DynaShake platform and dynamic source models for the southern San Andreas Fault ShakeOut scenario

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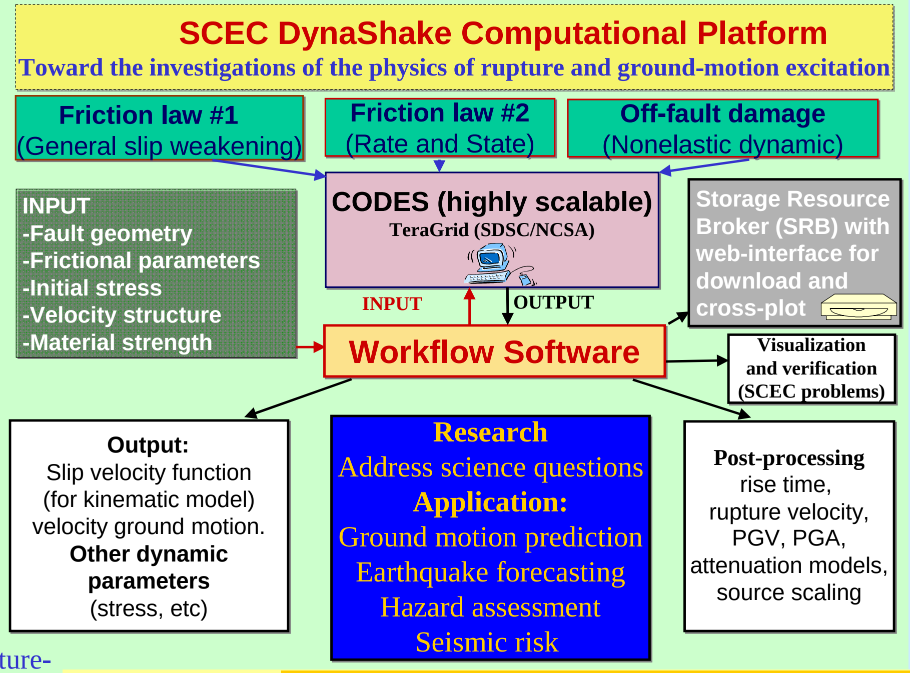
Overview

We are developing the DynaShake Computational Platform, as part of the SCEC PetaSHA project. DynaShake assembles algorithms, codes, and computational and geoscience expertise for high-performance simulation of dynamic rupture at high resolution, directed toward investigations of the physics of rupture and ground-motion excitation. An essential element of DynaShake is the development of highly scalable codes for 3D rupture simulation, with dynamic simulations of the SoSAFE (Southern San Andreas Fault Evaluation) ShakeOut scenario serving as a testbed for this development. The ShakeOut rupture scenario initiates near Bombay Beach and propagates unilaterally 300 km toward the northwest up to near Lake Hughes, posing a considerable computational challenge for dynamic rupture simulation because of the very large outerscale length of the problem.

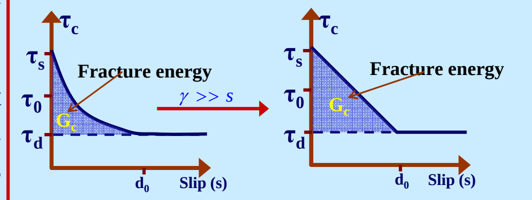
The ShakeOut scenario defines not only the rupture-surface and moment magnitude of the event, but also prescribes the final surface slip distribution resulting from the rupture. We developed a "slip-matching" technique for constraining initial (shear and normal) stress conditions in simulations such that they conform to scenarios defined in this form. The slip-matching method iteratively performs kinematic and dynamic simulations at low resolution to find initial stress distributions that (i) have stochastic irregularities compatible with seismological observations, (ii) satisfy frictional strength limits at shallow depth, (iii) are slip-matched to surface displacement scenarios, and (iv) rupture the full length of the specified scenario.



Friction Laws

The DynaShake platform includes friction modules for both linear and nonlinear slip-dependent frictions laws, as well as prototypes of rate- and state-dependent friction modules, including a generalized formulation with strong velocity weakening to represent thermal weakening. When the latter is integrated into the SGSN method, the coupled system (state variable, slip-rate vector, fault traction vector) can sometimes become very stiff, requiring an implicit ODE solver based on backward differentiation, as described in a companion poster presented by Rojas et al. These friction modules will be used to compare the effects of different friction laws on rupture behavior and examine their compatibility with ground-motion observational constraints.

Friction law #1 (slip weakening)



$$\tau_c = \begin{cases} \dfrac{\gamma\tau_s(d_0 - s)}{d_0(s+\gamma)} + \dfrac{\tau_d s(d_0+\gamma)}{d_0(s+\gamma)} & s < d_0 \\ \tau_d & s \ge d_0 \end{cases} \qquad \text{for } \gamma >> s \quad \approx \frac{\tau_s(d_0 - s)}{d_0} + \frac{\tau_d s}{d_0}$$

$\gamma =$ Define non-linearity $\quad \gamma >> s$ then ≈ linear weakening

$\tau_0 =$ Initial shear stress, $\tau_s =$ Static friction, $\tau_d =$ Dynamic friction

$d_0 =$ Critical slip-weakening

Nonlinear slip weakening friction models may emulate some characteristics of more realistic shear strength vs slip behavior, e.g., weakening due to thermal pressurization of pore fluid.

Friction law #2 (rate and state): In progress
(see poster by Rojas et al.)

Aging law:

$$\tau_c(V,\theta) = \sigma_n\left[f_0 + a\ln(V/V_0) + b\ln(V_0\theta/L)\right]$$

$$\dot{\theta} = 1 - V\theta/L$$

Slip law:

$$\tau_c(V,\theta) = \sigma_n\left[a\ln(V/V_0) + \psi\right]$$

$$\dot{\psi} = -\frac{-V}{L}\left[f - f_{ss}(V)\right]$$

$$f_{ss}(V) = f_0 - (b-a)\ln(V/V_0)$$

Slip law with flash heating: Same equations of slip law but

$$f_{ss}(V) = \begin{cases} f_{ss(aging)} = f_0 - (b-a)\ln(V/V_0) & if \quad V < V_w \\ f_w + \left[f_{ss(aging)} - f_w\right]V_w/V & if \quad V > V_w \end{cases}$$

θ and $\psi =$ State variables

$V =$ Slip rate ($V_0 =$ steady state reference, $V_w =$ weakening)

$f =$ Friction coeficient ($f_{ss} =$ steady state, $f_0 =$ at steady state V_0 , $f_w =$ weakening)

$a,b =$ Friction parameters

The Southern San Andreas Fault Evaluation (SoSAFE) ShakeOut Rupture Scenario (Mw=7.8)

SLIP MATCHING TECHNIQUE

Stochastic stress drop($\Delta\tau_{St}$) (Ripperger & Mai, GRL, 2004)

Stochastic slip (S_{St}) (Mai & Beroza, JGR, 2002)

Stress drop trial $\Delta\tau_{Tr}(x,z) = T(z)\mu'(x,z)\Delta\tau_{St}(x,z)$

$\mu'(x,z) = \dfrac{\mu(x,z)}{\mu_{max}}$, where $\mu =$ shear moduli; $\quad T(z) = \begin{cases} z/2 & \text{if } z \le 2 \\ 1 & \text{if } z > 2 \end{cases}$

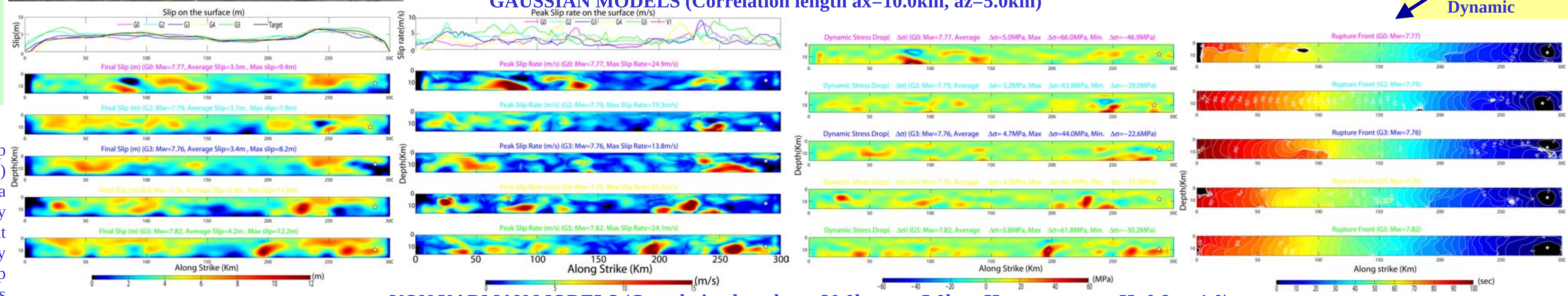
→ SGSN Dynamic → **Slip trial** (S_{Tr}) →

Slip scenario $S_{Sc}(x,z) = S_{tg}(x,z=0)\dfrac{S_{Tr}(x,z)}{S_{Tr}(x,z=0)}$

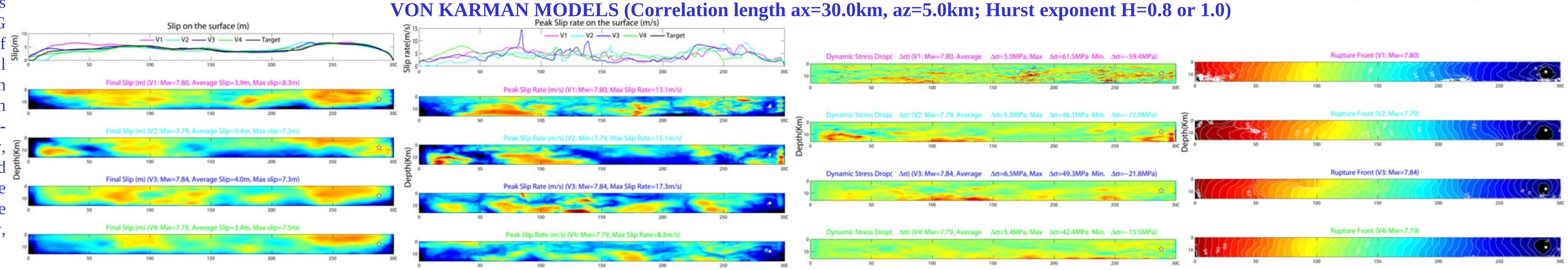
S_{Tg} = Target slip (ShakeOut surface slip)

→ SGSN Kinematic → **Strength excess and stress drop scenario** ($\Delta\tau_{Sc}$) → **Dynamic stress drop** $\Delta\tau = 0.9\Delta\tau_{Sc}T(z)$

GAUSSIAN MODELS (Correlation length ax=10.0km, az=5.0km)



VON KARMAN MODELS (Correlation length ax=30.0km, az=5.0km; Hurst exponent H=0.8 or 1.0)



Preliminary Findings

Source models were derived from stochastic slip distributions using Gaussian (G) and Von Karman (VK) correlation functions. While the series of models show a wide variety of complex rupture patterns, all closely reproduce the target surface-slip distribution and moment magnitude (Mw 7.8). The G and VK models vary greatly in their fault-plane distributions of stress drop, peak slip velocity, final slip and rupture time, even though averages are nearly identical. For example, compared with the G models, the VK stress models entail higher peak values of the dynamic stress drop, show smaller-scale spatial fluctuations in slip and the rupture front is developed with smaller wavelength structure. This work has thus far been done with 400m grid spacing, using the new Staggered-Grid Split-Node (SGSN) Method (Dalguer & Day, JGR,2007) for rupture simulation, which has well-verified accuracy and efficiency. The current results are guiding the design of higher-resolution models to investigate the effects of realistic friction laws, geologic heterogeneity, and stress states on rupture and wave propagation.