline

- PEER PBEE framework
- Target bridge structure and modeling
- Input Motions
- Bridge response
- Uncertainty in EDP
- Foundation Damage and loss
- **Bridge damage and loss**

Bridge Damage and Loss

A series of repair cost analyses were performed using the Matlab code developed by Mackie et al. (2006). This code is set up to produce conditional probabilities of various repair cost levels given an intensity measure, which was taken as peak velocity.

Performance Group	*EDP*
Column (4)	Maximum and residual tangential drift ratios
Expansion joint (2)	Longitudinal abutment displacement
Bearings (2)	Bearing displacement (absolute)
Back wall (2)	Back wall displacement
Approach slab (2)	Vertical abutment displacement
Deck segment (5)	Depth of spalling
Abutment pile groups (2)	Horizontal displacement
Interior pile groups (4)	Horizontal displacement

performance group → *damage model* → *repair method and cost*

↓

Total repair cost = S Repair methods and cost

IM → *Total repair cost*

Mackie & Stojadinovic damage and loss model

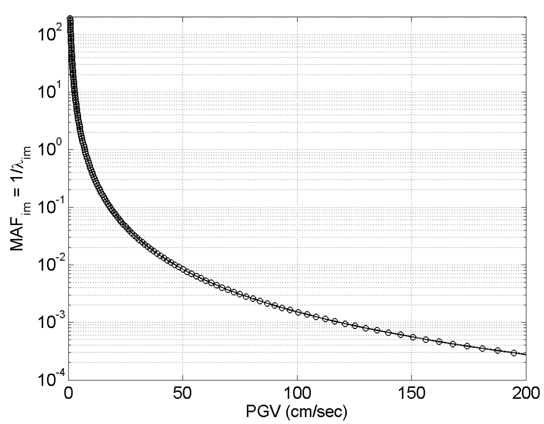
Bridge Damage and Loss

$$\lambda_{DV}(dv_l) = \sum_{i=1}^{N_{IM}} P[DV > dv_l \mid IM = im_i]\Delta\lambda_{IM}(im_i)$$

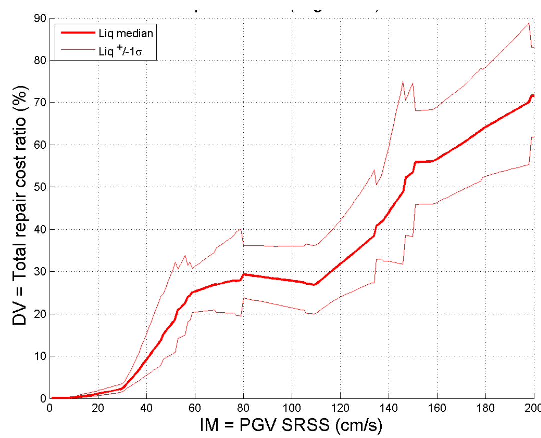
$$P[DV_l \mid IM_i] = \sum_{k=1}^{N_{DM}} \sum_{j=1}^{N_{EDP}} \sum_{i=1}^{N_{IM}} P[DV \mid DM_k]P[DM_k \mid EDP_j]P[EDP_j \mid IM_i]$$

Mackie & Stojadinovic damage and loss model

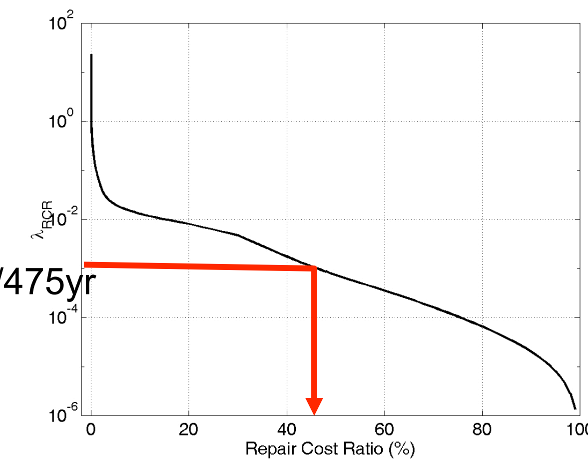
IM hazard



DV/IM fragility

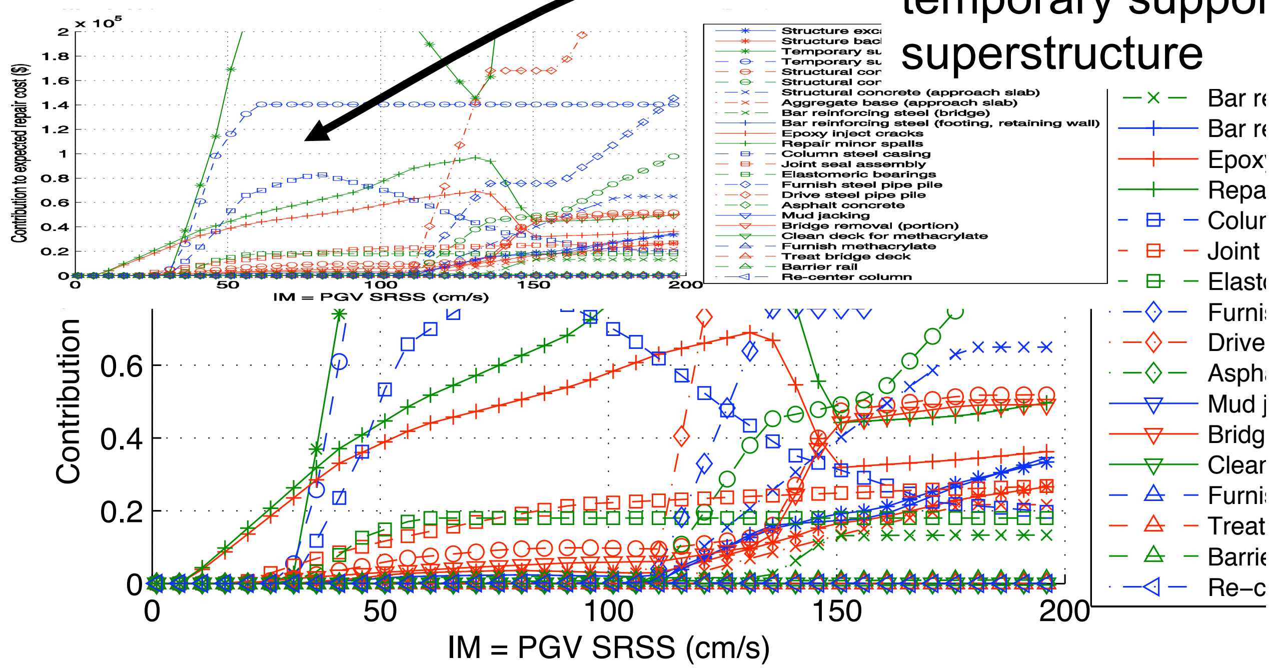


DV hazard



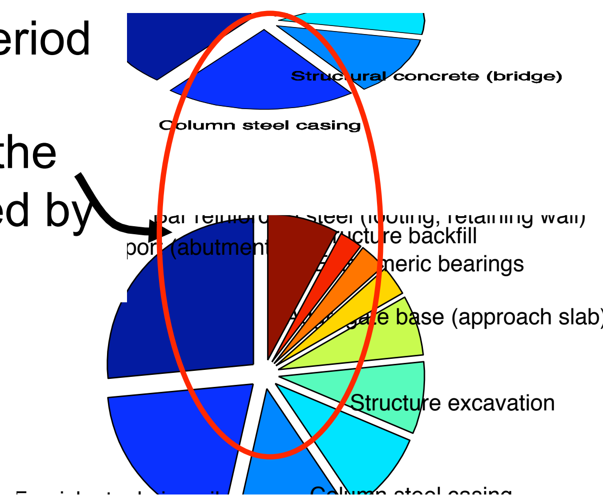
45% total repair cost

Deaggregation of Repair Cost

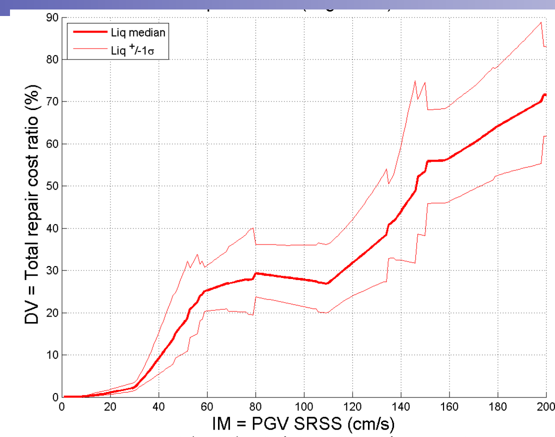


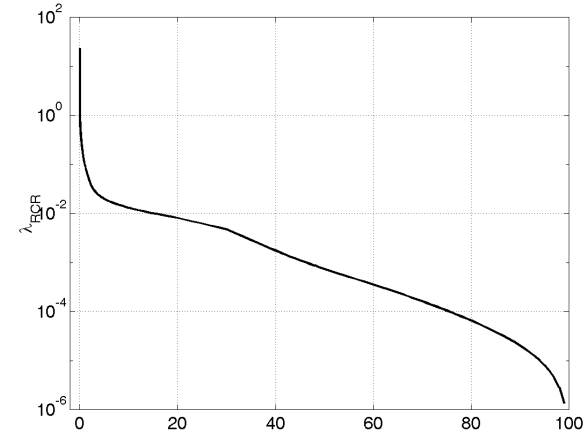
Greatest repair cost temporary support of the superstructure

For 475 year return period greatest repair cost is temporary support of the superstructure followed by additional piling

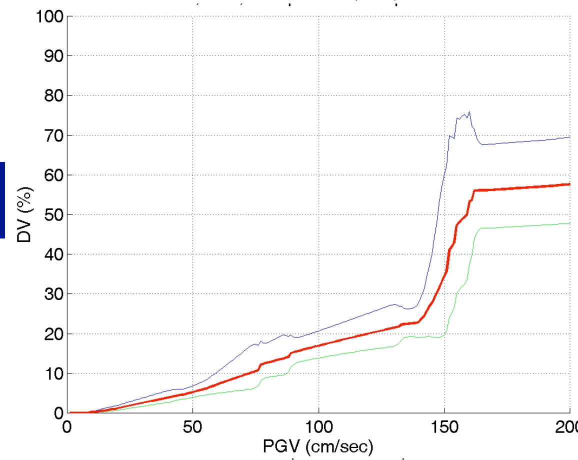


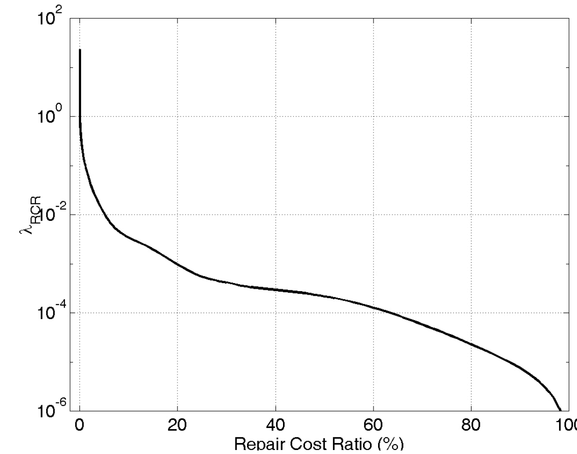
Liquefaction case



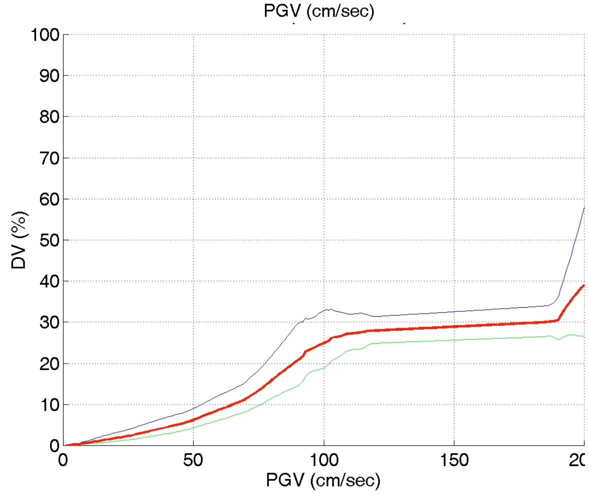


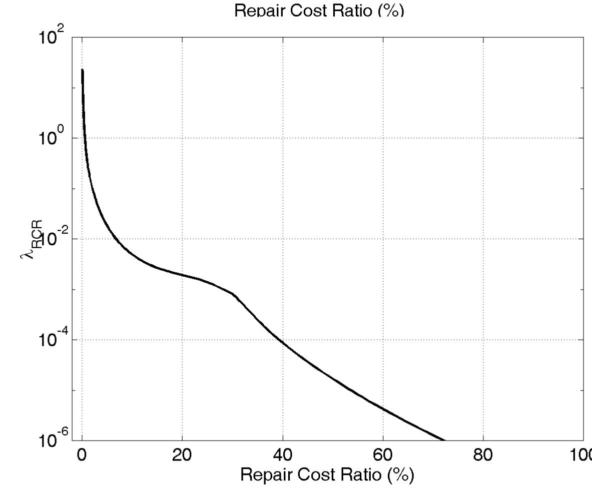
Non-Liquefaction case



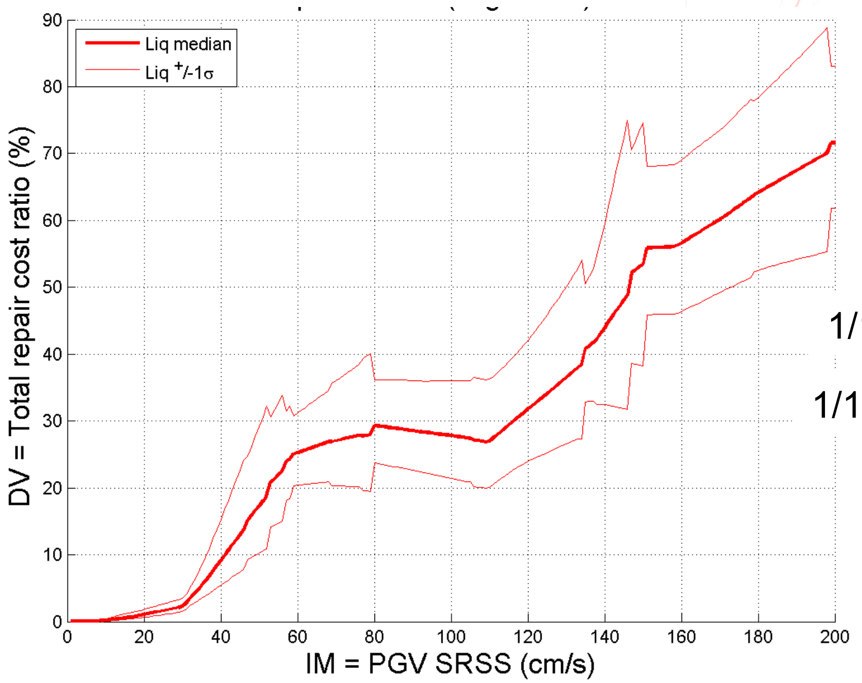


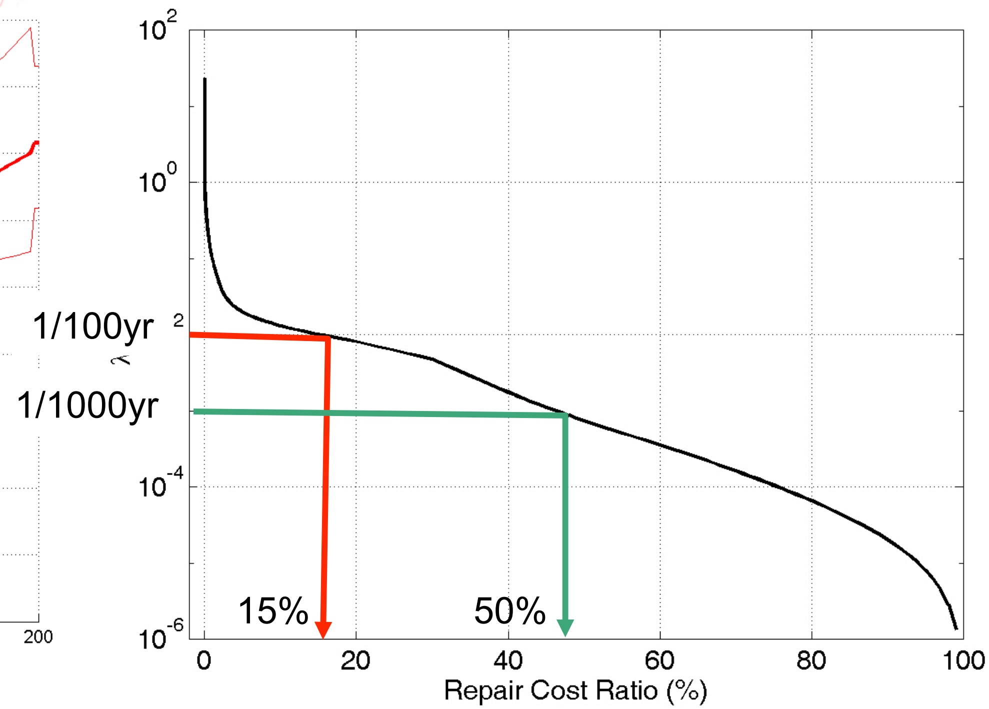
Fixed-base case





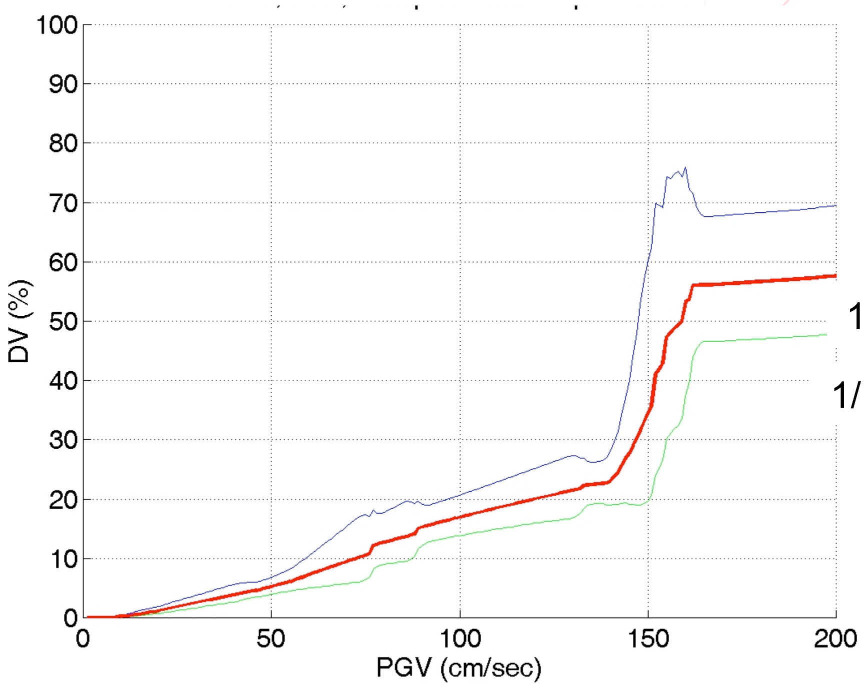
Liquefaction case

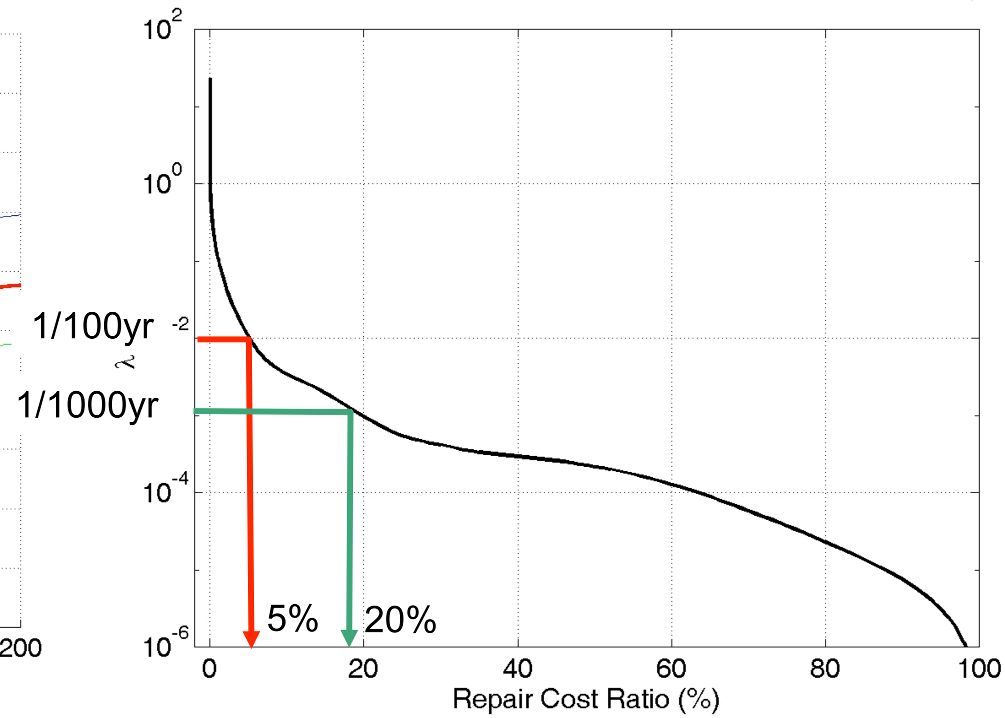




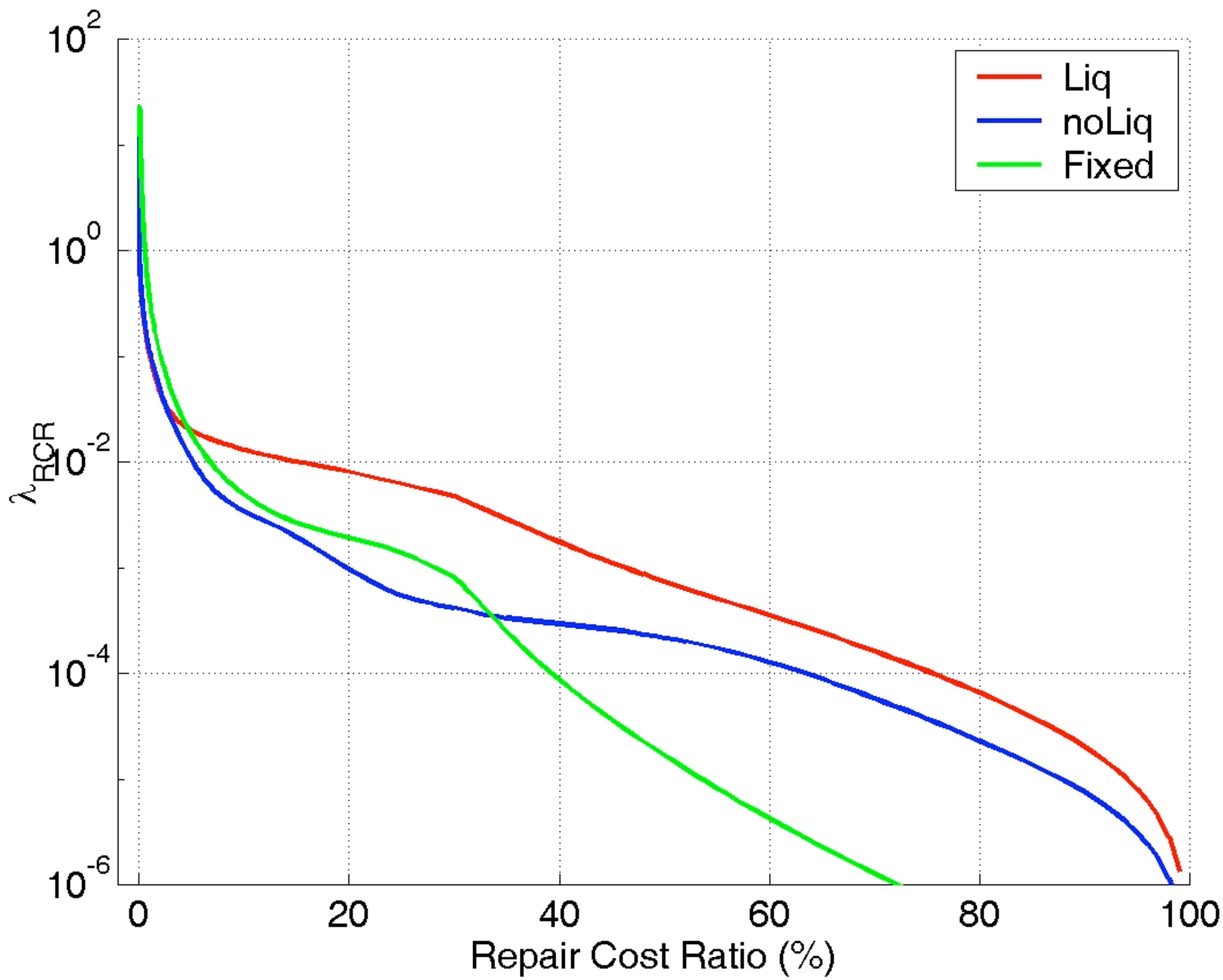
Fixed-base case

Non-Liquefaction case

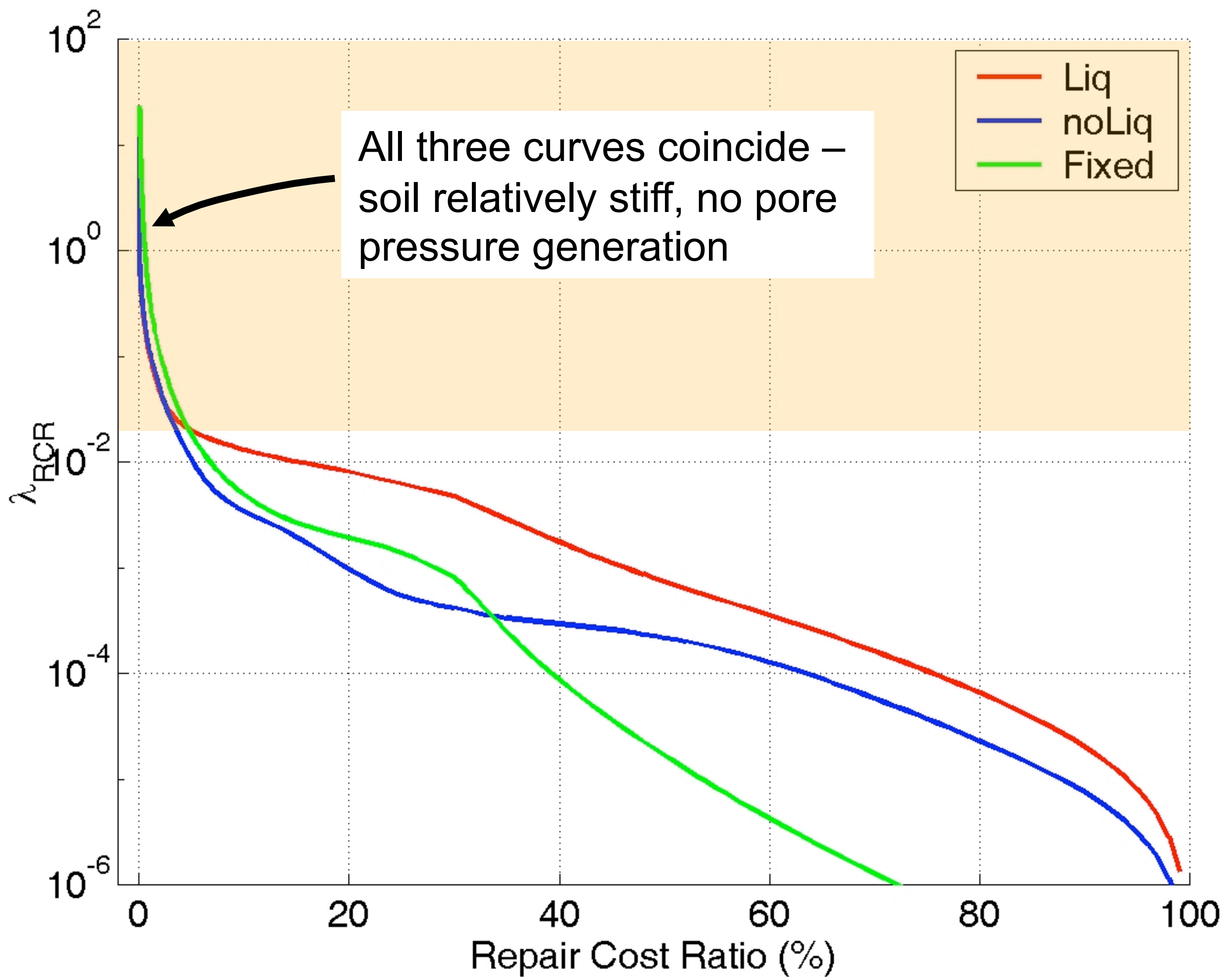




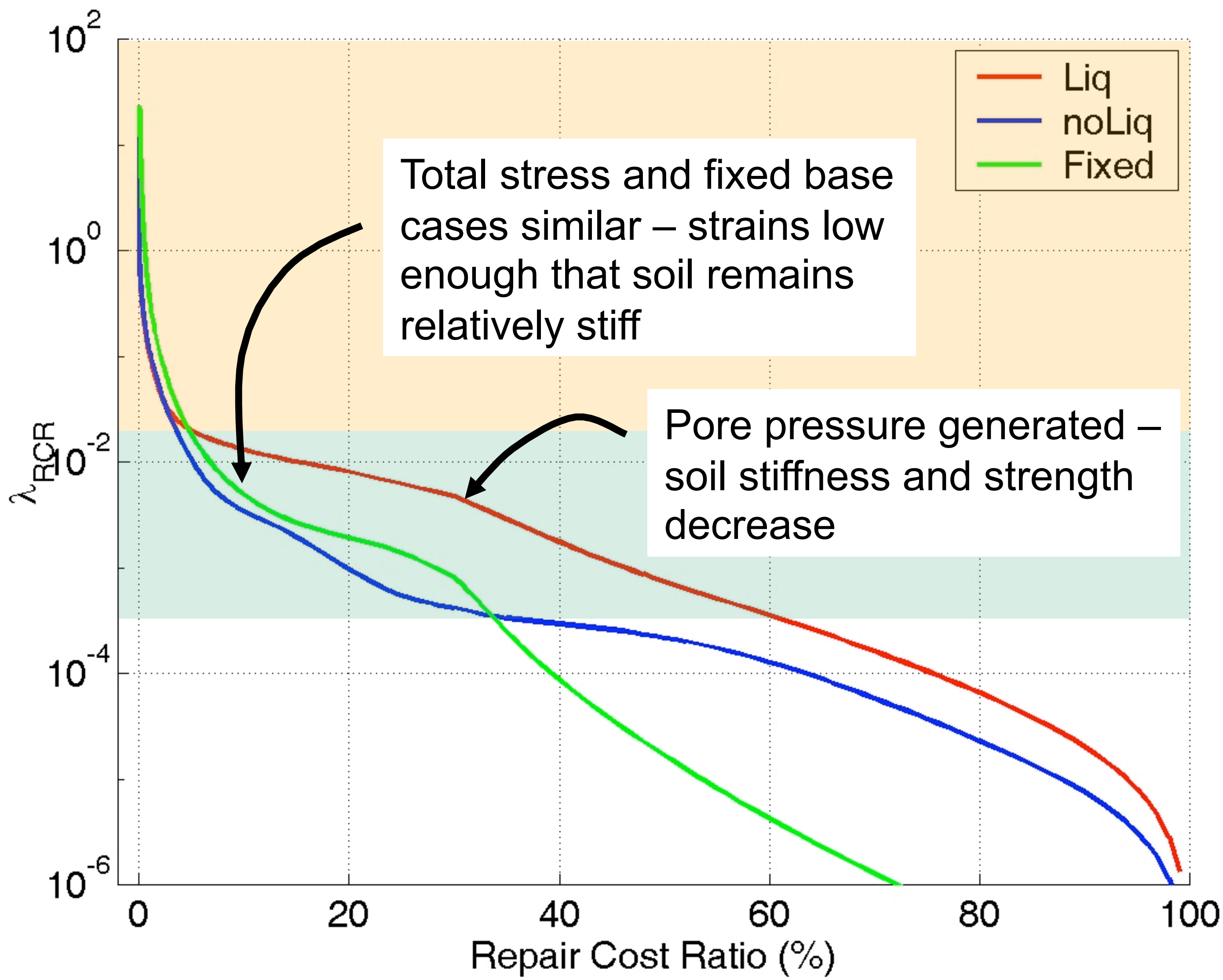
Sensitivity of Bridge Losses to Soil Conditions



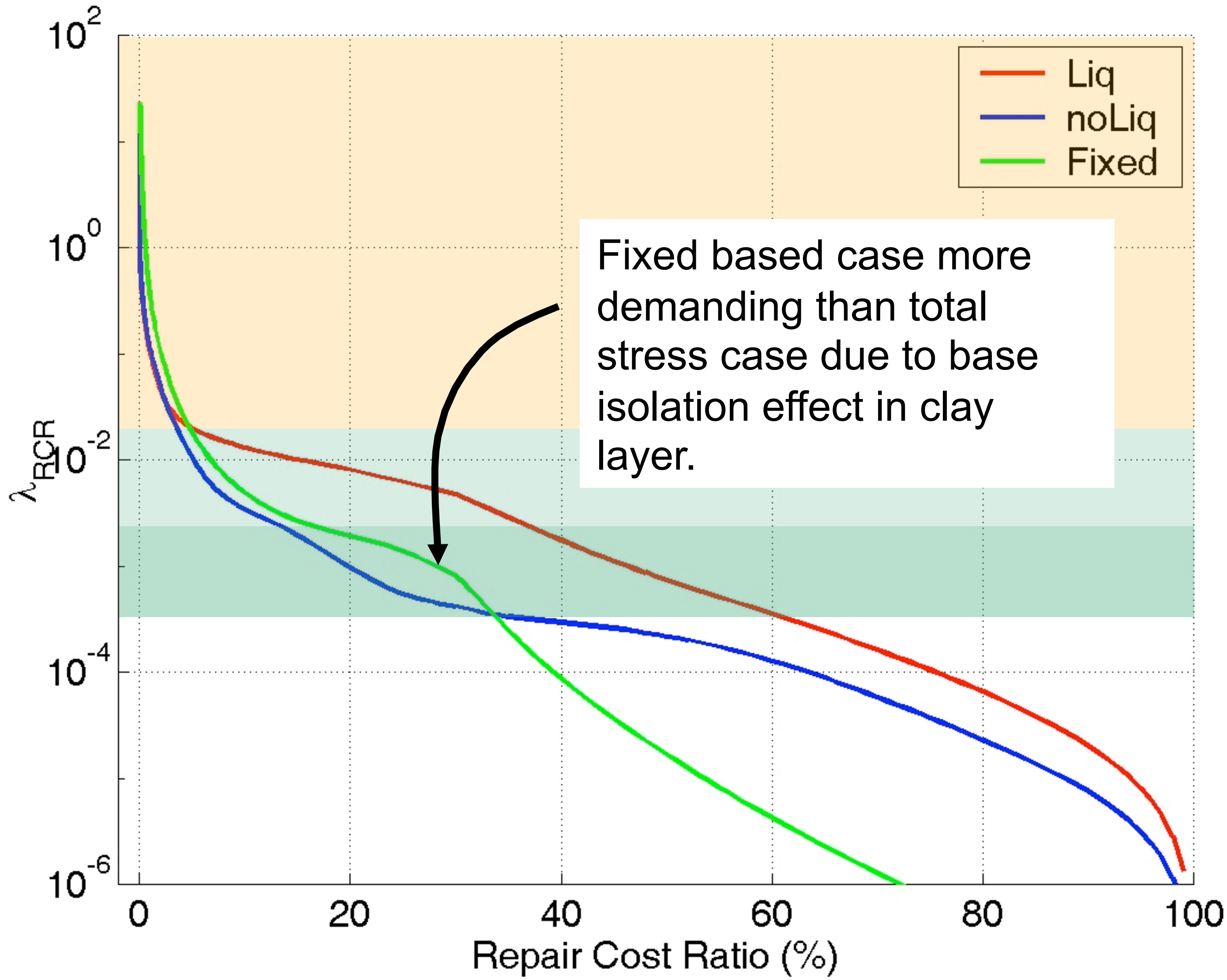
Sensitivity of Bridge Losses to Soil Conditions



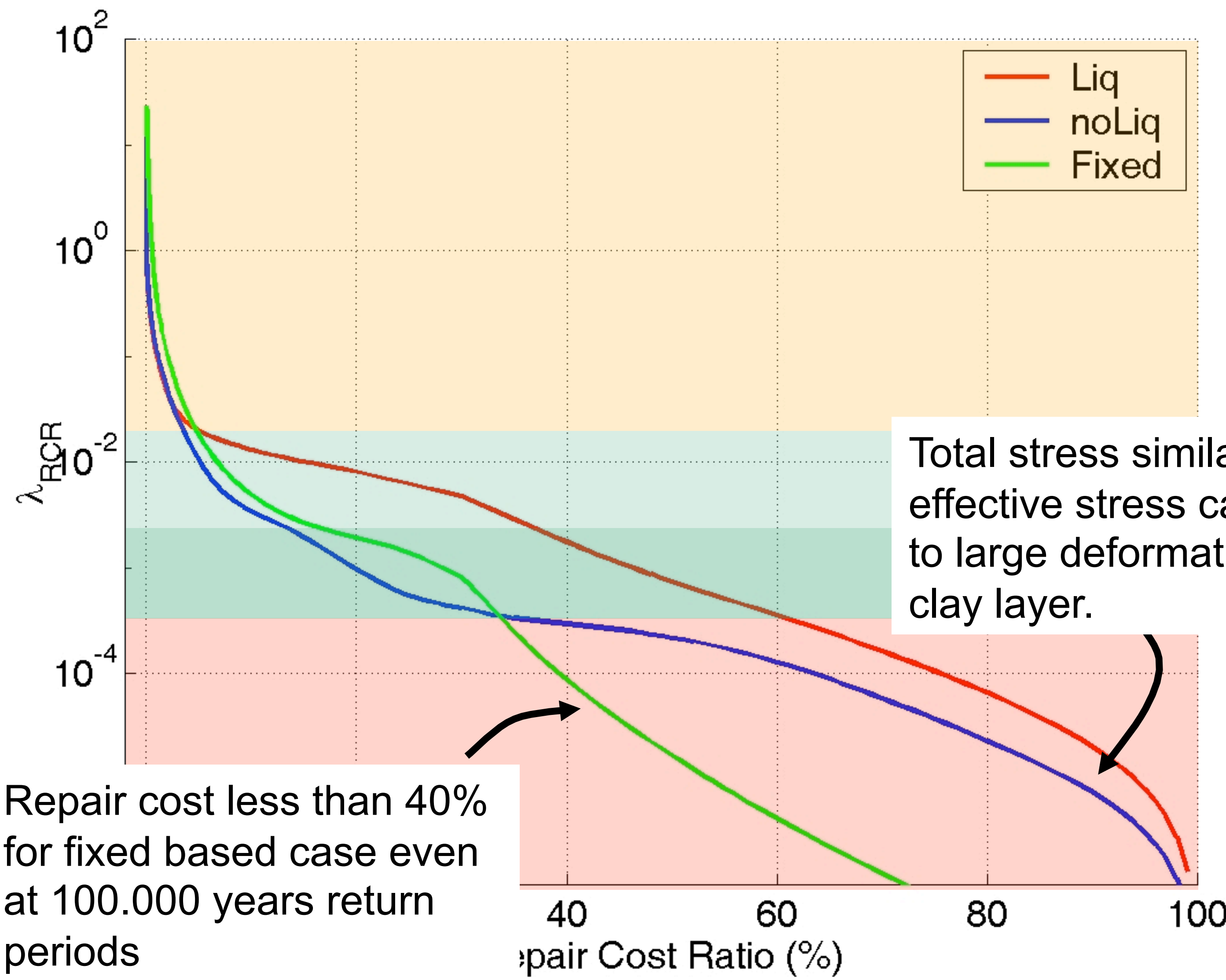
Sensitivity of Bridge Losses to Soil Conditions



Sensitivity of Bridge Losses to Soil Conditions



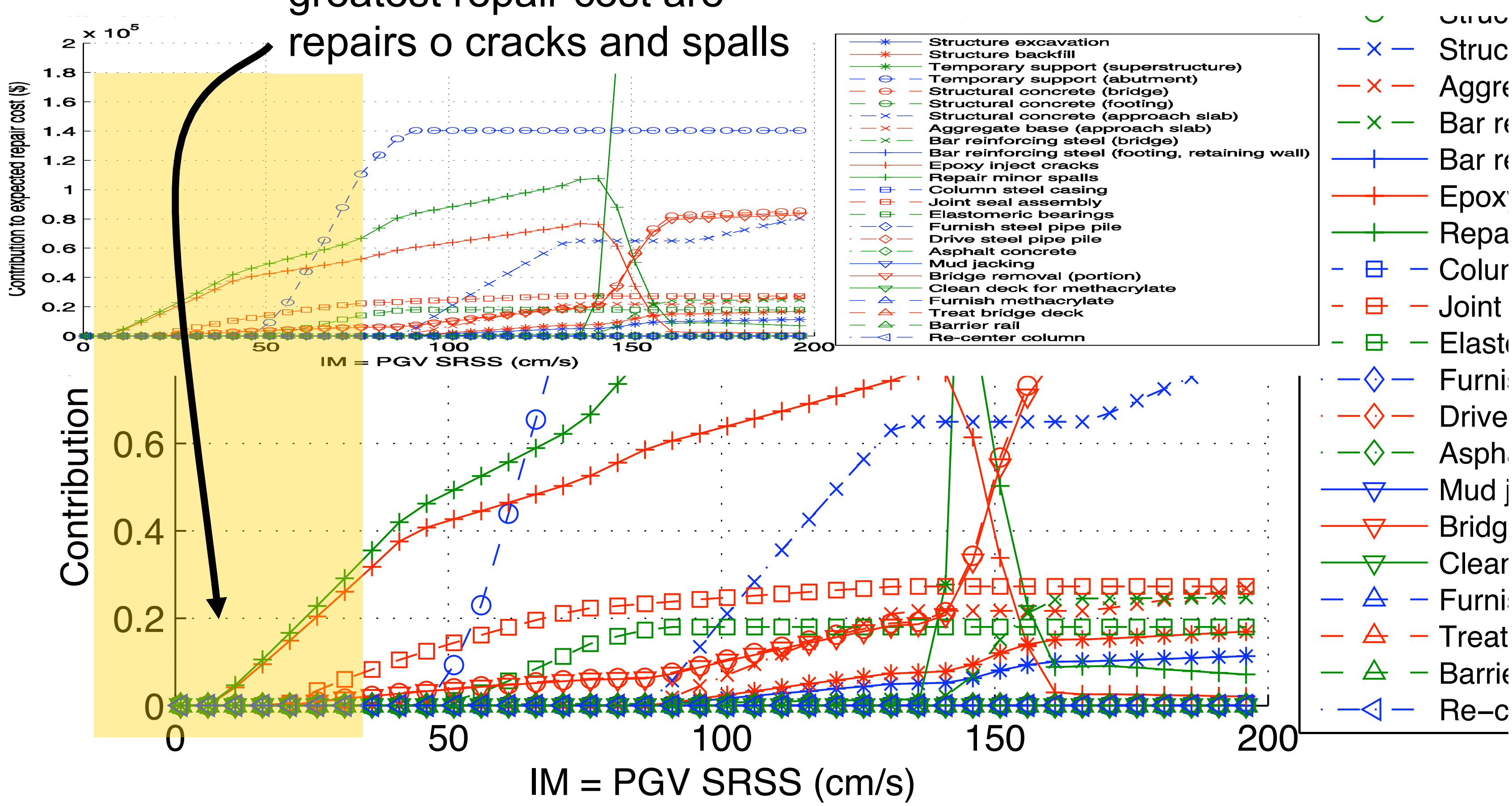
Sensitivity of Bridge Losses to Soil Conditions



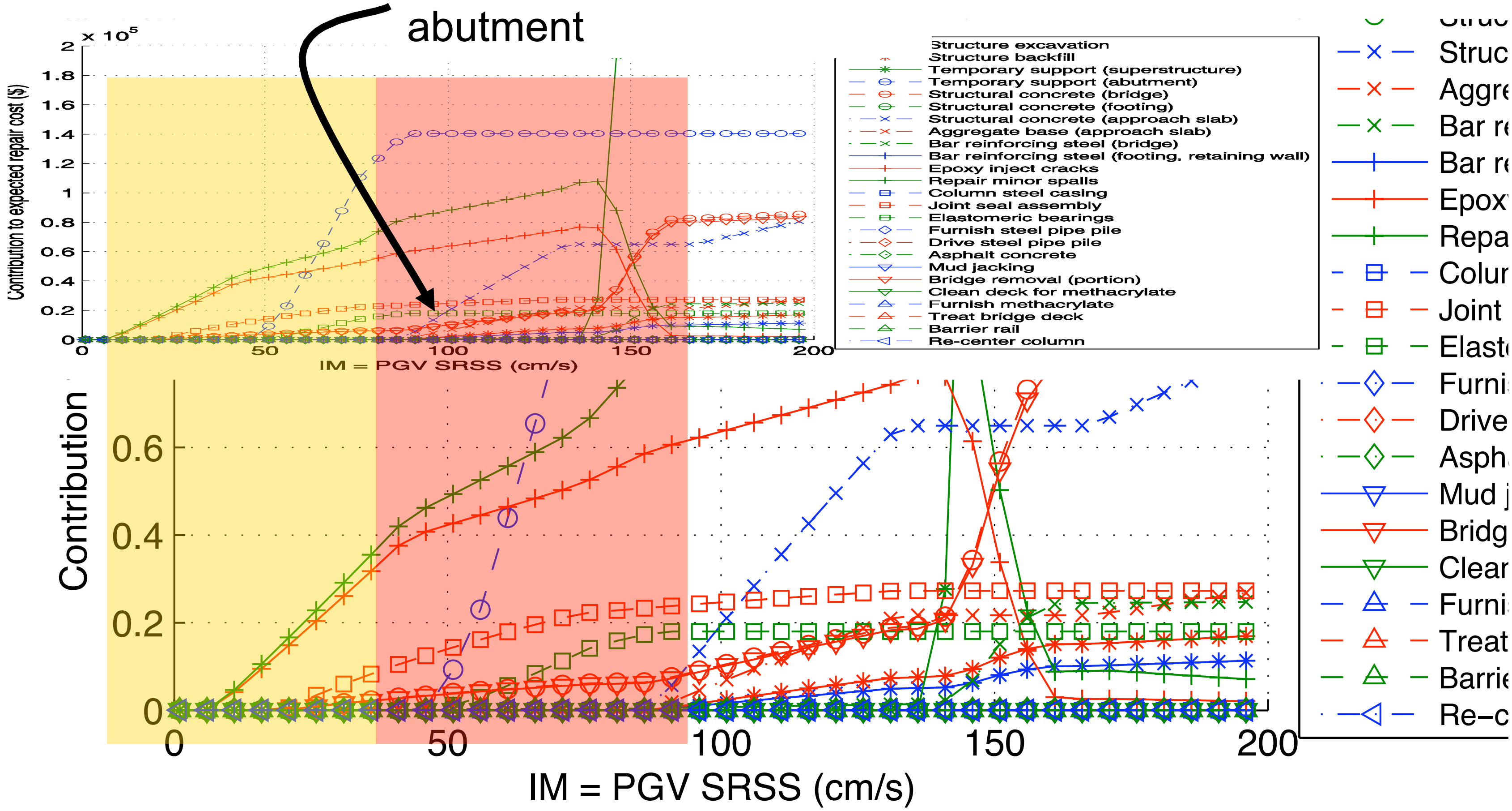
Total stress similar to effective stress case due to large deformations in clay layer.

Repair cost less than 40% for fixed based case even at 100.000 years return periods

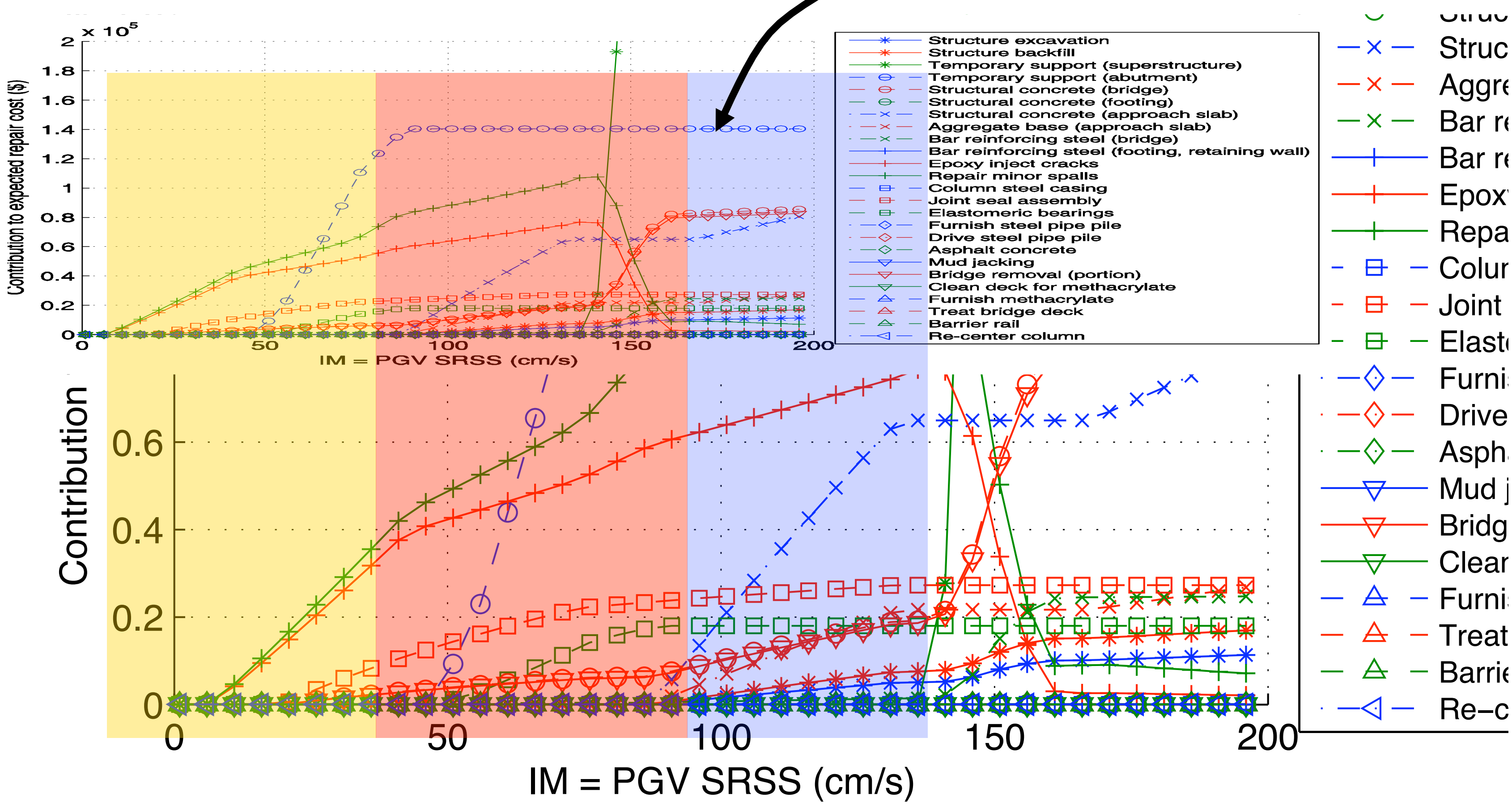
At PGV < 65 cm/sec greatest repair cost are repairs o cracks and spalls



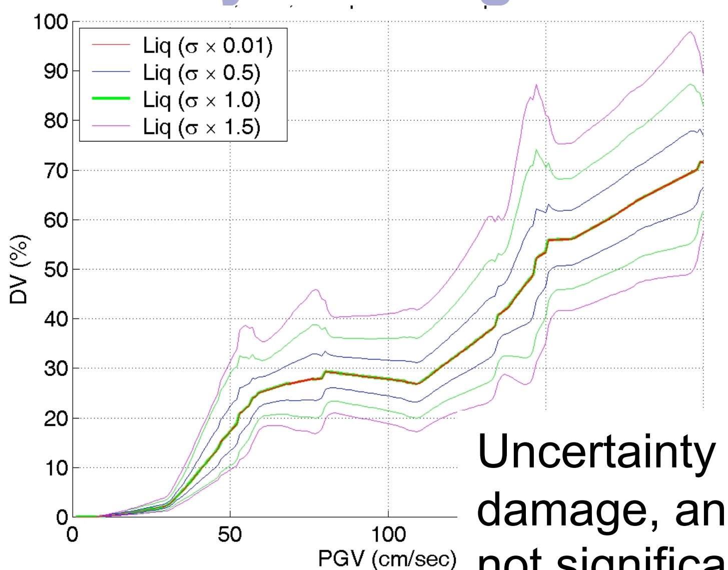
At PGV’s 65-140 cm/sec greatest repair cost is temporary support of the abutment



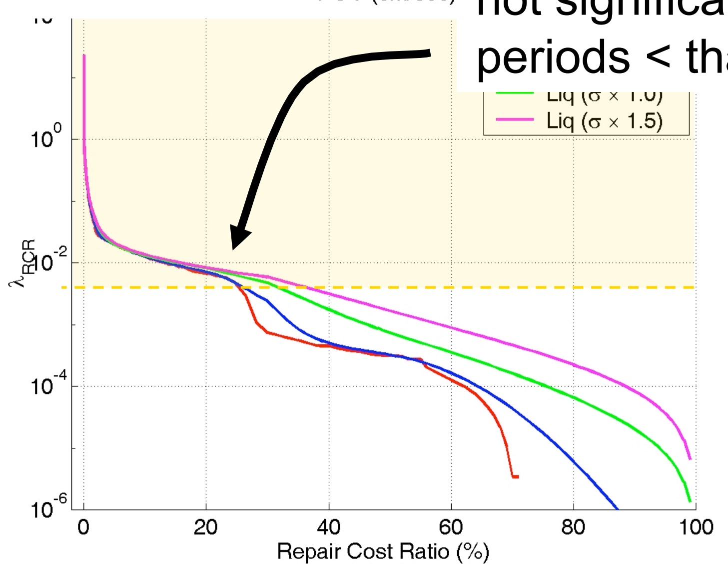
At PGV >140 cm/sec greatest repair cost is temporary support of the superstructure



Sensitivity of Bridge Losses to Uncertainty

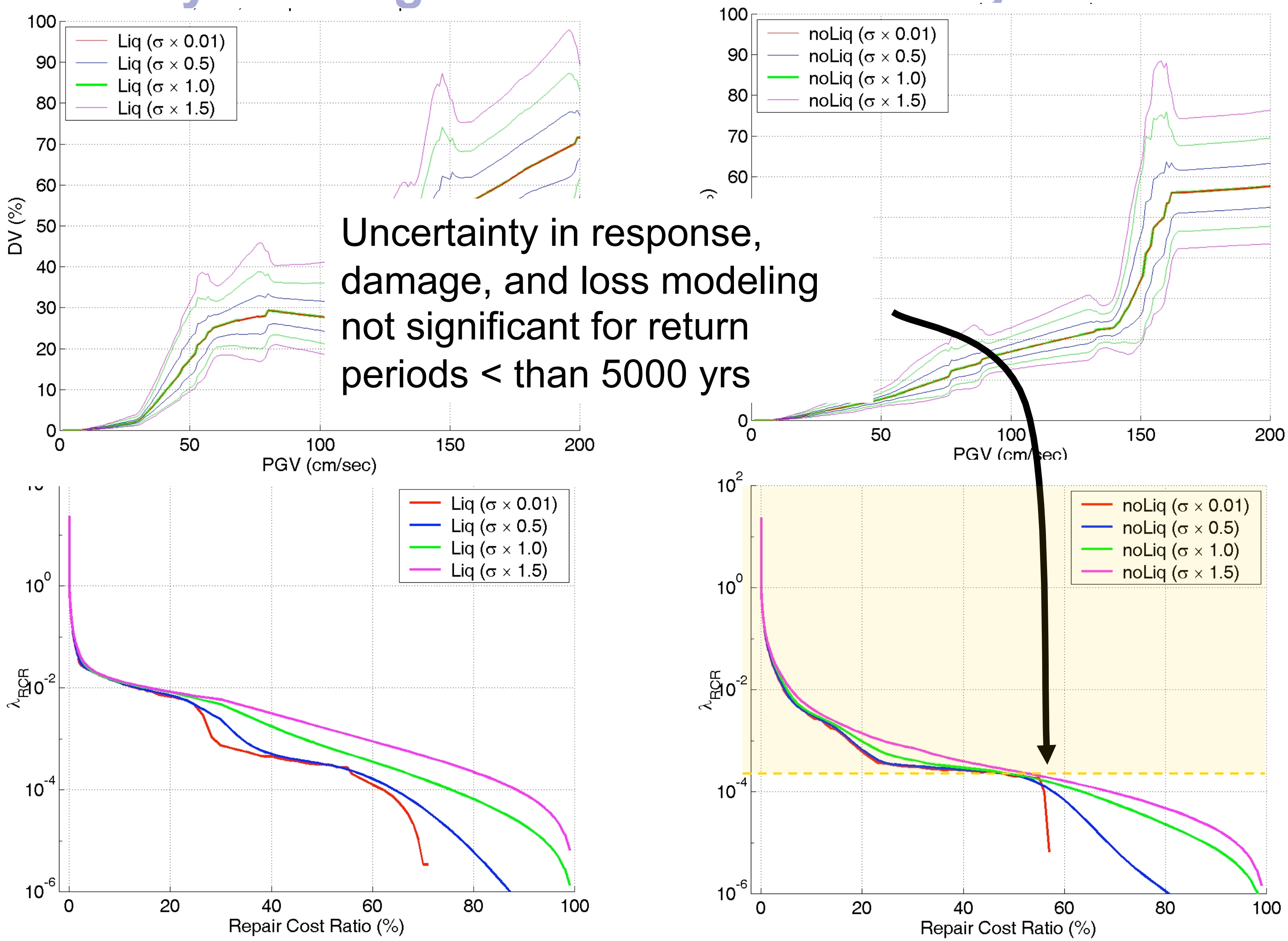


Uncertainty in response, damage, and loss modeling not significant for return periods < than 200 yrs



Liquefaction

Sensitivity of Bridge Losses to Uncertainty



Liquefaction

Non- Liquefaction

Thank You

Questions and Comments

Backup slides

Input Motions and Intensity Measures (IMs)

Table 1: Input motions (hazard: 50 % in 50 years)

Record	File	Earthquake	Magnitude	MSF	PGA_M
Coyote Lake Dam abutment	A01	Coyote Lake	5.7	2.247	0.672
Gilroy #6	A02	(6/ 8/1979)			
Temblor	A03	Parkfield	6.0	1.931	0.578
Array #5	A04	(6/27/1966)			
Array #8	A05				
Fagundes Ranch	A06	Livermore	5.5	2.497	0.747
Morgan Territory Park	A07	(6/27/1980)			
Coyote Lake Dam abutment	A08	Morgan Hill	6.2	1.753	0.524
Anderson Dam DS	A09	(4/24/1984)			
Halls Valley	A10				

Table 2: Input motions (hazard: 10 % in 50 years)

Record	File	Earthquake	Magnitude	MSF	PGA_M
Los Gatos Presentation Ctr	B01	Loma Prieta	7.0	1.226	0.799
Saratoga Aloha Avenue	B02				
Corralitos	B03				
Gavilan College	B04				
Gilroy Historic	B05				
Lexington Dam abutment	B06				
Kobe JMA	B07	Kobe, Japan	6.9	1.279	0.834
Kofu	B08	Tottori, Japan	6.6	1.458	0.951
Hino	B09	(10/6/2000)			
Erzincan	B10	Erzincan	6.7	1.395	0.909

Table 3: Input motions (hazard: 2 % in 50 years)

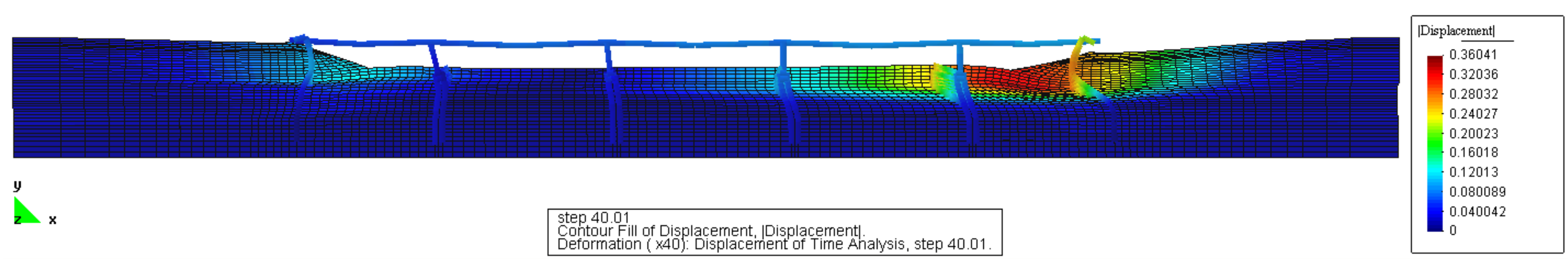
Record	File	Earthquake	Magnitude	MSF	PGA_M
Los Gatos Presentation Ctr	C01	Loma Prieta	7.0	1.226	1.228
Saratoga Aloha Avenue	C02				
Corralitos	C03				
Gavilan College	C04				
Gilroy Historic	C05				
Lexington Dam abutment	C06				
Kobe JMA	C07	Kobe, Japan	6.9	1.279	1.282
Kofu	C08	Tottori, Japan	6.6	1.458	1.461
Hino	C09	(10/6/2000)			
Erzincan	C10	Erzincan	6.7	1.395	1.398

Table 4: Input motions (hazard: 97 % in 50 years)

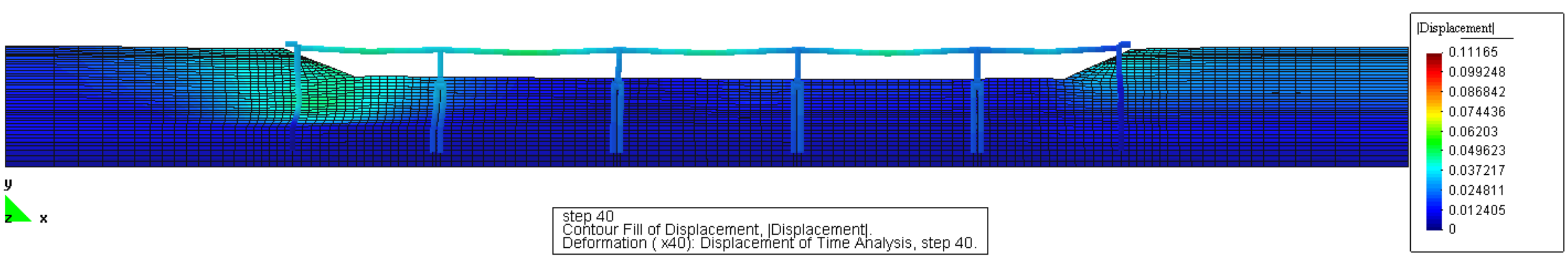
Record	File	Earthquake	Magnitude	MSF	PGA_M
Coyote Lake Dam abutment	D01	Coyote Lake	5.7	2.247	0.672
Gilroy #6	D02	(6/ 8/1979)			
Temblor	D03	Parkfield	6.0	1.931	0.578
Array #5	D04	(6/27/1966)			
Array #8	D05				
Fagundes Ranch	D06	Livermore	5.5	2.497	0.747
Morgan Territory Park	D07	(6/27/1980)			
Coyote Lake Dam abutment	D08	Morgan Hill	6.2	1.753	0.524
Anderson Dam DS	D09	(4/24/1984)			
Halls Valley	D10				

Liquefaction Effects

Soil displacement (liquefaction)



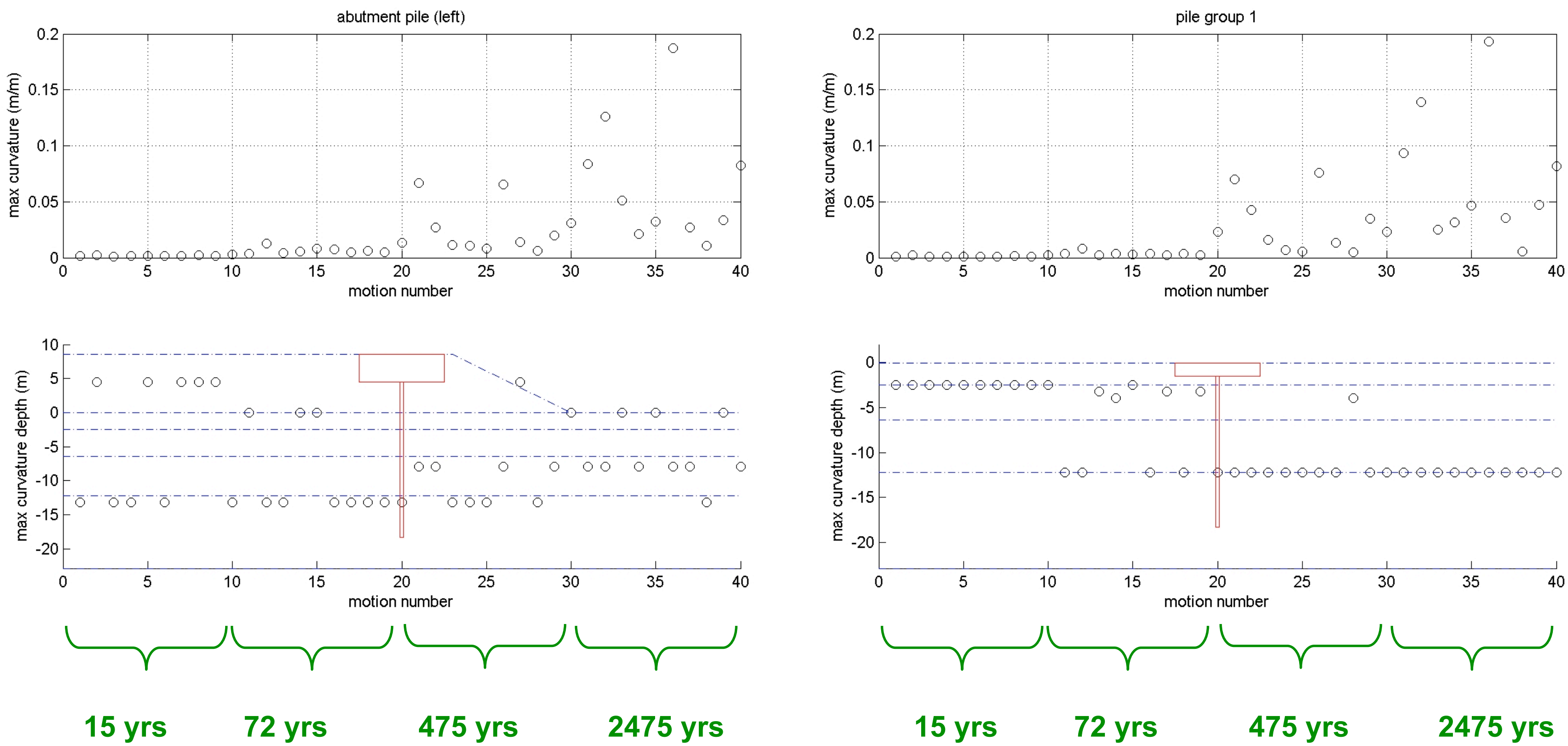
Soil displacement (no liquefaction)



After Northridge earthquake motion (PGA=0.224g)

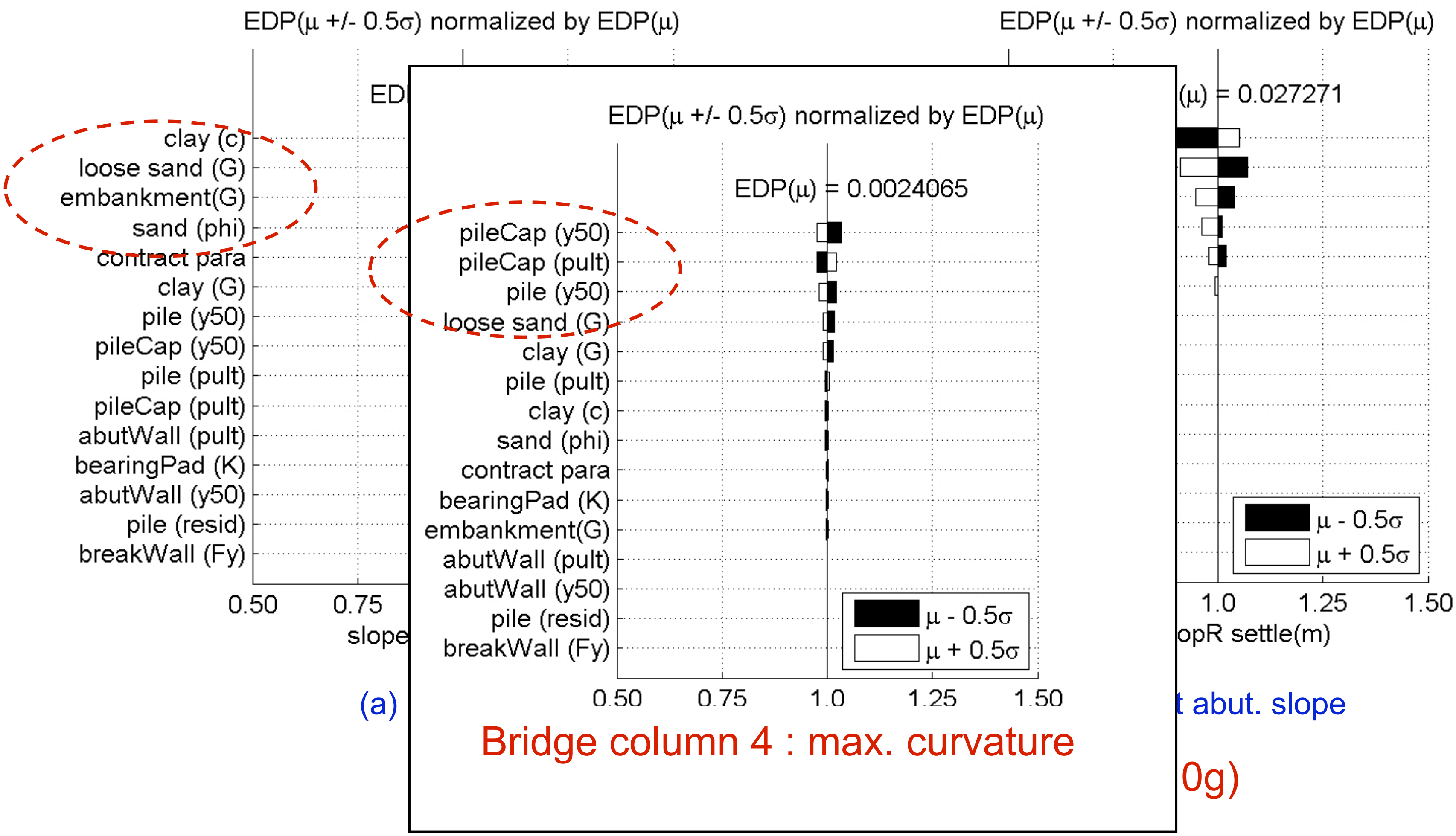
Local Responses

Locations of max. pile curvature (left abutment)



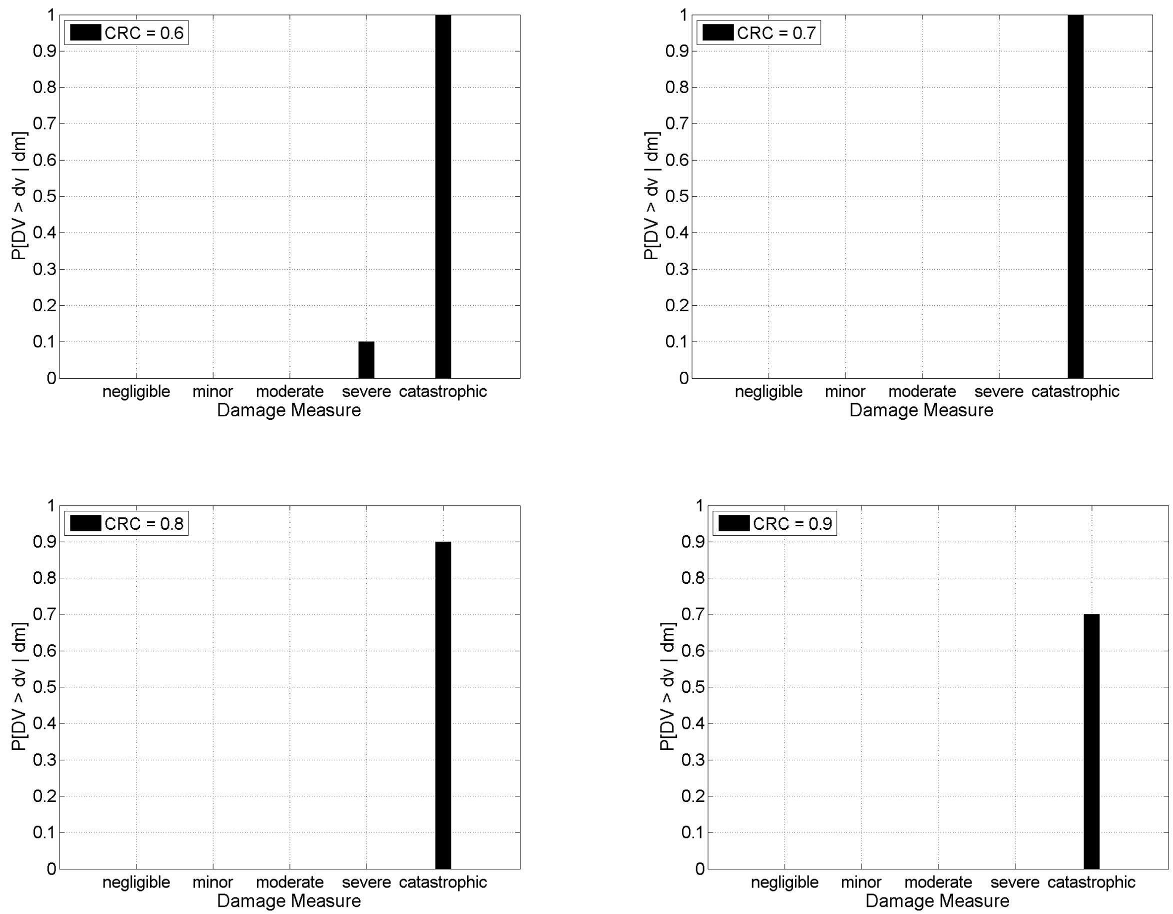
Parametric Uncertainty

Tornado diagrams (small shaking)



EDP Hazard to DM/DV Hazard

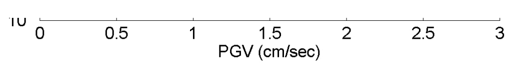
DV fragility curve



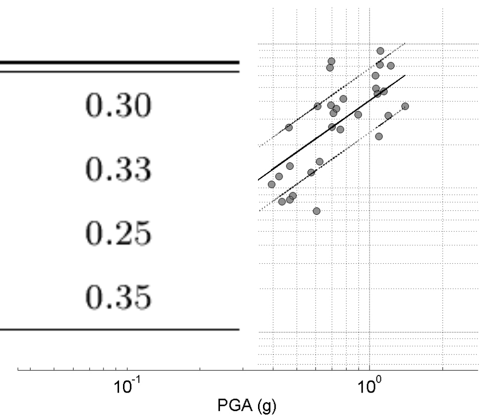
Integration of Uncertainties through PBEE Framework

Bridge column damage uncertainty

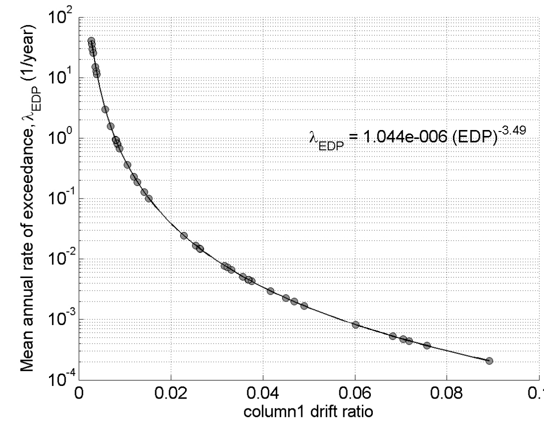
Damage State	Median EDP	$\sigma_{\ln(DM\|EDP)}$
DS1: cracking	0.50	0.30
DS2: spalling	2.04	0.33
DS3: bar buckling	6.46	0.25
DS4: failure	9.01	0.35



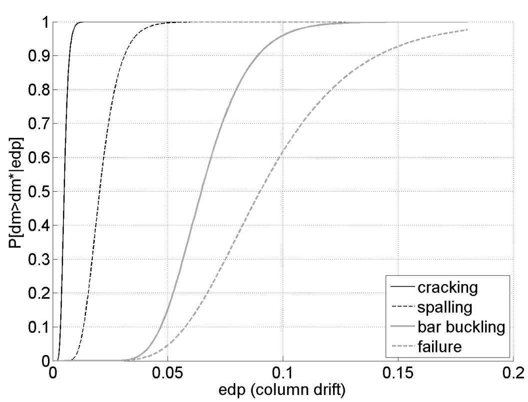
lationship



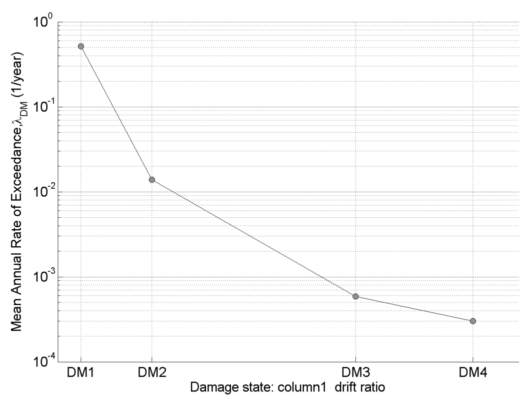
EDP hazard curve



DM fragility curves



DM hazard curve



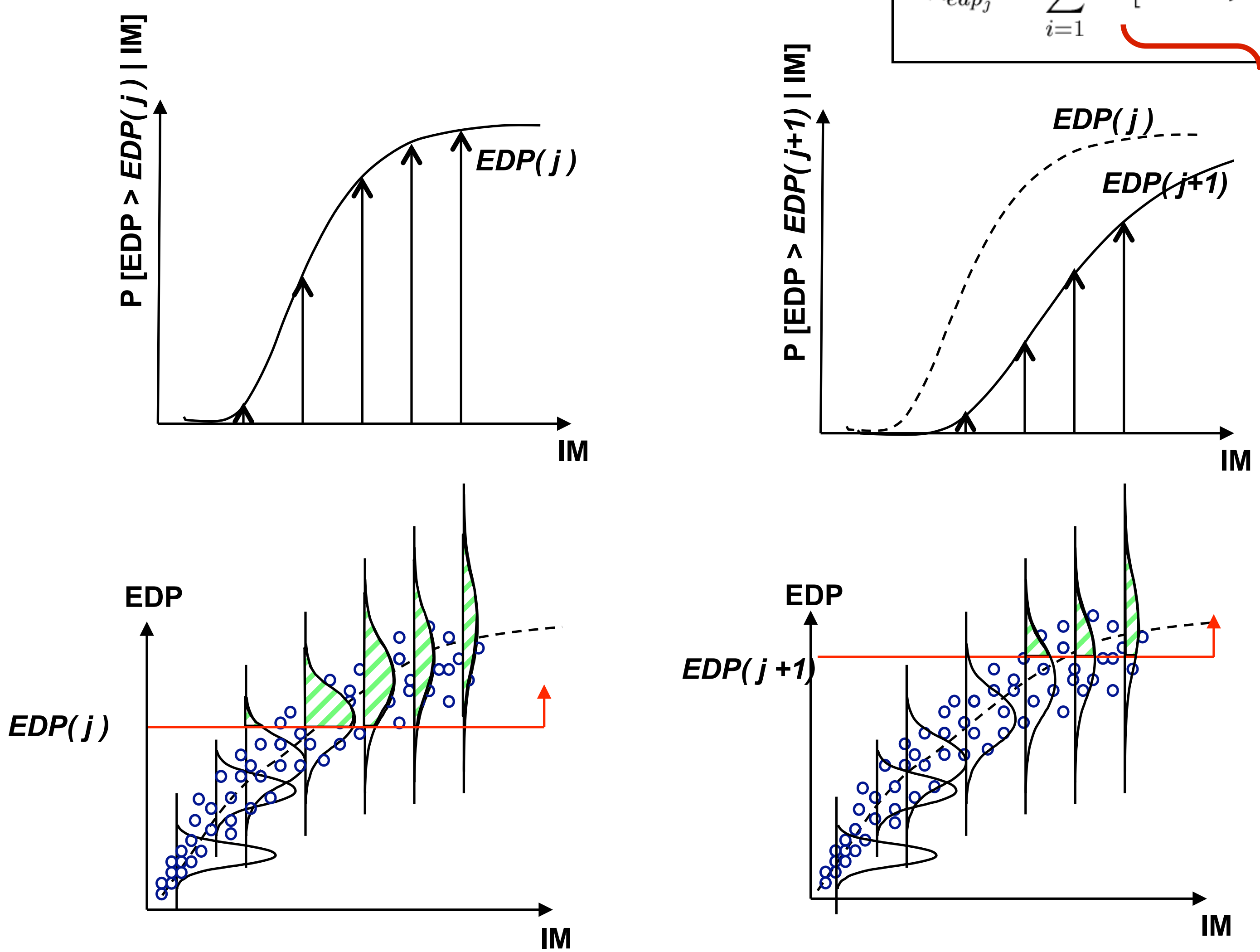
DV hazard curve

No uncertainty in repair cost estimation from DM

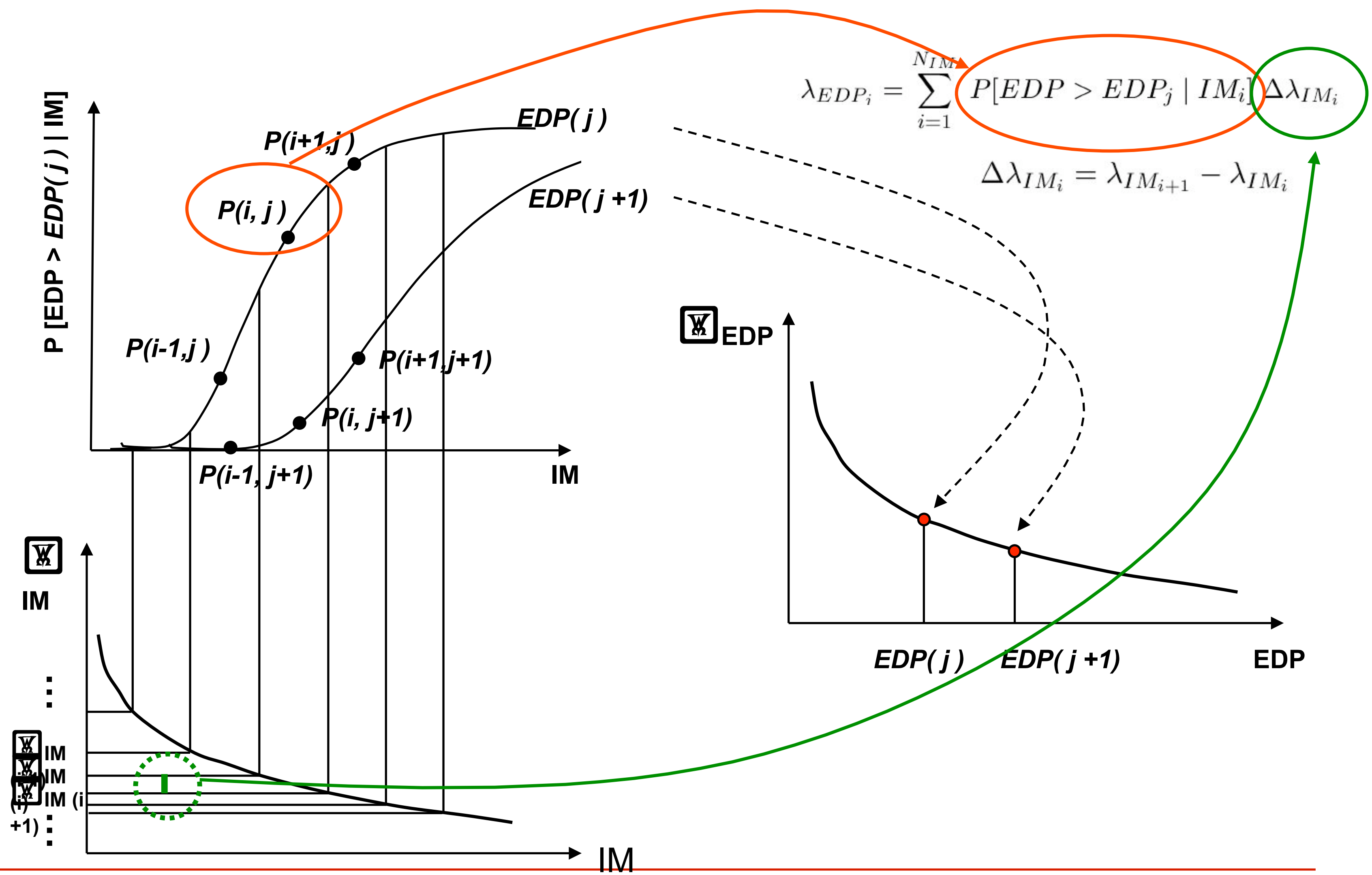
PEER Performance-Based Earthquake Engineering

$$\lambda_{edp_j} = \sum_{i=1}^{N_{IM}} P[EDP > edp_j \mid im_i] \, \Delta\lambda_{im_i}$$

EDP_j fragility curve



PEER Performance-Based Earthquake Engineering



$$\lambda_{EDP_i} = \sum_{i=1}^{N_{IM}} P[EDP > EDP_j \mid IM_i] \Delta\lambda_{IM_i}$$

$$\Delta\lambda_{IM_i} = \lambda_{IM_{i+1}} - \lambda_{IM_i}$$

PEER Performance-Based Earthquake Engineering

$$\lambda_{dv_l} = \sum_{k=1}^{N_{dm}} \sum_{j=1}^{N_{edp}} \sum_{i=1}^{N_{im}} P[DV > dv_l | dm_k] P[DM = dm_k | edp_j] P[EDP = edp_j | im_i] \Delta\lambda_{im_i}$$