Dynamic and quasi-dynamic modelling of earthquake sequences from zero to three dimensions: choose model complexity as needed

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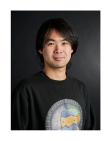

Abstract

We developed a C++ numerical library called GARNET to deal with the various dimensional models in one simulator. By adding dimensions, we simulate a more detailed structure of the seismic cycle. The higher dimensional models present both the validity and the limitations of the lower dimensional ones. However, some important observables, such as the maximum/ minimum stress and slip rates, are calculated accurately in lower dimensional models, which are much faster than higher dimensional ones. We also implemented and compared quasi- and fully dynamic models in the same way. These comparisons clarify the advantages and shortcomings of the models and could provide us with guidance to identify the appropriate model complexity for a specific problem. Finally, we present our results for the SCEC SEAS benchmarks BP1 and 3. The large agreement with other participating codes [1] proves the validity of our modeling tool.

Introduction

Large numerical models in 3D are still computational time and memory consuming and they may not be optimal if the aspects of lateral or depth variations within the results are not needed to answer a particular objective. This inspired us to investigate the advantages and limitations of various dimensional models by simulating seismic cycles on a strike-slip fault with rate-and-state friction law in 0D, 1D, 2D and ultimately 3D, with and without inertia. Successful solution to benchmarks validates these models.

Garnet

It's a public-domain code library with a staggered grid central finite difference discretization (Figure 1) for solving coupled nonlinear multi-physics systems in any number of spatial dimensions from one to three. [1].

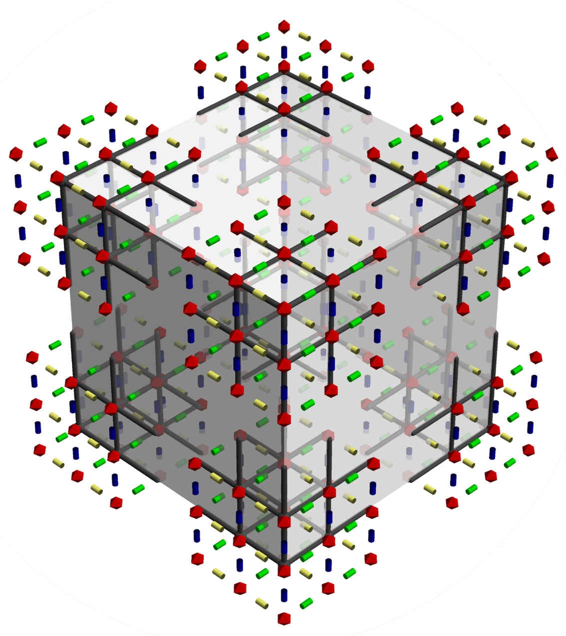

Figure 1 **Staggered spatial discretization in 3D.**

Benchmark model setup

This benchmark [2] is a 2D anti-plane problem, with a 1D planar vertical strike-slip fault obeying rate-and-state friction, embedded in a 2D homogeneous, linear elastic half-space with a free surface (Figure 2). The fault has a shallow seismogenic region with velocity-weakening (VW) friction and a deeper velocity-strengthening (VS) region, below which a relative plate motion rate is imposed.

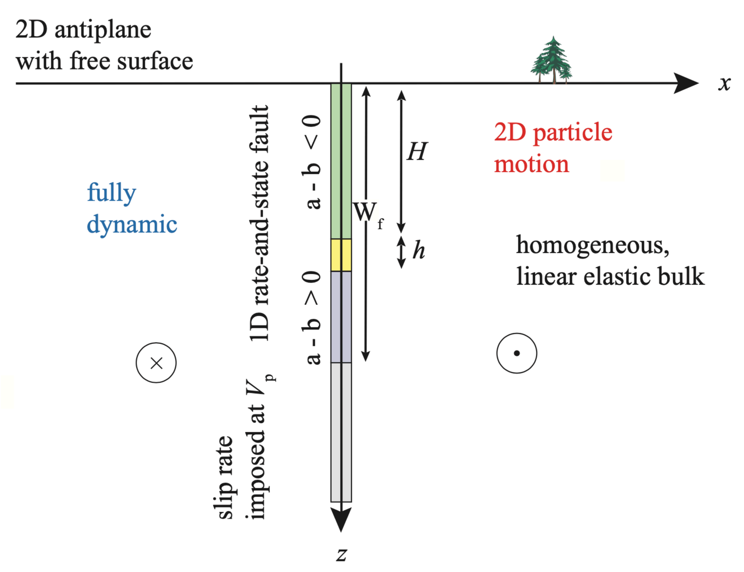

Figure 2 **The benchmark problem model setup. (After [2])**

Methodology

- **Medium behavior**
  - Elastic rheology
  - Mass conservation
  - Momentum conservation
- **Boundary condition**
  - Rate-and-state friction
  - Aging law
- **Adaptive time stepping**

$$\Delta t = \min\left\{\zeta \frac{L}{V_{\max}}, (1+\alpha)\Delta t_{\text{old}}, \Delta t_{\max}\right\}$$

Results: which dimension to use?

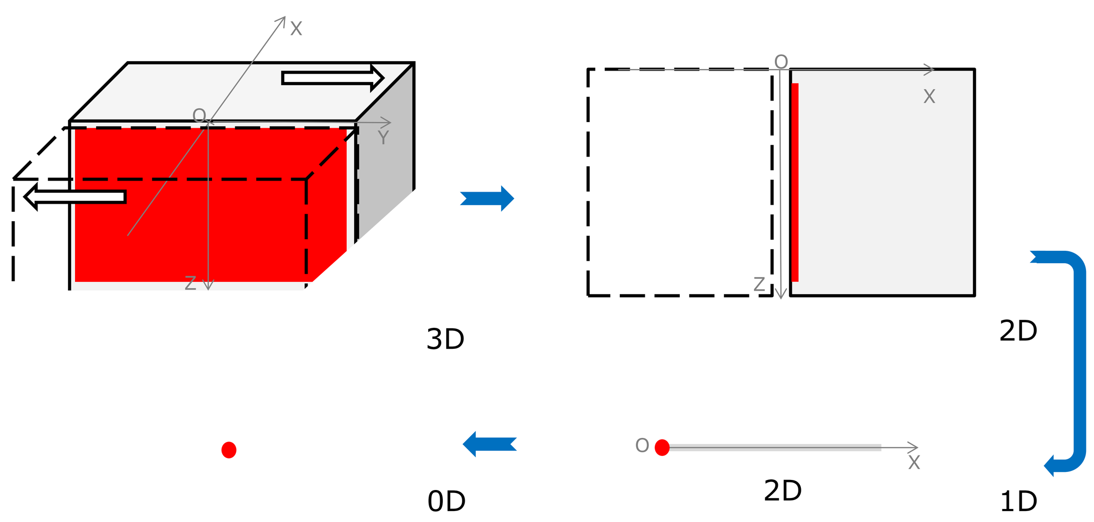

Figure 3 **The model setup in 0D, 1D, 2D and 3D.**

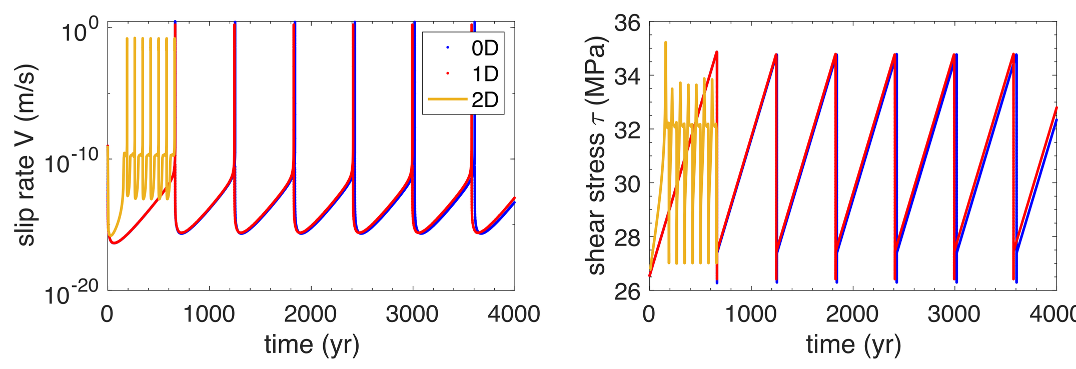

Figure 4 **The comparison of 0D, 1D and 2D seismic cycles with radiation damping. Only the results at depth of 13 km in 2D is plotted.**

Results: fully or quasi-dynamic modeling?

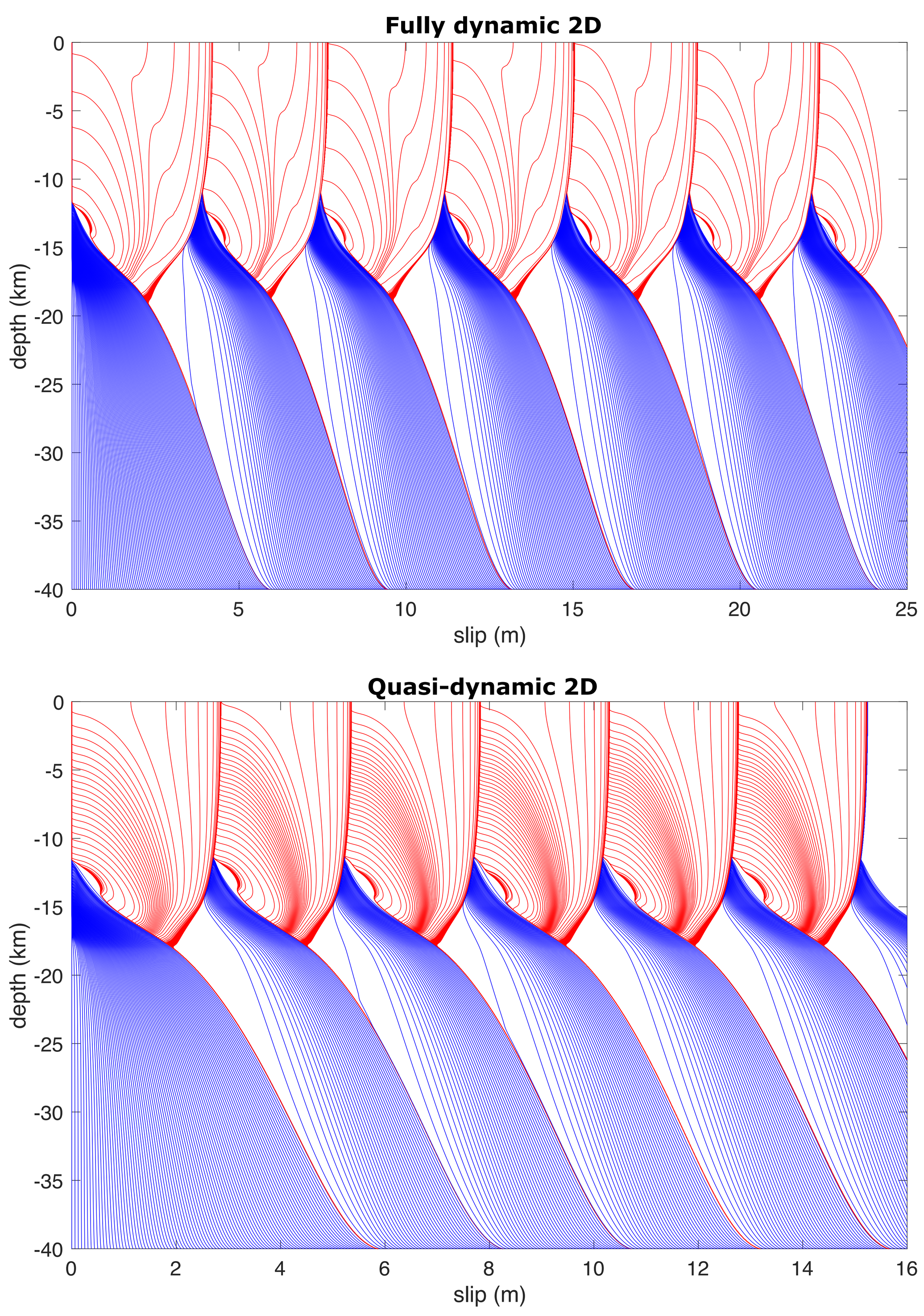

Figure 5 **The comparison of 2D seismic cycles in fully (top) and quasi-dynamic (bottom) simulations.**

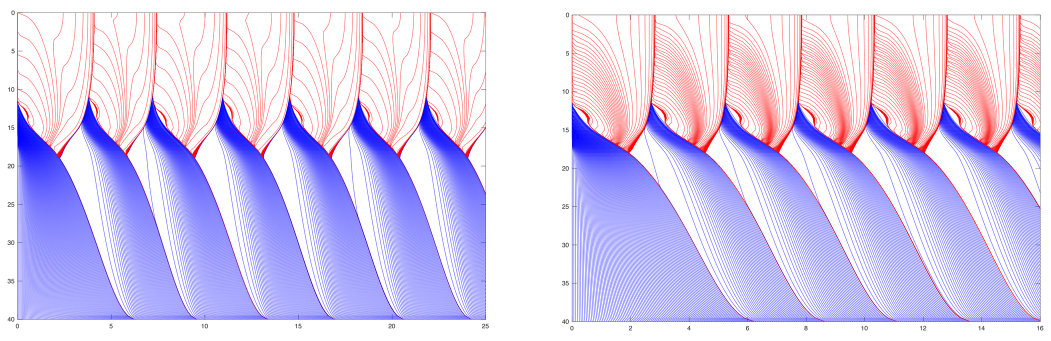

Figure 5 **The slip contour of 2D seismic cycles in fully (left) and quasi-dynamic (right) BICycIE model (provided by Valère Lambert, Caltech [3] for validation purpose).**

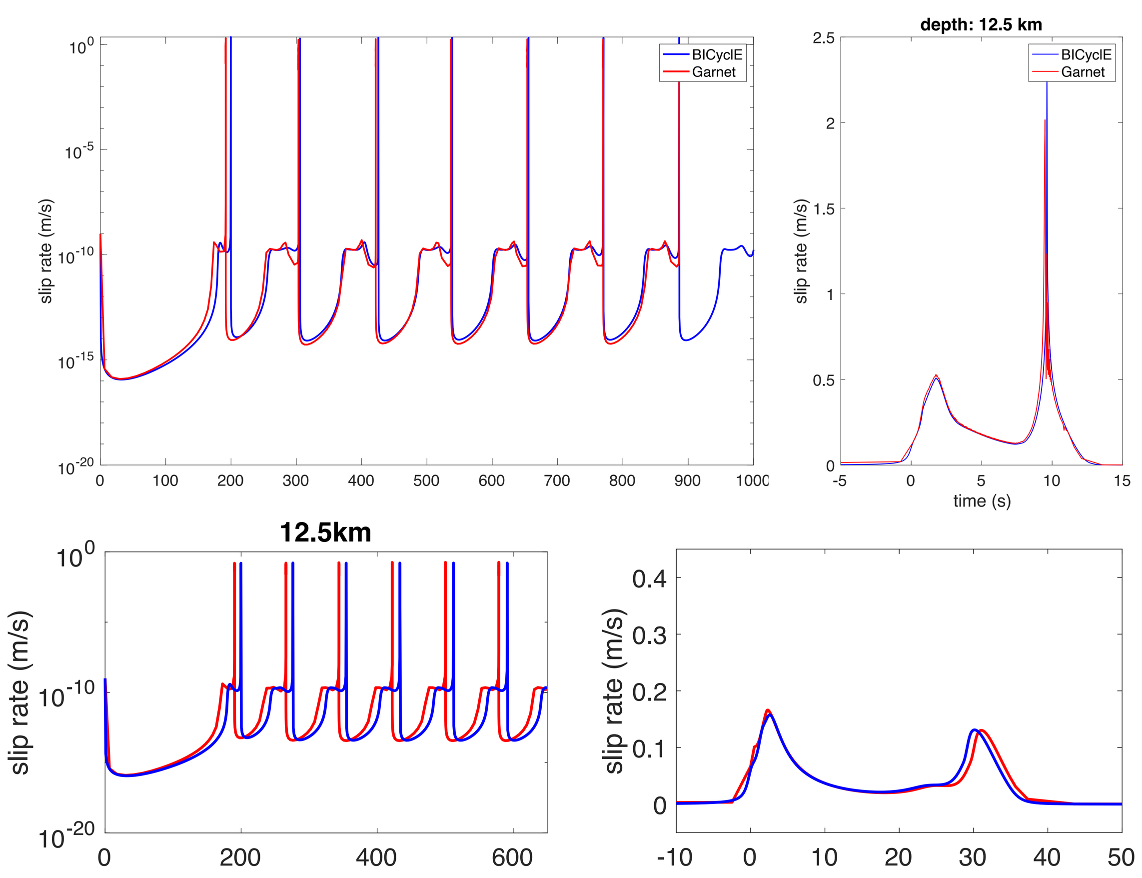

Figure 6 **The comparison of 2D (top) fully dynamic and (bottom) quasi-dynamic seismic cycle modeling between Garnet and BICycIE. Left: The overall time series of slip rate; Right: the coseismic time series with time origin reset to the rupture initiation time of the third event at the depth of 12.5 km for better comparison.**

Summary

- **In 0D, only quasi-dynamic model exists since seismic waves cannot be modeled without medium.**
- **In 0/1D, rate-weakening/strengthening transition is not possible such that nucleation phase is not observable.**
- **Even given the same material and frictional parameters, the seismic cycle period in 2D models is still much smaller than in 0/1D. However, some important observables, such as the maximum/minimum stress and slip rates, are calculated accurately in lower dimensional models, which are much faster than higher dimensional models.**
- **Fully and quasi-dynamic models have similar nucleation depth and rupture pattern reflected in similar slip contours.**
- **Fully dynamic models show larger maximum slip velocity and total slip comparing to quasi-dynamic models.**
- **Fully dynamic models show sharper wave front and surface reflection phase, as well as larger rupture speed. This makes the coseismic duration in fully dynamic models much shorter.**
- **Both models in 2D are validated by the agreement in comparison with BICycIE for solving the benchmarks.**

References

1. Pranger, C. P., Unstable physical processes operating on self-governing fault systems, improved modeling methodology, (2020) PhD thesis at ETH Zurich.
2. Erickson, B. A., et al. The community code verification exercise for simulating sequences of earthquakes and aseismic slip (seas). Seismological Research Letters 91.2A (2020): 874-890.
3. Lapusta, N., et al. Elastodynamic analysis for slow tectonic loading with spontaneous rupture episodes on faults with rate-and state-dependent friction. Journal of Geophysical Research: Solid Earth 105.B10 (2000): 23765-23789.