SIMULATION of NEAR-FAULT GROUND MOTIONS for SPECIFIED EARTHQUAKE SOURCE and SITE CHARACTERISTICS

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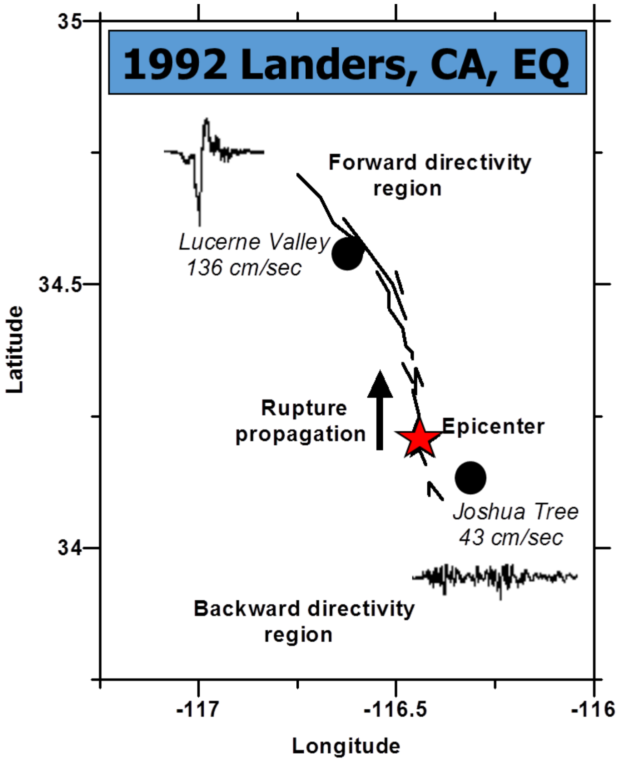
Motivation

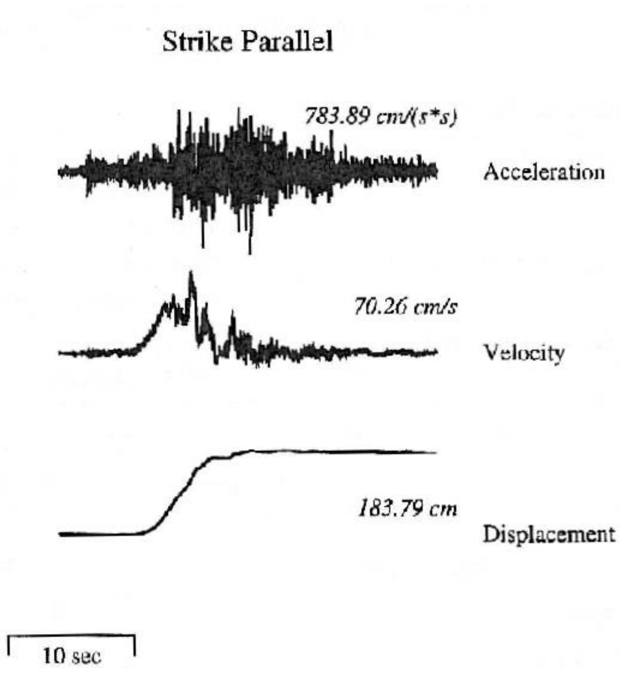
- Characteristics of near-fault (NF) ground motions (GM) are different from far-field GMs

Rupture directivity effect



(figure courtesy of Y. Bozorgnia, adopted from Somerville et al. [1997]).

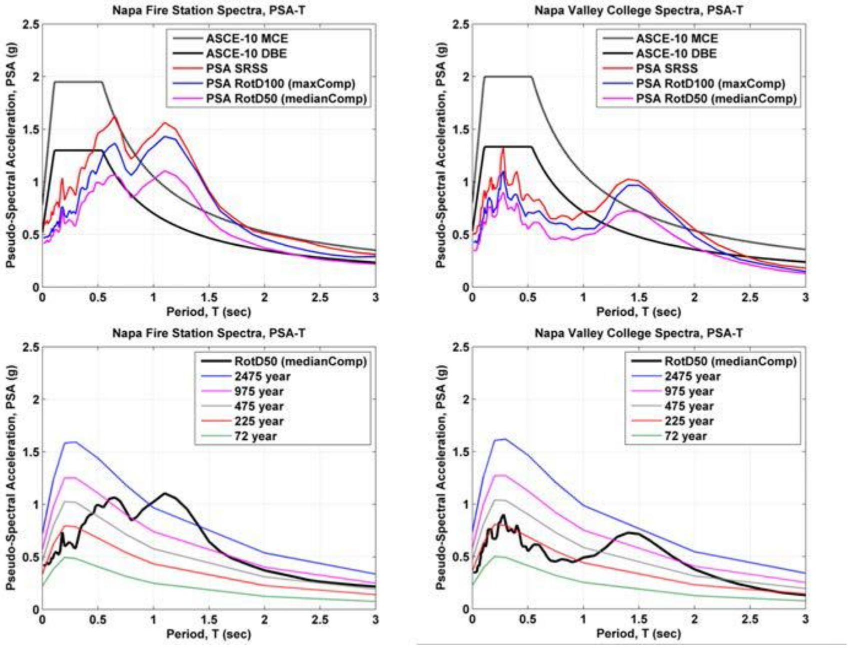
Fling Step



(after Somerville et al. [1997]).

Motivation

- NF effects not properly represented in modern codes and current ground motion prediction equations (GMPEs).
- May underestimate:
  - Elastic demands on long period structures
  - Damage potential to ductile short-period structures



NF records from 2014 South Napa EQ vs. code spectra and UHS *(directivity and/or site effects)*
(source: Bray et al., 2014).

- Attempt to develop NGA West2 directivity models (Spudich et al., 2014)

Motivation

- Recorded NF GMs remain scarce
- Ongoing effort to understand, model, and simulate NF GMs and their effects on the response of structures
- Proposed Methodology:
  - Site-based stochastic model of NF GMs in 2 orthogonal horizontal directions
  - Simulation procedure for specified EQ source and site characteristics

<u>*References:*</u>

- Dabaghi M, Der Kiureghian A. (2016). Stochastic model for simulation of near-fault ground motions, *submitted manuscript.*
- Dabaghi M, Der Kiureghian A. (2014). Stochastic modeling and simulation of near-fault ground motions for performance-based earthquake engineering, *PEER Report No. 2014/20*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.
- Rezaeian S, Der Kiureghian A. (2010). Simulation of synthetic ground motions for specified earthquake and site characteristics. *Earthquake Engineering & Structural Dynamics*; **39** (10): 1155-1180.

Outline

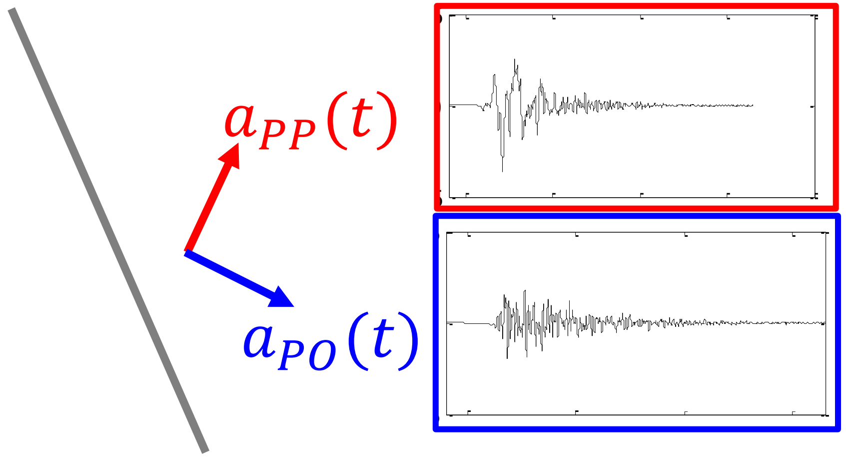
- Overview of NF Ground Motion Model
- Overview of Simulation Framework
- Illustrative Examples
  - #1: Forward vs. Backward Directivity Sites
  - #2: Hypothetical M6.5 Strike-Slip Earthquake Event
- Summary and Conclusions

Overview of Stochastic Model of NF Ground Motion

Pulse-like and Non-pulse-like

Pulse-like GM Model

- Pulse in at least one horizontal direction, due to rupture directivity…
- Model formulated in:
  - direction of the largest pulse: $a_{PP}(t)$
  - corresponding orthogonal direction: $a_{PO}(t)$



Pulse-like GM Model

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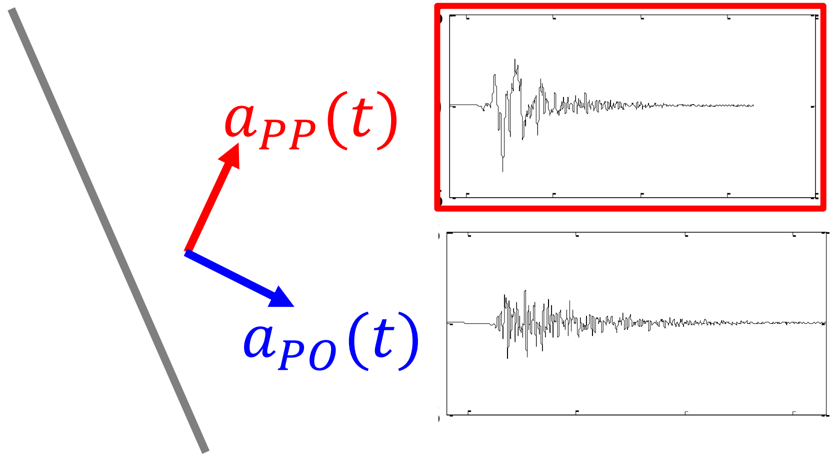

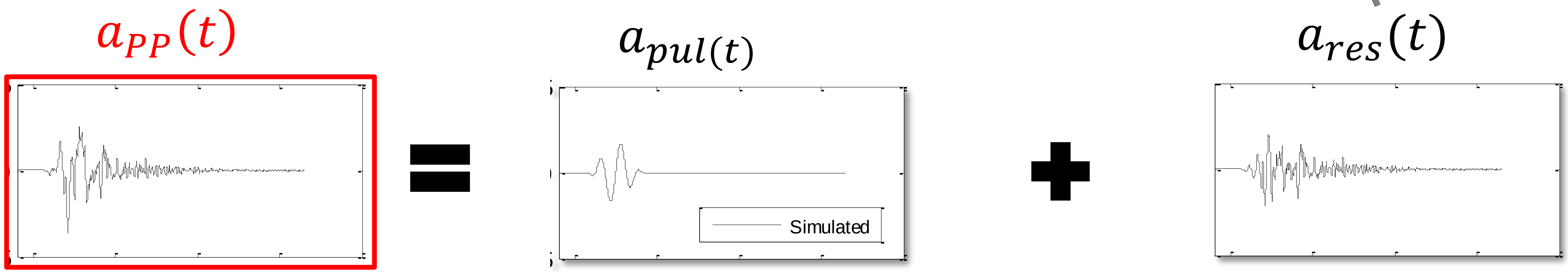

mMP: modified Mavroeidis & Papageorgiou (2003) pulse model

$(V_p, T_p, \gamma, \nu, t_{max,p})$

MFW: modified Rezaeian & Der Kiureghian (2010) modulated and filtered white noise model

$(I_a, D_{5-95}, D_{0-5}, D_{0-30}, f_{mid}, f', \zeta_f)$

Pulse-like GM Model

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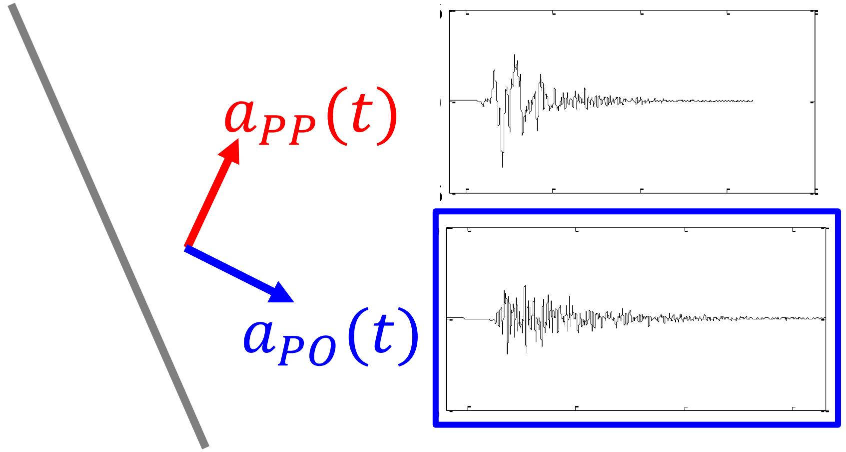
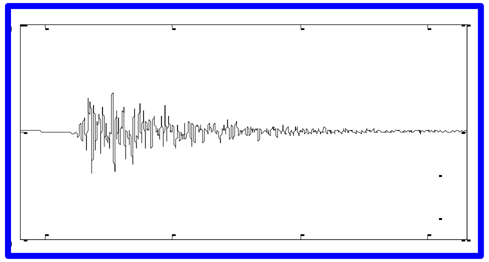


$a_{PO}(t)$



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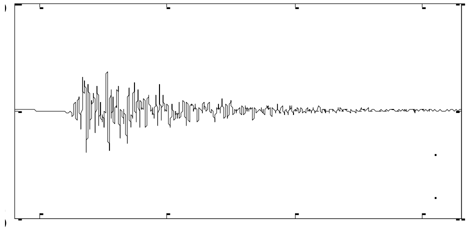


MFW: modified Rezaeian & Der Kiureghian (2010) modulated and filtered white noise model

$(I_a, D_{5-95}, D_{0-5}, D_{0-30}, f_{mid}, f', \zeta_f)$

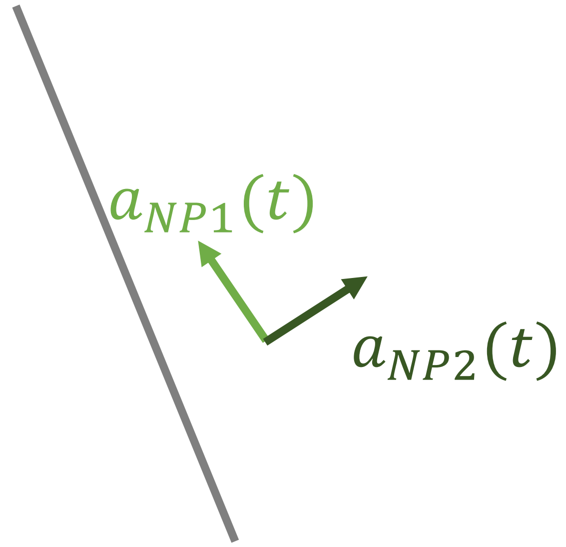
Pulse-like GM Model

Complete list of the parameters $\alpha_{P,i}$ of the pulse-like model, $i = 1, \dots, 19$.

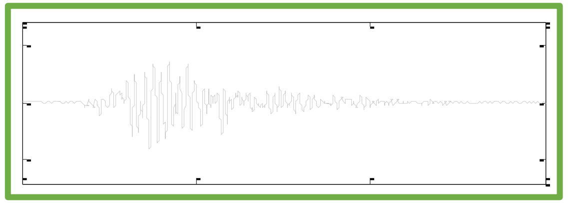
$a_{pul}(t)$:	Pulse	$\alpha_{P,1}$	$\alpha_{P,2}$	$\alpha_{P,3}$	$\alpha_{P,4}$	$\alpha_{P,5}$		
		V_p(cm/s)	T_p(s)	γ	ν/π(rad)	$t_{max,p}$(s)		
$a_{res}(t)$:	Residual	$\alpha_{P,6}$	$\alpha_{P,7}$	$\alpha_{P,8}$	$\alpha_{P,9}$	$\alpha_{P,10}$	$\alpha_{P,11}$	$\alpha_{P,12}$
		$I_{a,res}$(cm/s)	$D_{5-95,res}$(s)	$D_{0-5,res}$(s)	$D_{0-30,res}$(s)	$f_{mid,res}$ (Hz)	f'_{res}(Hz/s)	$\zeta_{f,res}$
$a_{PO}(t)$:	Orthogonal	$\alpha_{P,13}$	$\alpha_{P,14}$	$\alpha_{P,15}$	$\alpha_{P,16}$	$\alpha_{P,17}$	$\alpha_{P,18}$	$\alpha_{P,19}$
		$I_{a,PO}$(cm/s)	$D_{5-95,PO}$(s)	$D_{0-5,PO}$(s)	$D_{0-30,PO}$(s)	$f_{mid,PO}$(Hz)	f'_{PO}(Hz/s)	$\zeta_{f,PO}$

Non-pulse-like GM Model

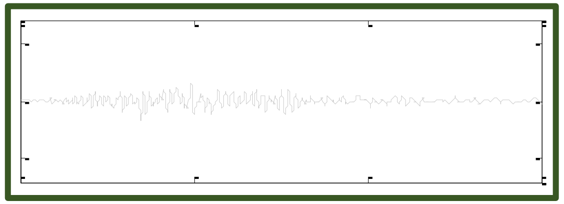
- No pulse in any horizontal direction
- Formulated in:
  - Major principal direction: $a_{NP1}(t)$
  - Intermediate principal direction: $a_{NP2}(t)$



$a_{NP1}(t)$



$a_{NP2}(t)$



MFW: modified Rezaeian & Der Kiureghian (2010) modulated and filtered white noise model

$(I_a, D_{5-95}, D_{0-5}, D_{0-30}, f_{mid}, f', \zeta_f)$

Non-pulse-like GM Model

Complete list of the parameters $\alpha_{NP,i}$ of the non-pulse-like model, $i = 1, \ldots, 14.$

$a_{NP1}(t)$:	Major	$\alpha_{NP,1}$	$\alpha_{NP,2}$	$\alpha_{NP,3}$	$\alpha_{NP,4}$	$\alpha_{NP,5}$	$\alpha_{NP,6}$	$\alpha_{NP,7}$
		$I_{a,NP1}$(cm/s)	$D_{5-95,NP1}$(s)	$D_{0-5,NP1}$(s)	$D_{0-30,NP1}$(s)	$f_{mid,NP1}$(Hz)	f'_{NP1}(Hz/s)	$\zeta_{f,NP1}$
$a_{NP2}(t)$:	Intermediate	$\alpha_{NP,8}$	$\alpha_{NP,9}$	$\alpha_{NP,10}$	$\alpha_{NP,11}$	$\alpha_{NP,12}$	$\alpha_{NP,13}$	$\alpha_{NP,14}$
		$I_{a,NP2}$(cm/s)	$D_{5-95,NP2}$(s)	$D_{0-5,NP2}$(s)	$D_{0-30,NP2}$(s)	$f_{mid,NP2}$(Hz)	f'_{NP2}(Hz/s)	$\zeta_{f,NP2}$

Overview of Simulation Framework

Simulation of 2 orthogonal NF GM components

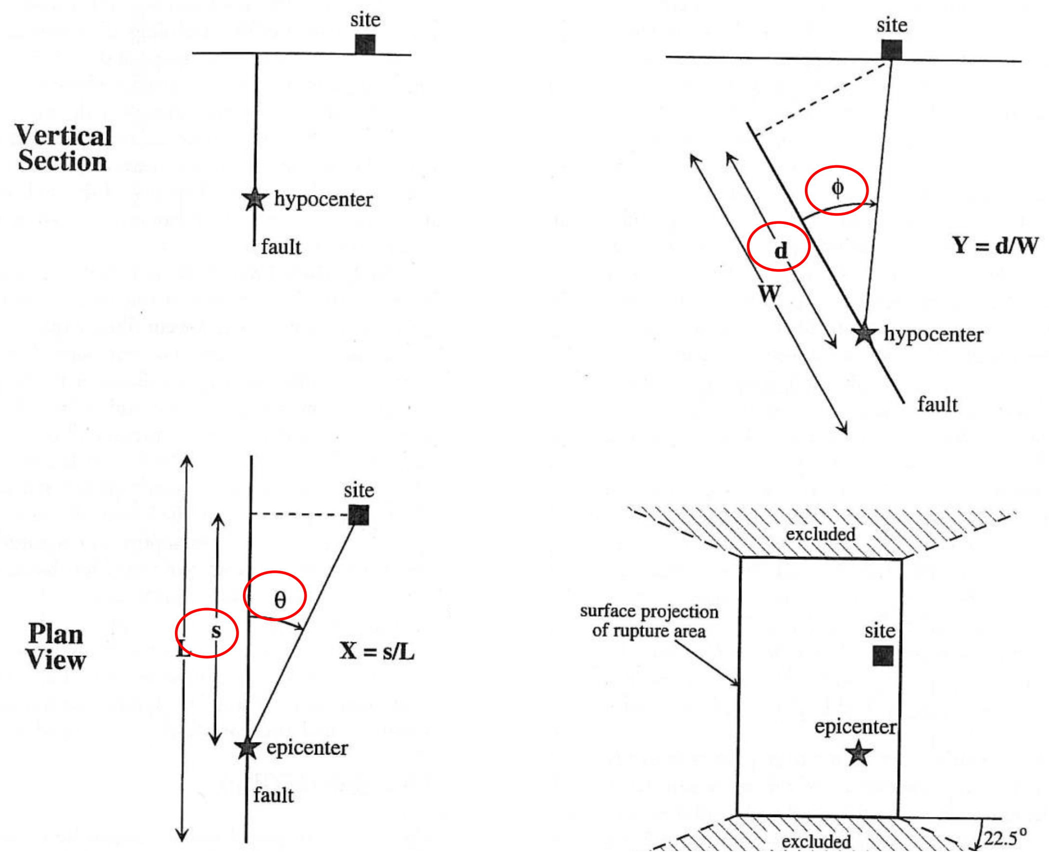
Predictive Models

- Input:
  - EQ source and site characteristics ($F, M_w, Z_{TOR}, R_{RUP}, V_{s30}, s_{or}d, \theta_{or}\phi$)
- Probability of occurrence of a pulse (Shahi and Baker, 2011)
- Empirical predictive relations:
  - for both pulse-like and non-pulse-like model parameters
- Orientation of the simulated components with respect to fault strike

Input Parameters (or Predictor Variables)

- EQ design scenario: $(F, M_w, Z_{TOR}, R_{RUP}, V_{s30}, s_{or}d, \theta_{or}\phi)$
  - description of the EQ source and site characteristics
  - including directivity parameters

Strike-Slip



Reverse
Reverse-Oblique

For any style of faulting, we use:

$s_{or}d = \max(s, d)$
If $s_{or}d = s, \quad \theta_{or}\phi = \theta$
If $s_{or}d = d, \quad \theta_{or}\phi = \phi$

Pulse Probability Model

- Input: $(F, R_{RUP}, s_{or}d, \theta_{or}\phi)$
- Output: Probability of occurrence of a directivity pulse in at least one direction at a site (Shahi and Baker, 2011)

$$\Pr[\text{pulselike}|F, R_{RUP}, s_{or}d, \theta_{or}\phi]$$

$$= \frac{1}{1+\exp(0.642+0.167R_{RUP}-0.075s_{or}d)}, \quad if\ F = 0$$

$$= \frac{1}{1+\exp(0.128+0.055R_{RUP}-0.061s_{or}d+0.036\theta_{or}\phi)}, \quad if\ F = 1$$

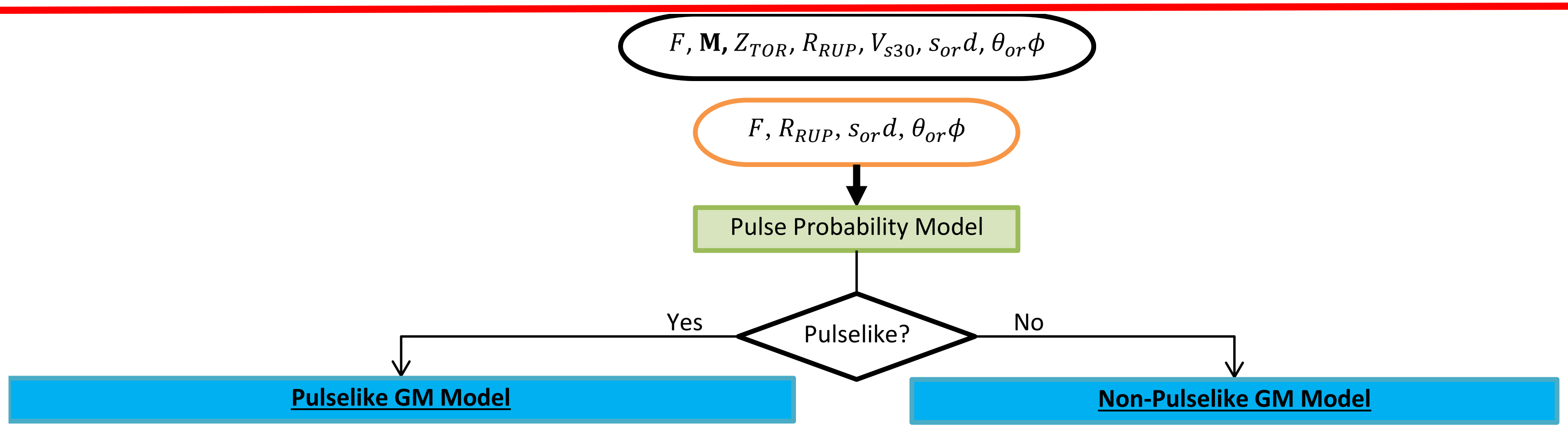
Empirical Predictive Relations for Model Parameters

- Input: $(F, M_w, Z_{TOR}, R_{RUP}, V_{s30}, s_{or}d)$
- Using: results of regression and correlation analyses
- Output: **<u>simulated</u>** parameters of pulse-like and non-pulse-like GM models
  - model parameters $z_{P,i}$, $z_{NP,i}$ in the *<u>normal</u>* space (**correlated,** and with **natural variability**)
  - transformed to *<u>original</u>* parameter space: $\alpha_{P,i}$, $\alpha_{NP,i}$

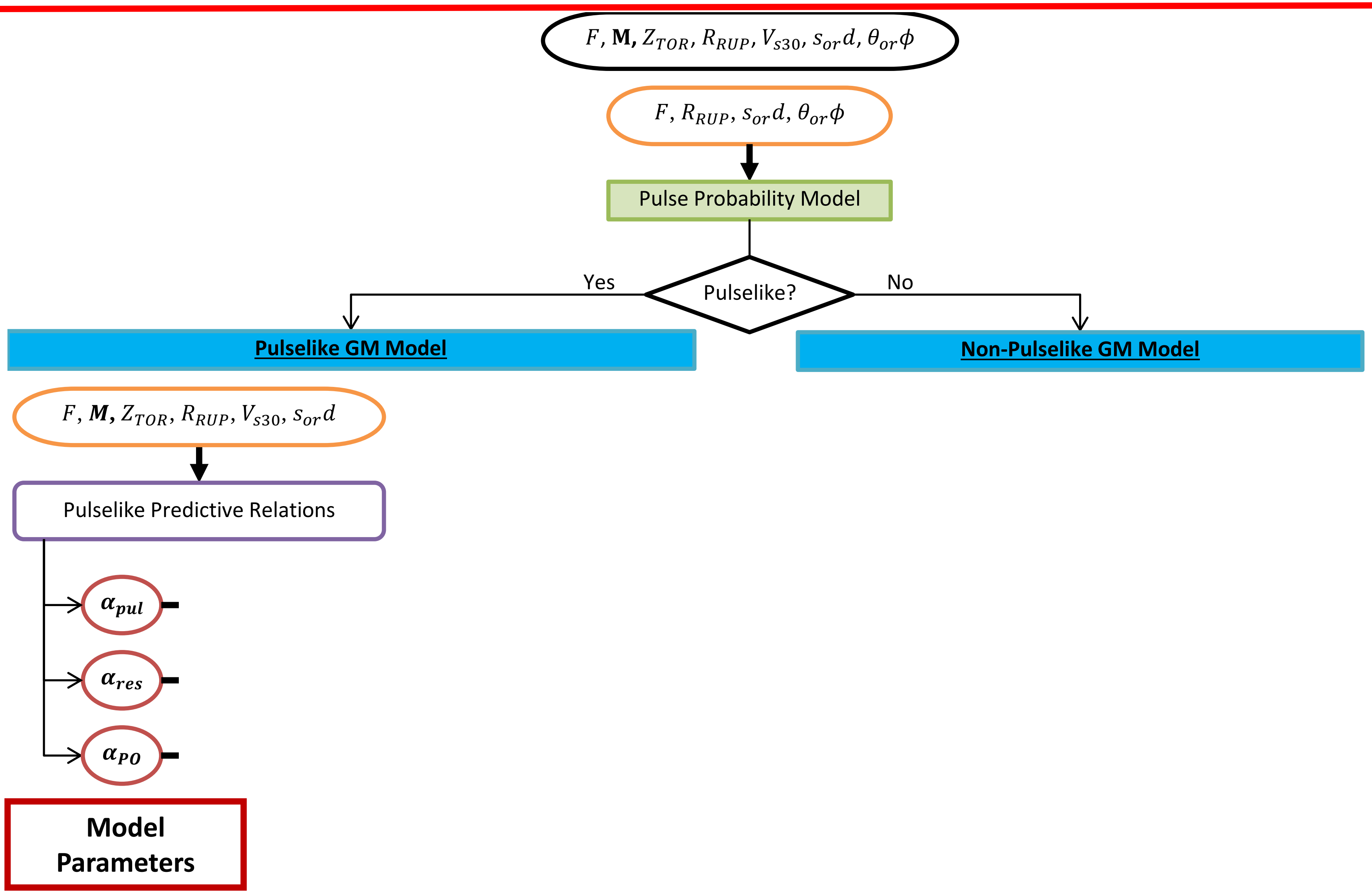
Functional forms chosen to be consistent with seismological theory

$$\mathrm{E}[z] = \beta_0 + \beta_1 M_w + \beta_2 (M_w - 6.5)\mathbb{I}(M_w > 6.5) + \beta_3 F f_{flt,Z} + \beta_4 \ln\left(\sqrt{R_{RUP}^2 + h^2}\right) + \beta_5 M_w . \ln\left(\sqrt{R_{RUP}^2 + h^2}\right) + \beta_6 \ln(\hat{V}_{s30}) + \beta_7 s_{or} d$$

Simulation Procedure



Simulation Procedure



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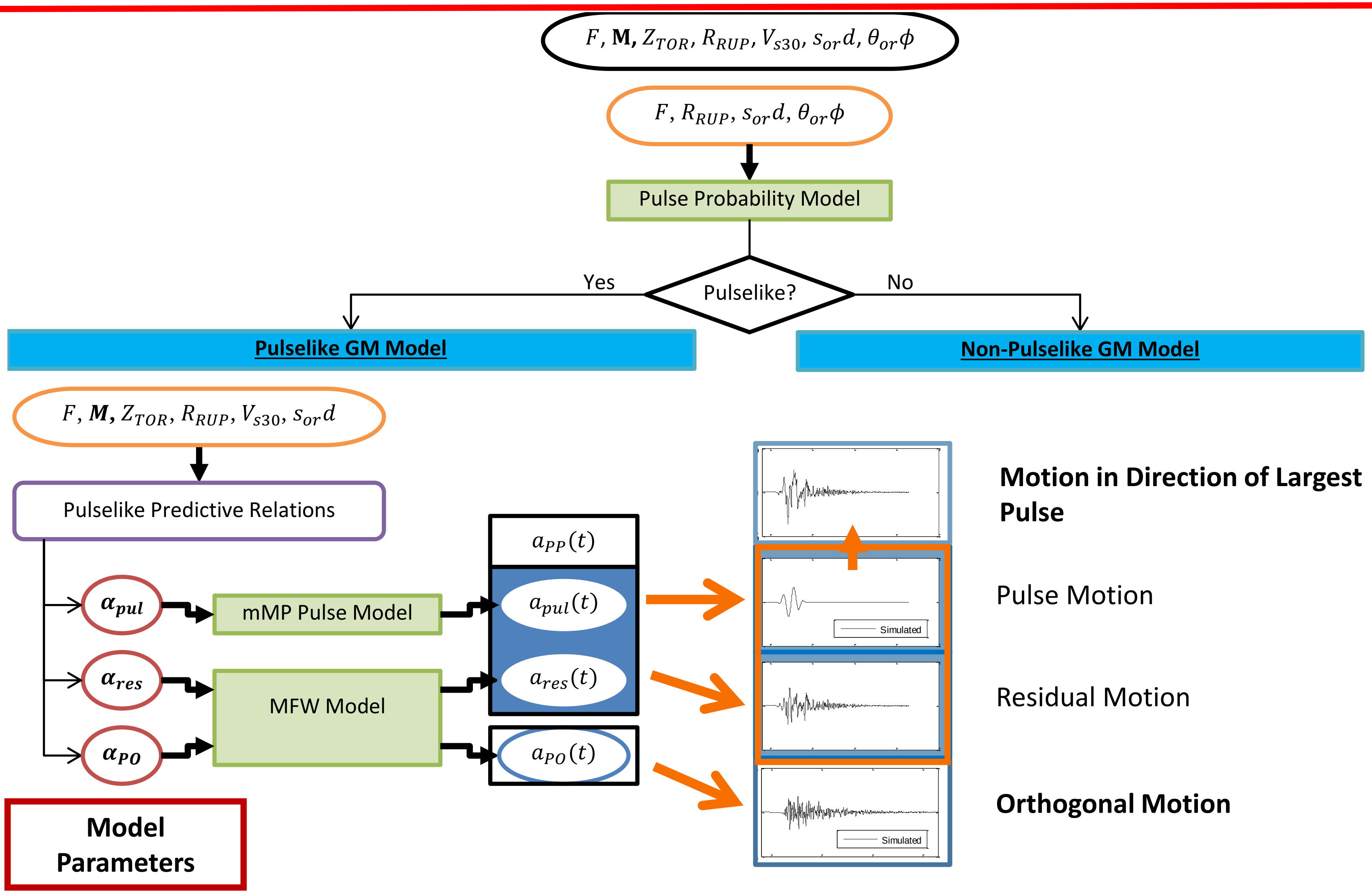
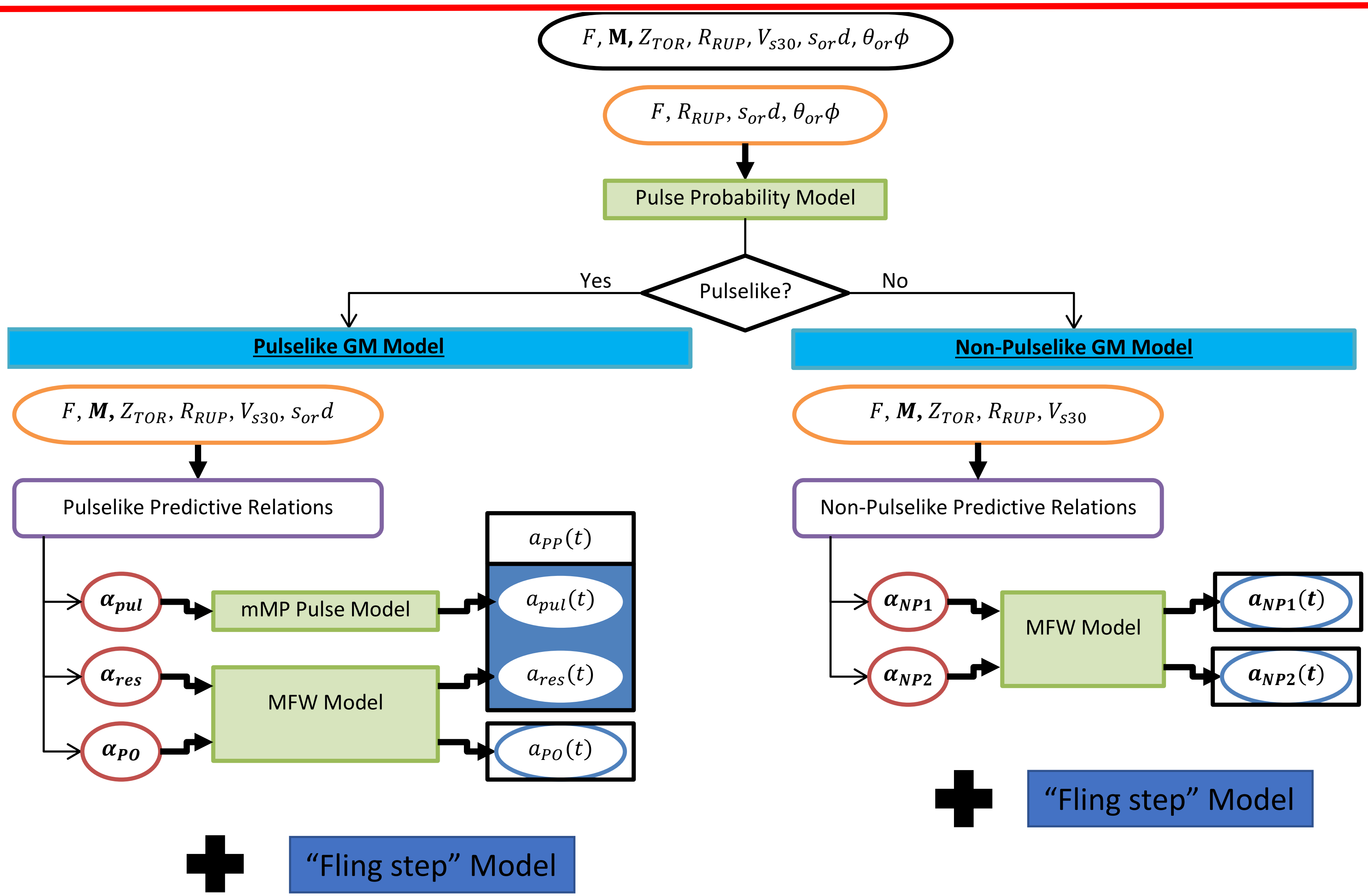


Simulation Procedure



Scope: Predictive Equations & Simulation Procedure

Recorded Pulselike GMs

	M_w	Z_{TOR} (km)	R_{RUP} (km)	V_{s30} (m/s)	$s_{or}\,d$ (km)	$\theta_{or}\phi$ (°)
min	5.74	0	0.07	139	4.97	0.1
max	7.90	5.92	30.49	2016	101.5	67.4

Shallow Crustal EQs

Subsets of PEER NGA-West2 Database

Recorded Non-Pulselike GMs

	M_w	Z_{TOR} (km)	R_{RUP} (km)	V_{s30} (m/s)	$s_{or}\,d$ (km)	$\theta_{or}\phi$ (°)
min	5.50	0	0.21	361	1.20	0.15
max	7.90	14.50	30.9	1428	135	84.4

Recommended Ranges

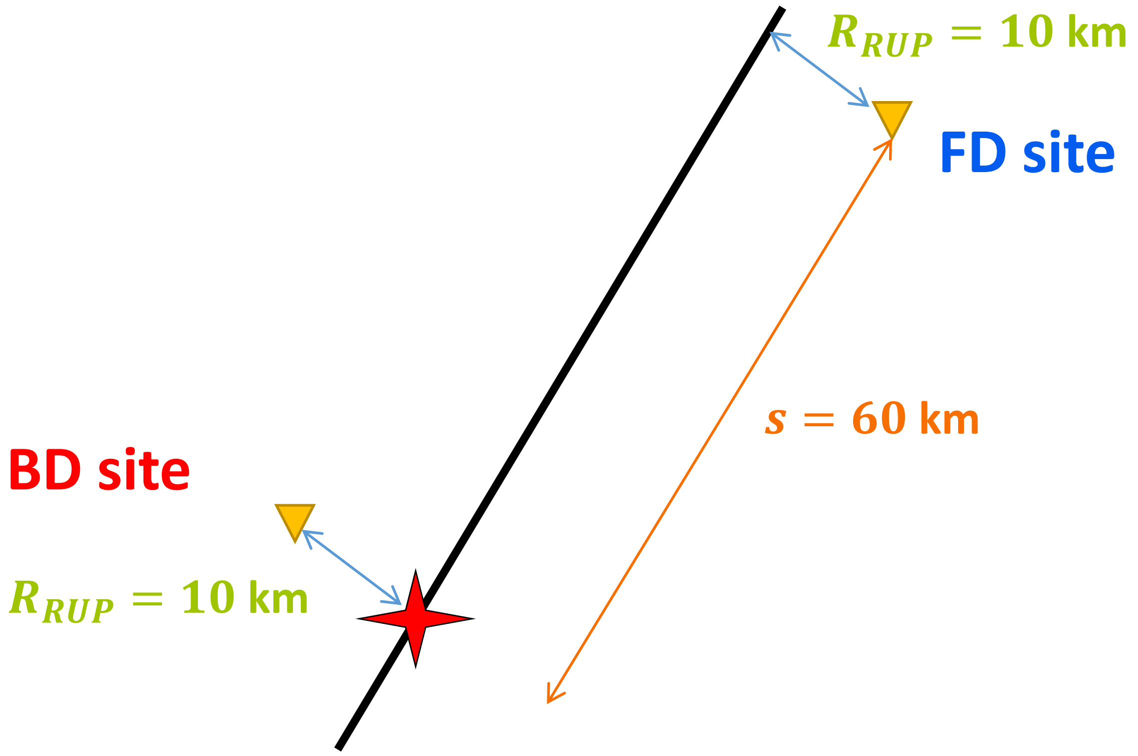
$$6 \leq M_w \leq 7.5$$
$$5 < R_{RUP} \leq 25 \text{ km}$$
$$400 < V_{S30} < 1000 \text{ m/s}$$

Illustrative Example # 1

Forward vs. Backward Directivity Sites

Forward vs. Backward Directivity Sites

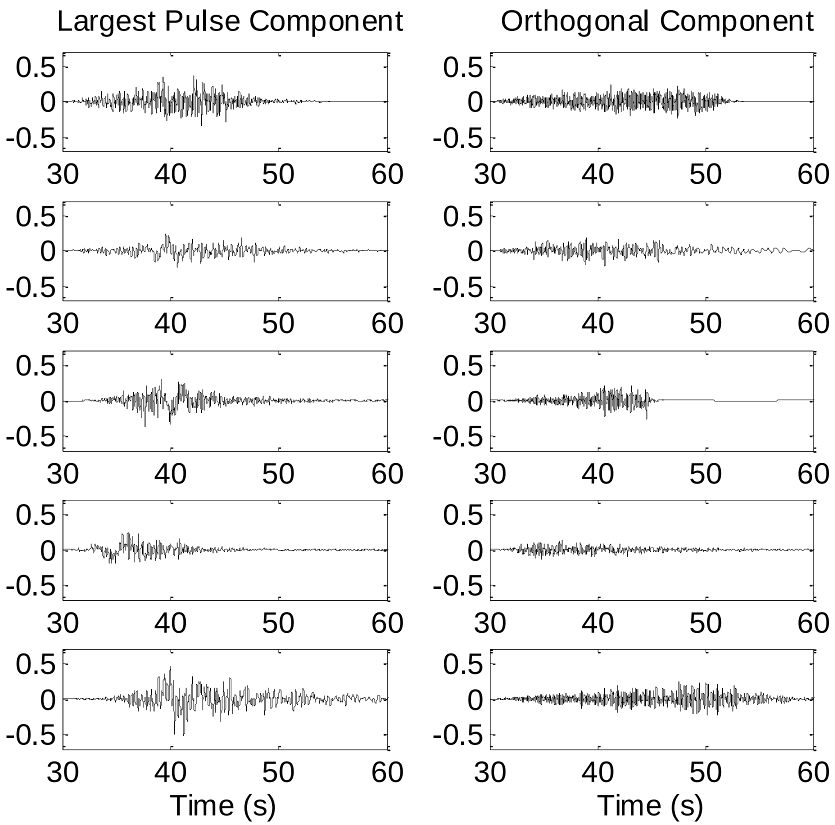
F	$\mathbf{M}$	Z_{TOR} (km)	R_{RUP} (km)	V_{s30} (m/s)	Directivity	s or d (km)	θ or ϕ (°)	P_{pulse}
0	7.0	0	10	760	FD	60	9.5	0.90
					BD	0	90	0.09



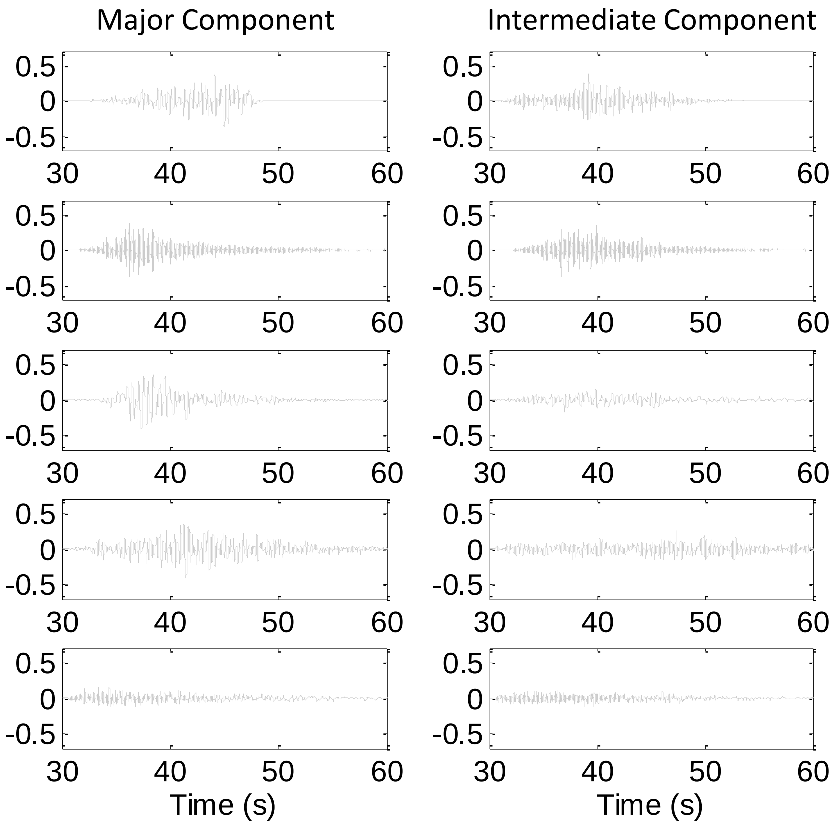
Simulated Time Series - Acceleration

F	$\mathbf{M}$	Z_{TOR} (km)	R_{RUP} (km)	V_{s30} (m/s)	Directivity	s or d (km)	θ or ϕ (°)	P_{pulse}
0	7.0	0	10	760	FD	60	9.5	0.90
					BD	0	90	0.09

Acceleration (g)

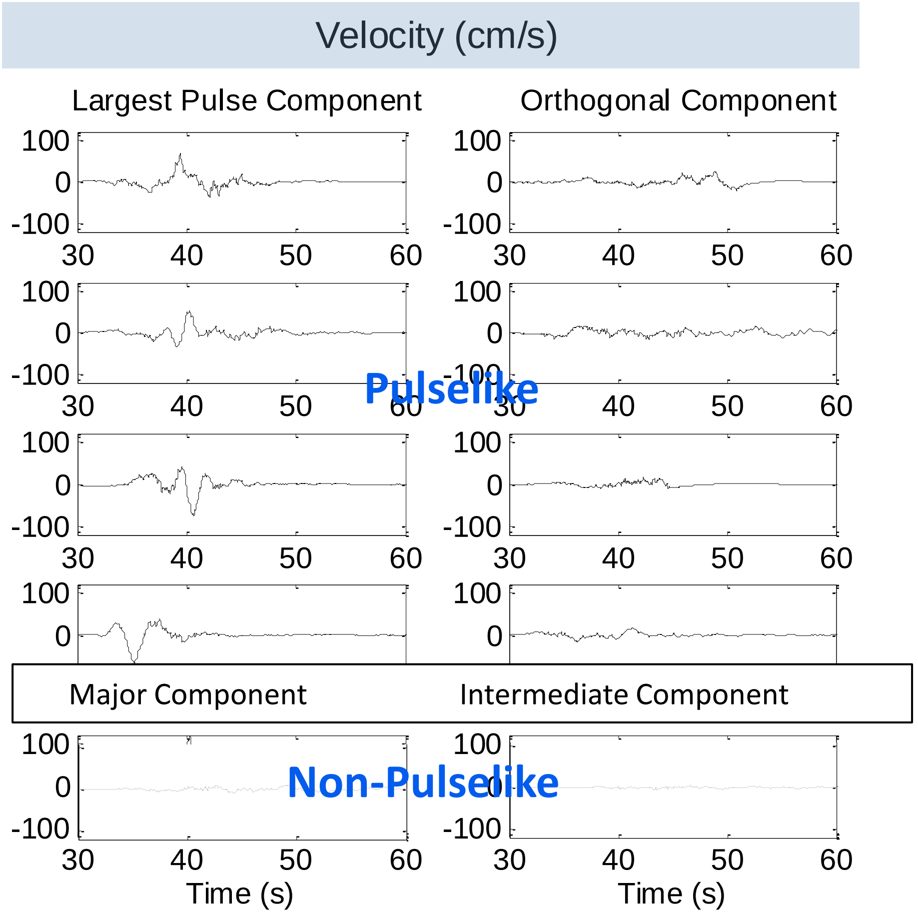


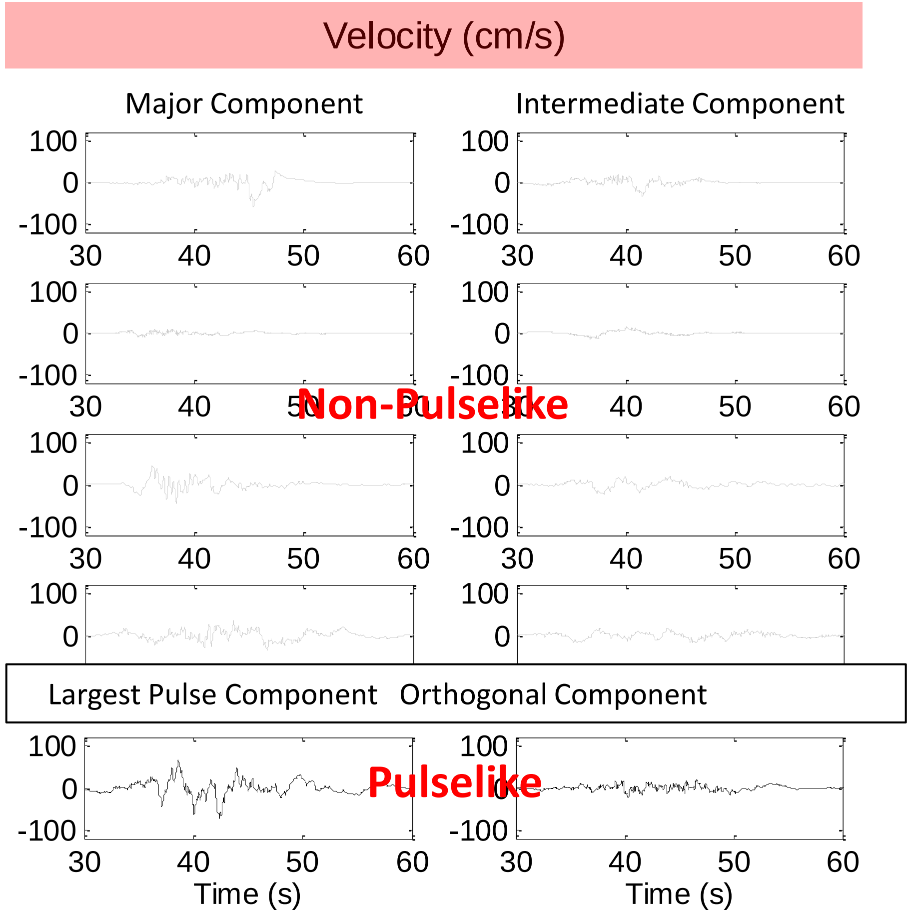
Acceleration (g)



Simulated Time Series - Velocity

F	$\mathbf{M}$	Z_{TOR} (km)	R_{RUP} (km)	V_{s30} (m/s)	Directivity	s or d (km)	θ or ϕ (°)	P_{pulse}
0	7.0	0	10	760	FD	60	9.5	0.90
					BD	0	90	0.09

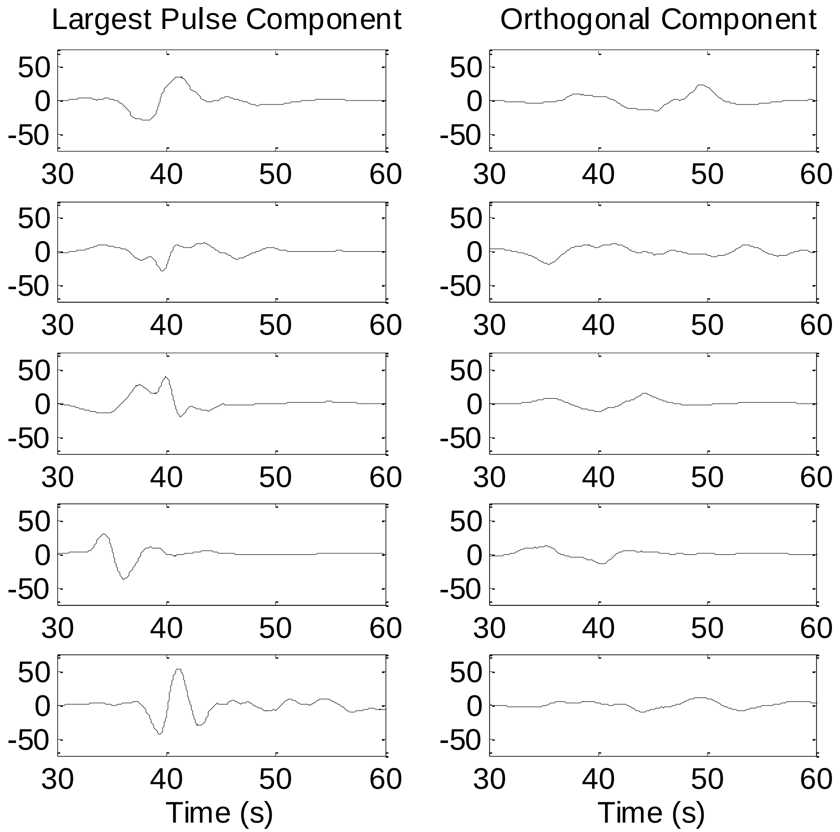




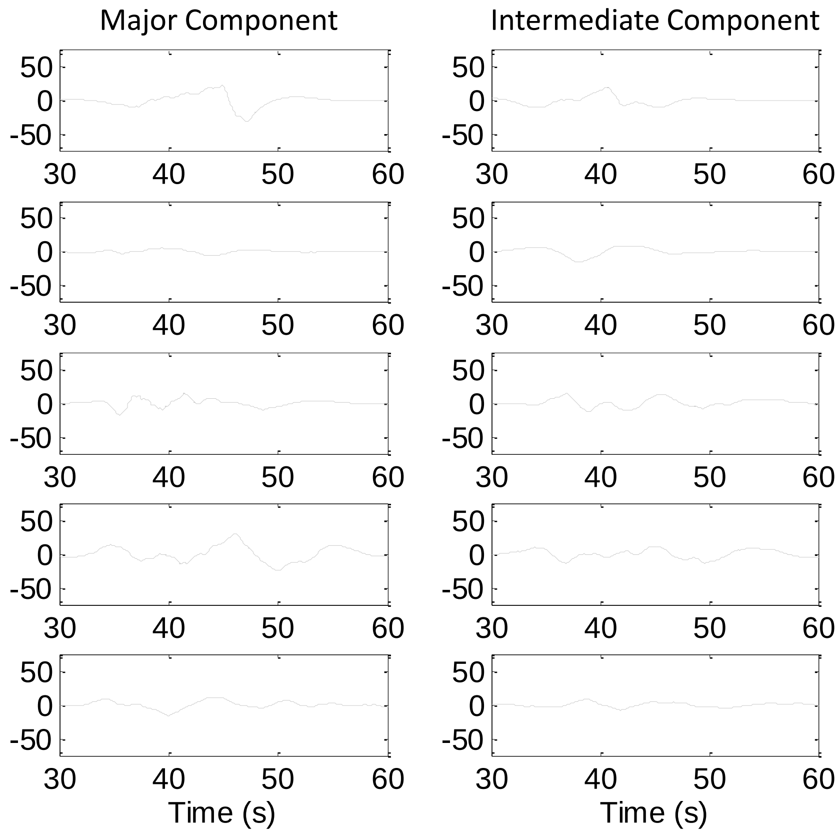
Simulated Time Series - Displacement

F	$\mathbf{M}$	Z_{TOR} (km)	R_{RUP} (km)	V_{s30} (m/s)	Directivity	s or d (km)	θ or ϕ (°)	P_{pulse}
0	7.0	0	10	760	FD	60	9.5	0.90
					BD	0	90	0.09

Displacement (cm)



Displacement (cm)



Illustrative Example # 2

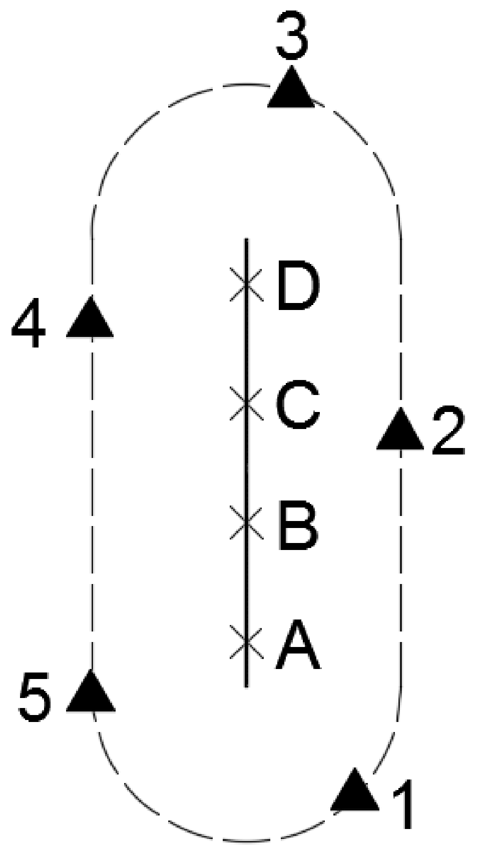
Hypothetical M6.5 Strike-Slip Earthquake Event

Earthquake Design Scenarios

- Hypothetical earthquake event
  - $F = 0, M_w = 6.5, Z_{TOR} = 0$
  - $L_{\mathrm{R}} = 29$ km (Wells and Coppersmith, 1994)

- Hypocenter locations:
  - uniformly distributed along the strike (buffer zones of length 0.1 L_{R} at the ends)
  - clustered into 4 discrete locations (A, B, C, and D)

- Site locations:
  - $R_{RUP} = 10$ km, $V_{s30} = 760$ m/s
  - 5 sites (1,2,…, 5) uniformly distributed around fault rupture



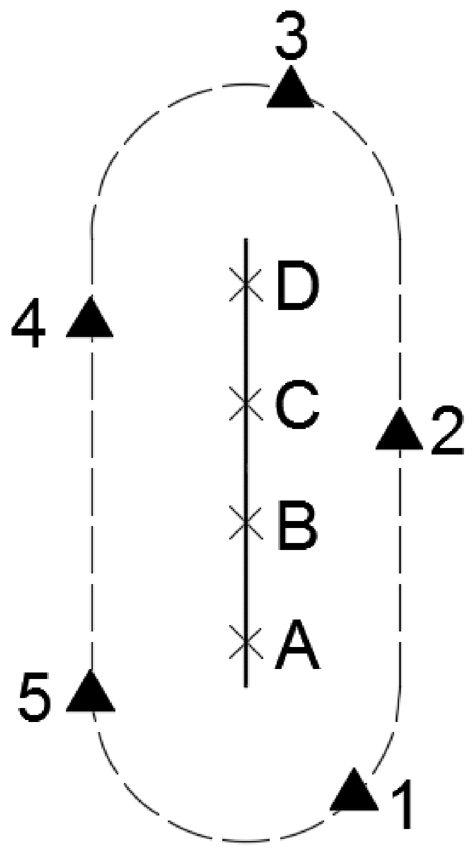
Earthquake Design Scenarios

- 20 equally probable scenarios (source-site combinations):
  - $F = 0, M_w = 6.5, Z_{TOR} = 0$ km, $R_{RUP} = 10$ km, $V_{s30} = 760$ m/s
- For each scenario, calculate:

$$s_{or}d = s, \qquad \theta_{or}\phi = \theta$$

$$\Pr[\text{pulse} - \text{like}|F, R_{RUP}, s_{or}d, \theta_{or}\phi]$$

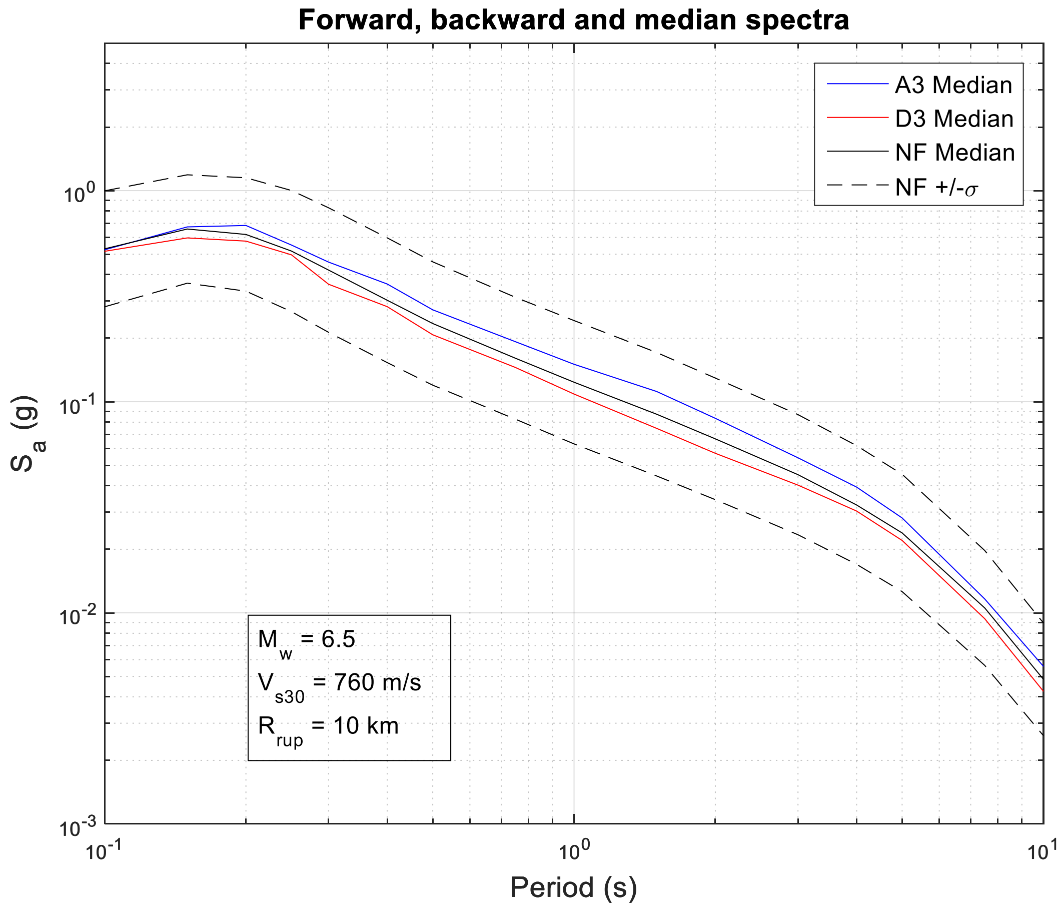
Site \ Source	A	B	C	D	
1	$s_{or}d = 2.9$ km $\theta_{or}\phi = 35.5°$ $P = 11.0\%$	$s_{or}d = 10.6$ km $\theta_{or}\phi = 21.7°$ $P = 18.0\%$	$s_{or}d = 18.4$ km $\theta_{or}\phi = 15.5°$ $P = 28.3\%$	$s_{or}d = 26.1$ km $\theta_{or}\phi = 12.0°$ $P = 41.2\%$	$\boldsymbol{P_1 = 24.6\%}$
2	$s_{or}d = 13.4$ km $\theta_{or}\phi = 36.7°$ $P = 21.3\%$	$s_{or}d = 5.7$ km $\theta_{or}\phi = 60.4°$ $P = 13.2\%$	$s_{or}d = 2.1$ km $\theta_{or}\phi = 78.3°$ $P = 10.4\%$	$s_{or}d = 9.8$ km $\theta_{or}\phi = 45.6°$ $P = 17.1\%$	$\boldsymbol{P_2 = 15.5\%}$
3	$s_{or}d = 26.1$ km $\theta_{or}\phi = 4.7°$ $P = 41.2\%$	$s_{or}d = 18.4$ km $\theta_{or}\phi = 6.0°$ $P = 28.3\%$	$s_{or}d = 10.6$ km $\theta_{or}\phi = 8.3°$ $P = 18.0\%$	$s_{or}d = 2.9$ km $\theta_{or}\phi = 13.2°$ $P = 11.0\%$	$\boldsymbol{P_3 = 24.6\%}$
4	$s_{or}d = 20.7$ km $\theta_{or}\phi = 25.8°$ $P = 31.8\%$	$s_{or}d = 12.9$ km $\theta_{or}\phi = 37.7°$ $P = 20.7\%$	$s_{or}d = 5.2$ km $\theta_{or}\phi = 62.7°$ $P = 12.7\%$	$s_{or}d = 2.5$ km $\theta_{or}\phi = 75.7°$ $P = 10.7\%$	$\boldsymbol{P_4 = 19.0\%}$
5	$s_{or}d = 2.9$ km $\theta_{or}\phi = 70.6°$ $P = 11.0\%$	$s_{or}d = 10.6$ km $\theta_{or}\phi = 41.6°$ $P = 18.0\%$	$s_{or}d = 18.4$ km $\theta_{or}\phi = 27.7°$ $P = 28.3\%$	$s_{or}d = 26.1$ km $\theta_{or}\phi = 20.5°$ $P = 41.2\%$	$\boldsymbol{P_5 = 24.6\%}$
	$\boldsymbol{P_A = 23.3\%}$	$\boldsymbol{P_B = 19.6\%}$	$\boldsymbol{P_C = 19.5\%}$	$\boldsymbol{P_D = 24.2\%}$	

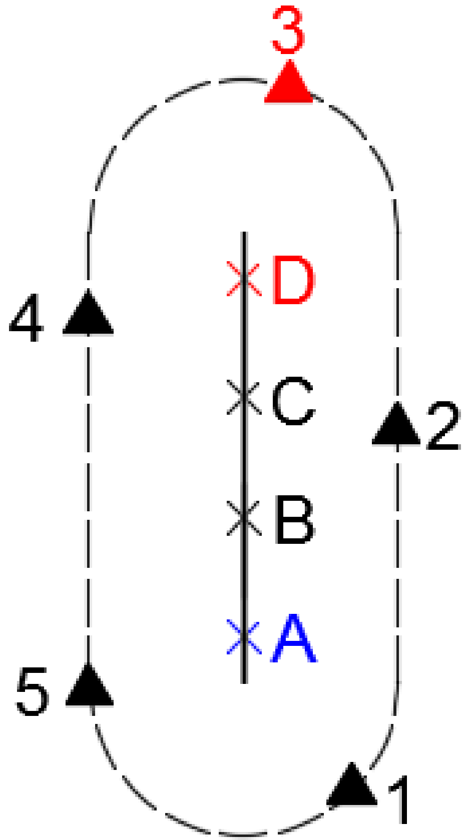


Forward vs. Backward Directivity Scenarios

Geometric mean spectra at 5% damping

- NF Median and Median +/- σ of 20x300 simulations
- A3 Median of 300 simulations
- D3 Median of 300 simulations





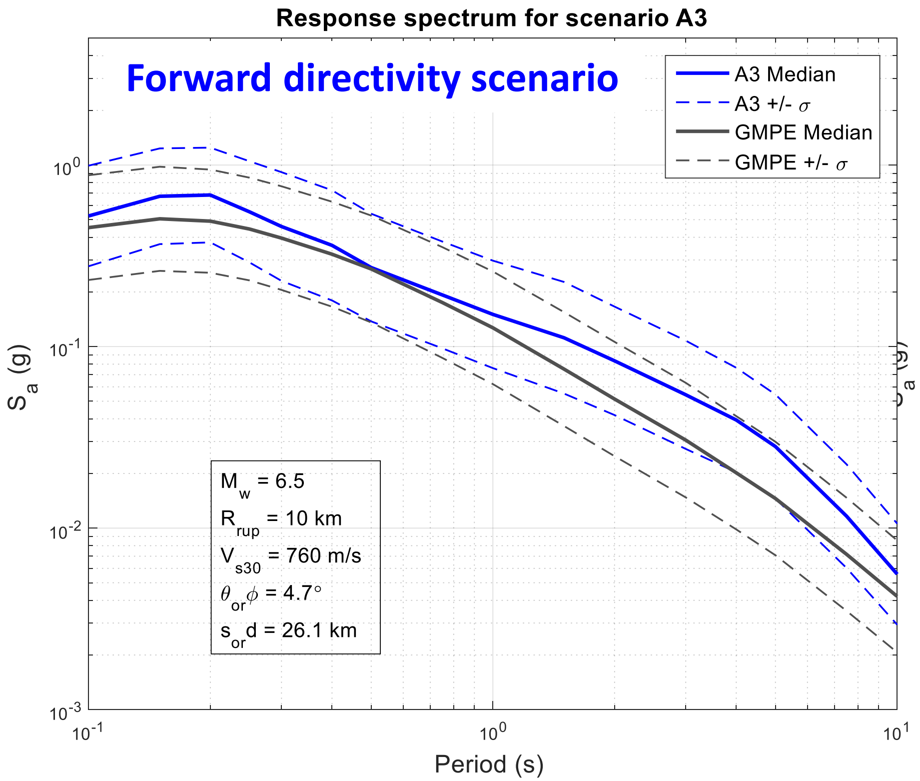
Near-Fault Simulations vs. GMPEs (NGA West 2)

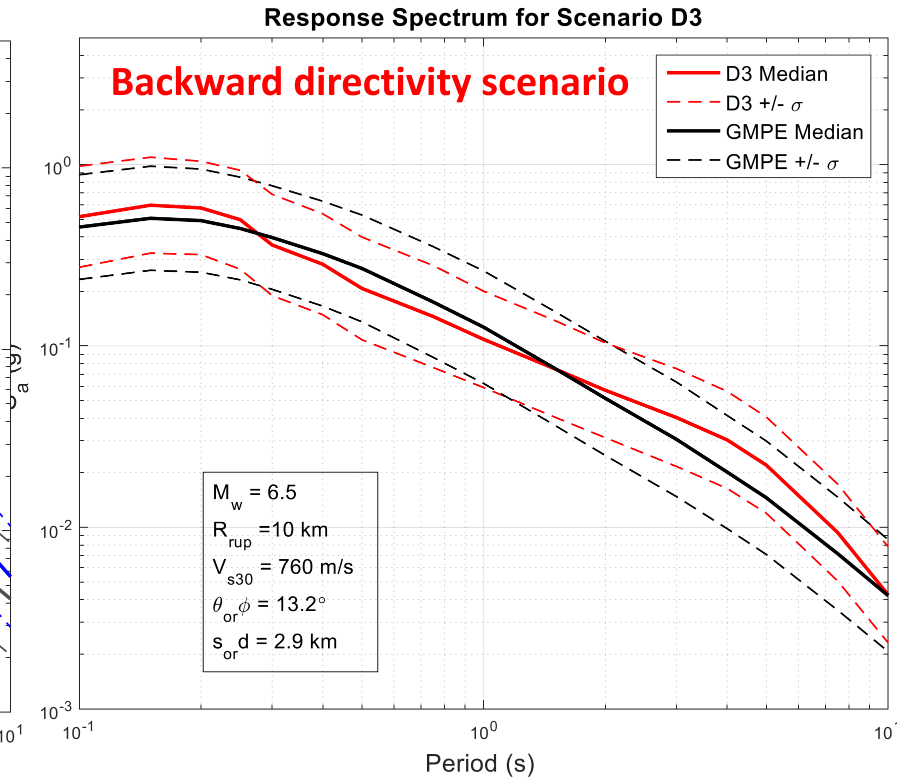
Geometric mean spectra at 5% damping

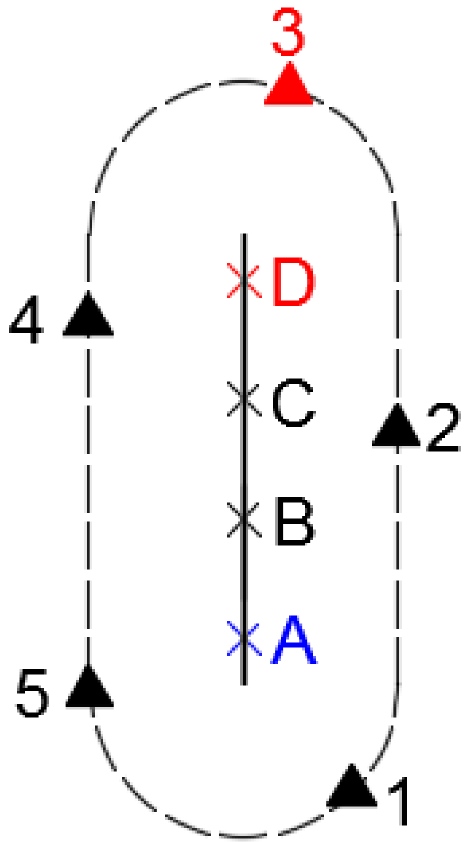
- A3 Median and Median +/- σ of 300 simulations
- D3 Median and Median +/- σ of 300 simulations

RotD50 spectra at 5% damping

- NGA-West2 GMPEs Median and Median +/- σ







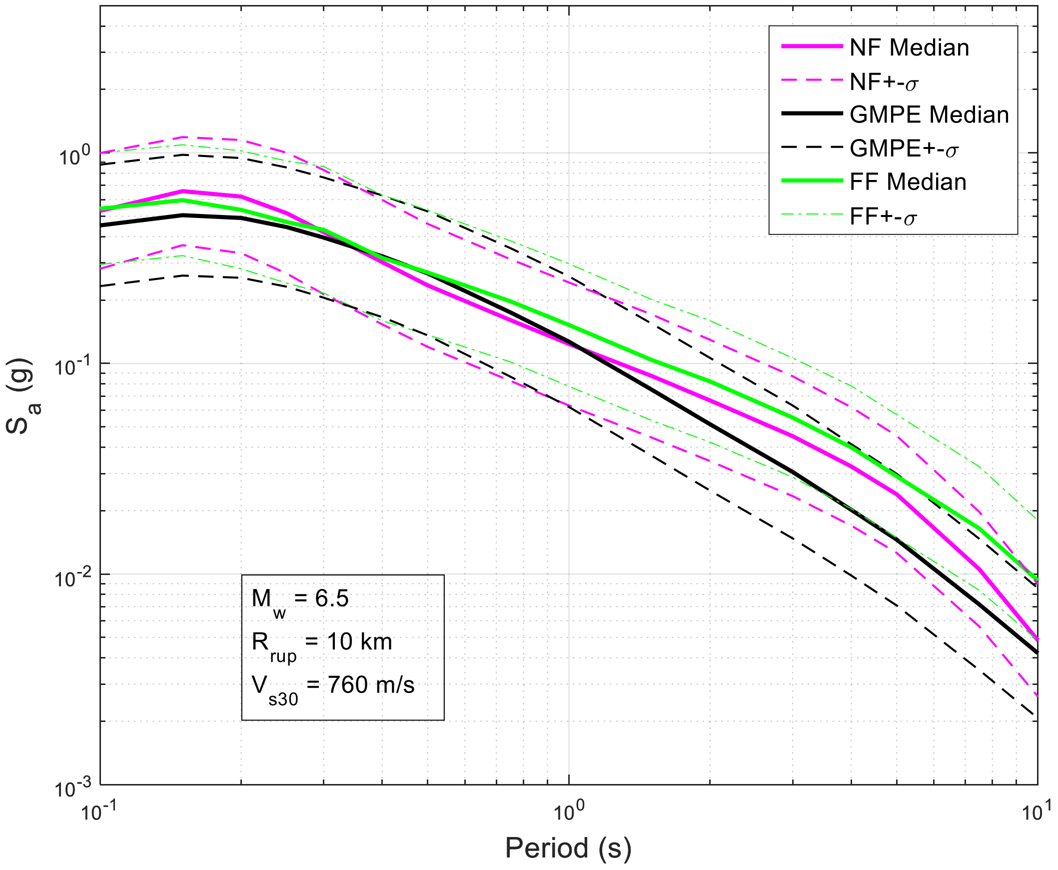
Near-Fault vs. Far Field Simulations (Rezaeian and Der Kiureghian, 2010)

Geometric mean spectra at 5% damping

- NF Median and Median +/- σ of 20x300 simulations
- FF Median and Median +/- σ of 300 simulations (Rezaeian and Der Kiureghian, 2010)

RotD50 spectra at 5% damping

- NGA-West2 GMPEs Median and Median +/- σ



Summary and Conclusions

Summary and Conclusions (1/3)

- Parameterized stochastic model of NF GM in 2 orthogonal horizontal directions

- Empirical (site-based) simulation method
  - practical and simple, computationally efficient
  - input can be readily available to the design engineer
  - forward directivity (FD) vs. backward directivity (BD) conditions (through $s_{or} d$ and $\theta_{or} \phi$)

Summary and Conclusions (2/3)

- Resulting ensemble of synthetic NF GMs
  - capture the important characteristics of recorded NF GMs (rupture directivity, pulse-like and non-pulse-like, intensity, duration, frequency characteristics)
  - replicate the natural variability
  - can be used in PSHA and PBEE

- Simulation procedure was illustrated for 20 NF EQ scenarios
  - same $(F, M_w, Z_{TOR}, R_{RUP}, V_{s30})$
  - range of different rupture directivity conditions

Summary and Conclusions (3/3)

- FD vs. BD simulations:
  - median GM level at a site depends on the directivity configuration
  - forward directivity sites: highest amplitudes in the long-period range

- NF GM simulations vs. NGA-West2 GMPEs
  - GMPEs ~ backward directivity scenarios
  - at forward directivity sites, GMPEs predict lower GM levels at longer periods
  - GMPEs do not adequately represent the rupture directivity effect

- NF vs. FF GM simulations
  - far-field model is not well constrained at a distance of 10 km

Thank You!

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