Overview of MOOSE-FARMS

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Mechanics of Complex Systems Group

MOOSE-FARMS | Outline

- What is MOOSE framework ?
- Code Structure/Capability
- Code Validation and Application
  - TPV Benchmark Cases
  - 2023 Turkey-Syria Earthquake
  - Coupling with Continuum Damage-Breakage Model
- QUAKEWORX Project
- Future Work and References

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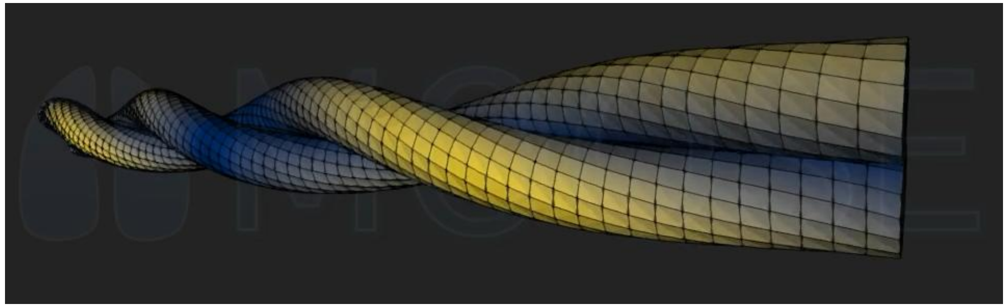
MOOSE-FARMS | What is MOOSE framework [1] ?

MOOSE Training Getting Started Documentation Gallery News Citing GitHub

MOOSE

Multiphysics Object-Oriented Simulation Environment

An open-source, parallel finite element framework



Proven Capability

- Scalability to over 30,000 cores
- R&D 100 winner in 2014
- Wide variety of applications

Rapid Development

- Simple installation
- Extensive tutorials
- Built-in physics modules
- Natural multi-scale capability

Active Community

- Active discussion forum
- Over 100 contributors
- Over 500 publications
- Over 10 million tests run per week

INL Idaho National Laboratory | Argonne National Laboratory | Los Alamos National Laboratory | Oak Ridge National Laboratory Leadership Computing Facility

Advantages:

- Parallelization and Scalability
- Multiphysics Coupling

MOOSE-FARMS: **Fault And Rupture Mechanics Simulations**
is an App Based on MOOSE.

Github:
https://github.com/chunhuizhao478/farms.git

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MOOSE-FARMS | Code Structure/Capability

- **Governing Equation / Flow Chart**

$$-\int_V \sigma \cdot \nabla\psi \; dV - q\int_V \bar{\sigma} \cdot \nabla\psi \, dV + \int_{S_f^+} T^{f^+} \psi \; dS + \int_{S_f^-} T^{f^-} \psi \; dS - \int_V \rho \ddot{u} \, \psi \; dV = 0$$

Cohesive Zone Model [2]

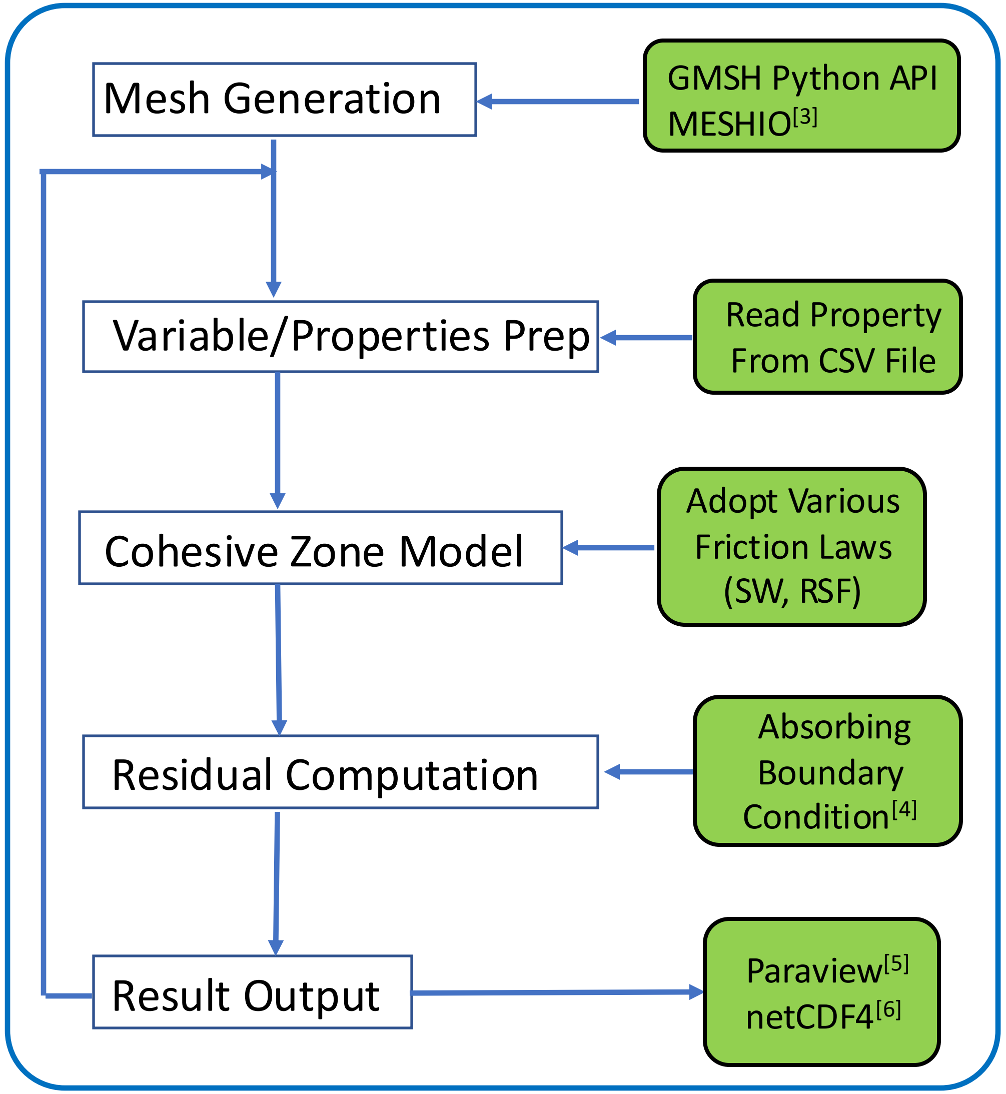
- **Time Integration**

Central Difference (Explicit), Lumped Mass

$$\mathbf{a}_n = \mathbf{M}^{-1}\mathbf{F}_n$$

$$\mathbf{v}_{n+\frac{1}{2}} = \mathbf{v}_{n-\frac{1}{2}} + \frac{\Delta t_{n-1} + \Delta t_n}{2}\mathbf{a}_n$$

$$\mathbf{u}_{n+1} = \mathbf{u}_n + \Delta t \mathbf{v}_{n+\frac{1}{2}}$$



$$-\int_V \sigma \cdot \nabla\psi \; dV - q\int_V \bar{\sigma} \cdot \nabla\psi \, dV + \int_{S_f^+} T^{f^+} \psi \; dS + \int_{S_f^-} T^{f^-} \psi \; dS - \int_V \rho \ddot{u} \, \psi \; dV = 0$$

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- What is MOOSE framework ?
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  - **TPV Benchmark Cases – TPV2052D & 3D, TPV142D, TPV1012D**
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MOOSE-FARMS Verification: TPV205-2D Benchmark

- **Mesh Setup**

Simulation Domain: 50km in both directions

Mesh Size: 100m

Element Type: QUAD4

NDOFs: 2,006,004

- **Numerical Simulation**

Time Integration Scheme: Central Difference

Solve Type: Lumped Mass

Time Step: $0.005s$. (Bounded by CFL condition)

Total Simulation Time: 12s

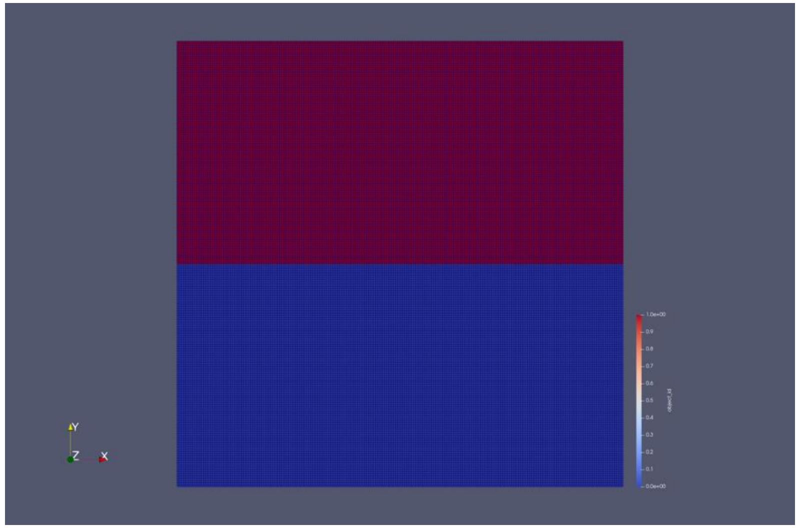

Figure: 2D Mesh Configuration

Variable	Value	Description
ρ	$2670\ kg/m^3$	Density
$\lambda = \mu$	$32.04\ GPa$	Lame Parameters
T_2^0	$120\ MPa$	Background Normal Stress
T_1^0	$\begin{cases} 81.6\ MPa, \lvert x\rvert < 1.5km \\ 78.0\ MPa, -8km \le x \le -6km \\ 62.0\ MPa, 6km \le x \le 8km \\ 70\ MPa, else \end{cases}$	Background Shear Stress
D_c	$0.4\ m$	Characteristic Length
μ_s	$\begin{cases} 0.677, & \lvert x\rvert < 15km \\ 10000, & \lvert x\rvert > 15km \end{cases}$	Static Friction Parameter
μ_d	0.525	Dynamic Friction Parameter
Δx	100 m	Mesh Size

Figure: Parameter Table

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MOOSE-FARMS Verification: TPV205-2D Benchmark

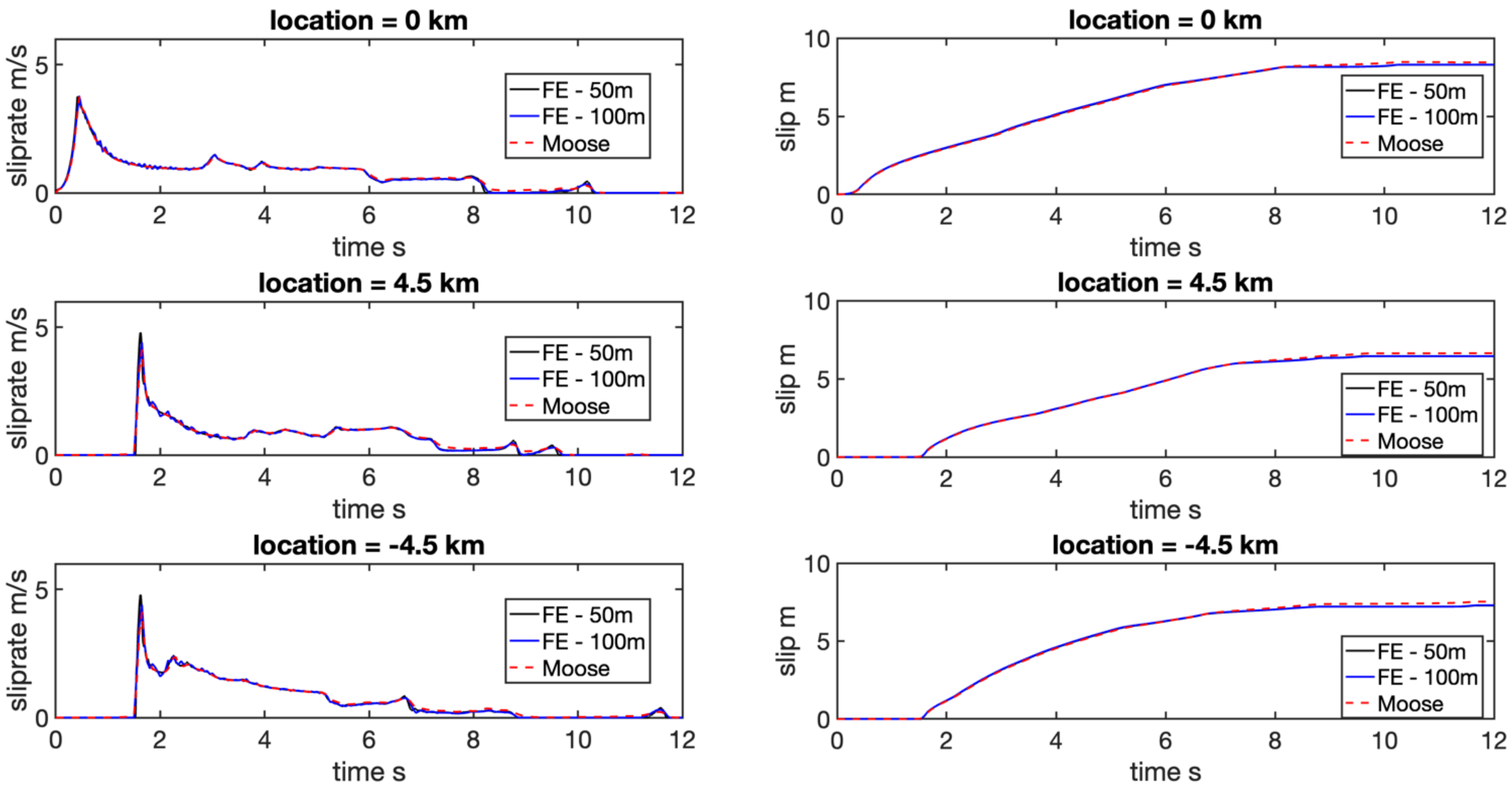

Figure: Time History of Slip rate (FE - 50m, FE - 100m, Moose) at locations 0 km, 4.5 km, -4.5 km

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MOOSE Implementation Verification: TPV205-3D Benchmark

- **Mesh Setup**

  Simulation Domain: (30km × 30km × 30km)

  Mesh Size: 200m

  Element Type: HEX8

  NDOFs: 10,397,256

- **Numerical Simulation**

  Time Integration Scheme: Central Difference

  Solve Type: Lumped Mass

  Time Step: 0.005s

  Total Simulation Time: 12s

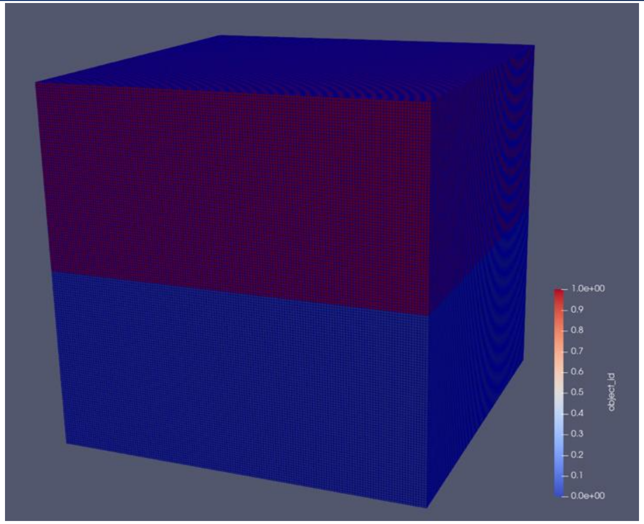

Figure: 3D Mesh Configuration

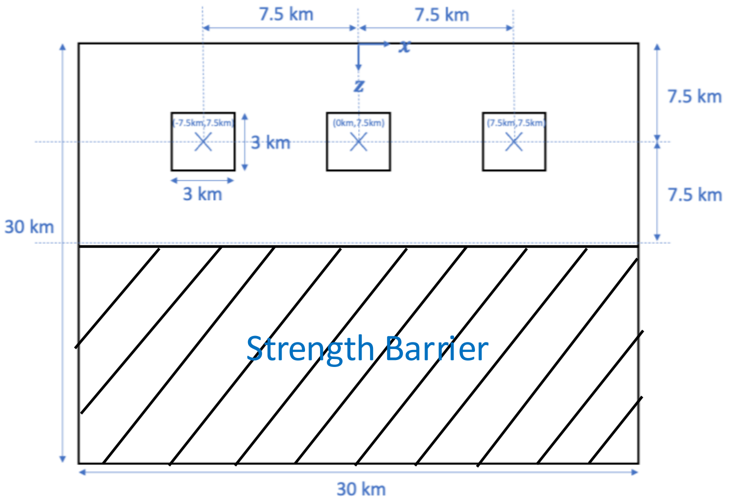

Figure: Fault Surface Background Shear Stress Distribution

Variable	Value	Description
$\boldsymbol{\rho}$	$2670\ kg/m^3$	Density
$\boldsymbol{\lambda = \mu}$	$32.04\ GPa$	Lame Parameters
$\boldsymbol{T_2^0}$	$120\ MPa$	Background Normal Stress
$\boldsymbol{T_1^0}$ $(\boldsymbol{6km \le z \le 9km})$	$\begin{cases} 81.6\ MPa, \lvert x\rvert < 1.5km \\ 78.0\ MPa, -9km \le x \le -6km \\ 62.0\ MPa, 6km \le x \le 9km \\ 70\ MPa, else \end{cases}$	Background Shear Stress
$\boldsymbol{D_c}$	$0.4\ m$	Characteristic Length
$\boldsymbol{\mu_s}$	$\begin{cases} 0.677, & \lvert x\rvert < 15km \\ 10000, & \lvert x\rvert > 15km \end{cases}$	Static Friction Parameter
$\boldsymbol{\mu_d}$	0.525	Dynamic Friction Parameter
$\boldsymbol{\Delta x}$	200 m	Mesh Size

Figure: Parameter Table

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MOOSE Implementation Verification: TPV205-3D Benchmark

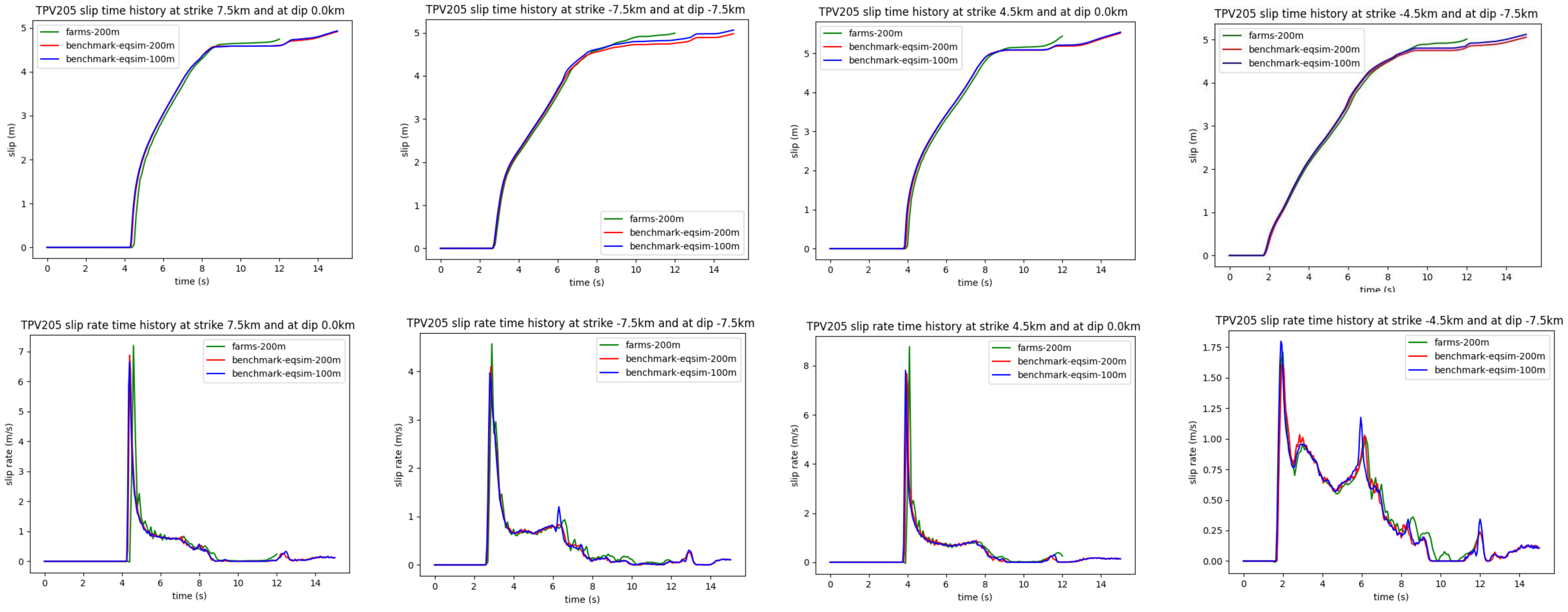
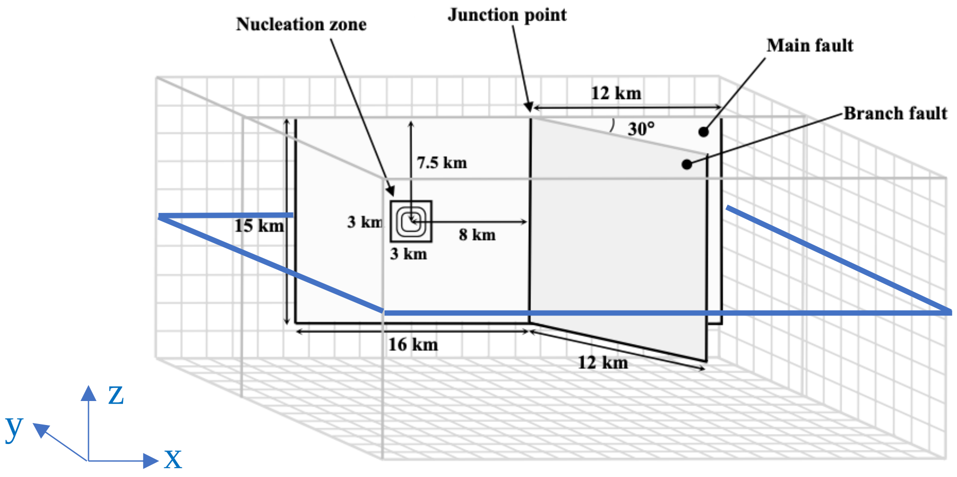
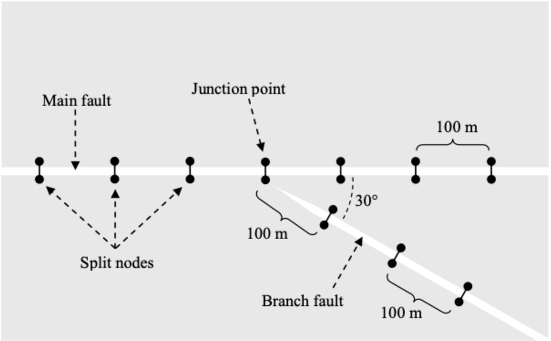


Figure: Time History of Slip rate and Slip (FE - 100m, Moose-100m-HEX8)

MOOSE-FARMS | Verification Benchmark Case[7]: TPV14-2D, TPV15-2D

- Problem Setup





Variable	Description		TPV14-2D
			Right-Lateral
ρ	Density		$2670kg/m^3$
$\lambda = \mu$	Lame Parameters		32.04GPa
T_1^o	Initial Shear Stress	Main Fault	70.0MPa
		Branch Fault	70.0MPa
		Nucleation Zone	81.6MPa
T_2^o	Initial Normal Stress		120.0MPa
D_c	Characteristic Length		0.4m
μ_s	Static Friction Parameter		0.677
μ_d	Dynamic Friction Parameter		0.525
Δx	Element Type & Size		TRIA3, 100m
L	Domain Size		40km in x direction 38km in y direction
Δt	Time Step		0.0025s
t	Total Simulation Time		12s

MOOSE-FARMS | Verification Benchmark Case: TPV14-2D, TPV15-2D

- TPV14 Slip/Slip Rate Plots

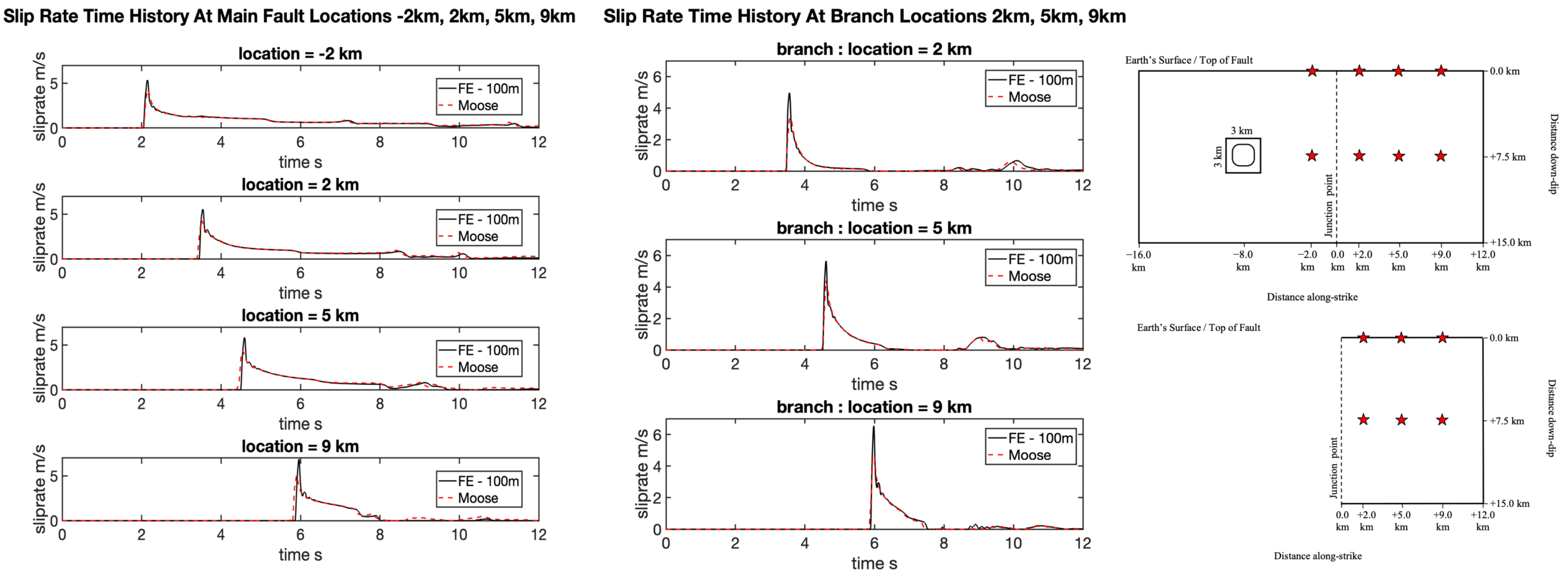


Figure: Time History of Slip rate (FE - 100m, Moose-100m-TRIA3) at locations -2km, 2 km, 5.5 km, 9 km

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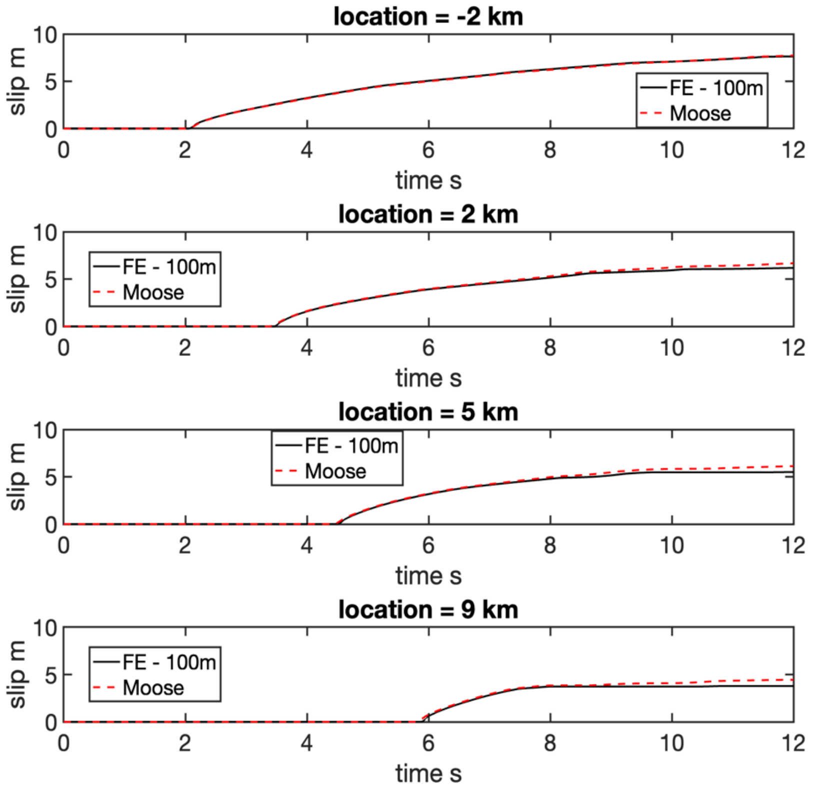
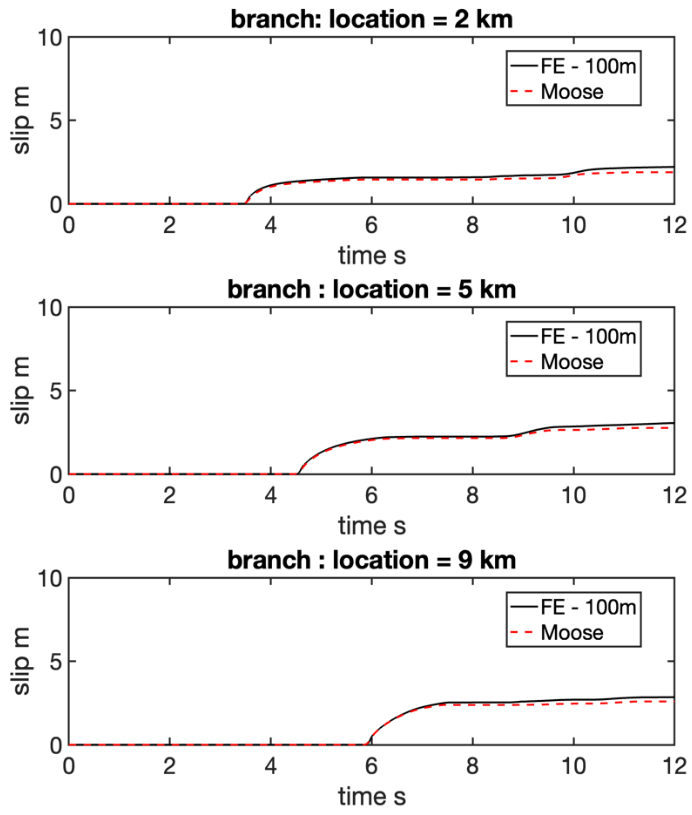
MOOSE-FARMS | Verification Benchmark Case: TPV14-2D, TPV15-2D

- TPV14 Slip/Slip Rate Plots

Slip Time History At Main Fault Locations -2km, 2km, 5km, 9km



Slip Time History At Branch Locations 2km, 5km, 9km



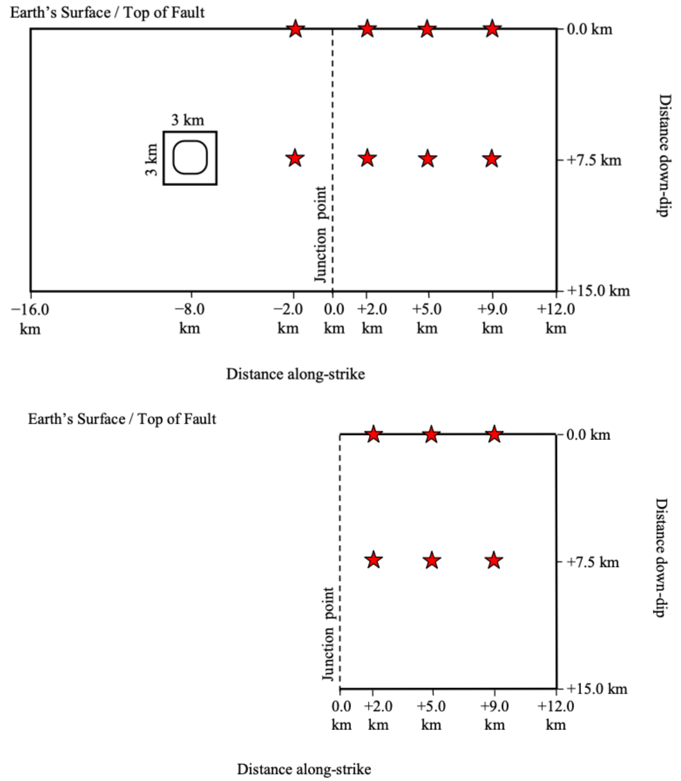
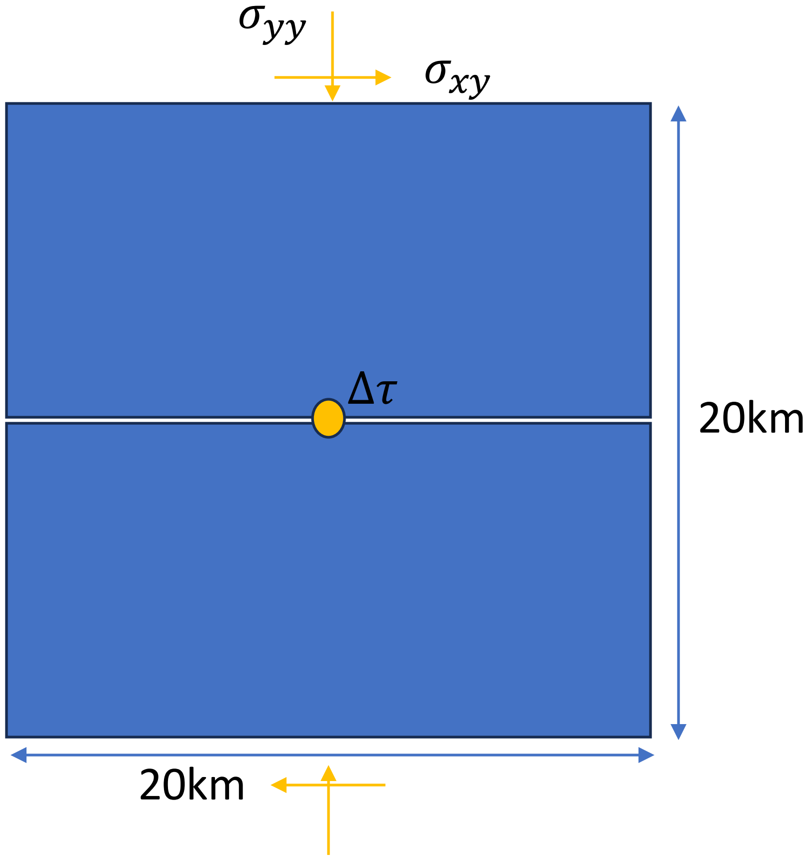


Figure: Time History of Slip (FE - 100m, Moose-100m-TRIA3) at locations -2km, 2 km, 5.5 km, 9 km

MOOSE-FARMS | Verification Benchmark Case: TPV101-2D

SCEC Benchmark TPV101



Rate-and-state friction law

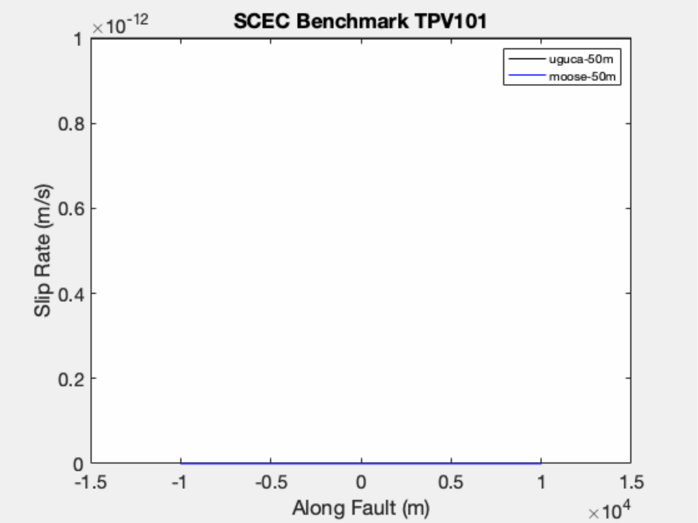
$$\tau = a\sigma\,\mathrm{arcsinh}\left[\frac{V}{2V_0}\exp\left(\frac{f_0 + b\ln(V_0\theta/L)}{a}\right)\right].$$

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}.$$

Stress perturbation at nucleation site

$$\Delta\tau(x,y,t) = \Delta\tau_0 F\left(\sqrt{(x-x_0)^2 + (y-y_0)^2}\right)G(t),$$

$$F(r) = \begin{cases} \exp\left(\frac{r^2}{r^2 - R^2}\right), & r < R \\ 0, & r \geq R \end{cases} \quad G(t) = \begin{cases} \exp\left[\frac{(t-T)^2}{t(t-2T)}\right], & 0 < t < T \\ 1, & t \geq T \end{cases}.$$



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MOOSE-FARMS | Verification Benchmark Case: TPV101-2D

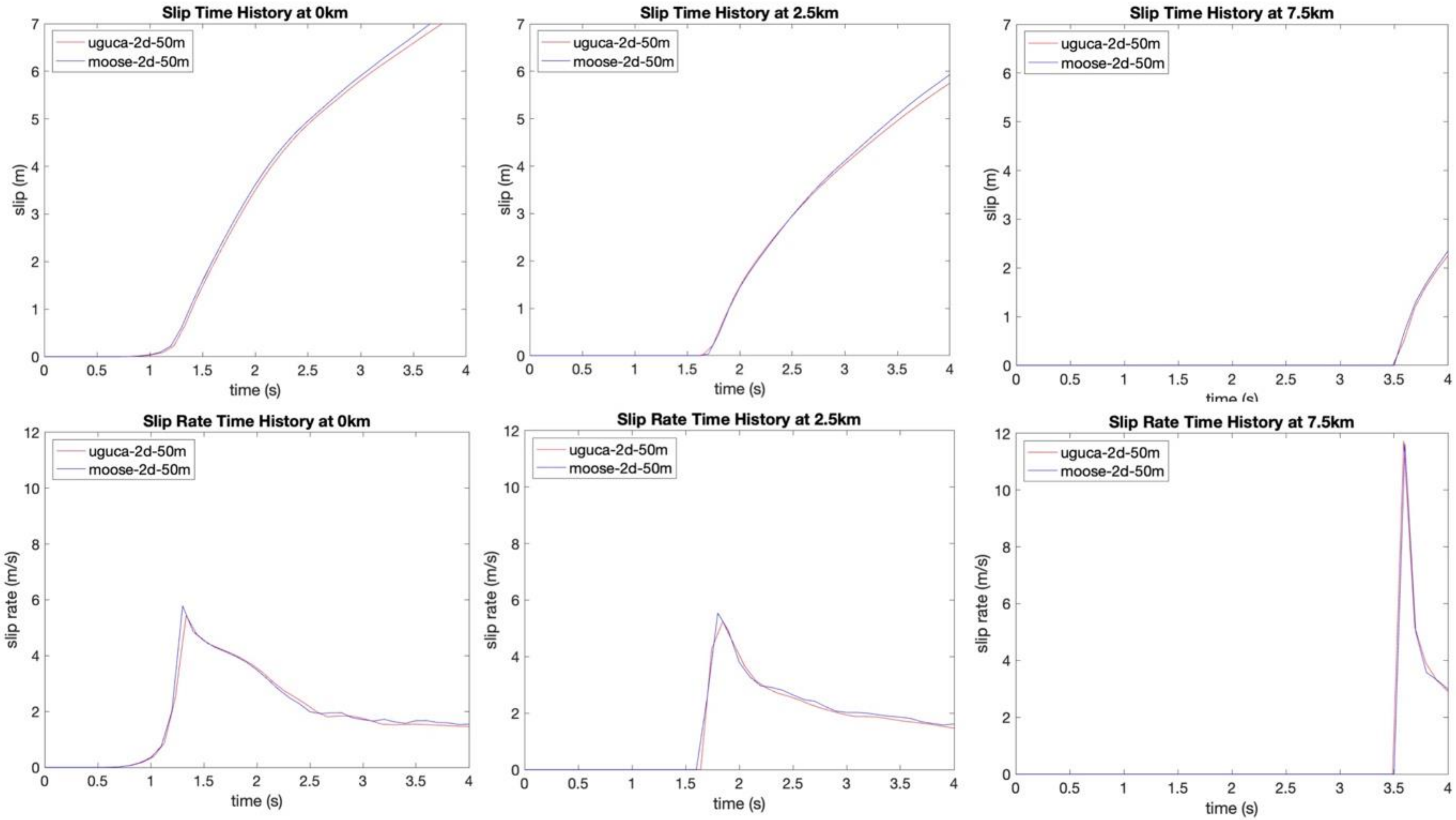

Figure Selected slip rate and slip time history for location 0km, 2.5km, 7.5km along the fault for SCEC Benchmark TPV101(Red lines are solution from uguca-2d, blue lines are from MOOSE-FARMS, the mesh size is 50m for both cases).

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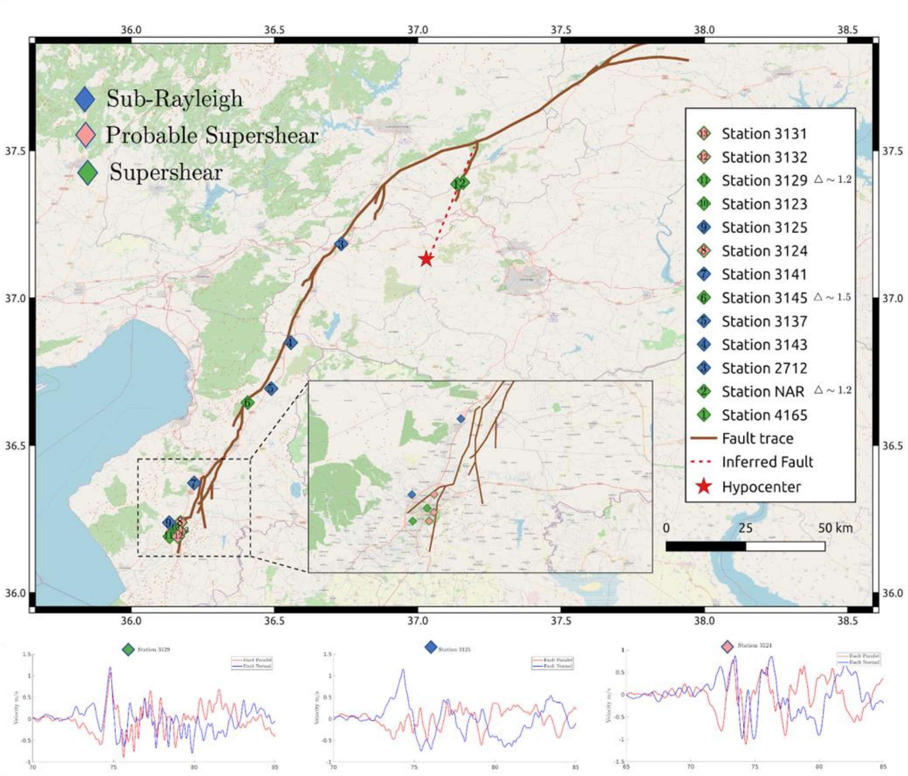
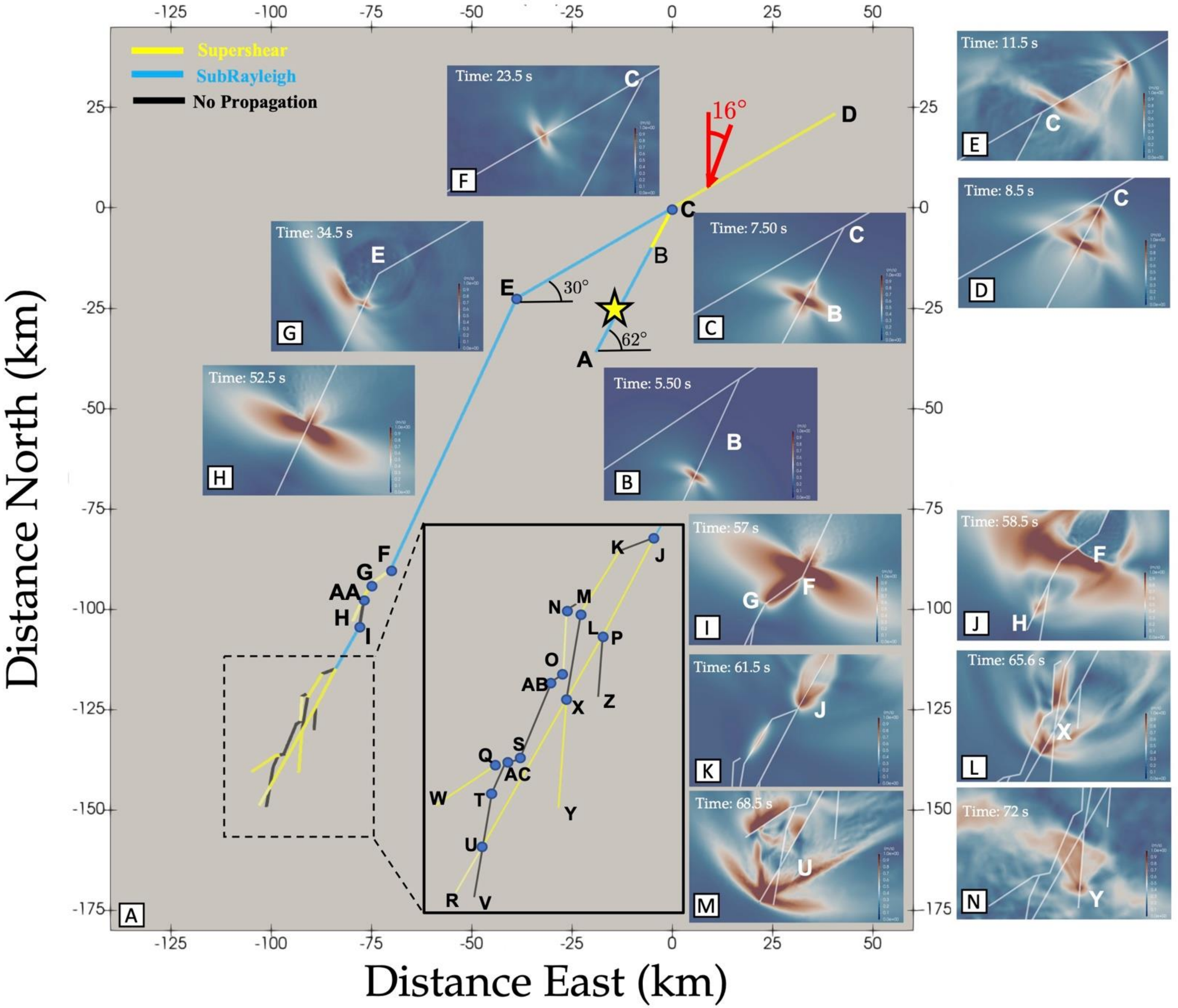
MOOSE-FARMS | Code Application: 2023 Turkey-Syria Earthquake

(Abdelmeguid et al, 2023)[8]





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MOOSE-FARMS | Code Application

Zhao et al (2024)[9], 2024 SCEC Annal Meeting Poster[10]

$$F(\epsilon^e, \alpha, \nabla\alpha, B) = (1-B)F_s(\epsilon^e, \alpha, \nabla\alpha) + BF_b(\epsilon^e)$$

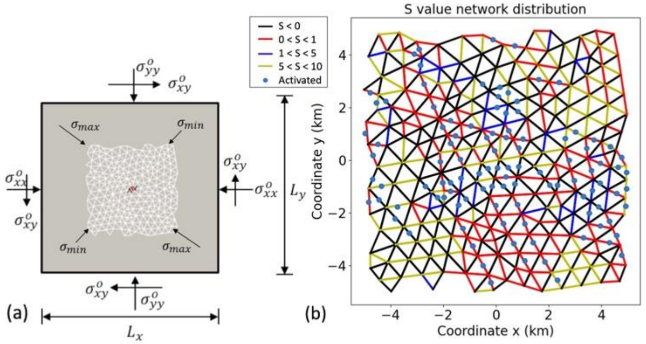
Where:

$$F_s(\epsilon, \alpha, \nabla\alpha) = \frac{1}{\rho}\left(\frac{\lambda}{2}I_1^2 + \mu I_2 - \gamma I_1\sqrt{I_2} + \frac{D}{2}\nabla\alpha \cdot \nabla\alpha\right)$$

$$F_b(\epsilon) = \frac{1}{\rho}\left(a_0 I_2 + a_1 I_1\sqrt{I_2} + a_2 I_1^2 + a_3\frac{I_1^3}{\sqrt{I_2}}\right)$$

$$\frac{\partial\alpha}{\partial t} = \begin{cases}(1-B)[C_d I_2(\xi-\xi_o)] + D\nabla^2\alpha, & \xi \geq \xi_o\\ (1-B)\left[C_1 exp\left(\frac{\alpha}{C_2}\right) I_2(\xi-\xi_o)\right], & \xi < \xi_o\end{cases}$$

$$\frac{\partial B}{\partial t} = \begin{cases}(1-B)[C_B I_2(\xi-\xi_d)], & \xi \geq \xi_d\\ C_{BH} I_2(\xi-\xi_d), & \xi < \xi_d\end{cases}$$



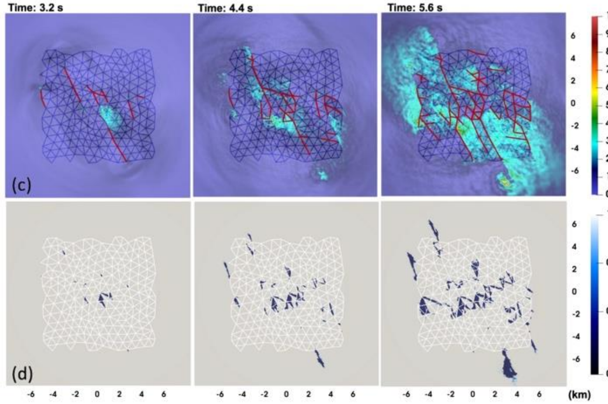
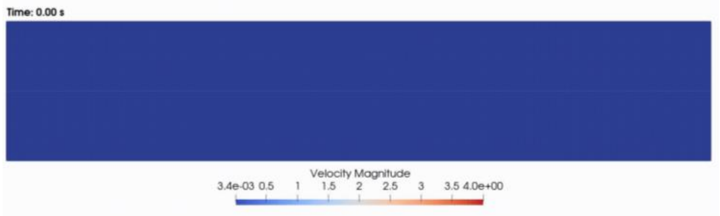


Figure: Interface friction couples with off-fault damage and breakage [9]



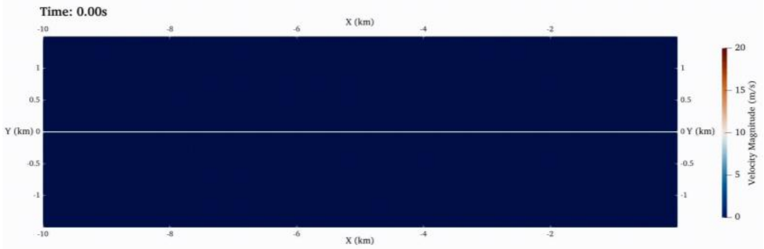
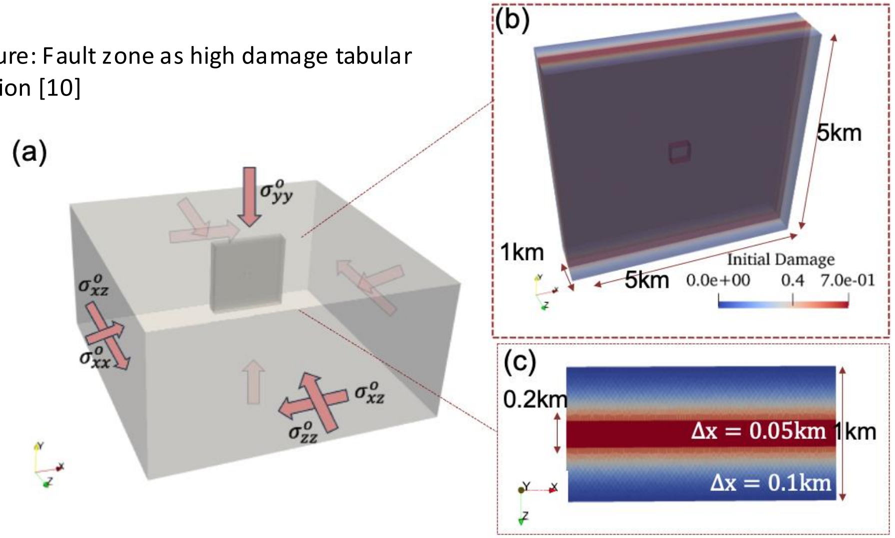
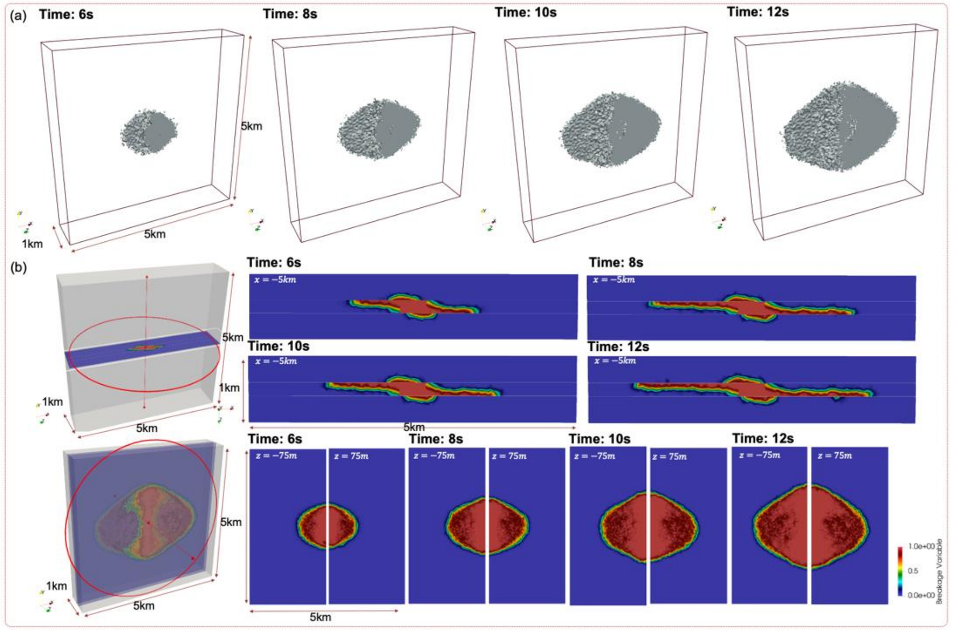


Figure: Fault zone as high damage tabular region [10]





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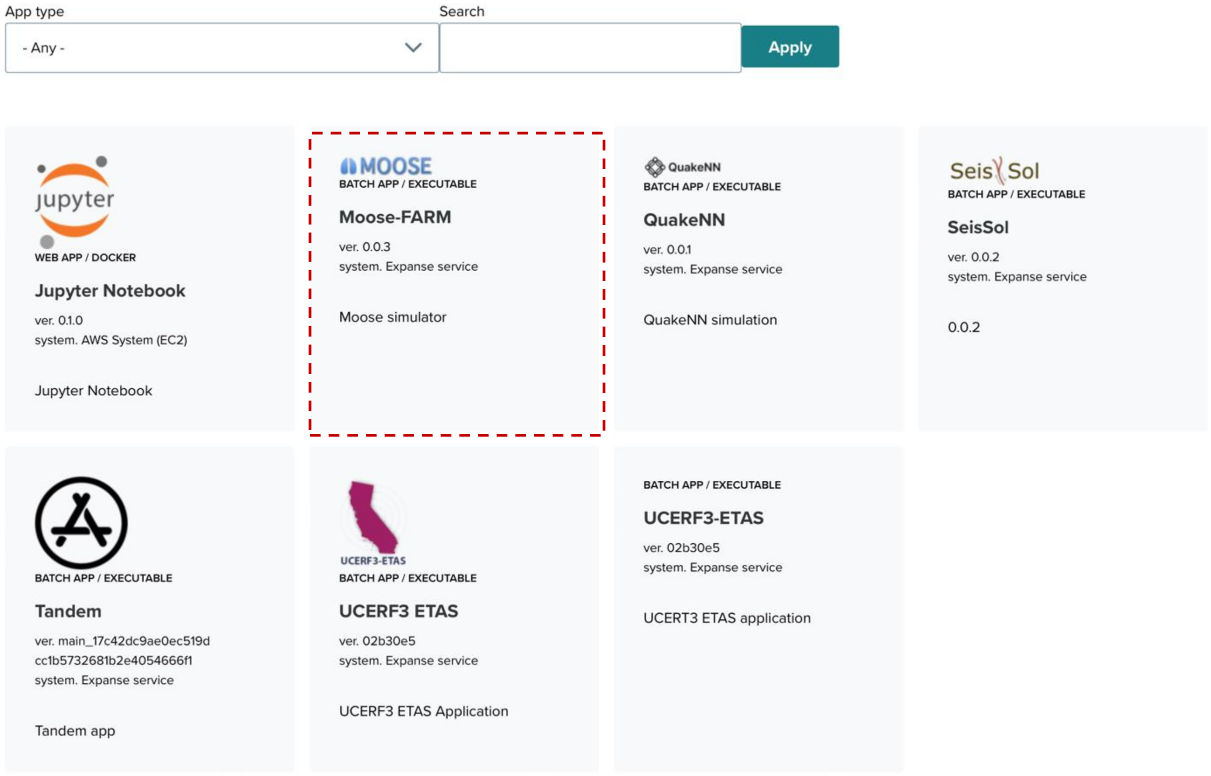
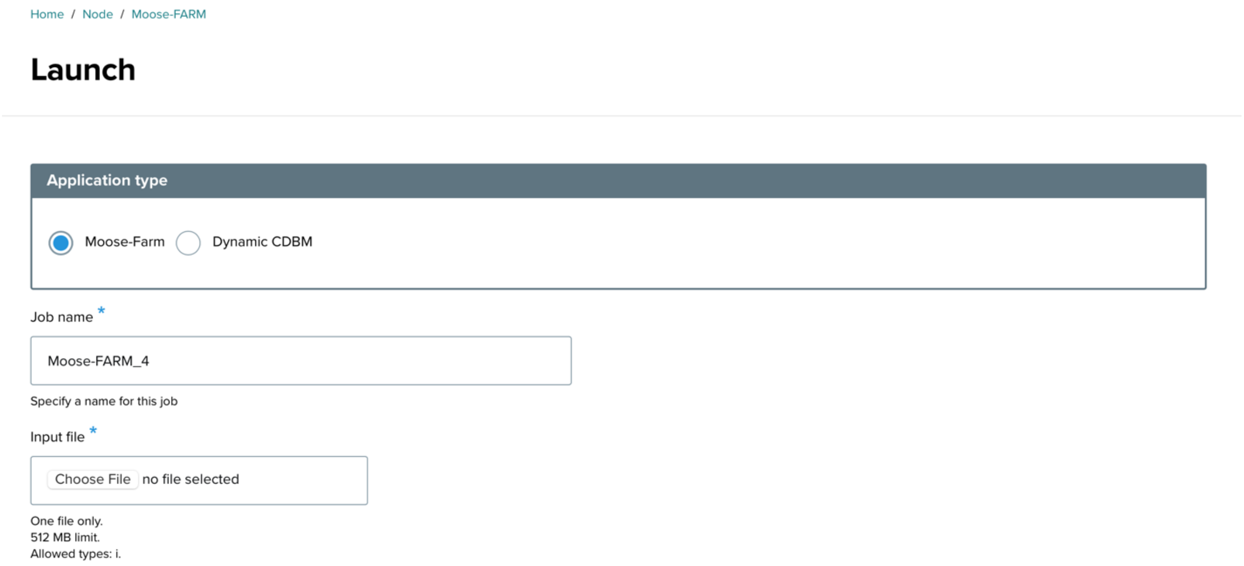
MOOSE-FARMS | QUAKEWORX

The simulators developed in **MOOSE-FARMS** are available (to-be available) on the **QUAKEWORX** science gateway for democratizing access to earthquake simulations and data.

https://qwx1.onescienceway.com/apps/all





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MOOSE-FARMS | References

- Future Work

  - Document the existing validation cases
  - Validate code with TPV10/TPV11 with dip-slip fault, 60 degrees angle
  - Contribute the results for TPV35 and TPV36

- References

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[9] Zhao, C., Mia, M. S., Elbanna, A., & Ben-Zion, Y. (2024). Dynamic rupture modeling in a complex fault zone with distributed and localized damage. *Mechanics of Materials*, *198*, 105139.

[10] Zhao, C., Elbanna, A. E., & Ben-Zion, Y. (2024, 09). Multiscale Dynamics of 3D Rupture Zones using a Continuum Damage Breakage Rheology. Poster Presentation at 2024 SCEC Annual Meeting.

Thanks for your listening! Any questions?