CYCLAPS
earthquake CYCLe simulator for Asperities under Poroelastic Stressing

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Contents

1 Introduction

CYCLAPS (earthquake CYCLe simulator for Asperities under Poroelastic Stressing) is an earthquake simulator based on rate-and-state friction and quasi-dynamic elasticity. It allows to compute slip, slip rate and shear stress history on 1d or 2d faults, embedded in 2d or 3d elastic media respectively, and undergoing slow tectonic loading. CYCLAPS is an asperity model specifically designed to simulate slip on faults with frictional and (normal and shear) stress heterogeneity. Arbitrary external normal and shear stress perturbation can be implemented. Poro-elastic coupling can be handled, with linear or non-lienar fluid diffusion restricted to the fault (impermeable bulk). CYCLAPS is parrallelized.

2 List of fault models

1. **fault_2d_infperiodic_aging** : 1d (mode II or III) fault between 2d elastic slabs of finite thickness. Spectral boundary integral approach (replication along strike). Aging law.
2. **fault_2d_infperiodic_aging_pnl** : same with non linear pore pressure diffusion.
3. **fault_2d_infperiodic_aging_press** : same with imposed pore pressure history.
4. **fault_2d_infperiodic_slip** : 1d (mode II or III) fault between 2d elastic slabs of finite thickness. Spectral boundary integral approach (replication along strike). Slip law.
5. **fault_2d_infperiodic_slip_pnl** : same with non linear pore pressure diffusion.
6. **fault_2d_infperiodic_slip_press** : same with imposed pore pressure history.
7. **fault_2d_freesurface_aging** : 1d strike-slip fault in a semi infinite elastic half space with free surface, aging law.
8. **fault_2d_freesurface_aging_pnl** : same with non linear pore pressure diffusion.
9. **fault_2d_freesurface_aging_press** : same with imposed pore pressure history.
10. **fault_2d_freesurface_slip** : 1d strike-slip fault in a semi infinite elastic half space with free surface, slip law.
11. **fault_2d_freesurface_slip_pnl** : same with non linear pore pressure diffusion.
12. **fault_2d_freesurface_slip_press** : same with imposed pore pressure history.
13. **fault_2d_cr_aging** : 1d (mode II or III) fault between 2d semi infinite elastic half spaces. Cochard and Rice [1997] spectral boundary integral approach (no replication along strike). Aging law.
14. **fault_2d_cr_aging_pnl** : same with non linear pore pressure diffusion.
15. **fault_2d_cr_aging_press** : same with imposed pore pressure history.
16. **fault_2d_cr_slip** : 1d (mode II or III) fault between 2d semi infinite elastic half spaces. Cochard and Rice [1997] spectral boundary integral approach (no replication along strike). Slip law.
17. **fault_2d_cr_slip_pnl** : same with non linear pore pressure diffusion.
18. **fault_2d_cr_slip_press** : same with imposed pore pressure history.
19. **fault_2d_cr_regage_pnl** : same with non linear pore pressure diffusion and regularized rate-and-state, aging law.
20. **fault_2d_cr_regslip_pnl** : same with non linear pore pressure diffusion and regularized rate-and-state, slip law.
21. **fault_3d_infperiodic_aging** : 2d fault between 3d elastic slabs of finite thickness. Spectral boundary integral approach (replication along depth and strike). Aging law.

22. **fault_3d_infperiodic_aging_pnl** : same with non linear pore pressure diffusion.

23. **fault_3d_infperiodic_aging_press** : same with imposed pore pressure history.

24. **fault_3d_infperiodic_slip** : 2d fault between 3d elastic slabs of finite thickness. Spectral boundary integral approach (replication along depth and strike). Slip law.

25. **fault_3d_infperiodic_slip_pnl** : same with non linear pore pressure diffusion.

26. **fault_3d_infperiodic_slip_press** : same with imposed pore pressure history.

27. **fault_3d_infperiodic_regage** : 2d fault between 3d elastic slabs of finite thickness. Spectral boundary integral approach (replication along depth and strike). Regularized rate-and-state, aging law.

28. **fault_3d_infperiodic_regslip** : same with regularized rate-and-state, slip law.

3 Model description

3.1 Geometry and constitutive equations

The fault geometry considered is a planar (1d or 2d) fault embedded in an elastic medium (2d or 3d, finite or infinite), as depicted in Figure 1. The fault is the $z = 0$ plane. For 2d configurations, the variables only depend on x coordinate, not on y. The fault simulated is a frictional interface, loaded by a (possibly heterogeneous) lithostatic normal stress $\sigma(x, y)$ (or $\sigma(x)$ for 2d). Fluid diffusion inside the fault leads to a pore pressure $p(x, y, t)$, so that the effective normal stress is $\sigma_e = \sigma - p$. A constant slip rate v_p is imposed either at a distance $\pm H$ from the fault (fault_xxx_infperiodic_xxx), or within the plane $z = 0$, around the frictional domain (fault_xxx_cr_xxx, fault_xxx_freesurface_xxx), forcing shear slip δ on the fault in the x direction.

In the special case of freesurface configuration (fault_2d_freesurface_xxx) the model is a vertical strike slip fault (dip angle $\beta = 90°$), with slip occuring in the y direction, $x > 0$ is the depth. The freesurface is situated at $x = -L/2$.

Slip is resisted on the fault by rate-and-state friction Dieterich [1979], Marone [1998], with a possible normal stress dependence on the state variable as formulated by Linker and Dieterich [1992]. For standard rate-and-state friction, the friction coefficient f writes:

$$f = f_0 + a \ln \frac{v}{v^*} + b \ln \frac{v^* \theta}{d_c}, \tag{1}$$

For regularized rate-and-state friction (fault_xxx_regage_xxx and fault_xxx_regslip_xxx), f is given by:

$$f = a \sinh^{-1} \left[\frac{v}{2v^*} \exp \left(\frac{f_0 + b \ln v^* \theta / d_c}{a} \right) \right] \tag{2}$$

where f_0, a, b and d_c are the rate-and-state parameters, v^* a reference slip rate, v the slip rate, and θ the state variable. a, b and d_c can be heterogeneous along the fault and depend on both x and y. f_0 and v^* are constant.

The distribution of a, b, d_c, σ, of the initial slip δ, slip rate v and state variable θ can either be specified in the form of circular patches with uniform values (asperities). Traditionally, velocity weakening (VW $a - b < 0$) patches are distributed on a velocity strengthening background (VS $a - b > 0$), as illustrated in Figure 1 (right). The other option is to specify these values at each point of the computational grid, and to provide the matrices as input (see input section for further details).

The following state evolution laws are used:

- aging law (fault_xxx_aging_xxx):
$$\frac{d\theta}{dt} = 1 - \frac{v\theta}{d_c} - \alpha \frac{\theta}{b\sigma_e} \frac{d\sigma_e}{dt}, \tag{3}$$

- slip law (fault_xxx_slip_xxx):
$$\frac{d\theta}{dt} = -\frac{v\theta}{d_c} \ln \frac{v\theta}{d_c} - \alpha \frac{\theta}{b\sigma_e} \frac{d\sigma_e}{dt}, \tag{4}$$

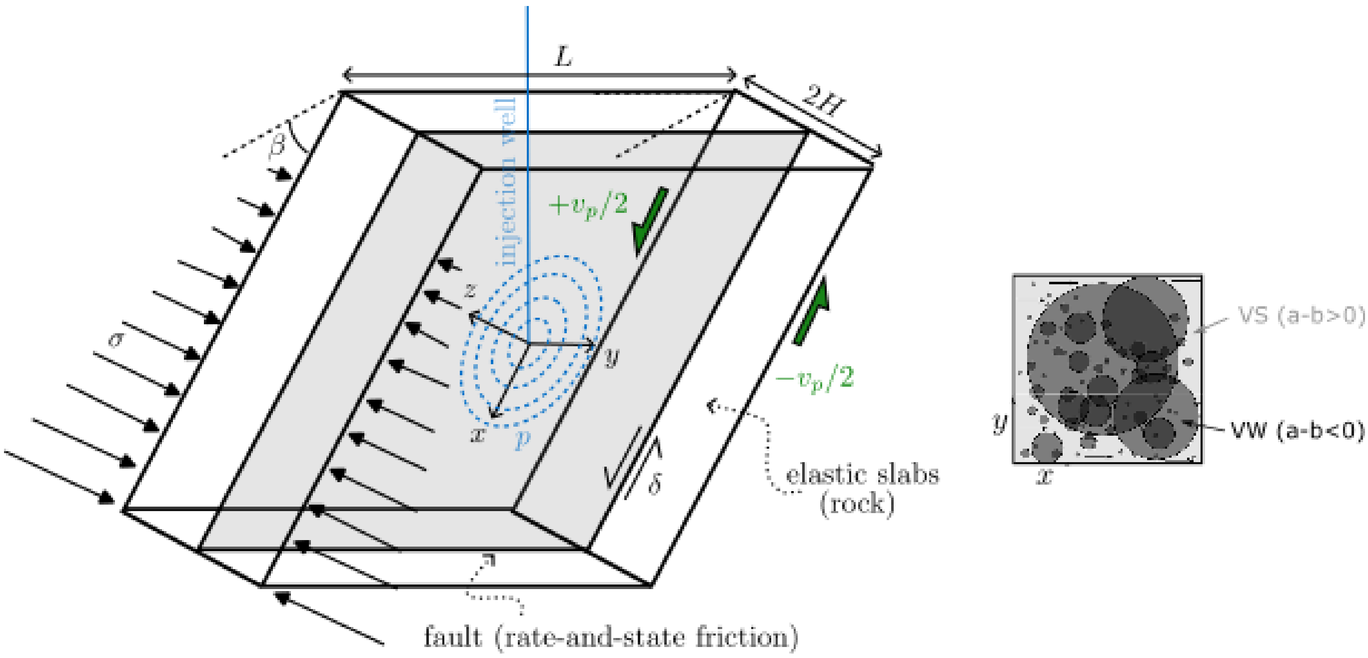

Figure 1: Fault model geometry (left) and asperity structure of the fault (right). VW: velocity weakening, VS: velocity strengthening.

where α is a constant coefficient, and σ_e is the effective normal stress $\sigma - p$.

The pore pressure evolution within the fault p can either be imposed (fault_xxx_press). In this case, the pore pressure and pore pressure rate histories have to be coded in the routines press_1d(2d).f90 and pressrate_1d(2d).f90 respectively.

The pore pressure can also be solved numerically (fault_xxx_pnl). In this case, p obeys the following non-linear diffusion equation:

$$\frac{\partial p}{\partial t} = \nabla \left(\frac{k}{\eta_f \phi C^*} \nabla p \right) + s(t) \delta_D (x - x_i, y - y_i), \tag{5}$$

where k is the fault permeability, η_f the fluid viscosity, ϕ the fault porosity and C^* the effective (fluid+pore space) compressibility, x_i, y_i the coordinates of a ponctual fluid source, with time evolution given by $s(t)$. δ_D is the dirac delta function. The permeability can be time, space, stress, slip, or slip-rate dependent. The routine diffu.f90 can be used to define the resulting hydraulic diffusivity law. The source term $s(t)$ has to be defined in the routines pressrate_nl1d(2d).f90.

The fault slip evolution is computed assuming a quasi-static balance of the form:

$$f \sigma_e = \tau_0 + \kappa * \delta - \frac{\mu}{2 c_s} v, \tag{6}$$

where $\tau_0(x, y, t)$ incorporates the initial shear stress (imposed by the initial slip rate and state variable), and a possible external shear stressing, arising either from the boundary conditions, or from another mechanism. An external transient shear stress perturbation can be imposed, but has to be coded in routines tbp_xxx.f90. $\kappa(x, y)$ is the stress interaction kernel, accounting for the stress redistribution associated with slip along the fault. $\kappa(x, y)$ depends on geometry of the fault and the boundary conditions. The convolution $\kappa * \delta$ is either computed using a spectral approach (infperiodic), a spectral approach avoiding the replication of the fault (cr, following Cochard and Rice [1997]), or in the space domain (freesurface). μ is the shear modulus of the elastic medium, and c_s the shear wave speed of the elastic medium.

3.2 Discretization

The constitutive equations are solved using finite differences. For 3d configurations (2d fault), the fault plane is discretized in $n_x \times n_y$ rectangular cells of size $\Delta x \times \Delta y$ ordered columnwise (Figure 2). For 2d configurations (1d fault), $n_y = 1$.

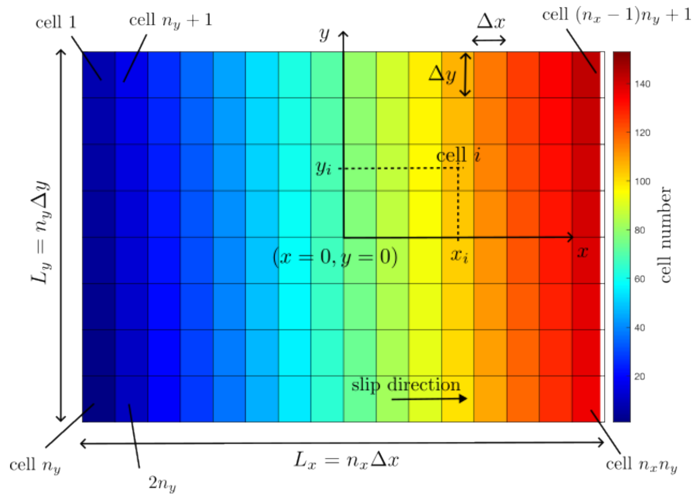

Figure 2: Fault discretization for 2d faults (3d configurations). The colorscale indicates the numbering of the computational cells. 1d faults (2d configuration) follow the same convention, with $n_y = 1$.

4 Third party source code and librairies

4.1 Third party source code

The source code of CYCLAPS includes external source codes (see licenses notices in licenses):

Name	License	URL	Copyright
FFTE	see licenses	`www.ffte.jp`	Copyright (c), 2000-2004, 2008-2014, 2020, Daisuke Takahashi
Special Functions	see licenses	`https://people.sc.fsu.edu/~jburkardt/f_src/special_functions/special_functions.html`	Copyright (c) 1996 Shanjie Zhang and Jianming Jin
CFGIO	MIT	`https://github.com/pkgpl/cfgio`	Copyright (c) 2017 Wansoo Ha

See Zhang and Jin [1996] for details about the computation of special functions.

4.2 Third party librairies

The source code of CYCLAPS uses external librairies (see licenses notices in licenses):

Name	License	URL	Copyright
MPICH	see licenses	`https://www.mpich.org/`	Copyright (c) 1998–2024, Argonne National Laboratory
NetCDF	see licenses	`https://www.unidata.ucar.edu/software/netcdf/`	Copyright (c) 1993-2014 University Corporation for Atmospheric Research/Unidata

5 Citation

If you use this software, please cite it as:

- Dublanchet [2018] for 2d versions without fluid injection
- Dublanchet [2019b] for 2d version with fluid injection,
- Dublanchet [2019a] for 3d version.

6 Install, compile, execute

6.1 Requirements

These instructions are valid for MacOS and LINUX.

- MPICH is needed. Details about the installation of MPICH are provided here: `https://www.mpich.org/downloads/` .
- NETCDF library (netcdf-fortran package for MacOS, or libnetcdff-dev package for LINUX) is necessary.

6.2 Install

Download and unzip CYCLAPS.zip. In the folder CYCLAPS, you will find:

- src : folder containing source files for CYCLAPS
- init: folder containing netcdf initiation files
- results: folder where model outputs (netcdf files) are stored
- makefile

6.3 Compile

Go to the root of CYCLAPS folder. Indicate in the makefile the path to the netcdf and netcdf-fortran librairies (variables NETCDF and NETCDFF), or create a symbolic link. Then, to compile fault model fault_xxx type:

```
>> make exec=fault_xxx
```

This will create an executable `fault_xxx`

6.4 Execute

Go to the root of CYCLAPS folder. To execute fault model fault_xxx:

```
>> mpiexec -n <np> fault_xxx
```

where `<np>` is the number of processes to use. The number of computational cells in x and y directions n_x and n_y have to be multiples of np.

7 Input data

7.1 Parameters file

The simulation parameters have to be written in the file parametres_fault_rns.cfg. parametres_fault_rns.cfg is a key-value parameter file. More information is provided in Table 1. The frictional properties (a, b, d_c), the lithostatic normal stress σ, the initial slip rate and state variable can be either specified in this file, in the form of circular asperities with uniform properties, or specified in init files (see section 7.2).

Table 1: List of parameters in parametres_fault_rns.cfg. n.u. indicates no physical units. n.c. indicates no comment.

key	*parameter*	*unit*	*comment*
simlab	label of fault model used (xxx in fault_xxx)	n.u.	n.c.
	Mechanical parameters		
slip_mode	2 for in-plane (mode II), 3 for anti-plane (mode III)	n.u.	Only for 1d fault in 2d medium
young_mod	Young's modulus E	Pa	n.c.
poisson_ratio	Poisson's ratio ν	n.u.	n.c.
rho_r	rock density ρ	kg.m^{-3}	n.c.
slab_thickness	thickness of elastic slabs in contact H	m	only used for infperiodic configuration (2d or 3d)
ext_shear_stressing	vector of shear stressing parameters	(see below)	only if external shear stress perturbation (used in tbp_xxx.f90 functions)
ext_shear_stressing(1)	constant shear stressing	Pa.s^{-1}	n.c.
ext_shear_stressing(2)	amplitude of shear stress perturbation	Pa	n.c.
ext_shear_stressing(3)	radius of stressed region	m	n.c.
ext_shear_stressing(4)	duration of transient stressing	s	n.c.
ext_shear_stressing(5,6)	x, y coordinates of the center of stressed region	m	n.c.
ref_fric_coeff	reference friction coefficient f_0	n.u.	n.c.
dl_coeff	Linker-Dieterich coefficient α (state dependance on normal stress)	n.u.	n.c.
vplate	tectonic plate rate v_p	m.s^{-1}	n.c.
vstar	reference slip rate v^*	m.s^{-1}	n.c.
vsis	radiative slip rate (for earthquake detection) v_{sis}	m.s^{-1}	n.c.
nasp	number of circular VW asperities	n.u.	Only if meth_init=0. nasp should be smaller than 20
a	direct effect rate-and-state parameter a (1: VS region, then 1 value/VW asperity)	n.u.	nasp+1 values should be provided
b	state effect rate-and-state parameter b (1: VS region, then 1 value/VW asperity)	n.u.	nasp+1 values should be provided
dcasp	critical slip d_c (1: VS region, then 1 value/VW asperity)	m	nasp+1 values should be provided
			continued next page

key	*parameter*	*unit*	*comment*
xcasp	x coordinate of asperity center (1: VS region, then 1 value/VW asperity)	m	nasp+1 values should be provided
ycasp	y coordinate of asperity center (1: VS region, then 1 value/VW asperity)	m	nasp+1 values should be provided
Rasp	radius of asperity (1: VS region, then 1 value/VW asperity)	m	nasp+1 values should be provided
sigasp	normal stress on asperity σ (1: VS region, then 1 value/VW asperity)	Pa	nasp+1 values should be provided
viasp	initial slip rate on asperity (1: VS region, then 1 value/VW asperity)	m.s^{-1}	nasp+1 values should be provided
thiasp	initial state variable on asperity (1: VS region, then 1 value/VW asperity)	s	nasp+1 values should be provided
uiasp	initial slip on asperity (1: VS region, then 1 value/VW asperity)	m	nasp+1 values should be provided
Hydraulic parameters (only for models involving fluid injection fault_xxx_press or fault_xxx_pnl)			
permea	fault reference permeability k	m^2	n.c.
porosity	fault reference porosity ϕ	n.u.	n.c.
compress	effective (fluid and pore space) compressibility c^*	Pa^{-1}	n.c.
viscosity	fluid viscosity η_f	Pa.s	n.c.
rho_f	fluid density ρ_f	kg.m^{-3}	n.c.
paraminj	vector of injection parameters	(see below)	all the parameters are not used, depending on the injection scenario considered (press_xxx.f90 and pressrate_xxx.f90 functions to define the injection scenario)
paraminj(1)	injection duration	s	n.c.
paraminj(2)	x coordinate of injection borehole	m	n.c.
paraminj(3)	y coordinate of injection borehole	m	n.c.
paraminj(4)	Darcy velocity at injection borehole	m.s^{-1}	n.c.
paraminj(5)	Pore pressure at injection borehole	Pa	n.c.
continued next page			

key	*parameter*	*unit*	*comment*
paraminj(6)	borehole radius	m	n.c.
Computational parameters			
nx	number of computational cells n_x in the x direction	n.u.	n.c.
ny	number of computational cells n_y in the y direction	n.u.	use ny=1 for 2d problems
dx	computational cell size Δx in the x direction	m	n.c.
dy	computational cell size Δy in the y direction	m	use dy=0.0 for 2d problems
niter	number of iterations	n.u.	n.c.
nit_screen	print code progression every nit_screen iteration	n.u.	n.c.
meth_init	method for initial conditions (0: use the a, b, dc, sigma, vi, thi defined in this file, 1: use the values defined in init.nc file)	n.u.	n.c.
paramdt	vector of time-step control parameters	(see below)	n.c.
paramdt(1)	maximum number of Runge-Kutta iterations to adapt the time step	n.u.	n.c.
paramdt(2)	absolute error tolerance at each time step (error on $\ln v$, $\ln \theta$, normalized pore pressure p/σ_0)	n.u.	n.c.
paramdt(3)	safety factor for time step adaptation	n.u.	should be between 0 and 1
paramdt(4)	maximum possible time step	s	n.c.
paramdt(5)	minimum possible time step	s	n.c.
pathinit	path to initial conditions directory (containing the init.nc file)	n.u.	n.c.
Output writing control parameters			
qcat	earthquake catalog production (1: yes, 0: no)	n.u.	file earthquake_catalog.nc
			continued next page

key	*parameter*	*unit*	*comment*
qmoy	average and extremal values history recording (1: yes, 0: no)	n.u.	file qmoy.nc
qprof	variable maps recording (1: yes, 0: no)	n.u.	files maps*.nc (one file = one time)
qprofhvc	x and y variable profiles recording (1: yes, 0: no)	n.u.	files profilsx*.nc and profilsy*.nc (one file = one time)
qloc	local variables history recording (1: yes, 0: no)	n.u.	nploc files qlloc*.nc (1 file per point on the fault)
vfrec	slip rate factor used to write outputs	n.u.	used if > 0. vfrec(1): for average extremal values, vfrec(2): for variable maps, vfrec(3): for local variables, vfrec(4) for x and y profils (only used in 3d geometry). The output is written when the max slip rate is multiplied or divided by vfrec(i).
tfrec	time factor used to write outputs	n.u.	same as vfrec, but for time instead of slip rate
dtfrec	time step between two output writings	s	used if > 0. Write outputs every dtfrec(i) seconds. The 4 components correspond to the same outputs as for vfrec and tfrec.
nitrec	number of iterations between two output writings	n.u.	same as tfrec, but in terms of number of iterations
pathres	path to results/output directory	n.u.	n.c.
nploc	number of locations where variables are written	n.u.	used if qloc=1
xrloc	x coordinates of locations where variable are written	m	used if qloc=1. nploc values should be provided
yrloc	y coordinates of locations where variable are written	m	used if qloc=1. nploc values should be provided
hboxm	size of the boundary zone not included in moment and maximum slip rate computation	m	only for 3d configuration with regularized friction law (fault_3d_infperiodic_regxxx)

7.2 Complex heterogeneous fault structure and initial conditions

For a more complex fault heterogeneity, or if the number of cricular asperities is larger than 20, (a, b, d_c, σ, v_i and θ_i, u_i and p_i) distribution can be specified for each of the $n_x \times n_y$ cell of the fault. The parameter meth_init has to be set to 1 in the parametres_fault_rns.cfg file. These values should be provided in a single netcdf file init.nc localized in the ./INIT/ directory. The init.nc file contains a dataset consisting of the 8 variables: a, b, dc, s, vi, ui, thi, vi and pi. Each variable is a $n_x n_y \times 1$ vector, where the fault cells are ordered columnwise, as illustrated in Figure 2.

8 Outputs

CYCLAPS produces five categories of outputs, along with four ways of controlling the frequency of output writing. The outputs are written in netcdf files located in the ./RESULTS/ directory The five categories of outputs are:

1. Earthquake catalogue (file earthquake_catalog.nc).
2. Average and extremal values time histories (file qmoy.nc)
3. Local variables time series (files qloc*.nc)
4. Maps of variables (files maps*.nc)
5. Profiles of variables along x and y directions (files profilsx*.nc and profilsy*.nc)

Details about these different outputs are provided in the next subsections. The writing of outputs in the files can be controlled in four different ways, except for the earthquake catalog. The four possibilities are:

1. one output is written each time the maximum slip rate is mutliplied or divided by a factor provided in vfrec parameter of parametres_fault_rns.cfg file (see table 1)
2. one output is written each time the absolute time since the start of the simulation is multiplied by a factor provided in tfrec parameter of parametres_fault_rns.cfg file (see table 1)
3. outputs are written at constant time steps. The time separating two output writings is specified in the dtfrec parameter of parametres_fault_rns.cfg file (see table 1)
4. outputs are written based on iterations. The number of iterations separating two output writings is specified in the nitrec parameter of parametres_fault_rns.cfg file (see table 1)

The four components of the vectors vfrec, tfrec, dtfrec and nitrec in the parametres_fault_rns.cfg file correspond to the 4 last categories of outputs (not the to the earthquake catalog). Details are provided in table 1.

8.1 Earthquake catalog

The file earthquake_catalog.nc contains a dataset consisting of 11 variables listed below:

1. onset time: onset time of earthquakes (in s)
2. onset time delai: time delai since the last earthquake on the fault (in s)
3. event duration: event duration (in s)
4. x initiation: x coordinate of the first point involved in the earthquake rupture (in m)
5. y initiation: x coordinate of the first point involved in the earthquake rupture (in m)
6. x barycenter: x coordinate of the barycenter of the earthquake rupture (in m)
7. y barycenter: x coordinate of the barycenter of the earthquake rupture (in m)
8. number of elements: number of computational cells involved in the earthquake rupture (n.u.)
9. coseismic moment: coseismic moment liberated by the earthquake (N.m)
10. coseismic stress drop: coseismic stress drop associated with the earthquake, averaged over the rupture area (Pa)
11. coseismic slip: coseismic slip associated with the earthquake, averaged over the rupture area (m)

The models fault_3d_infperiodic_regage and fault_3d_infperiodic_regslip produce two additionnal variables in the earthquake catalog file:

12. shear stress init: average shear stress in the rupture area before the onset of the earthquake (in Pa)

13. shear stress final: average shear stress in the rupture area right after the earthquake (in Pa)

The difference between shear stress final and shear stress init is the coseismic stress drop.

Each value contained in one of these variables corresponds to one earthquake. An earthquake occurs when the maximum slip rate exceeds the radiative threshold vsis defined in the parametres_fault_rns.cgf file. The earthquake rupture corresponds to all the fault elements having experienced a slip rate larger than vsis until the maximum slip rate decreases below vsis.

8.2 Average and extremal values time histories

The file qmoy.nc contains a dataset consisting of 7 variables capturing different time series. The 7 variables are:

1. time: absolute time of each variable writing (in s)
2. time delai: time delai since the last output writing (in s)
3. mean slip rate: time series of the spatial average of slip rate (in m.s^{-1})
4. max slip rate: time series of the maximum slip rate on the fault (in m.s^{-1})
5. mean slip: time series of the spatial average of slip on the fault (in m)
6. mean shear stress: time series of the spatial average of shear stress on the fault (in Pa)
7. mean state: time series of the spatial average of the state variable on the fault (in s)

The models fault_3d_infperiodic_regage and fault_3d_infperiodic_regslip produce one additionnal variable in qmoy.nc file:

8. mean slip rate vw: time series of the spatial average of the slip rate within the velocity weakening regions of the fault (in m.s^{-1})

Note also that only fault_3d_infperiodic_regage and fault_3d_infperiodic_regslip consider the parameter hboxm in the computation of mean slip rate (a zone of width hboxm is excluded). See table 1 for details.

8.3 Local variables time series

The time series of slip rate, state variable, shear stress, slip and eventually pore pressure and Darcy velocity can be written for nploc locations with coordinates specified in xrloc and yrloc of parametres_fault_rns.cfg (table 1). The times series are written in nploc files named qloc*.nc (time series of location i is stored in qloci.nc). The files qloc*.nc contain datasets consisting of 6 variables. The variables are:

1. time: absolute time (in s)
2. time delai: time delai since the last output writing (in s)
3. slip: total slip time series (in m)
4. slip rate: slip rate time series (in m.s^{-1})
5. state: state variable time series (in s)
6. shear stress: shear stress time series (in Pa)

For models considering fluid injection (fault_xxx_press or fault_xxx_pnl), qloc*.nc contain an additional variable:

7. pore pressure: pore pressure time series (in Pa).

Finally, models fault_2d_cr_regage_pnl and fault_2d_cr_regslip_pnl write an additional variable:

8. darcy vel: Darcy velocity time series (in m.s^{-1}).

8.4 Maps of variables

The slip rate, state, shear stress, slip, pore pressure values at each fault cell at given times can be written in the files maps*.nc. The file mapsi.nc contains a dataset consisting of 6 variables, characterizing the fault at time t_i. The vriables are:

1. time: absolute time t_i (in s)
2. time delai: time delai since the last output writing (in s)
3. slip: slip distribution (in m)
4. slip rate: slip rate distribution (in m.s^{-1})
5. state: state variable distribution (in s)
6. shear stress: shear stress distribution (in Pa)

For models considering fluid injection (fault_xxx_press or fault_xxx_pnl), maps*.nc contain an additional variable:

7. pore pressure: pore pressure time series (in Pa).

All the variables, except time and time delai are $n_x n_y \times 1$ vectors containing the values of slip, slip rate, shear stress, state, and pore pressure at each fault cell. The values are stored in the variables columnwise (Figure 2).

8.5 Profiles of variables along x and y directions

For 3d configuration, writing all the values of slip rate, state, shear stress, slip and pore pressure at a given time in a maps*.nc file can be consuming in time and memory. One can instead write only these values along two profiles: the first along x centered at $y = 0$, the second along y centered at $x = 0$. The results at time t_i are stored in two files: profilsxi.nc and profilsyi.nc. The files profilsx*.nc and profilsy*.nc contain a dataset consisting in the same variables as in maps*.nc (see previous section).

Note that this category of output is only relevant for 3d configurations (fault_3d_xxx), and is not accounted for in 2d configurations (fault_2d_xxx).

9 License

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References

Alain Cochard and James R Rice. A spectral method for numerical elastodynamic fracture analysis without spatial replication of the rupture event. *Journal of the Mechanics and Physics of Solids*, 45(8):1393–1418, 1997.

James H Dieterich. Modeling of rock friction: 1. experimental results and constitutive equations. *Journal of Geophysical Research: Solid Earth*, 84(B5):2161–2168, 1979.

Pierre Dublanchet. The dynamics of earthquake precursors controlled by effective friction. *Geophysical Journal International*, 212(2):853–871, 2018.

Pierre Dublanchet. Inferring fault slip rates from cumulative seismic moment in a multiple asperity context. *Geophysical Journal International*, 216(1):395–413, 2019a.

Pierre Dublanchet. Fluid driven shear cracks on a strengthening rate-and-state frictional fault. *Journal of the Mechanics and Physics of Solids*, 132:103672, 2019b.

MF Linker and James H Dieterich. Effects of variable normal stress on rock friction: Observations and constitutive equations. *Journal of Geophysical Research: Solid Earth*, 97(B4):4923–4940, 1992.

Chris Marone. Laboratory-derived friction laws and their application to seismic faulting. *Annual Review of Earth and Planetary Sciences*, 26(1):643–696, 1998.

S Zhang and J Jin. *Computation of special functions. Wiley.* Interscience Publications, 1996. ISBN 0-471-11963-6.