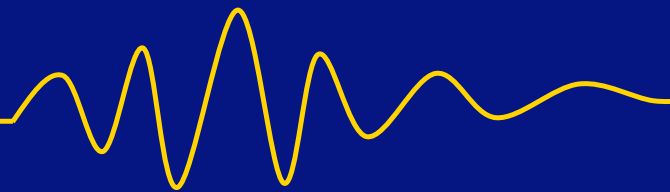


Simulation of Synthetic Ground Motions for Specified Earthquake and Site Characteristics



Sanaz Rezaeian (Doctoral Candidate)

Armen Der Kiureghian (PI)

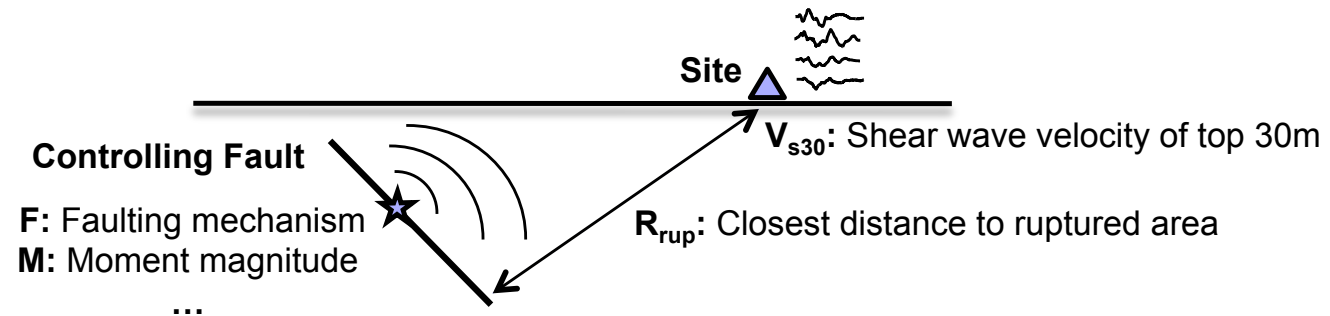
University of California, Berkeley

Sponsor: State of California through Transportation Systems Research Program of Pacific Earthquake Engineering Research (PEER) Center



Objective:

Our Goal: Earthquake and site characteristics → Suite of simulated design time-histories
($F, M, R_{rup}, V_{s30}, \dots$)



What we have done so far:

- Developed a stochastic site-based model for far-field strong ground motions.
- Developed empirical predictive equations for the model parameters.
- Compared elastic response spectra (median and variability) to NGA relations.

Ongoing activity and what we plan to accomplish by May 2010:

- Simulate orthogonal horizontal ground motion components.
- Extend the model to near-field ground motions.
- Scrutinize the simulated motions for inelastic structural responses.

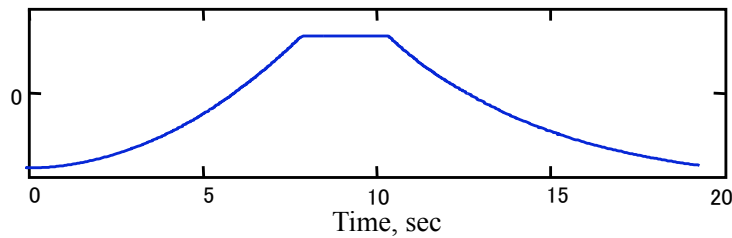
Ground Motion Model:

$$x(t) = q(t, \mathbf{a}) \left[\frac{1}{\sigma_h(t)} \int_{-\infty}^t h[t - \tau, \omega_f(\tau), \zeta_f(\tau)] w(\tau) d\tau \right]$$

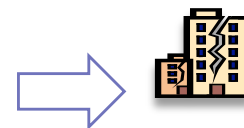
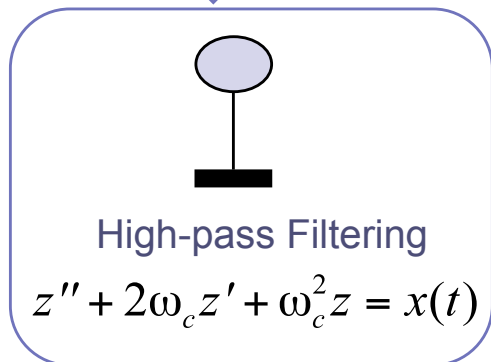
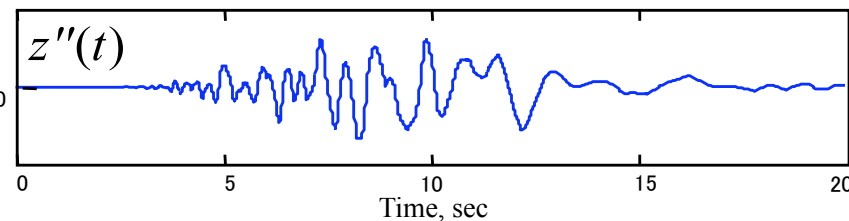
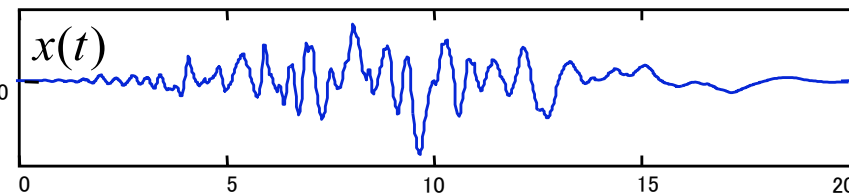
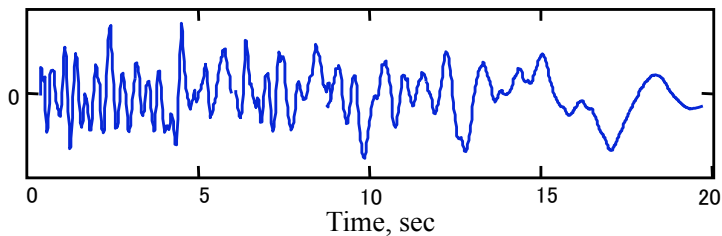
Acceleration

Time modulating function
Controls temporal nonstationarity

Unit-variance process
Controls spectral nonstationarity



×

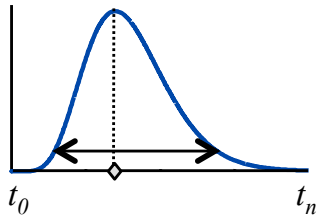


Ground Motion Model Parameters:

$$x(t) = q(t, \mathbf{\alpha}) \left[\frac{1}{\sigma_h(t)} \int_{-\infty}^t h[t - \tau, \omega_f(\tau), \zeta_f(\tau)] w(\tau) d\tau \right]$$

Let:

$$q(t, \mathbf{\alpha}) = \alpha_1 (t - t_0)^{\alpha_2 - 1} \exp[-\alpha_3 (t - t_0)] \quad t \geq t_0$$



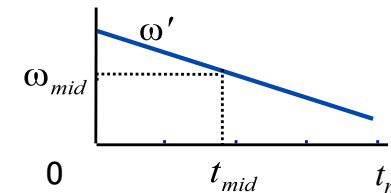
$\alpha_1, \alpha_2, \alpha_3$ \longleftrightarrow related $\rightarrow I_a, t_{mid}, D_{5-95}$

$$I_a = \frac{\pi}{2g} \int_{t_0}^{t_n} (\text{acceleration}(t))^2 dt \quad : \text{Arias intensity}$$

t_{mid} = time at $0.45I_a$: Time at the middle of strong shaking

D_{5-95} = time at $0.95I_a$ - time at $0.05I_a$: Effective duration

$$\omega_f(\tau) \cong \omega_{mid} + \omega'(\tau - t_{mid})$$



$$\zeta_f(\tau) \cong \zeta$$



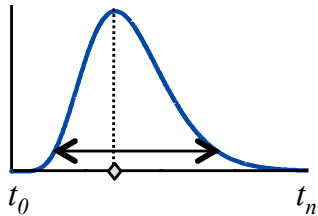
$$x(t) = q(t, I_a, t_{mid}, D_{5-95}) \times f(t, \omega_{mid}, \omega', \zeta, t_{mid})$$

Ground Motion Model Parameters:

$$x(t) = q(t, \mathbf{a}) \left[\frac{1}{\sigma_h(t)} \int_{-\infty}^t h[t - \tau, \omega_f(\tau), \zeta_f(\tau)] w(\tau) d\tau \right]$$

Let:

$$q(t, \mathbf{a}) = \alpha_1 (t - t_0)^{\alpha_2 - 1} \exp[-\alpha_3 (t - t_0)] \quad t \geq t_0$$



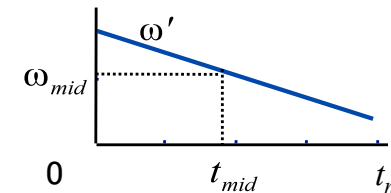
$\alpha_1, \alpha_2, \alpha_3 \xleftrightarrow{\text{related}} I_a, t_{mid}, D_{5-95}$

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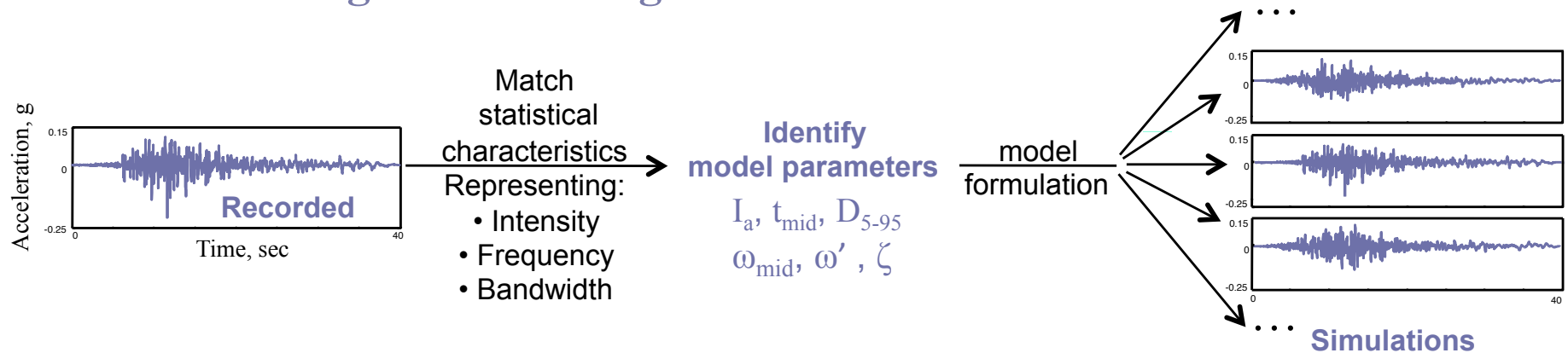


$$x(t) = q(t, I_a, t_{mid}, D_{5-95}) \times f(t, \omega_{mid}, \omega', \zeta, t_{mid})$$

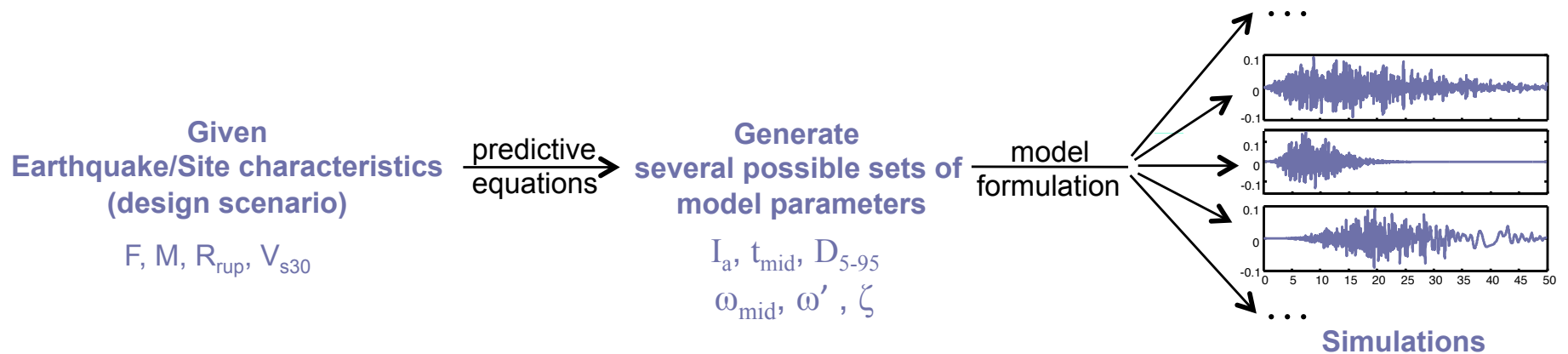
If the model parameters are given, time-histories can be simulated.

Applications in Practice:

➤ Simulate a given accelerogram:

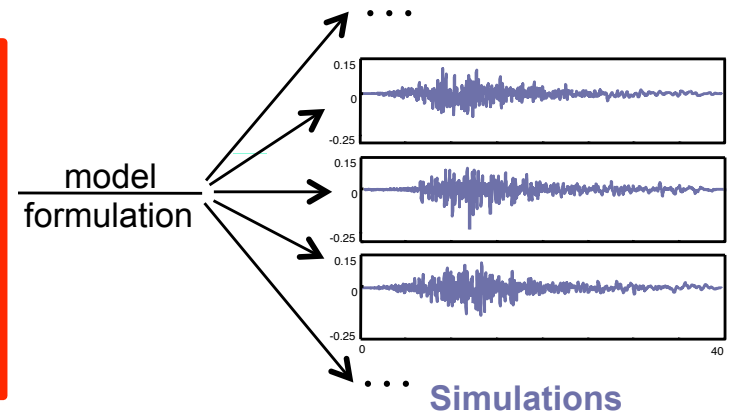
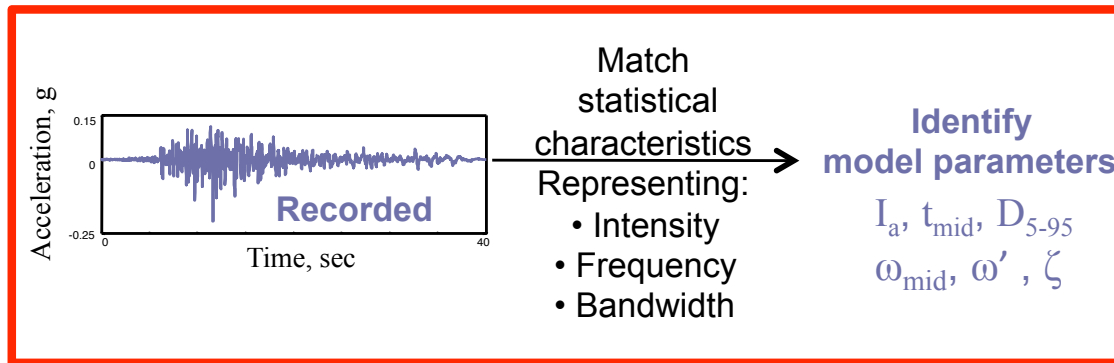


➤ Simulate a suite of ground motions for a given design scenario:



Applications in Practice:

➤ Simulate a given accelerogram:



Done for many records to get observational data for predictor and response variables

➤ Simulate a suite of ground motions for a given design scenario:

Given Earthquake/Site characteristics (design scenario)

F, M, R_{rup}, V_{s30}

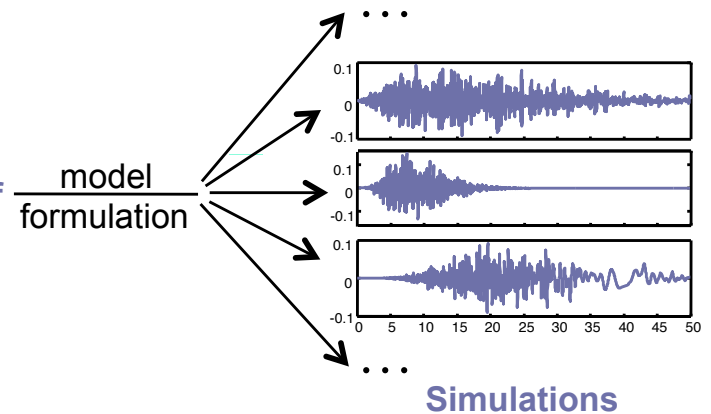
Predictor variables

predictive equations
Regression

Generate several possible sets of model parameters

I_a, t_{mid}, D_{5-95}
 $\omega_{mid}, \omega', \zeta$

Response variables



Ground Motion Database (far-field):

	Earthquake	# of records
1	Imperial Valley	2
2	Victoria, Mexico	2
3	Morgan hill	10
4	Landers	4
5	Big Bear	10
6	Kobe, Japan	4
7	Kocaeli, Turkey	4
8	Duzce, Turkey	2
9	Sitka, Alaska	2
10	Manjil, Iran	2
11	Hector Mine	16
12	Denali, Alaska	4
13	San Fernando	14
14	Tabas, Iran	2
15	Coalinga	2
16	N Palm Springs	12
17	Loma Prieta	28
18	Northridge	38
19	ChiChi, Taiwan	48

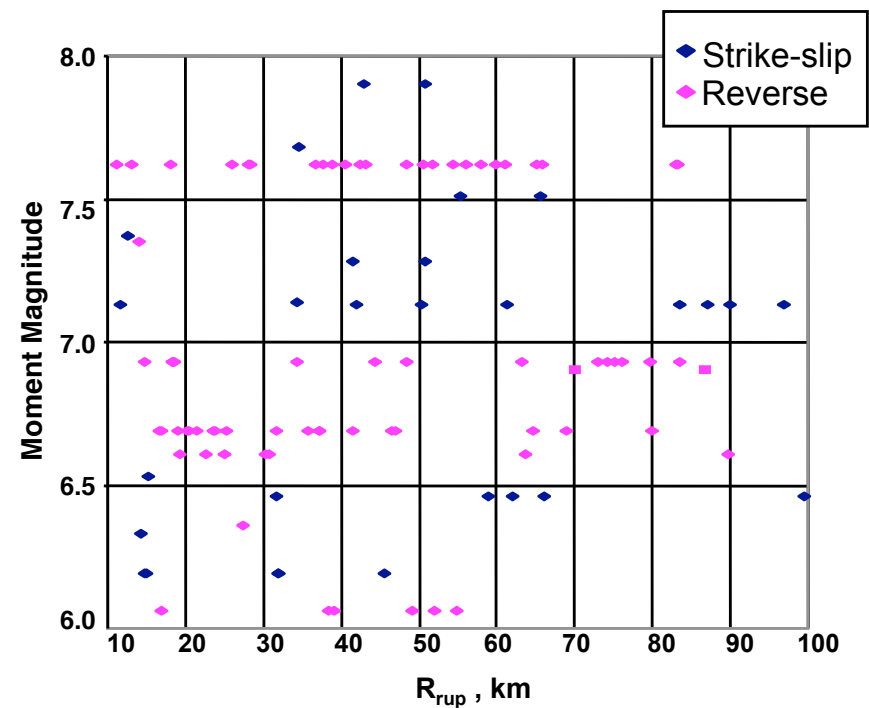
Strike-slip

Reverse

Shallow crustal earthquakes in tectonically active regions

$$V_{s30} > 600 \text{ m/sec}$$

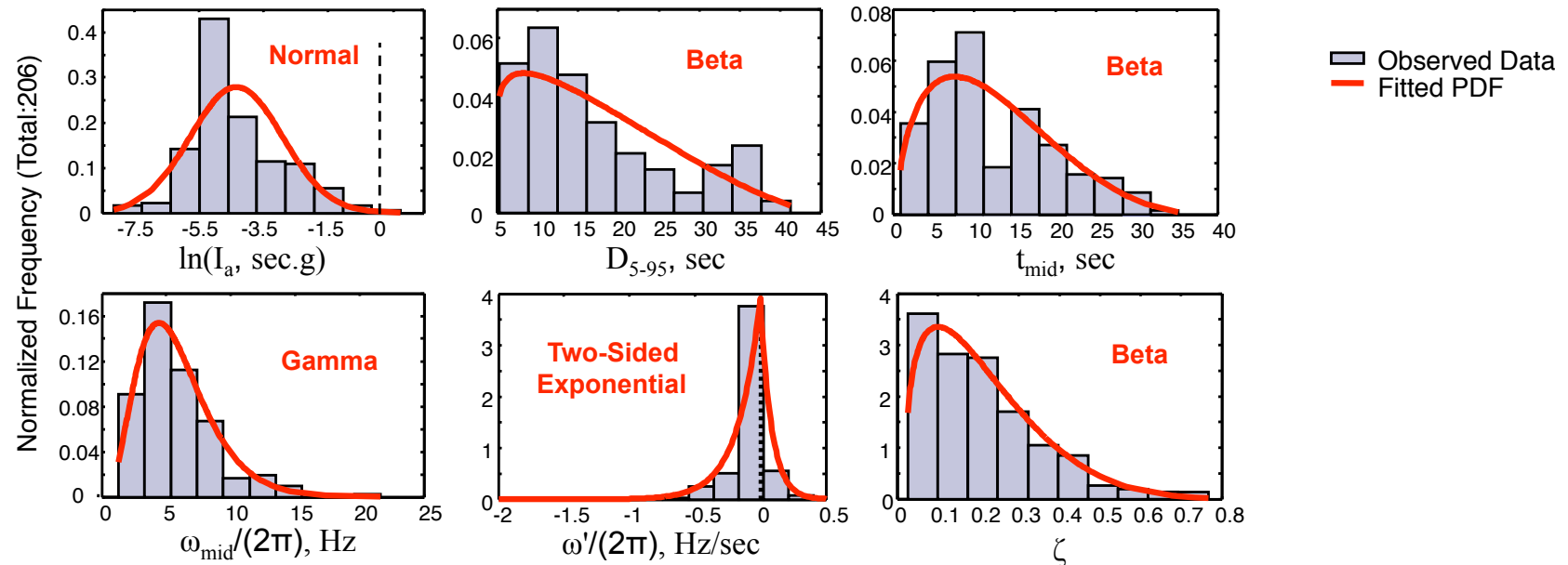
Two horizontal components



Total: 206 Accelerograms

Predictive Equations (Regression):

➤ Distributions assigned to the model parameters:



➤ Regression model (for j^{th} earthquake and k^{th} record of that earthquake):

$$\underbrace{\Phi^{-1}[F_{\theta}(\theta_{jk})]}_{\text{Model parameter } \theta \text{ transformed to the standard normal space}} = \underbrace{\mu(F_j, M_j, R_{\text{rup},jk}, V_{s30,k}, \boldsymbol{\beta})}_{\text{Predicted mean conditioned on earthquake and site characteristics}} + \underbrace{\hat{\eta}_j + \hat{\varepsilon}_{jk}}_{\text{Independent Normally-distributed errors}}$$

Regression Results (Predictive Equations):

Formulation:

$$\ln(I_a) = \beta_0 + \beta_1(F) + \beta_2\left(\frac{M}{7.0}\right) + \beta_3\left(\ln\frac{R_{rup}}{25 \text{ km}}\right) + \beta_4\left(\ln\frac{V_{s30}}{750 \text{ m/s}}\right) + \eta + \varepsilon \quad \text{if } \theta = I_a$$

$$\Phi^{-1}[F_\theta(\theta)] = \beta_0 + \beta_1(F) + \beta_2\left(\frac{M}{7.0}\right) + \beta_3\left(\frac{R_{rup}}{25 \text{ km}}\right) + \beta_4\left(\frac{V_{s30}}{750 \text{ m/s}}\right) + \eta + \varepsilon \quad \text{if } \theta = D_{5-95}, t_{mid}, \omega_{mid}, \omega', \zeta_f$$

Maximum Likelihood Estimation:

θ	β_0	β_1	β_2	β_3	β_4	Standard deviation of		
						η	ε	$\eta + \varepsilon$
I_a	-1.844	-0.071	2.944	-1.356	-0.265	0.27	0.59	0.65
D_{5-95}	-6.195	-0.703	6.792	0.219	-0.523	0.46	0.57	0.73
t_{mid}	-5.011	-0.345	4.638	0.348	-0.185	0.51	0.41	0.66
ω_{mid}	2.253	-0.081	-1.810	-0.211	0.012	0.69	0.72	1.00
ω'	-2.489	0.044	2.408	0.065	-0.081	0.13	0.95	0.96
ζ_f	-0.258	-0.477	0.905	-0.289	0.316	0.68	0.76	1.02

Regression Results (Correlations):

Transformed model parameters:

$$\begin{aligned}
 I_{a,tf} &= \Phi^{-1}[F_{I_a}(I_a)] & \omega_{mid,tf} &= \Phi^{-1}[F_{\omega_{mid}}(\omega_{mid})] \\
 D_{5-95,tf} &= \Phi^{-1}[F_{D_{5-95}}(D_{5-95})] & \omega'_{tf} &= \Phi^{-1}[F_{\omega'}(\omega')] \\
 t_{mid,tf} &= \Phi^{-1}[F_t(t_{mid})] & \zeta_{tf} &= \Phi^{-1}[F_{\zeta_f}(\zeta_f)]
 \end{aligned}$$

ρ	$I_{a,tf}$	$D_{5-95,tf}$	$t_{mid,tf}$	$\omega_{mid,tf}$	ω'_{tf}	ζ_{tf}
$I_{a,tf}$	1	-0.36	0.01	-0.15	0.13	-0.01
$D_{5-95,tf}$		1	0.67	-0.13	-0.16	-0.20
$t_{mid,tf}$			1	-0.28	-0.20	-0.22
$\omega_{mid,tf}$				1	-0.20	0.28
ω'_{tf}		Symmetric			1	-0.01
ζ_{tf}						1

(given the earthquake and site characteristics)

Example 1 : Acceleration

4 simulated motions and 1 real recording for the given design scenario:

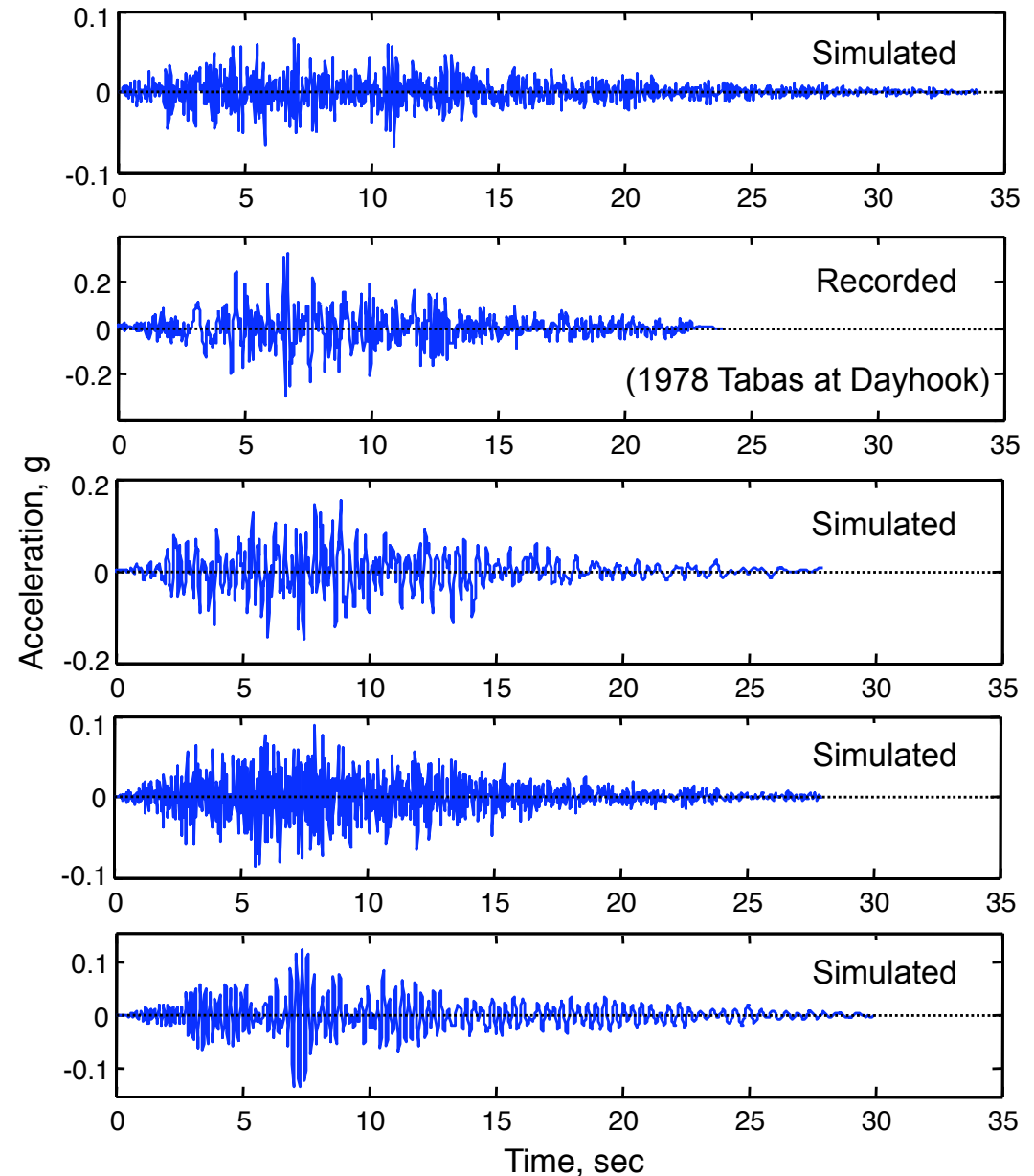
$F = 1$ (Reverse)

$M = 7.35$

$R_{rup} = 14$ km

$V_{S30} = 660$ m/sec

Realizations of model parameters:					
I_a sec.g	D_{5-95} sec	t_{mid} sec	$\omega_{mid}/(2\pi)$ Hz	$\omega'/(2\pi)$ Hz/sec	ζ
0.012	17.23	6.27	6.88	-0.01	0.14
0.145	12.30	6.78	5.90	0.12	0.26
0.055	14.22	7.22	4.48	-0.16	0.38
0.014	14.07	6.31	10.75	-0.24	0.26
0.036	14.87	8.32	4.36	-0.15	0.03



Example 1 : Velocity

4 simulated motions and 1 real recording for the given design scenario:

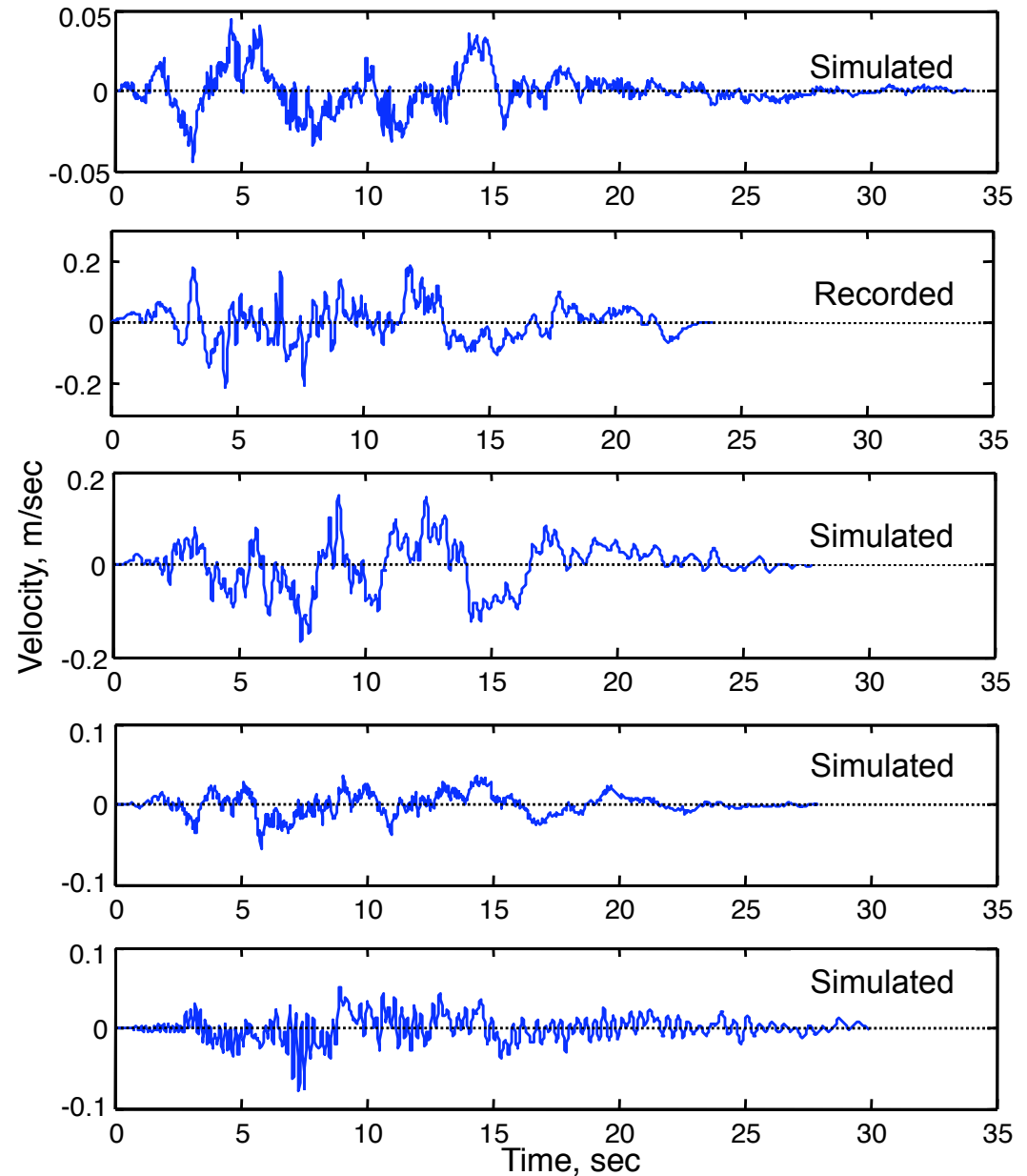
$F = 1$ (Reverse)

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$R_{rup} = 14$ km

$V_{S30} = 660$ m/sec

Realizations of model parameters:					
I_a sec.g	D_{5-95} sec	t_{mid} sec	$\omega_{mid}/(2\pi)$ Hz	$\omega'/(2\pi)$ Hz/sec	ζ
0.012	17.23	6.27	6.88	-0.01	0.14
0.145	12.30	6.78	5.90	0.12	0.26
0.055	14.22	7.22	4.48	-0.16	0.38
0.014	14.07	6.31	10.75	-0.24	0.26
0.036	14.87	8.32	4.36	-0.15	0.03



Example 1 : Displacement

4 simulated motions and 1 real recording for the given design scenario:

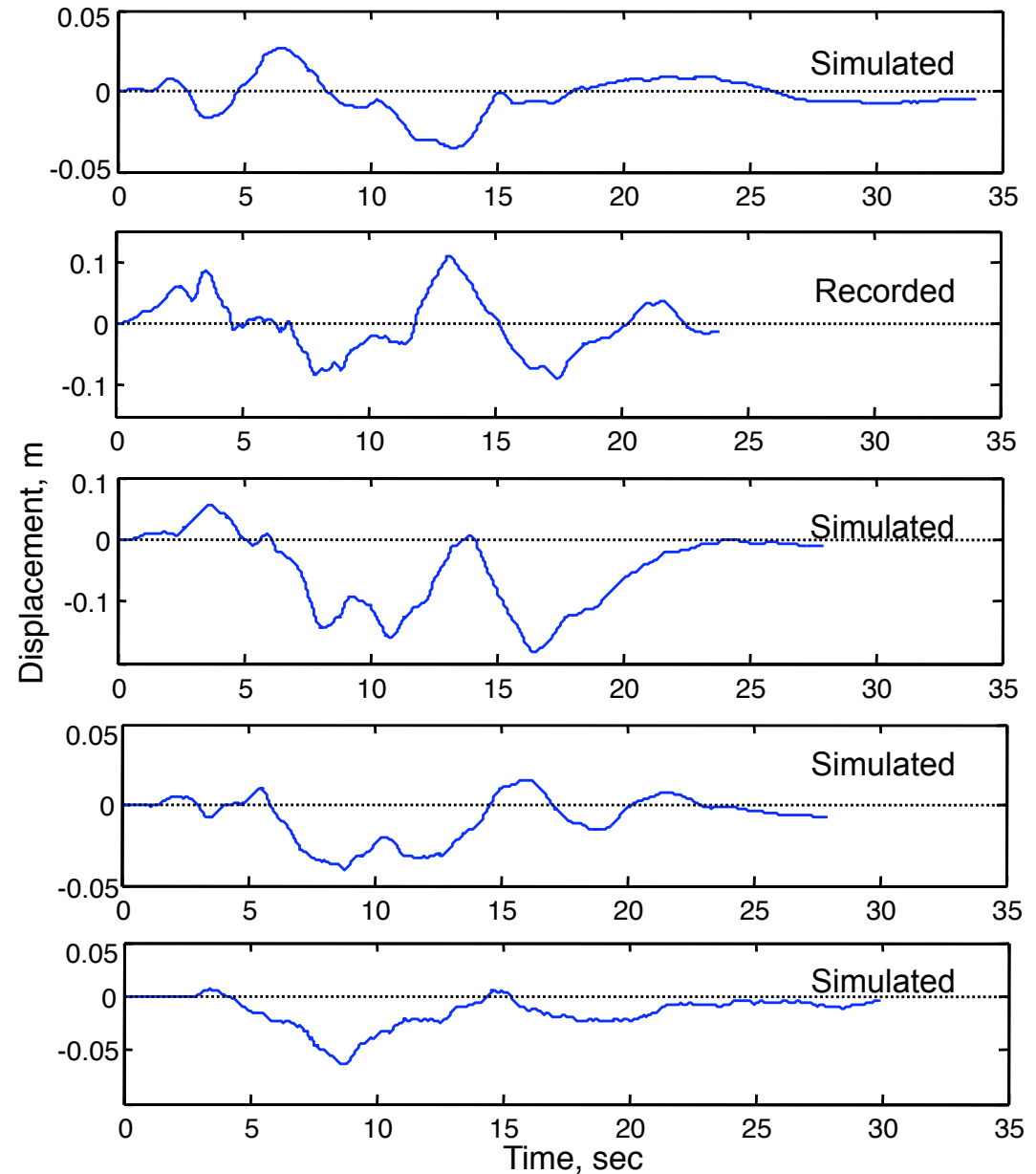
$F = 1$ (Reverse)

$M = 7.35$

$R_{rup} = 14$ km

$V_{S30} = 660$ m/sec

Realizations of model parameters:					
I_a sec.g	D_{5-95} sec	t_{mid} sec	$\omega_{mid}/(2\pi)$ Hz	$\omega'/(2\pi)$ Hz/sec	ζ
0.012	17.23	6.27	6.88	-0.01	0.14
0.145	12.30	6.78	5.90	0.12	0.26
0.055	14.22	7.22	4.48	-0.16	0.38
0.014	14.07	6.31	10.75	-0.24	0.26
0.036	14.87	8.32	4.36	-0.15	0.03



Example 2 :

If desired, a fixed value may be assigned to one or more of the model parameters:

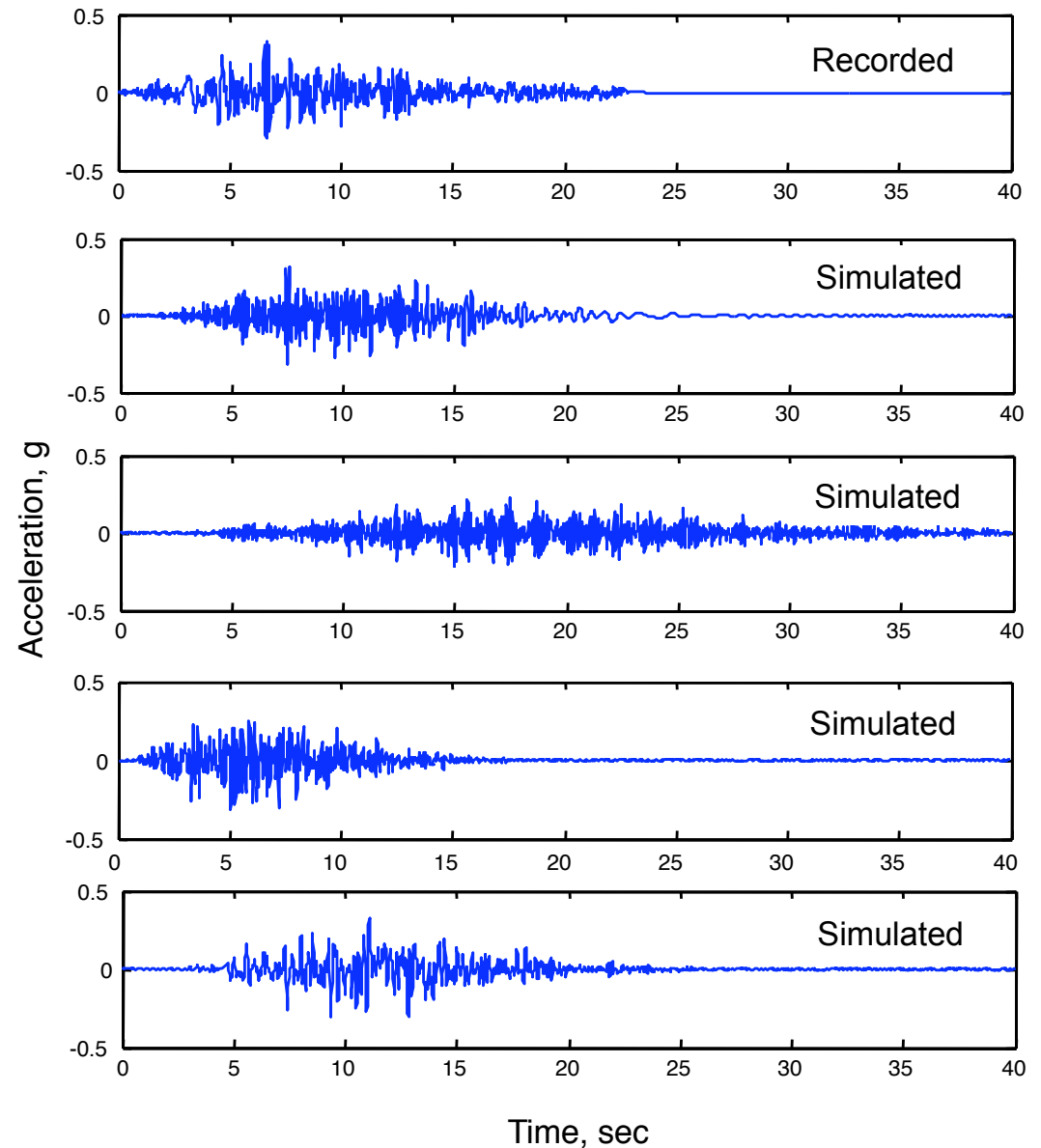
$F = 1$ (Reverse)

$M = 7.35$

$R_{rup} = 14$ km

$V_{S30} = 660$ m/sec

Realizations of model parameters:					
I_a sec.g	D_{5-95} sec	t_{mid} sec	$\omega_{mid}/(2\pi)$ Hz	$\omega'/(2\pi)$ Hz/sec	ζ
0.145	12.30	6.78	5.90	012	0.26
0.145	12.79	9.86	7.48	-0.52	0.13
0.145	22.11	16.24	8.05	-0.09	0.12
0.145	8.14	5.31	7.34	-0.02	0.30
0.145	11.01	10.30	4.43	0.12	0.29



Example 3 : Response Spectrum (5% damped)

2 horizontal components of a **recorded** motion (1994 Northridge at LA Wonderland Ave)

Vs.

50 **simulated** motions

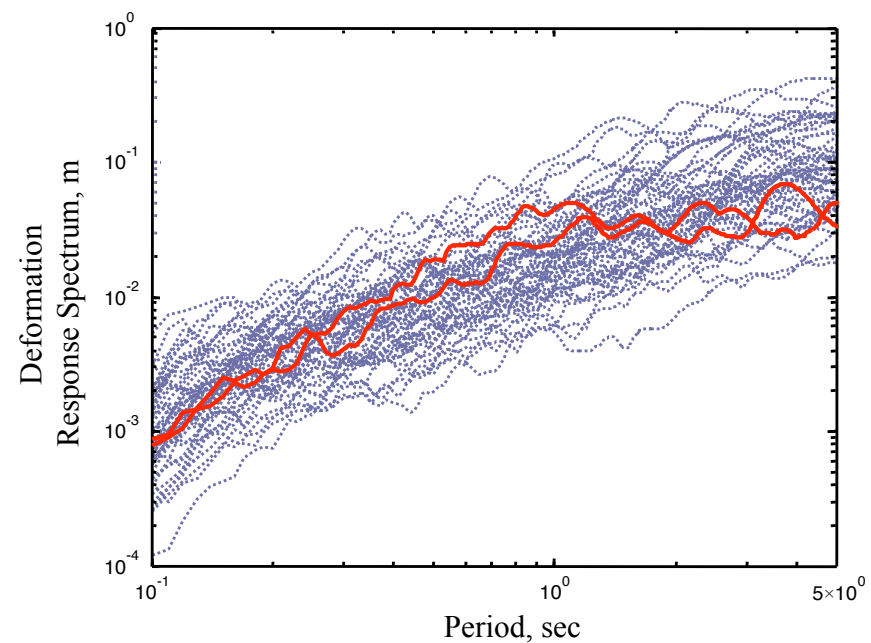
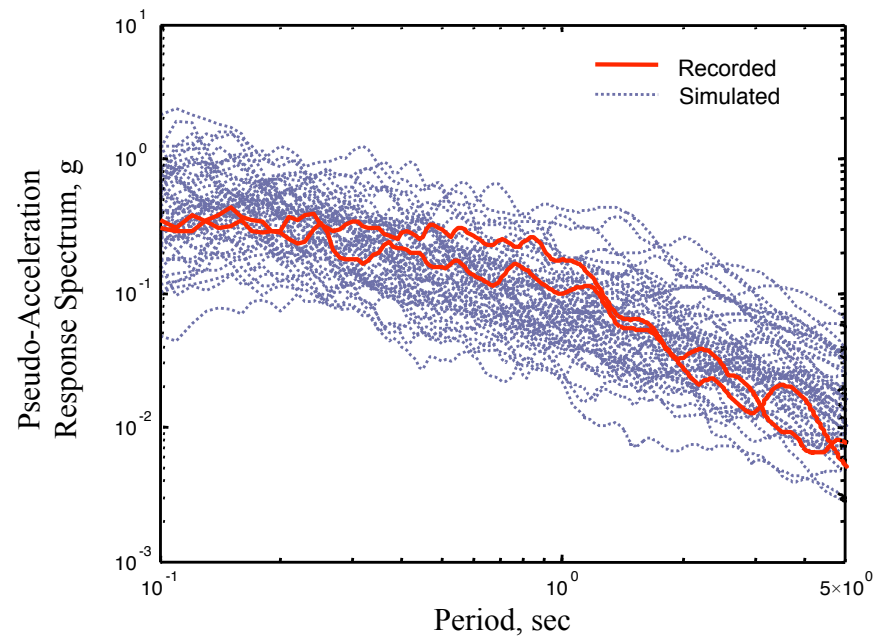
Corresponding to earthquake and site characteristics:

$F = 1$ (Reverse)

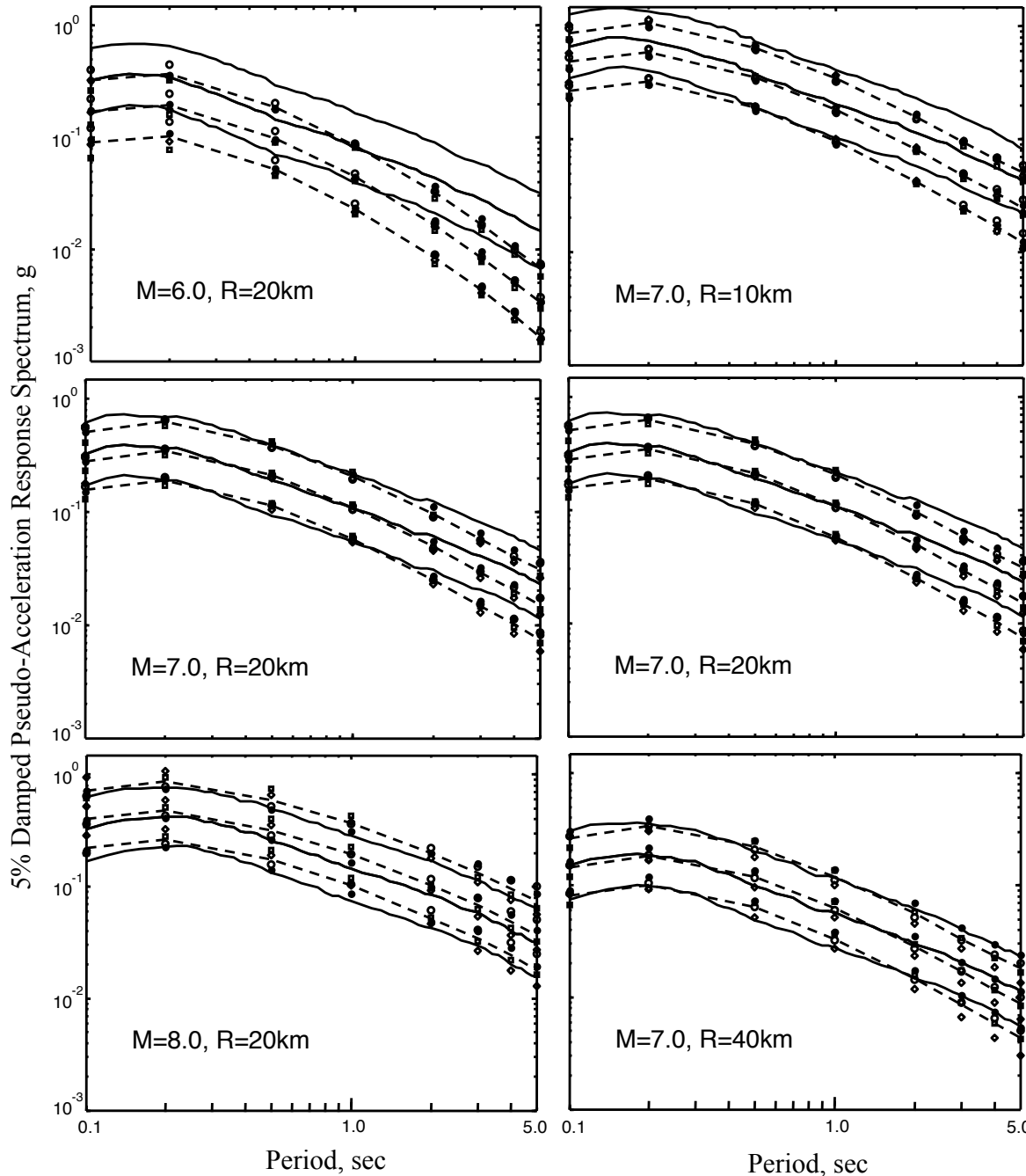
$M = 6.69$

$R_{rup} = 20.3$ km

$V_{S30} = 1223$ m/sec



Comparison with NGA Models:



Selected NGA Models:

- Campbell-Bozorgnia ($z_{2.5} = 1\text{km}$)
- Abrahamson-Silva ($z_{1.0} = 34\text{m}$)
- ◇ Chiou-Youngs ($z_{1.0} = 24\text{m}$)
- Boore-Atkinson

NGA Parameters:

Rupture width = 20km
Rupture depth = 1km

Avg NGA

500 Simulations

- Median +1 logarithmic stdv. _____
- Median _____
- Median -1 logarithmic stdv. _____

$F = 0$ (Strike-Slip)

$V_{s30} = 760$ m/sec

Note:

Models based on different subsets of NGA database.

Observe:

Except for $M=6.0$ (lower bound of database), deviations are much smaller than the variability present in the NGA prediction equations.

→ Synthetics are in close agreement with NGA.

Current & Future Developments:

- Simulating correlated orthogonal horizontal ground motion components.

$$\text{Component 1: } x_1(t) = q(t, \boldsymbol{\alpha}_1) \left[\frac{1}{\sigma_h(t)} \int_{-\infty}^t h[t - \tau, \boldsymbol{\lambda}_1(\tau)] w_1(\tau) d\tau \right]$$

$$\text{Component 2: } x_2(t) = q(t, \boldsymbol{\alpha}_2) \left[\frac{1}{\sigma_h(t)} \int_{-\infty}^t h[t - \tau, \boldsymbol{\lambda}_2(\tau)] w_2(\tau) d\tau \right]$$

Motions in the database are rotated to the principal axes so that $w_1(\tau)$ and $w_2(\tau)$ are statistically independent.

Model is fitted to the rotated database to estimate correlations: $\rho_{\boldsymbol{\alpha}_1, \boldsymbol{\alpha}_2}$ and $\rho_{\boldsymbol{\lambda}_1, \boldsymbol{\lambda}_2}$

Current & Future Developments:

- Simulating near-field ground motions.

Separately model and superimpose:

1) The directivity pulse

Long period pulse in the velocity time-series of the *fault-normal* component.

Develop prediction equations for characteristics of the pulse in terms of earthquake/site parameters.

Collaboration with Jack Baker:

Using wavelet analysis, directivity pulse extracted from a database of near-field motions, this database will be used to develop prediction equations.

2) The fling step

Permanent displacement may exist in the *fault-parallel* component.

Incorporate the available seismological models (e.g., Somerville 1998, Abrahamson 2001).

3) The residue motion

The total motion minus the directivity pulse and the fling step.

Model by a modified version of the far-field stochastic ground motion process.

Current & Future Developments:

- Scrutinize the simulated motions for inelastic structural responses.

Compare inelastic response spectra (for given ductility ratios) of synthetic motions with real recordings and existing prediction equations (e.g., Bozorgnia et. al., 2010).

Case Study:

Compare inelastic response of a multi-degree-of-freedom structure to simulated and recorded motions.

Related Publications:

Rezaeian, S. and A. Der Kiureghian,
"A stochastic ground motion model with separable temporal and spectral nonstationarities,"
Earthquake Engineering and Structural Dynamics, July 2008, Vol. 37, pp. 1565-1584.

Rezaeian, S. and A. Der Kiureghian,
"Simulation of synthetic ground motions for specified earthquake and site characteristics,"
Earthquake Engineering and Structural Dynamics, 2009. Submitted.

MATLAB software to be made available

Current abilities:

Fitting the stochastic model to a target accelerogram.

Simulating far-field strong motions on firm-ground for specified F , M , R_{rup} , V_{s30} .

Will be added by May 2010:

Two component simulation.

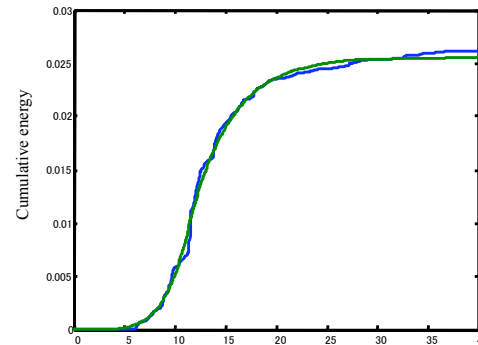
Near-field simulation.



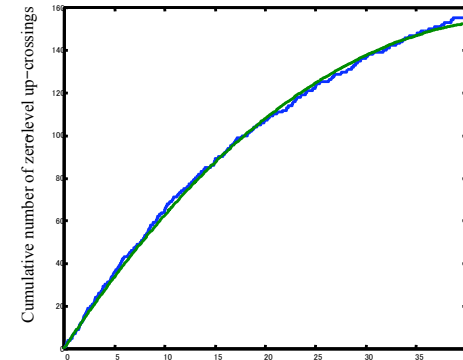
Thank You

Features of target accelerogram

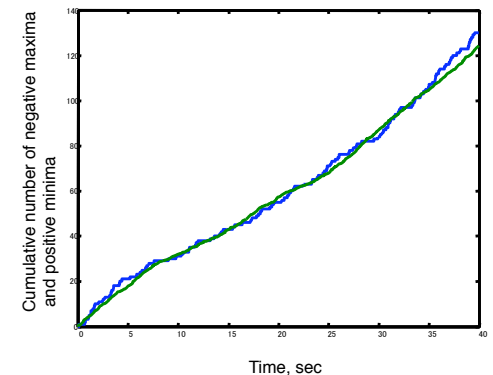
➤ Cumulative energy



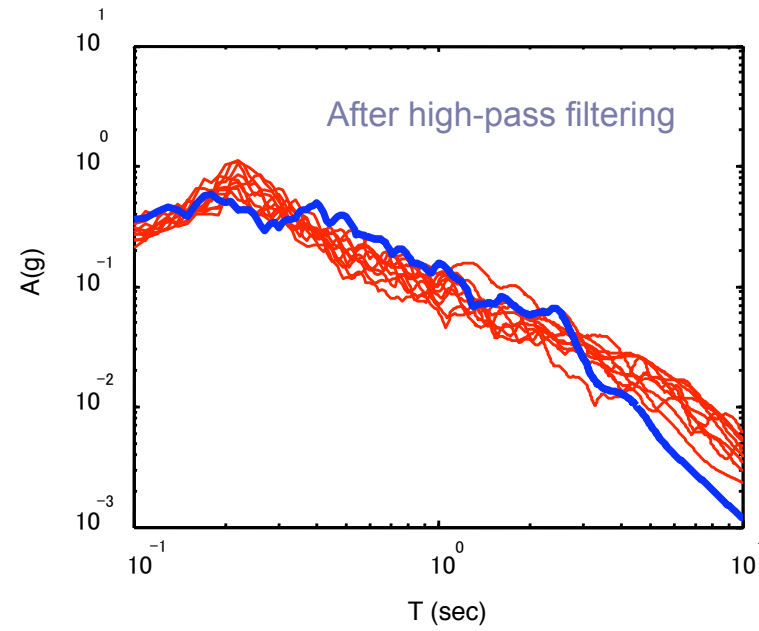
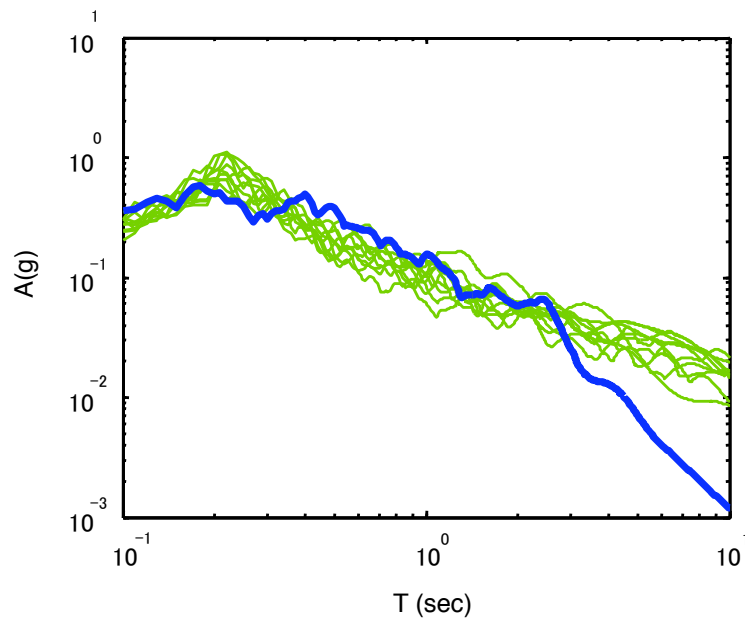
➤ Cumulative number of zero-level up crossings – a measure of dominant frequency



➤ Cumulative number of positive minima and negative maxima – a measure of bandwidth



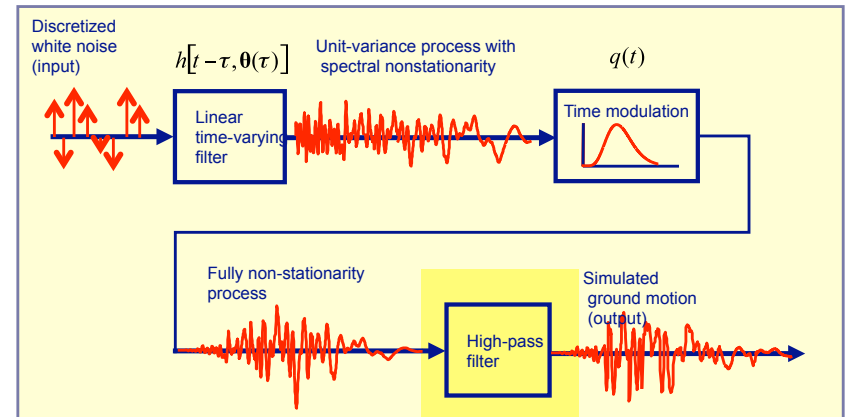
Response spectrum



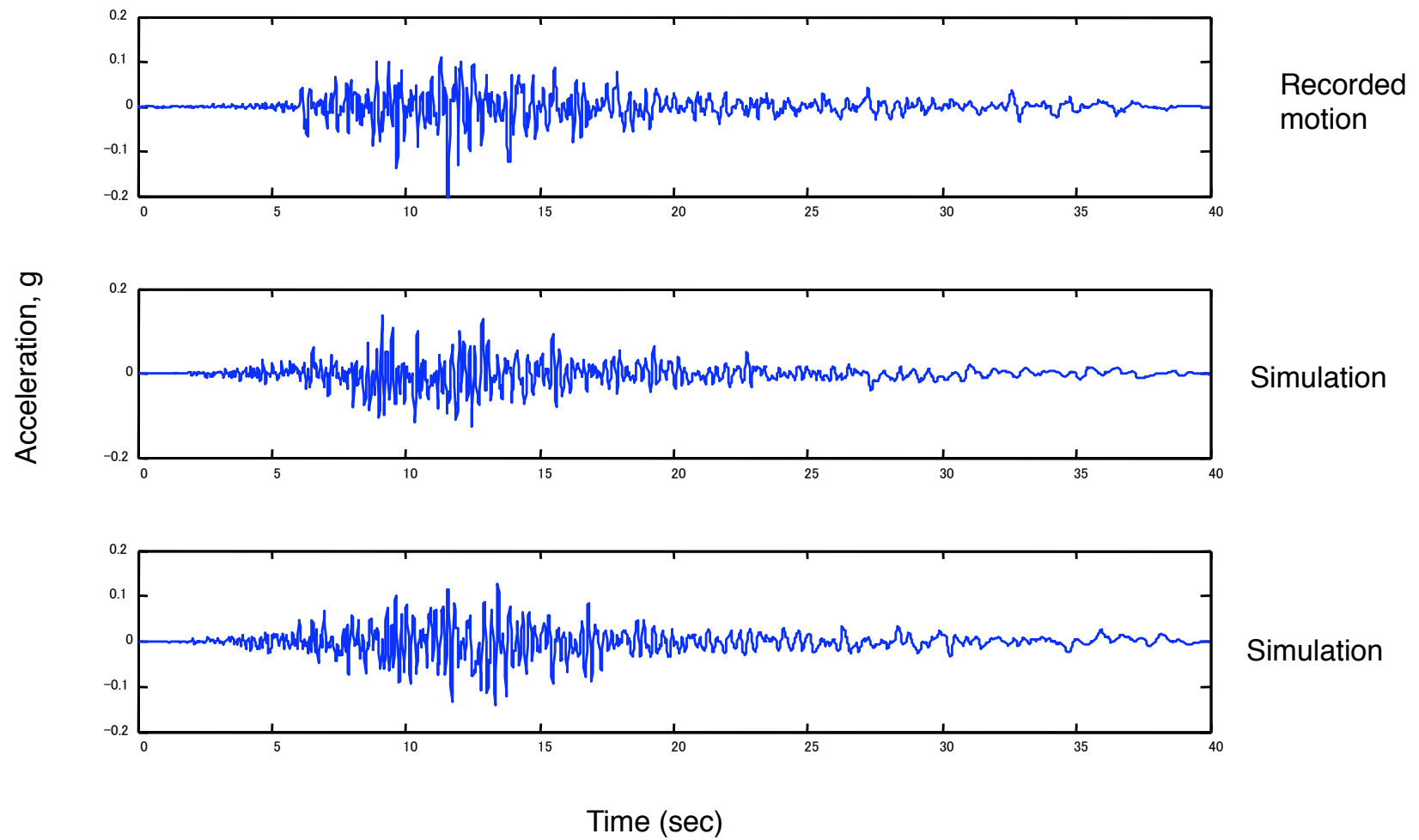
Post-processing is needed for long-period range. A critically damped oscillator is used as a high-pass filter.

$$\ddot{z} + 2\omega_c \dot{z} + \omega_c^2 z = \hat{x}(t)$$

ω_c = corner frequency



Northridge earthquake



Kobe earthquake

