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Motorcycle: A spectral boundary-integral method for seismic cycles on multiple faults

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Summary

Numerical simulations of seismic cycles constitute a useful tool to test the implications of various constitutive friction laws, materials properties, and boundary conditions. A unique challenge of numerical models of fault dynamics is the resolution of a wide range of time and length scales, going from milliseconds during seismic ruptures to years during seismic quiescence with a rupture front spanning a few meters to fault slip distributed over multiple kilometers. A well-suited approach for this problem is the boundary integral method (Barbot, 2019b; Liu & Rice, 2007; Ozawa & Ando, 2021; Segall & Bradley, 2012; Wang & Barbot, 2023), as the elastic medium is captured by appropriate Green's functions, and only the fault interface must be sampled numerically, resulting in orders of magnitude reduction in computational burden (M. Li et al., 2022), while still allowing realistic fault geometry (D. Li & Liu, 2016, 2017; Sathiakumar et al., 2020). Using the spectral boundary integral method (Lapusta & Liu, 2009) reduces the numerical complexity even further, allowing exploration of increasingly complex rheological models (Barbot et al., 2012; Gauriau et al., 2023; Miyake & Noda, 2019; Noda, 2022). However, the approach is often limited to a single fault (Romanet & Ozawa, 2022). Here, we provide a suite of numerical modeling software to simulate seismic cycles on multiple parallel faults combining the efficiency of Fourier methods and the complexity of an interacting fault network (Barbot, 2021).

The models include semi-infinite faults in conditions of two-dimensional anti-plane or in-plane strain, or along finite faults embedded in a three-dimensional full space. The fault dynamics is governed by a constitutive law with a slip-rate, state, and temperature dependence (Barbot, 2019a, 2022, 2023). The method is based on the quasi-dynamic approximation whereby the effect of seismic waves is approximated by radiation damping. The stress interactions are computed analytically in the Fourier domain (Barbot, 2021) and converted with the `FFTW3` fast Fourier transform (Frigo & Johnson, 2005). The calculations for a two-dimensional domain are parallelized with OpenMP. The spectrum of fault slip, including creep, slow-slip events, slow and fast earthquakes (Figure 1), is afforded by adaptive time steps with the Runge-Kutta method (Press et al., 1996). The simulations using finite faults are parallelized with `MPI` (Gabriel et al., 2004). The stress kernels allow the mechanical interactions of an arbitrary number of parallel faults, allowing structurally complex settings with a network of faults and multiple step-overs.

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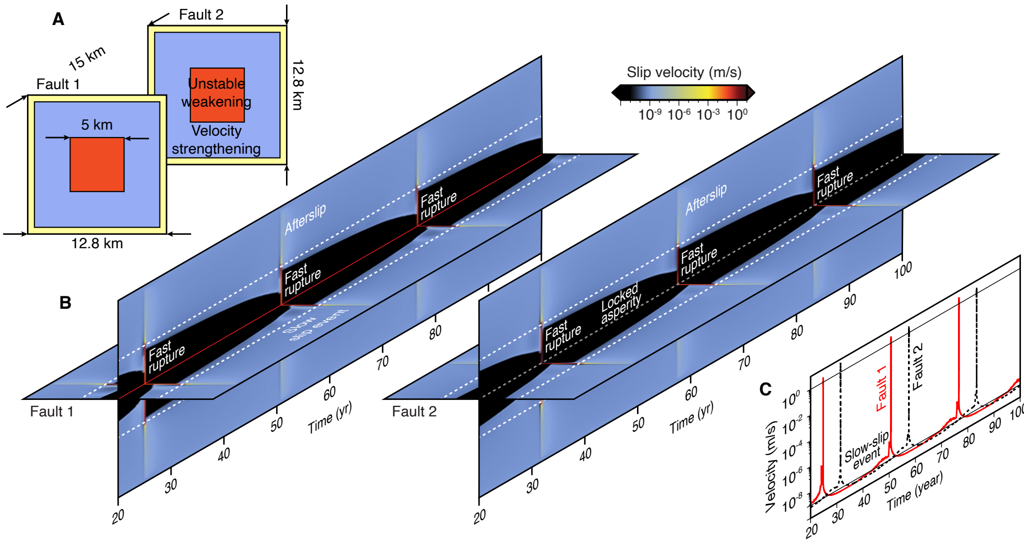

Figure 1: Example simulation of seismic cycles on two parallel faults. A) Model setup with the distribution of frictional and physical properties leading to unstable slip in a 5 km-wide asperity (red) surrounded by a velocity-strengthening region (blue). The thin surroundings of the fault surface (yellow) is subject to a kinematic boundary condition to enforce a long-term slip-rate of about 30 mm/yr, equivalent to 1 nm/s. The two faults are separated by 15 km. Each fault is sampled with 512x512 rectangle patches of 25 m. B) Sequences of fast ruptures followed by afterslip and slow-slip events late in the inter-seismic period corresponding to about 120,000 quasi-static time steps. The slices correspond to horizontal and vertical cross-sections through each fault. The dashed lines indicate the boundaries of the velocity-weakening region. C) Time series of peak velocity in the unstable asperities of faults 1 and 2. Velocities above 1 m/s are firmly in the seismic regime. Slow-slip events are more pronounced on fault 1. The simulation corresponds to the input file `3d/examples/tutorials/run2f.sh`.

Statement of need

`Motorcycle` is a series of Fortran90 standalone numerical modeling tools for fault dynamics. The numerical simulations are optimized for performance and stability, based on automatic time-stepping and meshing. The input file allows complex rheological or structural settings and the automatic exploration of the parameter space. The simulation output is provided in ASCII tables and netcdf files (Brown et al., 1993; Rew & Davis, 1990) for automatic visualization with typical geophysical software such as the Generic Mapping Tools (Wessel et al., 2019).

`Motorcycle` is designed for scientists conducting research in fault dynamics. Applications include the nucleation of frictional instabilities (e.g., slow-slip events), the propagation of earthquake ruptures (e.g., crack-like versus pulse-like), and the mechanical coupling of multiple faults. Successful simulation benchmarks based on comparison with other software can be found in Jiang et al. (2022). Applications of the method include the simulation of synchronized earthquakes on distant faults (Barbot, 2021), of complex slow-slip events generating tremors (Nie & Barbot, 2021), and of mainshock/aftershock sequences (Nie & Barbot, 2022).

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References

Barbot, S. (2019a). Modulation of fault strength during the seismic cycle by grain-size evolution around contact junctions. *Tectonophysics*, *765*, 129–145. https://doi.org/10.1016/j.tecto.2019.05.004

Barbot, S. (2019b). Slow-slip, slow earthquakes, period-two cycles, full and partial ruptures, and deterministic chaos in a single asperity fault. *Tectonophysics*, *768*, 228171. https://doi.org/10.1016/j.tecto.2019.228171

Barbot, S. (2021). A spectral boundary-integral method for quasi-dynamic ruptures of multiple parallel faults. *Bulletin of the Seismological Society of America*, *111*(3), 1614–1630. https://doi.org/10.1785/0120210004

Barbot, S. (2022). A rate-, state-, and temperature-dependent friction law with competing healing mechanisms. *Journal of Geophysical Research*, *127*, e2022JB025106. https://doi.org/10.1029/2022JB025106

Barbot, S. (2023). Constitutive behavior of rocks during the seismic cycle. *AGU Advances*, *4*(5). https://doi.org/10.1029/2023AV000972

Barbot, S., Lapusta, N., & Avouac, J. P. (2012). Under the hood of the earthquake machine: Towards predictive modeling of the seismic cycle. *Science*, *336*(6082), 707–710. https://doi.org/10.1126/science.1218796

Brown, S. A., Folk, M., Goucher, G., Rew, R., & Dubois, P. F. (1993). Software for portable scientific data management. *Computers in Physics*, *7*(3), 304–308. https://doi.org/10.1063/1.4823180

Frigo, M., & Johnson, S. G. (2005). The design and implementation of FFTW3. *Proceedings of the IEEE*, *93*(2), 216–231. https://doi.org/10.1109/JPROC.2004.840301

Gabriel, E., Fagg, G. E., Bosilca, G., Angskun, T., Dongarra, J. J., Squyres, J. M., Sahay, V., Kambadur, P., Barrett, B., Lumsdaine, A., & others. (2004). Open MPI: Goals, concept, and design of a next generation MPI implementation. *European Parallel Virtual Machine/Message Passing Interface Users' Group Meeting*, 97–104. https://doi.org/10.1007/978-3-540-30218-6_19

Gauriau, J., Barbot, S., & Dolan, J. F. (2023). Islands of chaos in a sea of periodic earthquakes. *Earth and Planetary Science Letters*, *618*, 118274. https://doi.org/10.1016/j.epsl.2023.118274

Jiang, J., Erickson, B. A., Lambert, V. R., Ampuero, J.-P., Ando, R., Barbot, S., Cattania, C., Zilio, L. D., Duan, B., Dunham, E. M., & others. (2022). Community-driven code comparisons for three-dimensional dynamic modeling of sequences of earthquakes and aseismic slip. *Journal of Geophysical Research*, *127*(3), e2021JB023519. https://doi.org/10.1029/2021JB023519

Lapusta, N., & Liu, Y. (2009). Three-dimensional boundary integral modeling of spontaneous earthquake sequences and aseismic slip. *Journal of Geophysical Research*, *114*(B09303), 25 PP. https://doi.org/10.1029/2008JB005934

Li, D., & Liu, Y. (2016). Spatiotemporal evolution of slow slip events in a nonplanar fault model for northern Cascadia subduction zone. *Journal of Geophysical Research*, *121*(9), 6828–6845. https://doi.org/10.1002/2016JB012857

Li, D., & Liu, Y. (2017). Modeling slow-slip segmentation in Cascadia subduction zone constrained by tremor locations and gravity anomalies. *Journal of Geophysical Research*, *122*(4), 3138–3157. https://doi.org/10.1002/2016JB013778

Li, M., Pranger, C., & Dinther, Y. van. (2022). Characteristics of earthquake cycles: A cross-dimensional comparison of 0D to 3D numerical models. *Journal of Geophysical Research*, e2021JB023726. https://doi.org/10.1029/2021JB023726

Liu, Y., & Rice, J. R. (2007). Spontaneous and triggered aseismic deformation transients in a subduction fault model. *Journal of Geophysical Research*, *112*(B09404). https://doi.org/10.1029/2007JB004930

Miyake, Y., & Noda, H. (2019). Fully dynamic earthquake sequence simulation of a fault in a viscoelastic medium using a spectral boundary integral equation method: Does interseismic stress relaxation promote aseismic transients? *Earth Planets Space*, *71*(1), 1–12. https://doi.org/10.1186/s40623-019-1113-8

Nie, S., & Barbot, S. (2021). Seismogenic and tremorgenic slow slip near the stability transition of frictional sliding. *Earth and Planetary Science Letters*, *569*, 117037. https://doi.org/10.1016/j.epsl.2021.117037

Nie, S., & Barbot, S. (2022). Rupture styles linked to recurrence patterns in seismic cycles with a compliant fault zone. *Earth and Planetary Science Letters*, *591*, 117593. https://doi.org/10.1016/j.epsl.2022.117593

Noda, H. (2022). Dynamic earthquake sequence simulation with an SBIEM accounting for interseismic poroelastic rebound. *Earth Planets Space*, *74*(1), 1–15. https://doi.org/10.1186/s40623-022-01649-8

Ozawa, S., & Ando, R. (2021). Mainshock and aftershock sequence simulation in geometrically complex fault zones. *Journal of Geophysical Research*, *126*(2), e2020JB020865. https://doi.org/10.1029/2020JB020865

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. (1996). *Numerical recipes in Fortran 90 the art of parallel scientific computing*. Cambridge University Press. ISBN: 0-521-57439-0

Rew, R., & Davis, G. (1990). NetCDF: an interface for scientific data access. *IEEE Computer Graphics and Applications*, *10*(4), 76–82. https://doi.org/10.1109/38.56302

Romanet, P., & Ozawa, S. (2022). Fully dynamic earthquake cycle simulations on a nonplanar fault using the spectral boundary integral element method (sBIEM). *Bulletin of the Seismological Society of America*, *112*(1), 78–97. https://doi.org/10.1785/0120210178

Sathiakumar, S., Barbot, S., & Hubbard, J. (2020). Seismic cycles in fault-bend folds. *Journal of Geophysical Research*, *125*(8), e2019JB018557. https://doi.org/10.1029/2019JB018557

Segall, P., & Bradley, A. M. (2012). The role of thermal pressurization and dilatancy in controlling the rate of fault slip. *Journal of Applied Mechanics*, *79*(3), 031013. https://doi.org/10.1115/1.4005896

Wang, B., & Barbot, S. (2023). Pulse-like ruptures, seismic swarms, and tremorgenic slow-slip events with thermally activated friction. *Earth and Planetary Science Letters*, *603*, 117983. https://doi.org/10.1016/j.epsl.2022.117983

Wessel, P., Luis, J., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H., & Tian, D. (2019). The generic mapping tools version 6. *Geochemistry, Geophysics, Geosystems*, *20*(11), 5556–5564. https://doi.org/10.1029/2019GC008515