Fast Dynamic Rupture and Earthquake Cycle Simulations with a Fourier Neural Operator–Based Framework

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1. Introduction

Earthquake modeling captures the multiscale nature of fault processes, spanning spatial and temporal scales from slow aseismic slip to rapid dynamic rupture. Classical physics-based modeling, while accurate, is computationally expensive. To address this challenge, we present a computationally efficient and quantitatively accurate surrogate modeling approach. Specifically, **we develop a Fourier Neural Operator (FNO)–based framework to approximate the nonlinear equations governing dynamic rupture and earthquake cycle simulations.**

The surrogate model is trained on synthetic data generated from multiple physics-based simulations and is then applied to previously unseen scenarios. We demonstrate its generalization capability under unseen conditions. Additionally, we apply the FNO-based framework to model aseismic slip within earthquake cycles. The code from this study will be made available through Quakeworx, an NSF-funded science gateway for earthquake simulations and data.

2. FNO for Dynamic Rupture Modeling

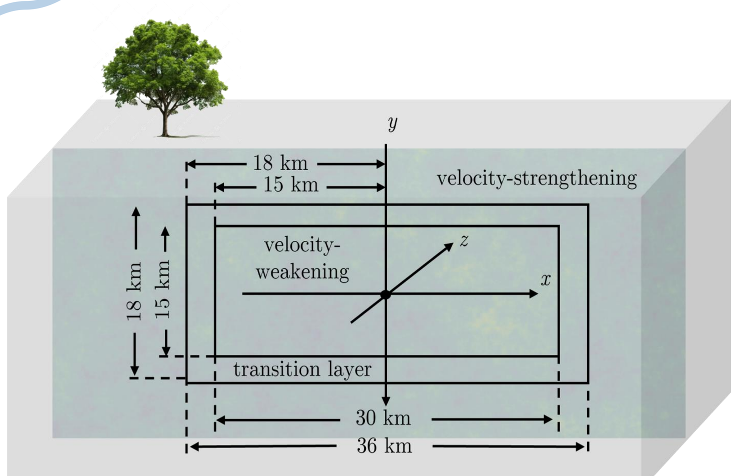
Methodology

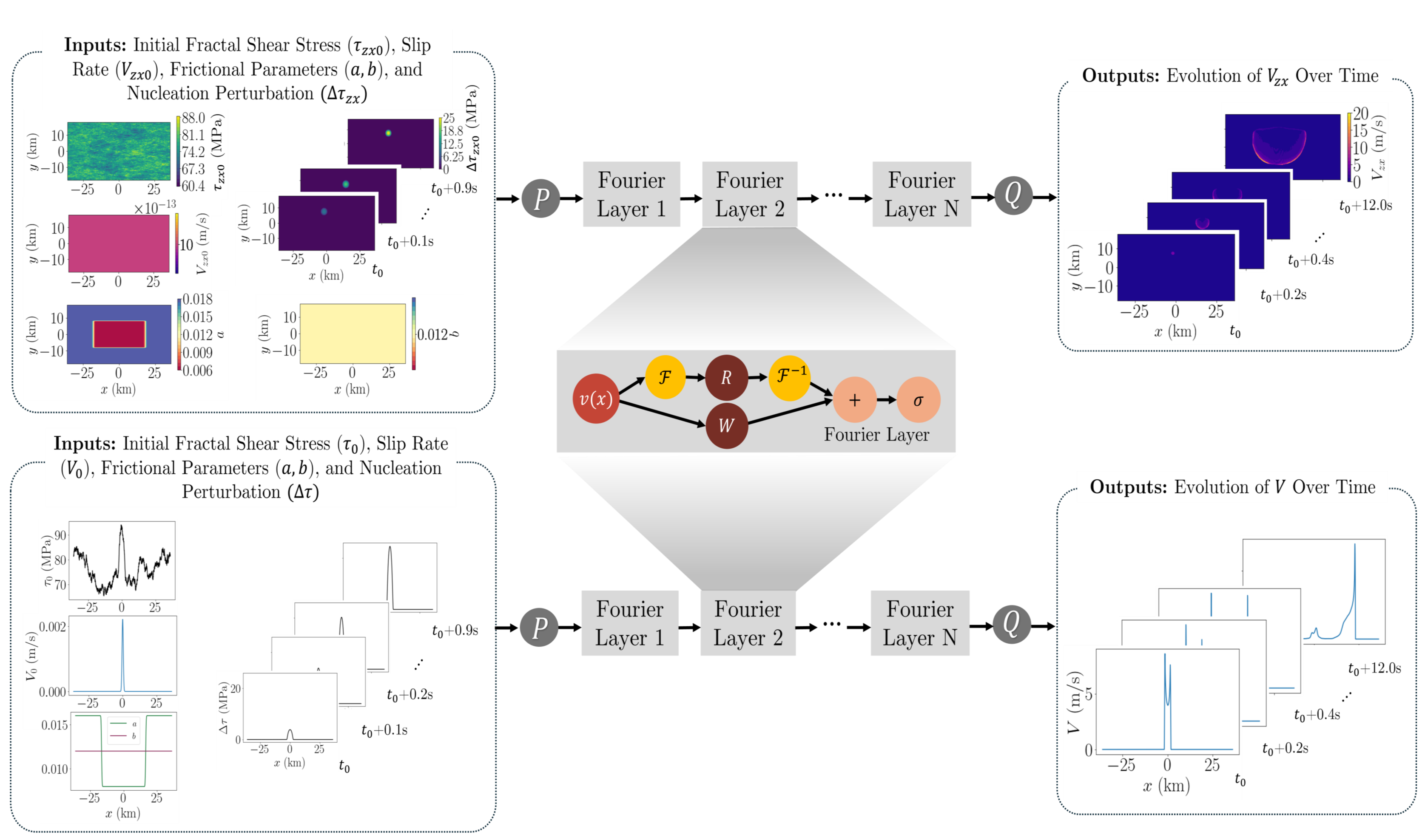
We develop an FNO-based framework for both 2D and 3D dynamic rupture, capturing the full spatiotemporal evolution of slip rate under rate-and-state friction. Training data are generated with the Spectral Boundary Integral (SBI) method, with variations in:

- **Initial shear stress:** Varying fractal dimensions(D)
- **Frictional parameters:** a and b
- **Initial slip rate:** Maximum value greater than V_{th}
- **Nucleation site**: Uniformly random, at the maximum shear location, or at the fault center

Model Parameters for Training:

D	b	a_{VW}	V_{th}
1.2, 1.5, 1.6	0.012, 0.014	0.009, 0.008, 0.007, 0.006, 0.0085, 0.0075, 0.0065	0, 10^{-4}, 10^{-3}, 10^{-2}

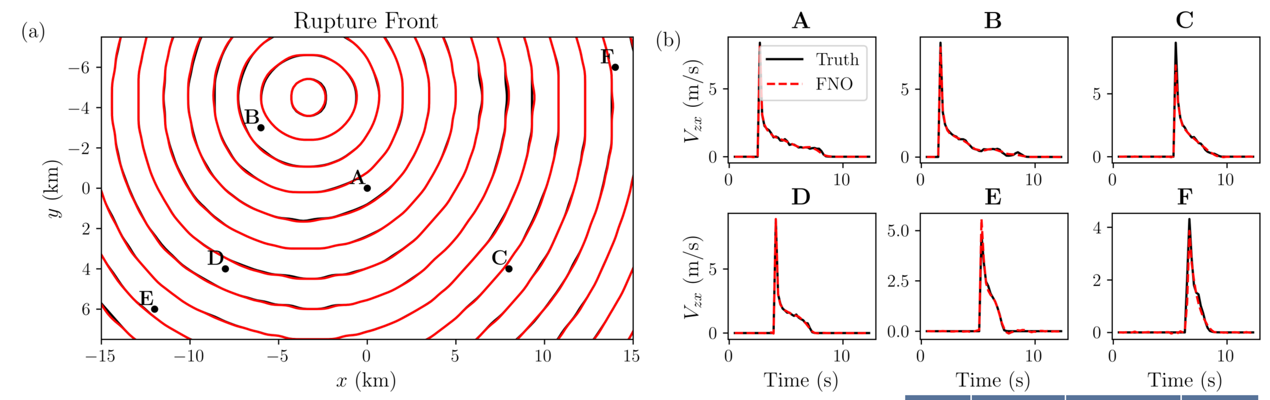




Results

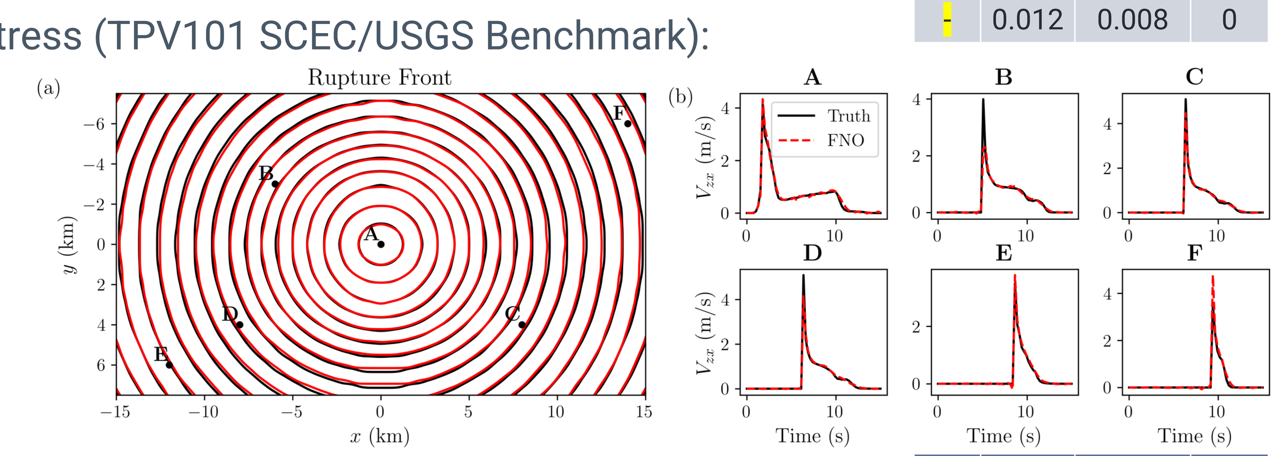
Performance on Testing Dataset:

D	b	a_{VW}	V_{th}
1.6	0.012	0.007	10^{-3}



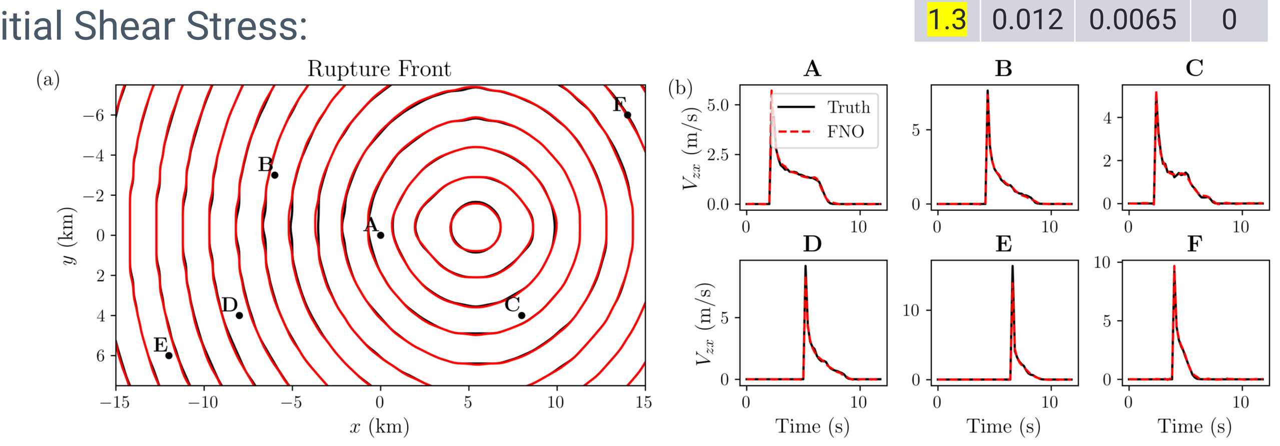
Generalization to Unseen Distribution of Initial Shear Stress (TPV101 SCEC/USGS Benchmark):

D	b	a_{VW}	V_{th}
-	0.012	0.008	0



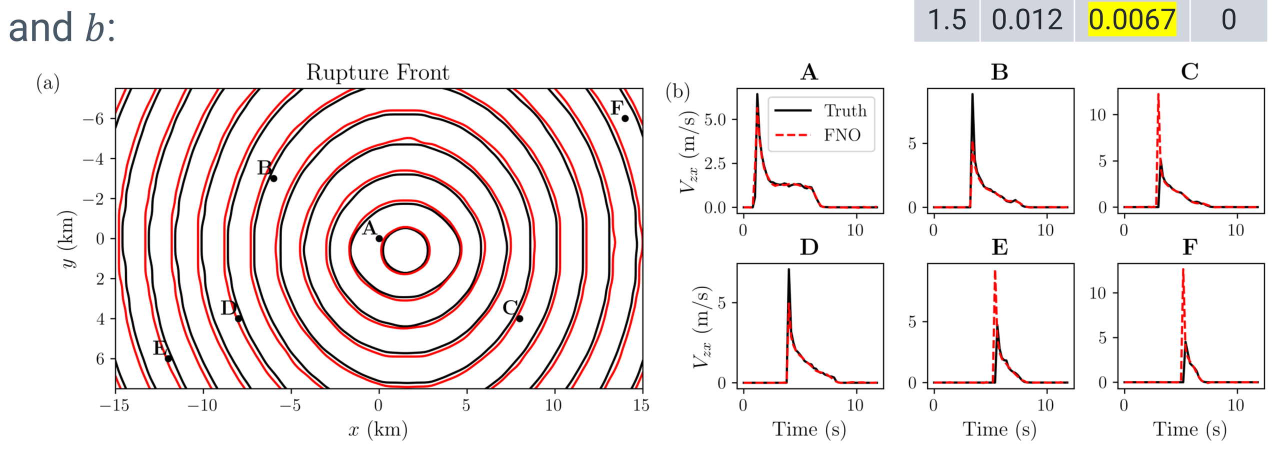
Generalization to Unseen Fractal Dimension of Initial Shear Stress:

D	b	a_{VW}	V_{th}
1.3	0.012	0.0065	0

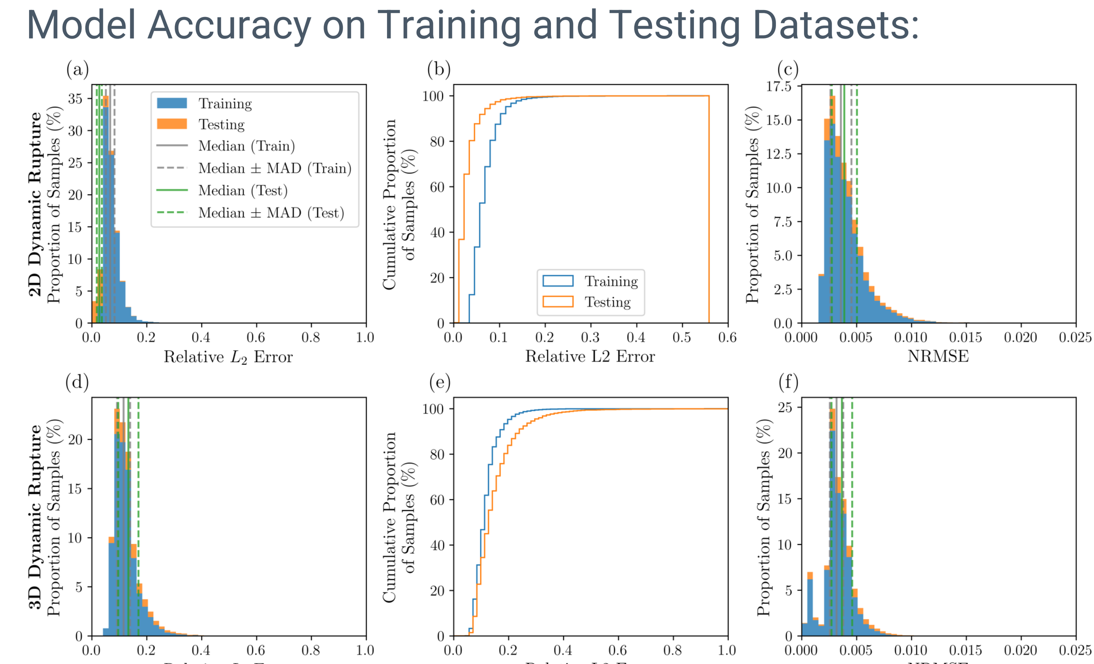


Generalization to Unseen Frictional Parameters a and b:

D	b	a_{VW}	V_{th}
1.5	0.012	0.0067	0



Model Accuracy on Training and Testing Datasets:



Computational Speed-up:

Model	# Parameter	Training (s/epoch)	Testing Speed-up vs. SBI
3D	2.7×10^{8}	594	4×10^{5}
2D	2.3×10^{6}	30	2×10^{5}

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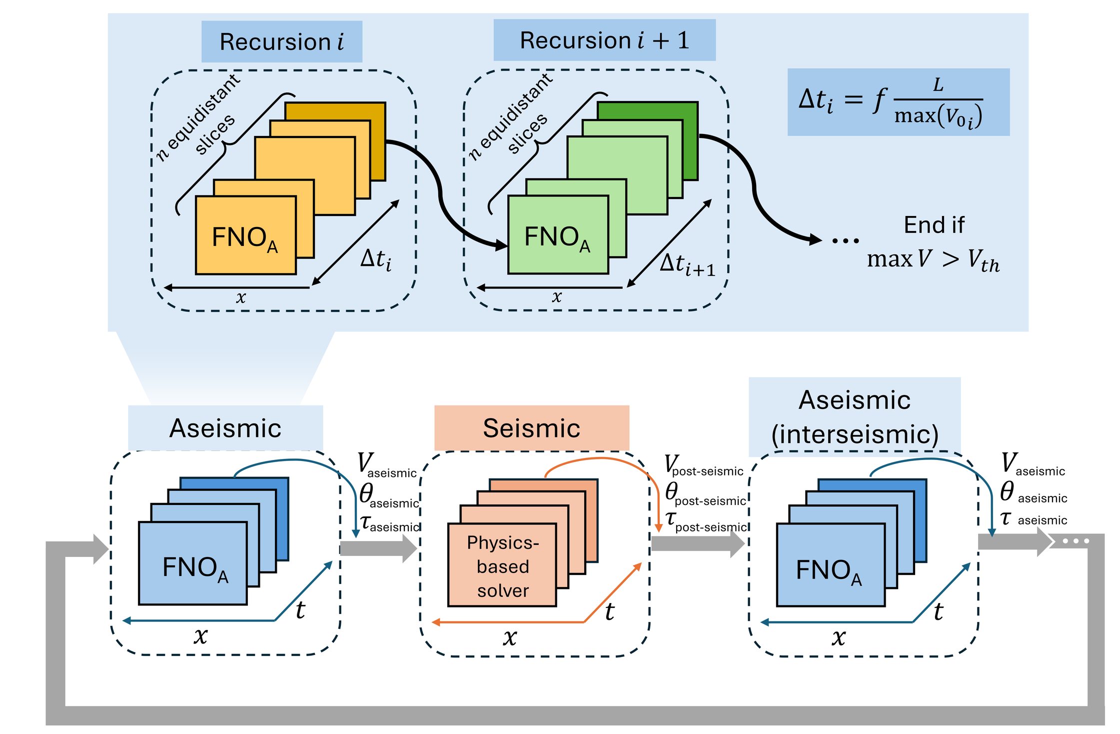
3. FNO for Earthquake Cycle Simulation

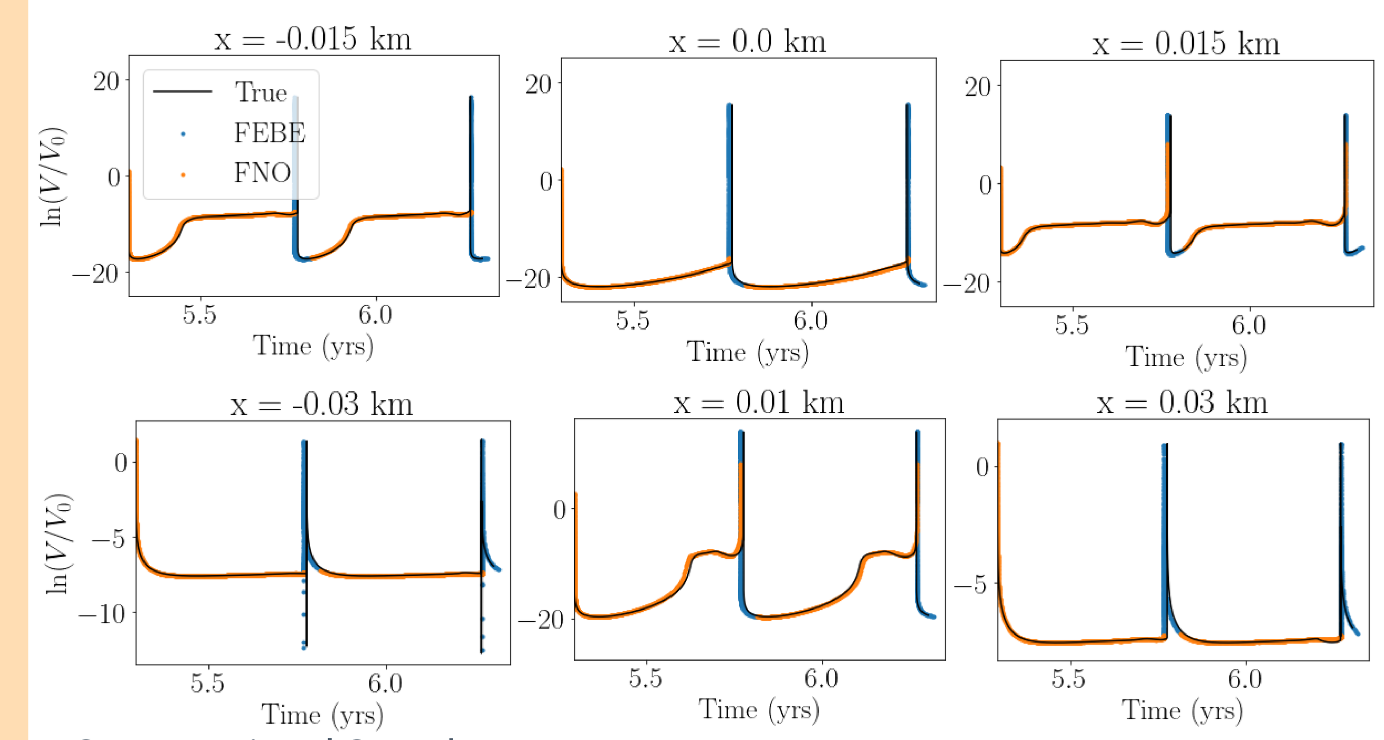
Methodology

- **Goal:** Model full earthquake cycles with a physics–FNO hybrid.
- **Aseismic phase:** Approximated by recursive FNO predictions, trained on overlapping slip windows with adaptive time stepping.
- **Seismic phase:** The final aseismic state is passed to a hybrid finite element–spectral boundary (FEBE) scheme for dynamic rupture.



Results

Time series of the hybrid FEBE–FNO model compared with ground-truth solutions from the unseen test set:



Computational Speed-up:

Simulation Phase	FEBE Running Time (s)	Hybrid scheme running time (s)	Speed-up vs. FEBE
Aseismic period	8,290	0.288	28,785
Two seismic cycles	31,865	15,191	2.1

4. Conclusion

- FNO provides a speed-up compared to numerical simulations. For dynamic rupture simulations, we achieve up to 4×10^{5} times speed-up, and 28,785 times in aseismic phase modeling.
- We demonstrate that FNO can generalize to unseen cases involving initial stress, slip rate, and frictional parameters.
- This increase in computational speed-up, in combination with the demonstrated generalizability of FNO, may enable dynamic source inversion, large-scale statistical analysis, systematic parameter exploration, and probabilistic hazard assessment.

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