On boundary−element models of elastic fault interaction

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Abstract

We present the modular boundary element program *interact*, distributed under the GNU public license. It is yet another implementation of Crouch and Starfield's (1983) 2−D and Okada's (1992) half−space solutions for constant slip on planar fault segments in an elastic medium. Using standard matrix solvers, the code can compute slip distributions on faults given stress boundary conditions, or vice versa. We show examples of complex fault geometries from the *SCEC Community Fault Model* and discuss the effects of different stress boundary conditions on the predicted slip. Such one−step calculations are useful to estimate the moment release efficiency of alternative fault geometries and tectonic settings, and so to evaluate the mechanics of plate boundaries.

A further example application of the program is the simulation of cyclic rupture based on simple friction laws. We comment on two issues: First, that of the appropriate rupture algorithm. Cellular models of seismicity often employ an exhaustive rupture scheme: fault cells fail if some critical stress is reached, then cells slip once−only by a given amount, and subsequently the redistributed stress is used to check for triggered activations on other cells. We show that this procedure can lead to artificial complexity in seismicity if time−to−failure is not calculated carefully because of numerical noise.

Second, we address the question if foreshocks can be viewed as a direct consequence of a random distribution of frictional strength on individual faults. Models for a single fault with a statistical distribution of friction coefficients initially show irregular seismicity under continuous loading. By repeatedly selecting weaker patches, the fault then evolves into a quasi−periodic cycle. Each time, the pre−mainshock events build up the cumulative moment release in a non−linear but deterministic fashion. These temporal seismicity patterns roughly resemble the accelerated moment−release that is sometimes observed in nature.

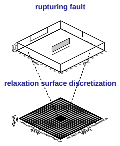
interact

Our software implements halfspace and 2−D boundary element (BEM) formulae to calculate the stress tensor in a purely elastic medium surrounding a displacement discontinuity for a specified slip, or vice versa. In the latter case, systems of equations have to be solved based on the Greens' functions for stress given constant unity slip. Similar to the approach by previous authors, *interact* uses standard LU, SVD, or non−negative least squares solvers for this purpose, depending on the geometry and boundary conditions for slip, which can be restricted to, *e.g.*, only opening motion for "explosive" sources. In the framework of potential future work on a community boundary element modeling tool, we hope to implement parallel solvers, possibly based on the *PetSc* package.

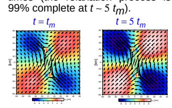
(1) post−seismic benchmark

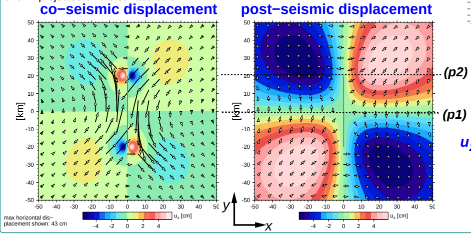
with Yuri Fialko (IGPP, UCSD)

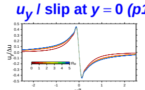
The long−term post−seismic state of the crust after an earthquake can be approximated with BEM by solving for stress−free conditions at some asthenospheric reference depth (here: 15 km, approximated by a large horizontal grid of dislocation patches). Below, we show co−seismic displacement at the surface (background is vertical motion) and the post−seismic displacement (completely relaxed state minus co−seismic displacements). The 'earthquake' has constant right−lateral slip of 1 m on the fault surface depicted on the right and shown projected on the surface below.

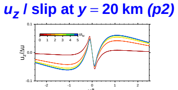


For linear creep, relaxation can be approximated by the response of a dashpot with Maxwell time t_m. The total (co + post) displacement fields and profiles are shown below for non−dimensionalized times (the relaxation process is 99% complete at $t \sim 5\, t_m$).







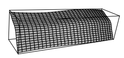


(2) irregular fault geometries

One application of *interact* is the calculation of potential slip given various fault−geometries, frictional laws, and stress boundary conditions. *interact* is an alternative to programs such as *POLY3D* by the Stanford group.

An application of such calculations is the evaluation of the mechanical workings of proposed alternative fault geometries from structural geology. Taking stress interactions into account, we can calculate the effectiveness of fault systems in terms of long−term moment release in a given tectonic setting.

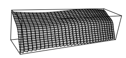
test geometry



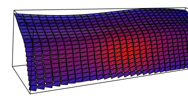
Right now, the fault segment geometry in *interact* is limited by the integration of point sources as given by Okada (1992), only allowing for rectangular patches without 'geometrical rake'.

Therefore, general geometries have to be approximated by fitting patches to the original structure. This is done such that the total area for the approximate surface is equal to that of the original.

fit with patches



slip distribution



Slip for complete relaxation of background shear stress. Note that the distribution is smooth even though the fault has holes. Linear colorscale for slip from blue (minimum) to red (maximum),

Application to Southern California Fault Systems

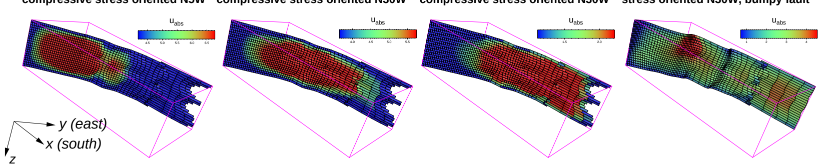
with Chris Guzofski (Harvard) and Spina Cianetti (INGV, Roma)

We study elastic fault interactions in Southern California using an adaptation of SCEC's *Community Fault Model* (1.0b), as provided by A. Plesch of the Harvard Structural Geology group.

The results we show should be understood as inital sensitivity tests and are not (yet) meant to include any geological realism as such. We focus on the static slip response of faults subjected to background stress, either for stress−free conditions on the dislocation elements or for friction with coefficient of 0.4.

All visualizations are either done with Wessel and Smith's *GMT* or the Geometry centre's *geomview* software, a nifty and freely available 3−D geometry viewer. We show absolute slip on a linear scale (red = high, blue = low), arbitrary units.

Landers



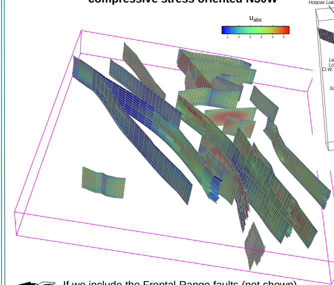
Not surprisingly, given the fault geometry, a more easterly trending compressive stress (N30W for max hor. compressive direction is appropriate for the Mojave region (J. Hardebeck, pers. comm.)) leads to more slip on the southern segments of the Landers earthquake faults. See also Cianetti, Giunchi, and Cocco's poster (S52B−1111).

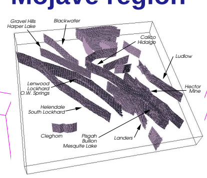
The surface parameterization of the fault is very important for the predicted slip. In our example, the edgier surface fit used for the three cases to the left leads to smoother large−scale slip distributions, while the smoother (less 'tension' in GMT's surface gridding algorithm) but more bumpy (and less realistic) surface leads to higher large scale irregularity in slip.

For individual earthquakes, the effects of dynamic rupture will clearly be important for earthquake slip but static calculations such as ours can be useful in guiding us as to the long term seismic moment release on individual faults and in fault systems.

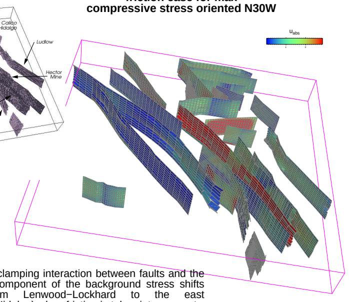
Mojave region

shear stress free case for max compressive stress oriented N30W





friction case for max compressive stress oriented N30W



If we include the Frontal Range faults (not shown) slip patterns are similar on the main other faults.

The (un)clamping interaction between faults and the normal component of the background stress shifts slip from Lenwood−Lockhard to the east (Calico−Hidalgo) when friction is taken into account.

(3) cyclic rupture

Besides the one−step scheme which is used for evaluating the slip on complex fault surfaces given specified stress boundary conditions, *interact also* allows for the simulation of repeated earthquake rupture. The earthquake cycle is modeled using a simple static/kinetic friction law without any dependence of the coefficient of friction on slip velocity or hold−time. As in previous studies, the model does not include any dynamic (inertia) effects. The model is thus an extreme simplification of earthquake rupture with the specific focus to understand the effects of elastic interactions.

Rupture on fault patches initiates under continuously increased stress−loading when the local static Coulomb−stress, σ_{Cs}, becomes critical,

$$\sigma_{Cs} = |\tau| - \mu_s * \sigma_n = 0.$$

Here, τ and σ_n are shear and normal stress, respectively, and μ_s is the static coefficient of friction.

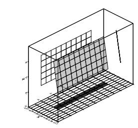
The algorithm then calculates the slip needed on the patch to achieve critical kinematic Coulomb−stress,

$$\sigma_{Ck} = |\tau| - \mu_k * \sigma_n = 0, \text{ with } \mu_s\ (= 0.6) > \mu_k\ (= 0.5),$$

taking the change in normal stress during slip into account. The stress conditions are fulfilled simultaneously on all patches which are active at the time of rupture. If slip on the patch under consideration would trigger rupture elsewhere, the program allows the triggered patch (regardless of distance from the main source and time) to slip, and the combined slip equations are solved again, iteratively until no more triggering occurs. This scheme contrasts with an exhaustive scheme used by some previous studies, where cells slip only once and triggered slip occurs in the already modified stress regime.

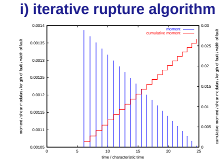
a) homogeneous fault properties and stress

We study simple fault loading by continuously increasing σ_{xy}; slip on patches is allowed both in strike and in dip direction according to the friction law described above. Irregularities in the seismic cycle for i) arise due to the fault having a dip angle of 80 degrees. The self−stressing in the normal component modifies the stress drop (which depends on the normal stress) and hence the seismic cycle (Becker & Schmeling, 1998; Bonafede & Neri, 2000).

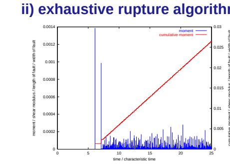


i) iterative rupture algorithm

Plots to the right show individual and cumulative moment release of a single fault versus non−dimensionalizd time. $\Delta\sigma$ = stress drop, L, W = half length and width of fault.



ii) exhaustive rupture algorithm

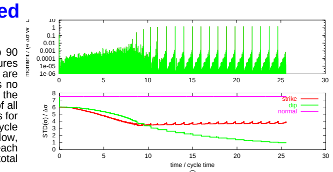


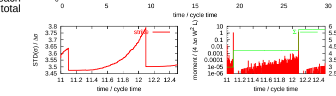
Numerical inaccuracies in the determination of the critical Coulomb−stress on individual patches lead to a segmentation of the fault during rupture in ii). Thus, spurious irregularities in the seismic cycle may arise if the failure criterion is not calculated carefully.

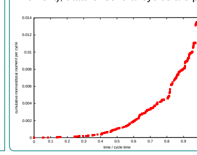
b) initial stress normally distributed

A simple foreshock model:

Consider a single fault (60 x 30 patches, aspect ratio 2 : 1, dip 90 degrees) and loading conditions such that perfectly periodic ruptures would result without any stress heterogeneities. The patches are initialized with a random, normally distributed pre−stress that has no spatial coherence and a standard deviation (STD) of 7.5 times the stress drop. On the right, we show moment release and the STD of all three stress components versus time (top two plots), and zoom−ins for along−strike stress and moment (Σ: cumulative) for an individual cycle in the regular regime (times >~12 cycle times, bottom figures). Below, we show cumulative moment over total moment released in each cycle (wihout the mainshock, which releases ~98% of the total moment), data for several cycles are plotted on top of each other.







Under continuous loading, the fault organizes itself into periodic rupture with pre−mainshock activity due to slip on higher than average stressed patches. While irregularly looking, the 'foreshock' activity and the accompanying 'accelerating moment−release' is deterministic and almost perfectly repeated in each cycle. Since the simulation has no intrinsic time−dependence and the main rupture takes all stronger than average patches with it, there are no aftershocks in this conceptual model.