UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

QuakeCoRE
NZ Centre for Earthquake Resilience

Ground Motion Simulation Uncertainty Quantification through Validation

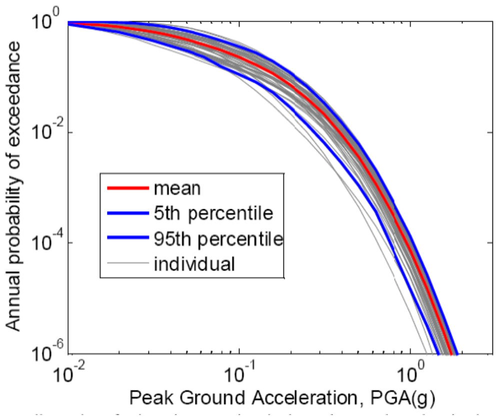
QuakeCoRE Flagship 1 meeting

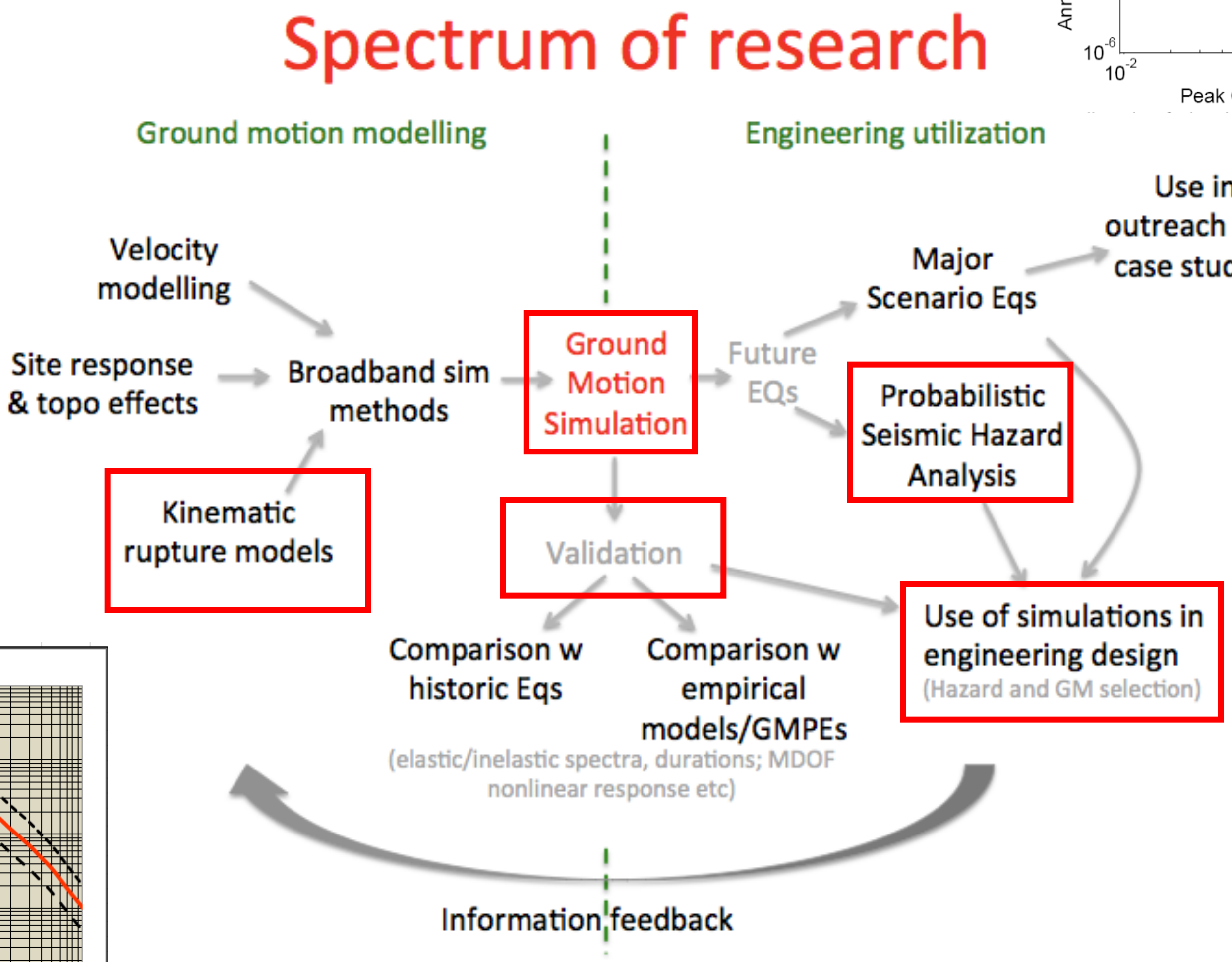
Sarah Neill

22-11-2018

$\nu(Sa>z) = \Sigma\ Rate_i\ \mathbf{P(Sa(T)>z|M_i,R_i,..)}$

Motivation





Spectrum of research

Ground motion modelling

Engineering utilization

Velocity modelling

Site response & topo effects

Broadband sim methods

Kinematic rupture models

Ground Motion Simulation

Future EQs

Major Scenario Eqs

Use in outreach and case studies

Probabilistic Seismic Hazard Analysis

Validation

Comparison w historic Eqs

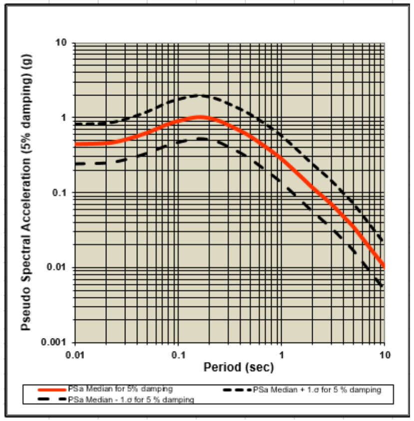
Comparison w empirical models/GMPEs

(elastic/inelastic spectra, durations; MDOF nonlinear response etc)

Use of simulations in engineering design

(Hazard and GM selection)

Information feedback



Bradley

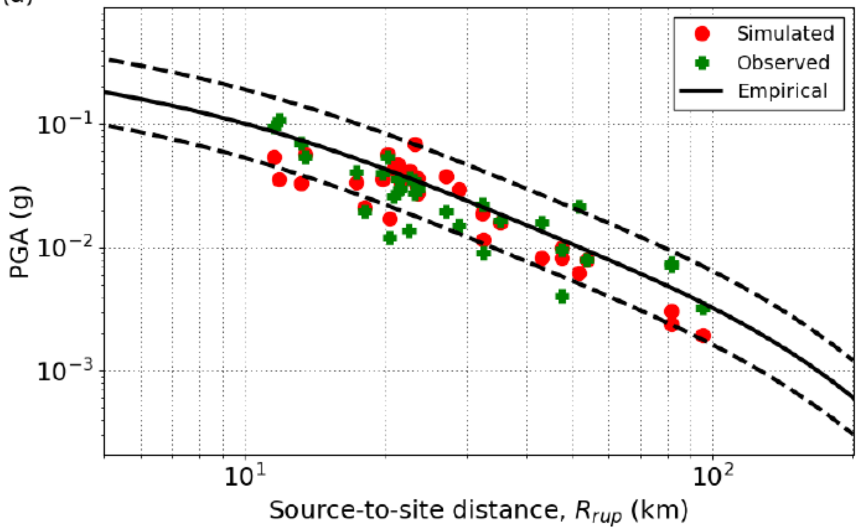
Background Validation Work

Lee et al. (2018)

Validation of GM Sim w/o Modelling Uncertainty

- Median input parameters for validation
- Small and large magnitude events
- Comparisons w/ GMPEs
- Residual analysis

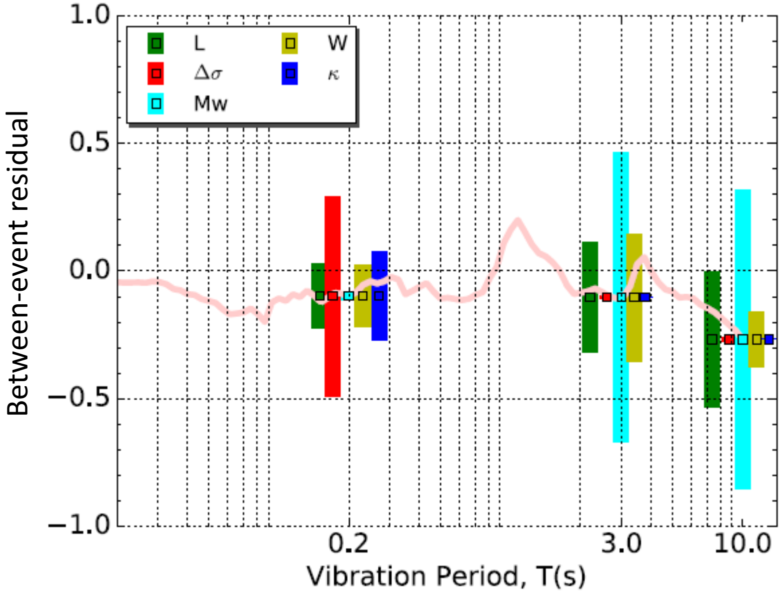
(a)



Razafindrakoto et al. (2017)

Pilot Study on Source Modelling Sensitivity

- February 22 & September 4 events
- Perturbations to Mw, A, Ti, Δσ, κ
- Mw and Δσ dominant for between event residuals

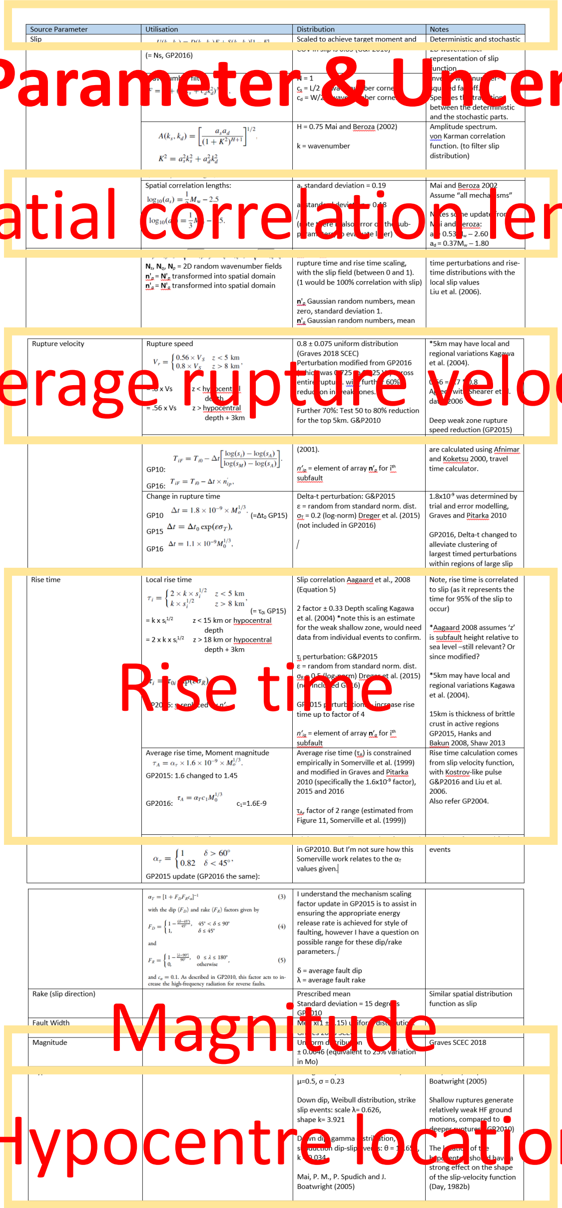


Method – High Level

- Sources of uncertainty:
  - Source model, crustal velocity model, site modelling
- Using FF sim. and data, identify dominant model params
- Using small Mw events, vary source parameters → IM variability
- Provides insight into source, path site model uncertainty
- Quantify σ using residuals
- Identify variability for future events

Method - Detailed

Key Source Parameters - LF



Source Parameter & Uncertainty

Slip spatial correlation lengths

Average rupture velocity

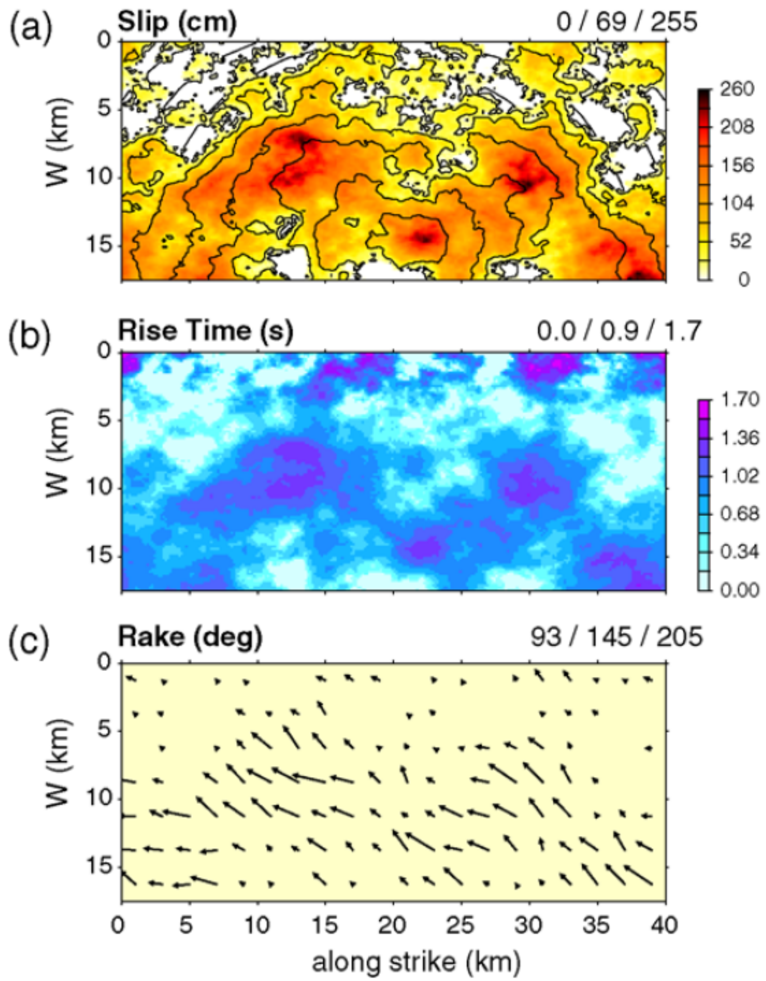
Rise time

Magnitude

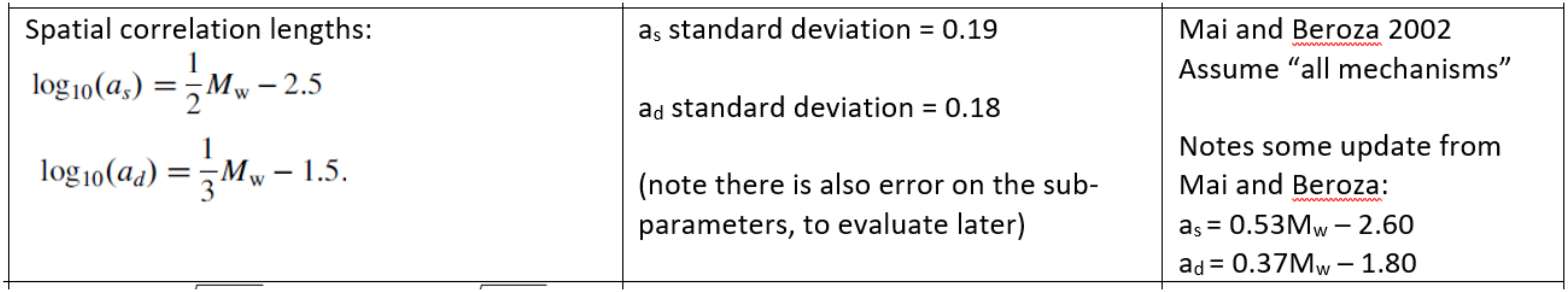
Hypocentre location

Source Parameter	Utilisation	Distribution	Notes
Slip	[illegible] (= Ns, GP2016)	Scaled to achieve target moment and [illegible]	Deterministic and stochastic 2D wavenumber representation of slip function
	[illegible]	N = 1 c_s = L/2 [illegible] ber corne[illegible] c_d = W/2 [illegible] ber corne[illegible]	Inve[illegible] squ[illegible] fa[illegible] off. Spe[illegible] es t[illegible] between the deterministic and the stochastic parts.
	$A(k_s, k_d) = \left[\frac{a_s a_d}{(1+K^2)^{H+1}}\right]^{1/2}$ $K^2 = a_s^2 k_s^2 + a_d^2 k_d^2$	H = 0.75 Mai and Beroza (2002) k = wavenumber	Amplitude spectrum. von Karman correlation function. (to filter slip distribution)
	Spatial correlation lengths: $\log_{10}(a_s) = \frac{1}{[illegible]}M_w - 2.5$ $\log_{10}(a$[illegible]$) = \frac{1}{3}$[illegible]$.$	a_s standard deviation = 0.19 a[illegible] standard deviation = 0.[illegible]8 / (note there is also error on the sub-parameters, to evaluate later)	Mai and Beroza 2002 Assume "all mecha[illegible]sms" N[illegible]tes some update from M[illegible]i and [illegible]eroza: a[illegible] 0.53[illegible]$_w$ – 2.60 a_d = 0.37M_w – 1.80
	N_s, N_q, N_p = 2D random wavenumber fields n'_p = N'_p transformed into spatial domain n'_q = N'_q transformed into spatial domain	rupture time and rise time scaling, with the slip field (between 0 and 1). (1 would be 100% correlation with slip) n'_p Gaussian random numbers, mean zero, standard deviation 1. n'_q Gaussian random numbers, mean	time perturbations and rise-time distributions with the local slip values Liu et al. (2006).
Rupture velocity	Rupture speed $V_r = \begin{cases} 0.56 \times V_S & z < 5\ \text{km} \\ 0.8 \times V_S & z > 8\ \text{km} \end{cases}$ = [illegible]8 x Vs z < hy[illegible]centr[illegible]l de[illegible]th = .56 x Vs z > hypocentral depth + 3km	0.8 ± 0.075 uniform distribution (Graves 2018 SCEC) Perturbation modified from GP2016 ([illegible]hic[illegible] was 0.725 [illegible] 0.[illegible]25 [illegible] across entire [illegible]uptu[illegible]. wi[illegible] furth[illegible] 60% redu[illegible]on in [illegible]eak [illegible]ones. Further 70%: Test 50 to 80% reduction for the top 5km. G&P2010	*5km may have local and regional variations Kagawa et al. (2004). 0.56 = [illegible].7 * [illegible].8 A[illegible]ee[illegible] wit[illegible] Shearer et [illegible]. dat[illegible] 2006 Deep weak zone rupture speed reduction (GP2015)
	GP10: $T_{iF} = T_{i0} - \Delta t\left[\frac{\log(s_i) - \log(s_A)}{\log(s_M) - \log(s_A)}\right].$ GP16: $T_{iF} = T_{i0} - \Delta t \times n'_{ip},$	(2001). n'_{ip} = element of array n'_p for ith subfault	are calculated using Afnimar and Koketsu 2000, travel time calculator.
	Change in rupture time GP10 $\Delta t = 1.8 \times 10^{-9} \times M_o^{1/3}.$ (=Δt$_0$ GP15) GP15 $\Delta t = \Delta t_0 \exp(\varepsilon\sigma_T),$ GP16 $\Delta t = 1.1 \times 10^{-9} M_0^{1/3},$	Delta-t perturbation: G&P2015 ε = random from standard norm. dist. σ_T = 0.2 (log-norm) Dreger et al. (2015) (not included in GP2016) /	1.8x10^{-9} was determined by trial and error modelling, Graves and Pitarka 2010 GP2016, Delta-t changed to alleviate clustering of largest timed perturbations within regions of large slip
Rise time	Local rise time $\tau_i = \begin{cases} 2 \times k \times s_i^{1/2} & z < 5\ \text{km} \\ k \times s_i^{1/2} & z > 8\ \text{km} \end{cases},$ (= τ_{0i} GP15) = k x s$_i^{1/2}$ z < 15 km or hypocentral depth = 2 x k x s$_i^{1/2}$ z > 18 km or hypocentral depth + 3km $\tau_i = \tau_{0i}$ [illegible]$p(\varepsilon\sigma_R)$ [illegible]P20[illegible]6: s replaced [illegible] n'[illegible]	Slip correlation Aagaard et al., 2008 (Equation 5) 2 factor ± 0.33 Depth scaling Kagawa et al. (2004) *note this is an estimate for the weak shallow zone, would need data from individual events to confirm. τ_i perturbation: G&P2015 ε = random from standard norm. dist. σ_R = 0.[illegible] (log-[illegible]rm) Dre[illegible] et al. (2015) (n[illegible] incl[illegible]ed G[illegible]16) G[illegible]015 [illegible]turb[illegible]tion [illegible] increase rise time up to factor of 4 n'_{iq} = element of array n'_q for ith subfault	Note, rise time is correlated to slip (as it represents the time for 95% of the slip to occur) *Aagaard 2008 assumes 'z' is subfault height relative to sea level –still relevant? Or since modified? *5km may have local and regional variations Kagawa et al. (2004). 15km is thickness of brittle crust in active regions GP2015, Hanks and Bakun 2008, Shaw 2013
	Average rise time, Moment magnitude $\tau_A = \alpha_\tau \times 1.6 \times 10^{-9} \times M_o^{1/3}.$ GP2015: 1.6 changed to 1.45 GP2016: $\tau_A = \alpha_T c_1 M_0^{1/3}$ c_1=1.6E-9	Average rise time (τ_A) is constrained empirically in Somerville et al. (1999) and modified in Graves and Pitarka 2010 (specifically the 1.6x10^{-9} factor), 2015 and 2016 τ_A, factor of 2 range (estimated from Figure 11, Somerville et al. (1999))	Rise time calculation comes from slip velocity function, with Kostrov-like pulse G&P2016 and Liu et al. 2006. Also refer GP2004.
	$\alpha_\tau = \begin{cases} 1 & \delta > 60^\circ \\ 0.82 & \delta < 45^\circ \end{cases},$ GP2015 update (GP2016 the same):	in GP2010. But I'm not sure how this Somerville work relates to the α_T values given.	events
	$\alpha_T = [1 + F_D F_R c_\alpha]^{-1}$ (3) with the dip (F_D) and rake (F_R) factors given by $F_D = \begin{cases} 1 - \frac{(\delta - 45^\circ)}{45^\circ}, & 45^\circ < \delta \le 90^\circ \\ 1, & \delta \le 45^\circ \end{cases}$ (4) and $F_R = \begin{cases} 1 - \frac{\lvert\lambda - 90^\circ\rvert}{90^\circ}, & 0 \le \lambda \le 180^\circ \\ 0, & \text{otherwise} \end{cases},$ (5) and $c_\alpha = 0.1$. As described in GP2010, this factor acts to increase the high-frequency radiation for reverse faults.	I understand the mechanism scaling factor update in GP2015 is to assist in ensuring the appropriate energy release rate is achieved for style of faulting, however I have a question on possible range for these dip/rake parameters. / δ = average fault dip λ = average fault rake	
Rake (slip direction)		Prescribed mean Standard deviation = 15 degr[illegible]s GP[illegible]010	Similar spatial distribution function as slip
Fault Width		Me[illegible] x(1 ± [illegible].15) u[illegible]for[illegible] distr[illegible]utio[illegible]. [illegible]	
Magnitude		Un[illegible]orm d[illegible]tribu[illegible]n ± 0.0[illegible]46 (equivalent to 2[illegible]% variation in Mo)	Graves SCEC 2018
[illegible]		[illegible] μ=0.5, σ = 0.23 Down dip, Weibull distribution, strike slip events: scale λ= 0.626, shape k= 3.921 D[illegible]wn di[illegible] gamma [illegible]stri[illegible]tion, s[illegible]duction dip-slip [illegible]ve[illegible]s: θ = 1[illegible], k [illegible].034 Mai, P. M., P. Spudich and J. Boatwright (2005)	[illegible] Boatwright (2005) Shallow ruptures generate relatively weak HF ground motions, compared to deeper ruptures (GP2010) The l[illegible]ation of t[illegible]e h[illegible]po[illegible]entr[illegible] sho[illegible]d hav[illegible] a strong effect on the shape of the slip-velocity function (Day, 1982b)

Graves and Pitarka 2010



Key Source Parameters - LF



Spatial correlation lengths: $\log_{10}(a_s) = \frac{1}{2}M_\mathrm{w} - 2.5$ $\log_{10}(a_d) = \frac{1}{3}M_\mathrm{w} - 1.5.$	a_s standard deviation = 0.19 a_d standard deviation = 0.18 (note there is also error on the sub-parameters, to evaluate later)	Mai and Beroza 2002 Assume “all mechanisms” Notes some update from Mai and Beroza: $a_s = 0.53M_w – 2.60$ $a_d = 0.37M_w – 1.80$

Key Source Parameters - LF

Rupture speed $V_r = \begin{cases} 0.56 \times V_S & z < 5 \text{ km} \\ 0.8 \times V_S & z > 8 \text{ km} \end{cases},$ = .8 x Vs z < hypocentral depth = .56 x Vs z > hypocentral depth + 3km	0.8 ± 0.075 uniform distribution (Graves 2018 SCEC) Perturbation modified from GP2016 (which was 0.725 to 0.825 Vs) across entire rupture. with further 60% reduction in weak zones. Further 70%: Test 50 to 80% reduction for the top 5km. G&P2010	*5km may have local and regional variations Kagawa et al. (2004). 0.56 = 0.7 * 0.8 Agrees with Shearer et al. data, 2006 Deep weak zone rupture speed reduction (GP2015)

Key Source Parameters - LF

Local rise time $\tau_i = \begin{cases} 2\times k\times s_i^{1/2} & z<5\text{ km} \\ k\times s_i^{1/2} & z>8\text{ km} \end{cases},$ (= τ_{0i} GP15) = k x $s_i^{1/2}$ z < 15 km or hypocentral depth = 2 x k x $s_i^{1/2}$ z > 18 km or hypocentral depth + 3km $\tau_i = \tau_{0i}\exp(\varepsilon\sigma_R),$ GP2016: s_i replaced by n'_{iq}	Slip correlation Aagaard et al., 2008 (Equation 5) 2 factor ± 0.33 Depth scaling Kagawa et al. (2004) *note this is an estimate for the weak shallow zone, would need data from individual events to confirm. τ_i perturbation: G&P2015 ε = random from standard norm. dist. σ_R = 0.5 (log-norm) Dreger et al. (2015) (not included GP16) GP2015 perturbations – increase rise time up to factor of 4 n'_{iq} = element of array $\mathbf{n}'_q$ for ith subfault	Note, rise time is correlated to slip (as it represents the time for 95% of the slip to occur) *Aagaard 2008 assumes 'z' is subfault height relative to sea level –still relevant? Or since modified? *5km may have local and regional variations Kagawa et al. (2004). 15km is thickness of brittle crust in active regions GP2015, Hanks and Bakun 2008, Shaw 2013
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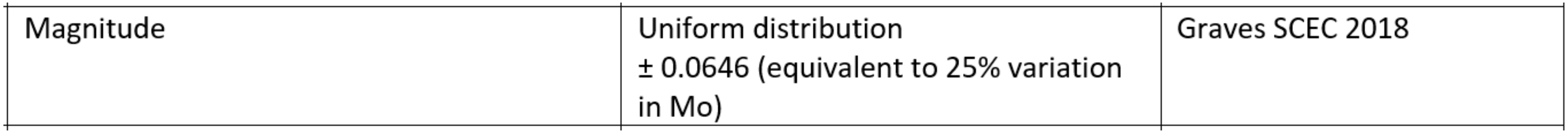
Key Source Parameters - LF



Magnitude	Uniform distribution ± 0.0646 (equivalent to 25% variation in Mo)	Graves SCEC 2018

Key Source Parameters - LF

Hypocentre location	Along strike, normal distribution, $\mu=0.5$, $\sigma = 0.23$ Down dip, Weibull distribution, strike slip events: scale $\lambda= 0.626$, shape $k= 3.921$ Down dip, gamma distribution, subduction dip-slip events: $\theta = 12.658$, $k = 0.034$ Mai, P. M., P. Spudich and J. Boatwright (2005)	Mai, P. M., P. Spudich and J. Boatwright (2005) Shallow ruptures generate relatively weak HF ground motions, compared to deeper ruptures. (GP2010) The location of the hypocenter, should have a strong effect on the shape of the slip-velocity function (Day, 1982b)

Questions?