How We Learned to Stop Worrying and Start Loving Bulk Nonlinearities

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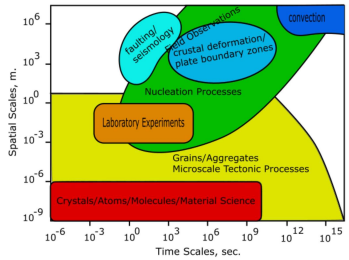
1- Motivation

Earthquake rupture is a highly nonlinear phenomenon with spatiotemporal complexity at multiple scales.



Spatio-temporal complexity of earthquake cycles (John Rundle (2000), Geocomplexity and the Physics of Earthquakes).

It is imperative to devise numerical methods that are capable of resolving these scales.

	Pros	Cons
Finite Difference Method	• Applicable to a wide range of problems including ones with bulk nonlinearities and heterogeneities	• Low-order formulations suffer from artificial dispersion • Computationally demanding due to bulk discretization
Boundary Integral Method	• Fast and computationally efficient because of the spectral formulation and no bulk discretization • Much faster and more computationally efficient than other bulk methods	• Its application is restricted to linear elastic bulk and planar faults

2- Objective

Develop a numerical method (Hybrid Method) capable of long time simulation of earthquake cycles in a bulk that may have *material heterogeneity/nonlinearity* or *fault surface complexity*.

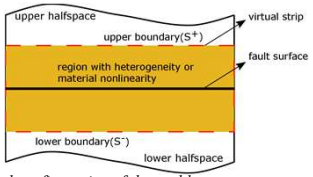
3- Methodology

1. Enclose the near fault inhomgeneities in a virtual strip.
2. Discretize the strip using FD.
3. Model the elastodynamic response of the two halfspaces by an Independent Spectral Formulation.

$$\tau^{+}(x_1,t) = \tau_3^{0+}(x_1,t) - \frac{\mu}{c_s}\dot{u}_3^{+} + f_3^{+}(x_1,t)$$

$$\tau^{-}(x_1,t) = \tau_3^{0-}(x_1,t) + \frac{\mu}{c_s}\dot{u}_3^{-} + f_3^{-}(x_1,t)$$

4. Couple the strip and the halfspaces with the appropriate boundary conditions.



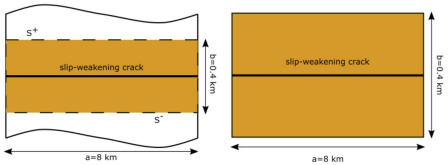
General configuration of the problem.

Advantages

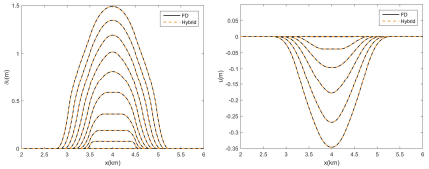
- Eradicates the need for discretizing the whole bulk.
- The Spectral BIEM is very accurate in both dynamic and quasidynamic /static limits. Hence the coupling in the interseismic period will make the method superior to other absorbing boundary conditions/ layers.

4- Results

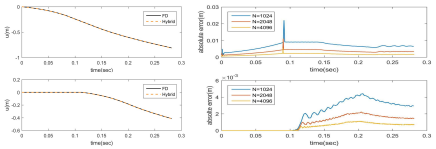
Antiplane slip-weakening shear crack



Right: Configuration of the problem in the FD method. Left: Configuration of the problem in the Hybrid method.

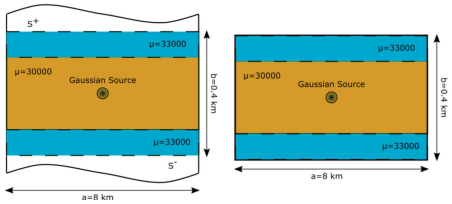


Right: Comparison of the displacement profiles along the boundary. Left: Comparison of slip profiles. Plots are given every 100 time steps.



Right: error analysis plots of a point at the middle of the crack (top) and at the middle of the boundary (bottom) for three meshes. Left: time history plots of these points.

Linear elastic heterogeneous material with a Gaussian source



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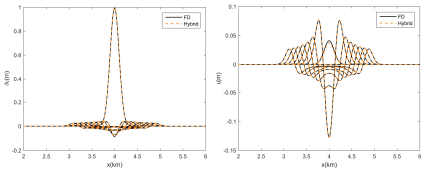
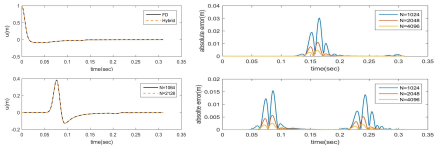
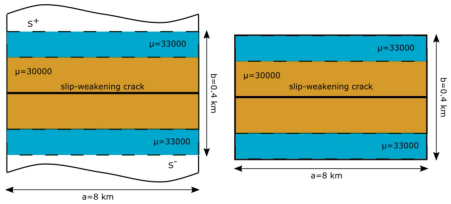


Right: Comparison of the displacement profiles along the boundary. Left: Comparison of displacement profiles along the centerline. Plots are given every 100 time steps.



Right: Error analysis plots of a point at the middle of the crack (top) and at the middle of the boundary (bottom) for three meshes. Left: Time history plots of these points.

Slip-weakening crack with low velocity fault zone



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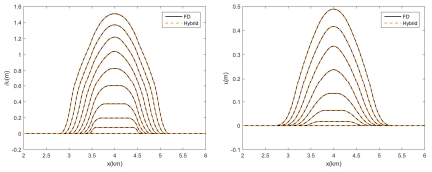
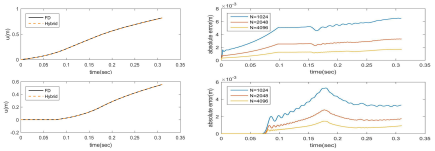


Right: Comparison of the displacement profiles along the boundary. Left: Comparison of slip profiles. Plots are given every 100 time steps.



Right: Error analysis plots of a point at the middle of the crack (top) and at the middle of the boundary (bottom) for three meshes. Left: Time history plots of these points.

5- Conclusions and future work

- The hybrid method has proved to be successful in modeling various problems—from volumetric sources in linear elastic media to cracks embedded in a continuum with heterogeneities.
- This method will provide us with an efficient tool to study nonplanar faults, faults with plasticity or multiple cracks, and most importantly earthquake cycles for a bulk containing heterogeneities.

6- References

Geubelle, P. H., & Rice, J. R. (1995). A spectral method for three-dimensional elastodynamic fracture problems. *Journal of the Mechanics and Physics of Solids*

Lapusta, N., Rice, J. R., Ben-Zion, Y., & Gutuan, Z. (2000). Elastodynamic analysis for slow tectonic loading with spontaneous rupture episodes on faults with rate- and state-dependent friction. *Journal of Geophysical Research*