Coulomb Rate State

A parallel code to calculate rate-state seismicity evolution induced by time dependent, heterogeneous Coulomb stress changes

C. Cattania, F. Khalid

Tutorial

Introduction

CRS is a C program to calculate the evolution of seismicity from time dependent stress changes. A full description of the code can be found in the following article: *Cattania, C., Khalid, F., A parallel code to calculate rate-state seismicity evolution induced by time dependent, heterogeneous Coulomb stress changes, Computers and Geosciences (2016)*, doi:10.1016/j.cageo.2016.06.007.

This document contains a short tutorial on how to use CRS.

Installing and compiling CRS

Installation instructions can be found in the file: `readme`.

Input file

After compiling the serial version of CRS, the tutorial can be run as follows:

`Release/run_crs tutorial/input/input.txt`

Here is the input file `tutorial/input/input.txt`:

```
OutputForecastFile=tutorial/output/out
Logfile=tutorial/output/log
InputModelParametersFile=tutorial/input/parameters.txt
InputCatalogFocMecFile=tutorial/input/YSH_preParkfield.dat
ForecastStartDate=2004-10-10T17:15:24Z
ForecastEndDate=2004-11-10T17:15:24Z
IssueDate=2004-10-10T17:15:24Z
InputCatalogFile=tutorial/input/ANSS_Park.dat
InputListSlipModels=tutorial/input/slipmodels.txt
ForecastTemplate=tutorial/input/template_grid.dat
RandomSeedValue=-37284630
InversionStartDate=2004-09-28T17:15:24Z
```

In this example we will model seismicity triggered by the $M_w 6.0$ Parkfield earthquake, which occurred on $28/09/2004$ at $17:15:24$. This example reproduces a pseudo-prospective forecast: `IssueDate` and `ForecastStartDate` are the same. CRS will perform a parameter search starting at the time of the mainshock (`InversionStartDate`) up to $10/10/2004$ (`IssueDate`) and forecast seismicity for the following month (between `ForecastStartDate` and `ForecastEndDate`). Rate-State parameters are fitted to the catalog `InputCatalogFile=tutorial/input/ANSS_Park.dat` provided by the ANSS(http://www.quake.geo.berkeley.edu/anss/catalog-search.html).
A list of all possible input parameters and the formats of each file listed above (catalog file, template, etc.) are described in the file `doc/inputformats.readme`.

Parameter file

Several aspects of model behavior are determined in the parameter file:

`InputModelParametersFile=tutorial/input/parameters.txt`.

Each line is explained in the file itself. Here we outline some of the reasons behind the choice of parameters.

The first section controls the basic aspects of Coulomb stress calculations, such as the magnitude of the events to be included as sources and the internal resolution to be used for Coulomb stress calculations. Here all events above $M_w 4.0$ are included as stress sources (ln. 15), either by estimating a slip model from the focal mechanisms (the first mechanism given in
`InputCatalogFocMecFile=tutorial/input/YSH_preParkfield.dat`),
or by assuming an isotropic field if no focal mechanism is available (ln.16, `iso`). A real slip model will always be used for events above $M_w 4.0$ which can be matched to a slip model listed in
`InputListSlipModels=tutorial/input/slipmodels.txt`.
In this example the horizontal/vertical resolutions are set to 20km (ln.19), a larger value than the grid size in the template file (`ForecastTemplate=tutorial/input/template_grid.dat`), so that the grid will not be refined and the resolution of the template file is used for stress calculations. In general, consider setting a model resolution comparable to the patch size of the mainshock slip models, or to the source size of the smallest source earthquakes. Note that the format of the template file must be a uniform grid for the model to be refined (see `doc/inputformats.readme`)
The resolution of the slip models (ln. 17) is also set to a large number so the models will not be refined. This implies that slip models derived from focal mechanisms will have a single patch and uniform slip. If a smaller resolution was used, they would be tapered at the edges.

```
16  4.0        0.0
17  fm         iso
18  3000
19  80       1e6
20  20.0         20.0
```

The next section controls the parameter inversion. Line 49 indicates the minimum magnitude of events to be used for the inversion, in this case chosen to match the completeness magnitude. Line 50 sets a time period which is excluded after each large event. In this case, it is set to slightly less than 2 min after events above 5.95, the period during which the catalog is estimated to be incomplete above $M_w 2.0$ following the Parkfield $M_w 6.0$ mainshock.

```
46 1
47 1      0.022
48 0      8000   12000   2       lin
49 0      7000   10000   2       lin
50 2.0
51 0.0012  5.95
```

The next section controls the inclusion of uncertainties. In this case we consider both uncertainties from variable receiver faults (ln 60, ``focmec'') and from the finite grid size (ln 61). On ln. 60 we also have a flag determining whether the optimal rake should be used. Here it is set to 1, so CRS will ignore the rake from the focal mechanisms file and use the rake on which the total (background + coseismic) shear stress is maximum. The receiver faults will be sampled from the catalog: `InputCatalogFocMecFile=tutorial/input/YSH_preParkfield.dat`.
The number of Monte Carlo iterations (ln. 62) is set to a small value for computational efficiency. The ideal number depends on the size of the focal mechanisms catalog (there is no benefit in setting it larger than the number of available mechanisms, unless only few focal mechanisms are present and a larger number of iterations allows to better describe the uncertainty from finite grid size).

```
63 focmec        1
64 1
65 10
```

The next section describes other model parameters, including the tolerance between the earthquakes catalog (`InputCatalogFile`) and the focal mechanisms catalog (`InputCatalogFocMecFile`), lines 76-80. CRS uses the `InputCatalogFile` to select events to be used as sources, and then searches candidate focal mechanisms which will be used to estimate synthetic slip models. Event time, magnitude and location are used. The tolerances should be set to the smallest possible values which allow most focal mechanisms to find a match in the earthquake catalog.

```
78 1        0.1
79 0.0005
80 0.9
81 1
82 5
83 5.0
```

Finally, the last 7 lines describe crustal properties (elastic parameters and background stress field).

Slip models file

In this example we will use 3 slip models from the finite source slip model database SrcMod maintained by ETH (http://equake-rc.info/SRCMOD/), in `fsp` format. This file lists the paths to the model files. For each model, CRS estimates a set of RS parameters and produces a separate forecast. If more than one events have slip models, multiple blocks similar to lines 12-15 will be present. In this case a forecast is produced for each combination of models.
The number preceding the path is a flag set to 1 if the slip model crosses the surface: in this case, CRS will shift the free surface to the upper edge of the model and only calculate Coulomb stresses for grid points below this depth. This is implemented to avoid the stresses at the top of a blind fault

when the rupture is known to reach the surface. If using this option, make sure that all grid points in the forecast template file are below the upper edge of the fault.

```
fsp        0
2004-09-28T17:15:24Z        6.0        3
0 tutorial/input/fsp/s2004PARKFI01DREG.fsp
0 tutorial/input/fsp/s2004PARKFI01CUST.fsp
0 tutorial/input/fsp/s2004PARKFI01JIxx.fsp
```

Output files

In addition to the log file, CRS produces the following files:

- A copy of the input and parameter files (`out_inputfile.txt`, `out_parameters.txt`) ;
- A summary of the parameter search results (`out_ParamSearch.dat`);
- The LogLikelihood of each set of input slip models during the forecast period (`out_LogLikelihood.dat`);
- A list of the slip models used (`out_slipmodlist.dat`)

For each of the slip model combinations, these files are created:

- A file with seismicity as a function of time (`out1_forecast.dat`), and the results of all Monte Carlo iterations (`out1_forecast_all_nev.dat`, `out1_forecast_all_rate.dat`);
- A file with the gridded forecast (`out1_foremap.dat`), and single Monte Carlo iterations (`out1_foremap_all.dat`);
- A file with the LogLikelihood of individual events during the forecast period (`out1_LLevents.dat`)

The number in the file names refers to the slip model combination. The corresponding slip models are listed in `out_slipmodlist.dat`.
The format of each file is described in `doc/outputformats.readme`.

Temporal evolution of seismicity

We illustrate the content of the forecast files by plotting them in MATLAB.

```
fore=load('crs/tutorial/output/out1_forecast.dat');
no_ev=load('crs/tutorial/output/out1_forecast_all_nev.dat');
rate=load('crs/tutorial/output/out1_forecast_all_rate.dat');

%Plot cumulative seismicity for all Monte Carlo iterations:
```

```
    plot(fore(:,1),cumsum(no_ev'),'--','color',0.7*[1 1 1])
    hold on
%Column 2 contains the total no. of events in each time bin:
    plot(fore(:,1),cumsum(fore(:,2)),'k','LineWidth',2)

    figure
%Plot seismicity rate for all Monte Carlo iterations:
    plot(fore(:,1),rate','--','color',0.7*[1 1 1])
    hold on
%Column 3 contains the seismicity rate at each time:
plot(fore(:,1),fore(:,3),'k','LineWidth',2)
```

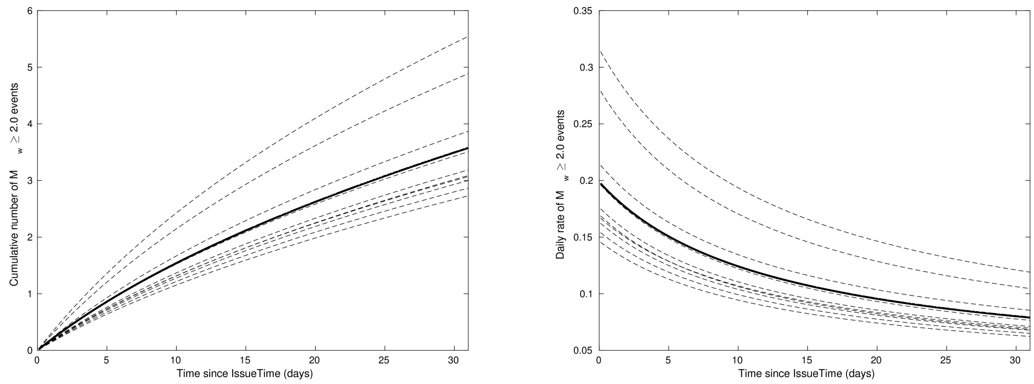

Figure 1: Left: cumulative seismicity. Right: seismicity rate. The dotted lines are individual Monte Carlo iterations, the thick lines are the final forecast (i.e. the average).

Seismicity maps

We plot the final seismicity maps and the single Monte Carlo iterations.

```
%The forecast file is a grid with [lat x lon x depth]=[46x41x2] points).
    map=load('testE4_foremap.dat');
    lat=unique(mean(map(:,[3 4])'));
    lon=unique(mean(map(:,[1 2])'));
    dep=unique(mean(map(:,[5 6])'));

%reshape into a matrix:
    seis=reshape(map(:,9),length(lat),length(lon),length(dep));
%plot seismicity integrated over depth:
    subplot(1,3,1)
    pcolor(lon, lat, log10(sum(seis,3)));
    shading flat

%plot individual Monte Carlo iterations:
allmaps=load('testE4_foremap_all.dat');
    for mc=1:length(allmaps(:,1))
        seis=reshape(allmaps(mc,:),length(lat),length(lon),length(dep));
        subplot(2,7,mc+2+2*floor((mc-1)/5))
            pcolor(lon, lat, log10(sum(seis,3)));
            caxis([-6 -1])
            shading flat
            set(gca,'yticklabel',[]);
            if (mc<=5) set(gca,'xticklabel',[]); end
    end
```

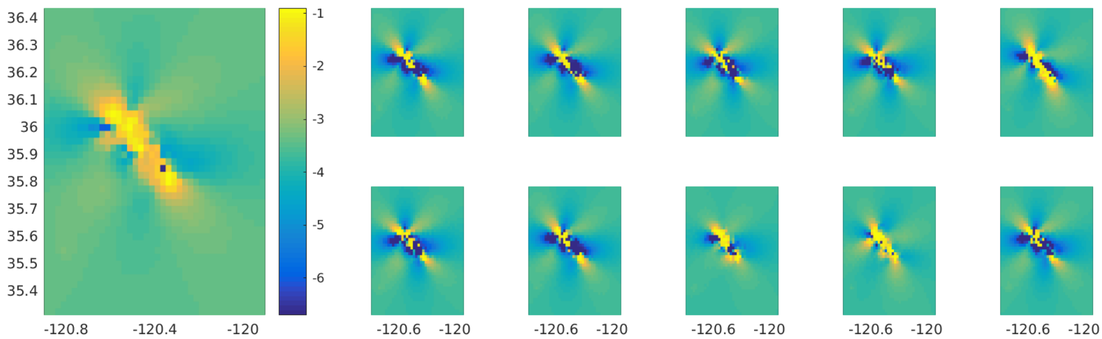

Figure 2: Left: Final seismicity map, integrated over depth, on a log scale. Right: maps for single Monte Carlo iterations.