Fast boundary element method for fault mechanics and earthquake control

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Abstract

This work focuses on the simulation of sequences of seismic and aseismic slip events using Fast boundary element methods (BEMs). An algorithm based on FFT-accelerated BEMs is first considered, validated and results are shown for a basic problem in crustal faulting. These developments target the formulation of efficient computational tools for studying human-induced seismicity and to investigate its control numerically. A first multi-physics case using accelerated BEMs to solve the previous crustal faulting problem with fluid injection is considered.

Keywords: (Fast) Boundary element methods, Fault mechanics, Seismic control, Induced seismicity.

1 Motivations : Assessment of earthquake control strategies by fluid injection

Earthquakes due to either natural or anthropogenic sources cause important human and material damage. This justifies the development of efficient numerical tools for modeling the earthquake instability. Particularly, we aim at simulating problems in unbounded domains incorporating seismic and aseismic time scales (1 s and 1 yr respectively). Here, we propose to introduce Fast BEM formulations [1] to meet the expectations of a multi-physic large-scale robust model required for modeling earthquake processes, human-induced seismicity and their control [4]. These methods are known to be efficient for solving elastodynamic problems in large-scale unbounded domains. The challenge of this work is thus to enhance the capabilities of Fast BEMs to model large crustal faulting problems incorporating thermo-hydro-mechanical couplings.

2 Existing methods for fault mechanics

BEMs already allow to solve basic problems in crustal faulting. In order to assess their ability to simulate these problems, we use a well-kown method consisting in BEMs accelerated by FFT for 2D antiplane problems. Let us consider a 1D planar vertical strike-slip fault, embedded in a 2D homogeneous, linear elastic infinite space (Figure 1). The antiplane shear movement assumed in the x direction leads to a displacement on either side of the fault independent of the x coordinate. BEMs applied to the equilibrium combined with Hooke's law, leads to a relation between the jump in displacement denoted δ across the fault and the shear stress f due to quasi-static deformation:

$$f(z,t) = \frac{\mu}{2\pi}\int_\Gamma \frac{1}{z-z'}\frac{\partial \delta}{\partial z'}(z',t)dz',$$

which simplifies in the Fourier space:

$$F(\xi,t) = -\frac{\mu|k|}{2}D(\xi,t), \quad k = 2\pi\xi.$$

This technique is only valid for planar faults. The fault is obeying an empirical rate-and-state friction law:

$$\tau(z,t) = \overline{\sigma}(z)a(z)\sinh^{-1}\left[\frac{V(z,t)}{2V_0}\exp\left(\frac{f_0 + b(z)\ln(V_0\theta(z,t)/L(z))}{a(z)}\right)\right],$$

completed by the aging law:

$$\frac{\partial \theta}{\partial t} = 1 - \frac{V(z,t)\theta(z,t)}{L(z)}.$$

Where $\tau = \tau^0 + f - \eta V$ is the sum of the prestress, the shear stress due to quasi-static deformation, and the radiation damping approximation to inertia, where $\eta = \mu/(2c_s)$ is half the shear-wave impedance for shear wave velocity $c_s = \sqrt{\mu/\rho}$. $V = \partial\delta/\partial t$ is the slip rate, and θ is the state variable. σ_n is the effective normal stress on the fault. The algorithm used to solve this problem is based on the prediction-correction method in the spirit of a second-order Runge-Kutta procedure proposed by [2]. The unknowns are δ, V, τ, θ. We verify this approach considering the case where the slip rate is constant in time equal to V_{pl}, which leads to have the unknowns equal to their initial values.

3 1D planar vertical strike-slip fault, embedded in a 2D homogeneous, linear elastic half-space

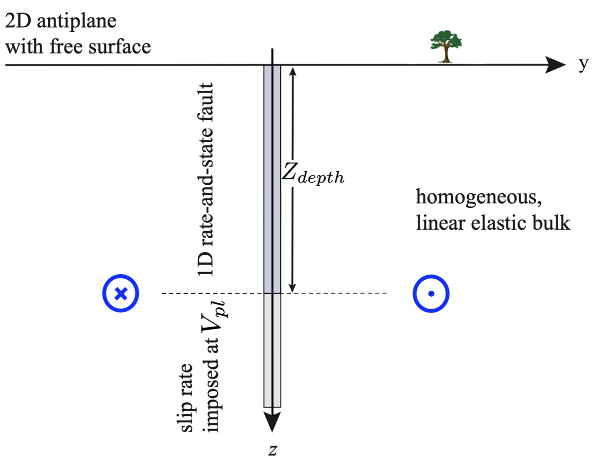

Figure 1: Representation of the 1D antiplane problem

In this case the equations at stake are the same and the free surface condition is taken into account using the image method. Figure 2 shows sequences of seismic and aseismic phases (which last about 108 s and 84 yrs in average respectively).

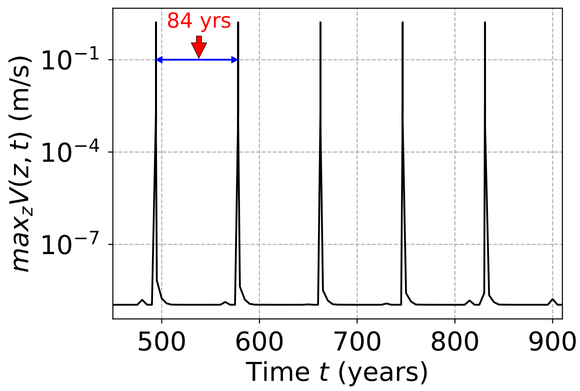

Figure 2: Maximal slip rate at depth evolution with respect to time

4 Perspectives

The objective is now to explore the advantages and limitations of novel strategies of earthquake control using fluid injection to drive the fault from an unstable state of high potential energy to a stable state of lower potential energy [4]. Ongoing work concerns the use of Fast BEMs to solve more realistic problems in crustal faulting. The main challenge is the extension of accelerated BEMs from single physic problems to incorporate thermo-hydro-mechanical couplings due to fluid injection. Some works have already shown that poroelasticity can be modeled with BEMs [3] but these methods have never been used in elastodynamics and multi-physics. We will first apply Fast BEMs to the previous antiplane - shear case incorporating fluid injection. We will validate this formulation on the quasi-dynamic and fully dynamic version of the previous problem. The BEM used in this ongoing work will be accelerated using Hierarchical Matrices. Increasing pore fluid pressure induces variations in the effective normal stress on the fault. The modeling assumptions of which poroelastodynamic framework we will use will depend on the specific problem we are solving. Fast BEMs will be considered to calculate both shear and normal stresses which contain similar terms. Our final goal is to develop an efficient formulation of this multi-physics problem and show that fluid injection can induce a controllable aseismic slip numerically.

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