XCII CONGRESSO NAZIONALE atticon3122 IVa – C – 13

PRESSURIZZAZIONE DI FLUIDI IN MODELLI DI ROTTURA 3D DINAMICI E SPONTANEI

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Goals

- Comprendere l' evoluzione della trazione ed il meccanismo di weakening durante un evento sismico;
- Quantificare l' importanza di uno dei cosiddetti effetti del secondo ordine in una legge costitutiva realistica;
- Modellare il dynamic fault weakening includendo la pressurizzazione termica dei fluidi;
- Quantificare il calore prodotto per attrito durante il movimento dinamico su faglia;
- Enfatizzare le implicazioni sui valori inferiti della distanza di slip – weakening caratteristica d_0 e dell' energia di frattura E_G;
- Esplorare come una porosità variabile nel tempo possa modificare i processi di breakdown;
- Inferire relazioni di scala tra le quantità fisicamente rilevanti ed i parametri della thermal pressurization.

Statement of the problem and methodology

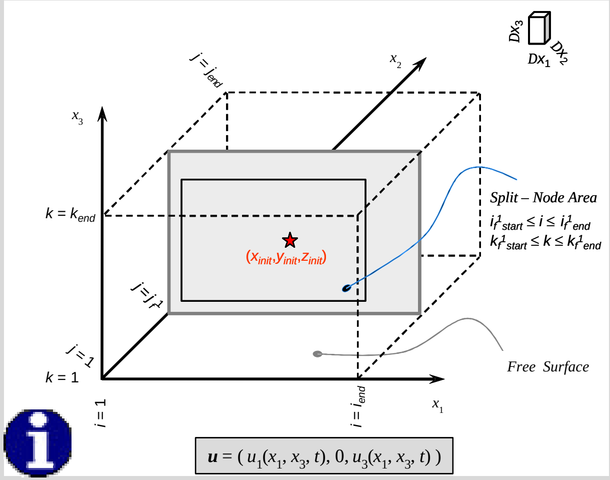
We solve *fully* dynamic, spontaneous problem (the fundamental elasto–dynamic equation), without body forces **f**

$$r\ddot{U}_i = s_{ij,j} + f_i$$

We consider *truly* 3–D (not mixed – mode) problem, for which solutions (for instance the fault slip, i. e. the particle displacement discontinuity) are in the form: $\mathbf{u} = (u_1(x_1,x_3,t), 0, u_3(x_1,x_3,t))$

Numerical experiments refer to a vertical fault

truly 3 – D **problem**



The spatial computational domain is discretized using cubic building blocks in a conventional grid. The medium is linearly elastic except that in the fault plane …

… that obeys to the Fault Boundary Condition, i. e. to the governing law, that relates the fault friction t to some physical observables. In general is:

$$t = m(u, v, \mathrm{Y}, T, H, l_c, h, g, C_e)\ s_n^{eff}(s_n, p_{fluid})$$

where m is the friction coefficient and s_n^{eff} the effective normal stress that can change during time.

Slip – weakening law (Barenblatt

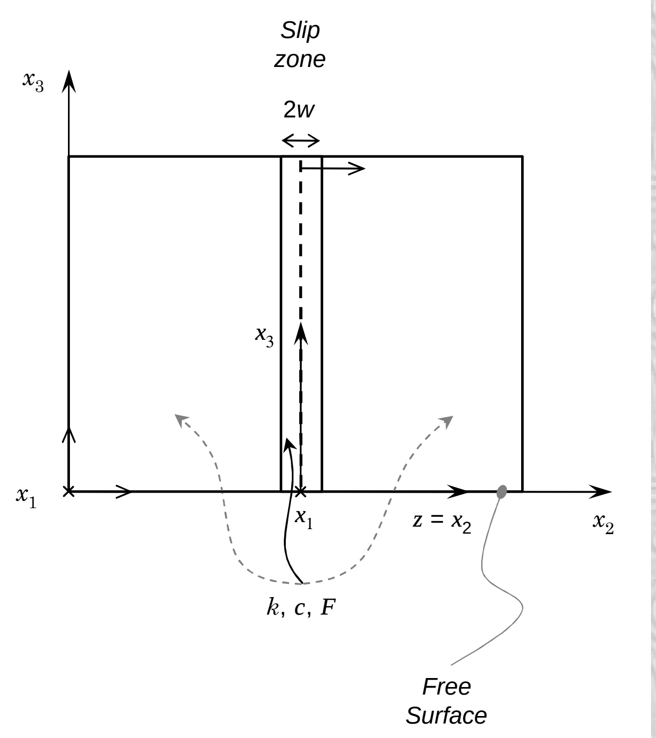
$$t = \begin{cases} \left[m_u - (m_u - m_f)\,\frac{u}{d_0} \right] s_n^{eff} & ,u < d_0 \\ m_f s_n^{eff} & ,u \ge d_0 \end{cases}$$

$$\begin{cases} t = \left[m_* - a \ln\left(\frac{v_*}{v} \right) + b \ln\left(\frac{Y\, v_*}{L} \right) \right] s_n^{eff} \\ \frac{\mathrm{d}}{\mathrm{d}t} Y = 1 - \frac{Y\, v}{L} - \left(\frac{a_{LD} Y}{b\, s_n^{eff}} \right) \frac{\mathrm{d}}{\mathrm{d}t} s_n^{eff} \end{cases}$$

An explicit displacement discontinuity is assumed between the two sides of the fault: **Traction–at–Split–Nodes** scheme (Day, 1982a, 1982b; Andrews, 1999)

The numerical details and the implementations of constitutive equations is given in Bizzarri and Cocco (2005, Ann. Geophys, *48*, 2, 279-299)

Mathematical background



1 – D Fourier' s heat conduction equation:

$$\frac{\partial}{\partial t}T = c\,\frac{\partial^2}{\partial z^2}T + \frac{1}{c}q$$

Coupling of temperature *T* with pore fluid pressure p_{fluid}:

$$\frac{\partial}{\partial t}p_{fluid} = \frac{a_{fluid}}{b_{fluid}}\frac{\partial}{\partial t}T - \frac{1}{b_{fluid}F}\frac{\partial}{\partial t}F + w\,\frac{\partial^2}{\partial z^2}p_{fluid}$$

where *c* is the thermal diffusivity, *c* the heat capacity for unit volume, a_{fluid} the coefficient of thermal expansion, b_{fluid} the compressibility coefficient, *F* the porosity and $w = k/h_{fluid}b_{fluid}F$ the hydraulic diffusivity (being *k* the permeability of the medium and h_{fluid} the dynamic fluid viscosity). Analytical solutions at $z = 0$ are:

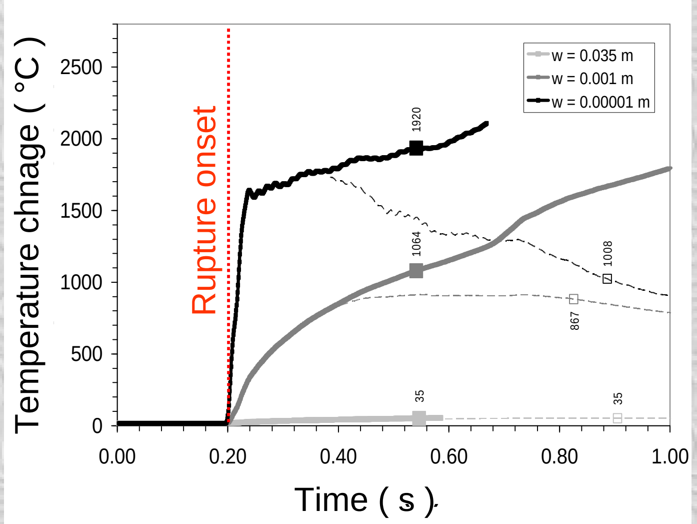
$$T^{wf}(x_1,x_3,t) = T_0^{\,f} + \frac{1}{2\,c\,w(x_1,x_3)}\int_0^{t-e} \mathrm{d}t' \,\mathrm{erf}\left(\frac{w(x_1,x_3)}{2\sqrt{c\,(t-t')}}\right) t(x_1,x_3,t')\,v(x_1,x_3,t')$$

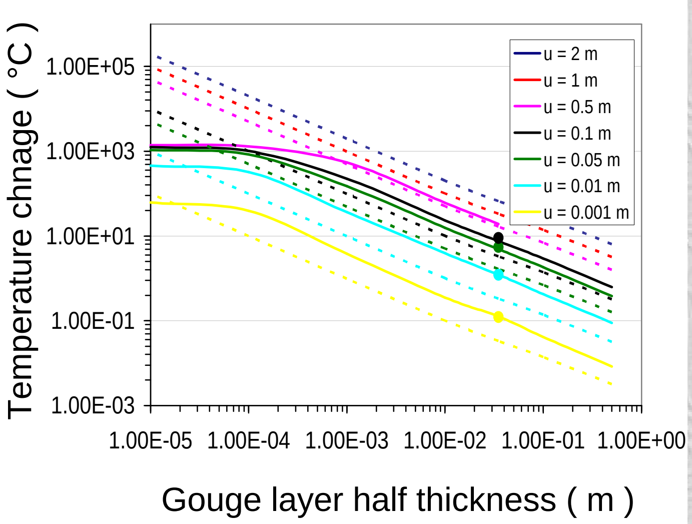
$$\tilde{p}_{fluid}^{\;wf}(x_1,x_3,t) = p_{fluid_0}^{\;\;f} + \frac{g}{2\,w(x_1,x_3)}\int_0^{t-e}\mathrm{d}t' \left\{-\frac{c}{w-c}\,\mathrm{erf}\left(\frac{w(x_1,x_3)}{2\sqrt{c\,(t-t')}}\right) + \frac{w}{w-c}\,\mathrm{erf}\left(\frac{w(x_1,x_3)}{2\sqrt{w\,(t-t')}}\right)\right\}$$

$$\left\{ t(x_1,x_3,t')\,v(x_1,x_3,t') - \frac{2\,w(x_1,x_3)}{g}\frac{1}{b_{fluid}F(t')}\frac{\partial}{\partial t'}F(x_1,0,x_3,t') \right\}$$

Bizzarri and Cocco (2006a, 2006b, *JGR*, 111, B05303 and B05304)

Temperature change on the fault





——— Crack like models

- - - - - Pulse like models (with healing and finite slip duration)

——— Numerical experiments

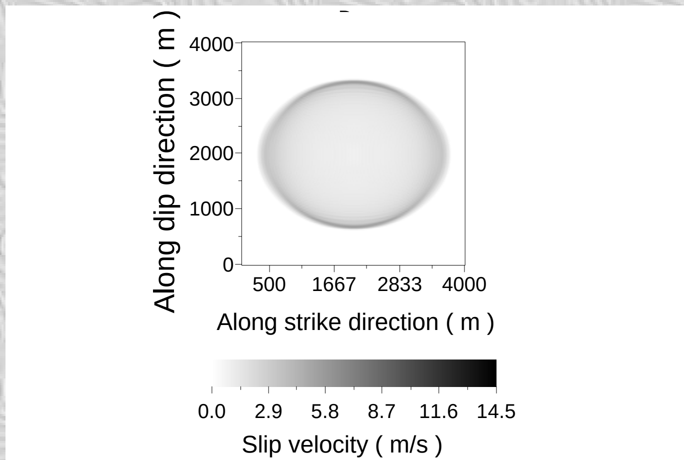
- - - - - Adiabatic prediction:

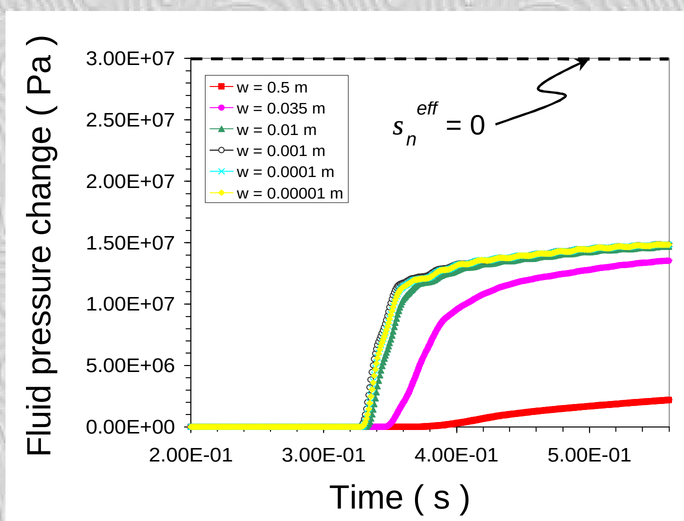
$$DT^{(adiab)} \cong \frac{t_f\, u}{2\, cw}$$

Bizzarri and Cocco (2006a, 2006b, *JGR*, 111, B05303 and B05304)

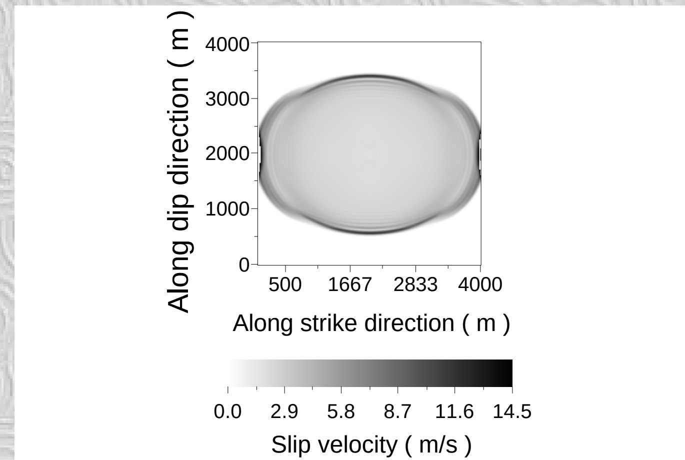
Results with SW law

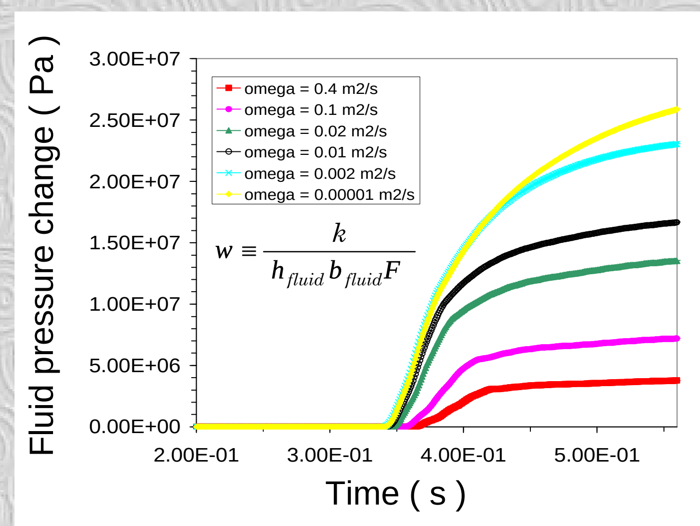
Dry fault (s_n^{eff} = const)



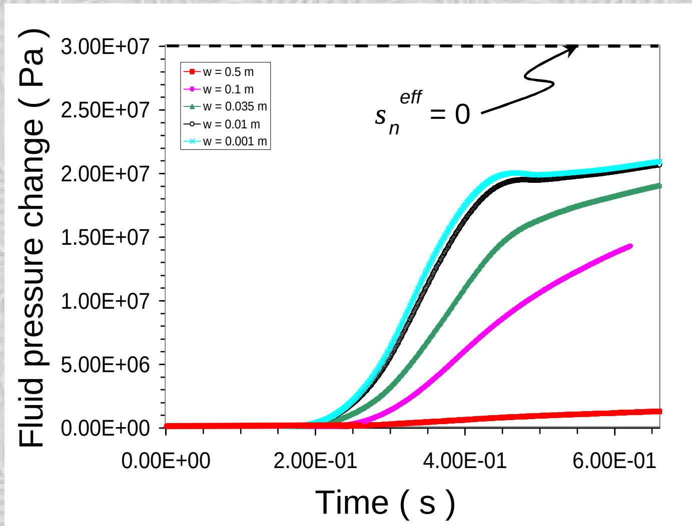


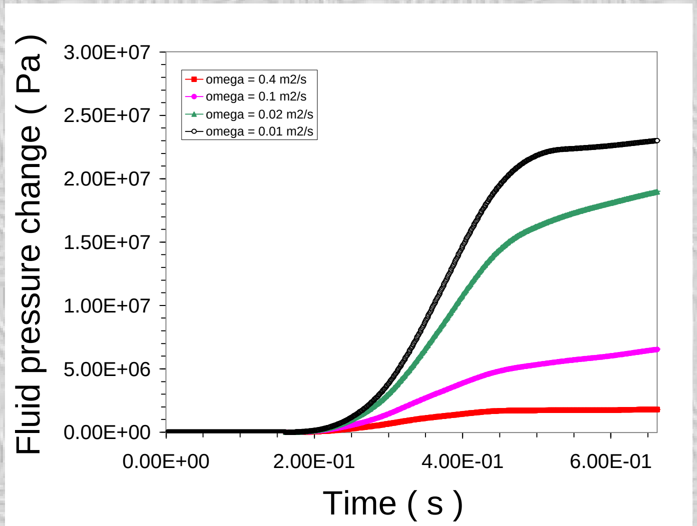
Wet fault (s_n^{eff} varies)





Results with DR law





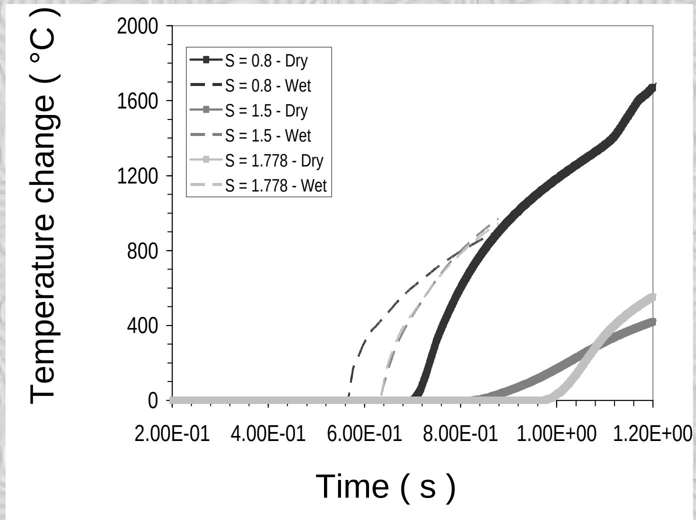
Bizzarri and Cocco (2006a, 2006b, *JGR*, 111, B05303 and B05304)

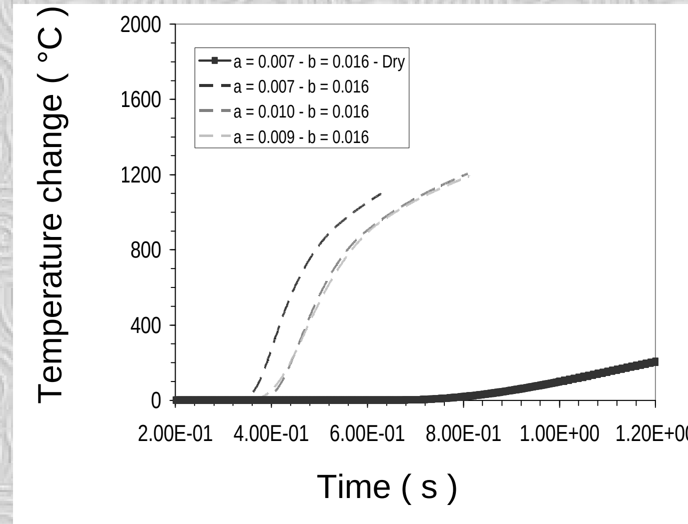
$$t = \left[m_* + a \ln\left(\frac{v}{v_*} \right) + b \ln\left(\frac{Y\, v_*}{L} \right) \right] s_n$$

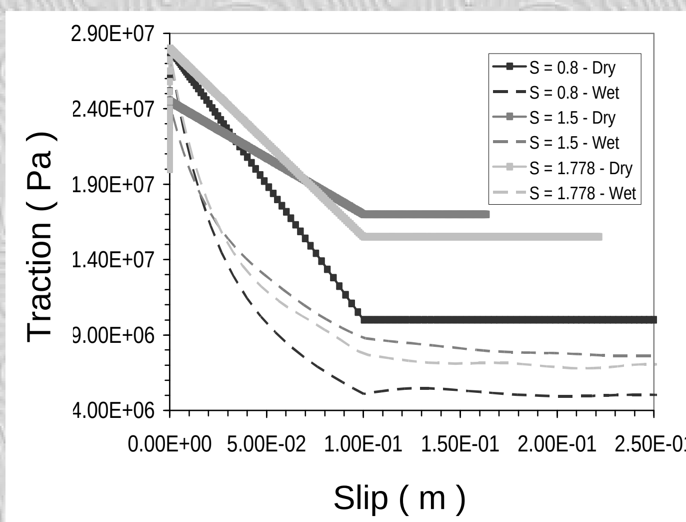
$$\frac{\mathrm{d}}{\mathrm{d}t} Y = 1 - \frac{Y\, v}{L}$$

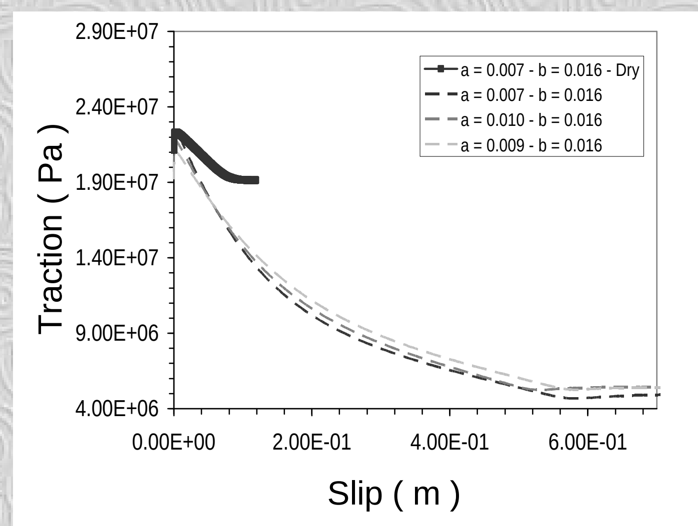
Dry fault

Dependence on friction parameters

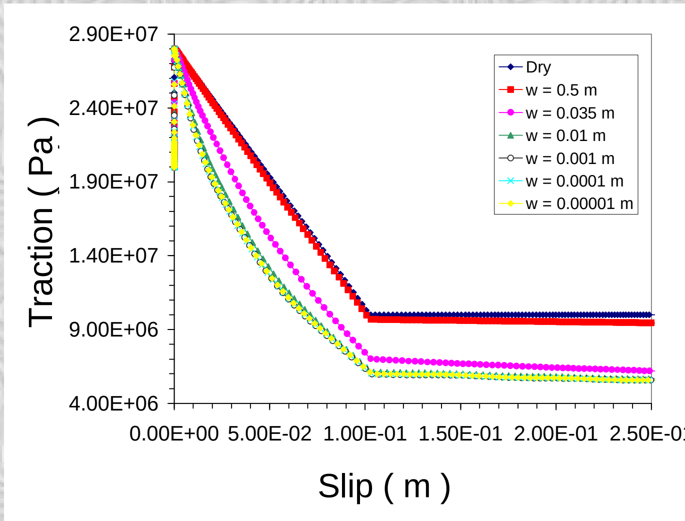


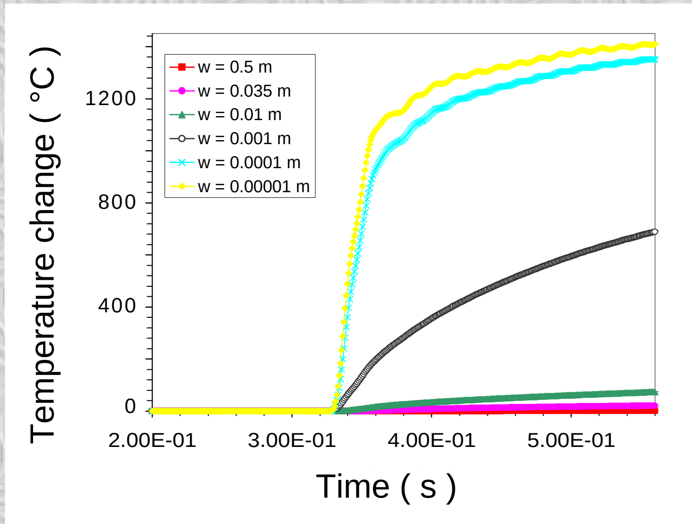


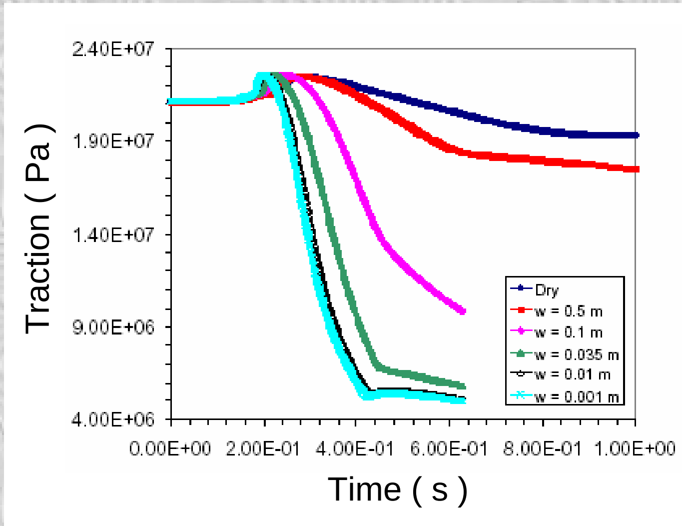


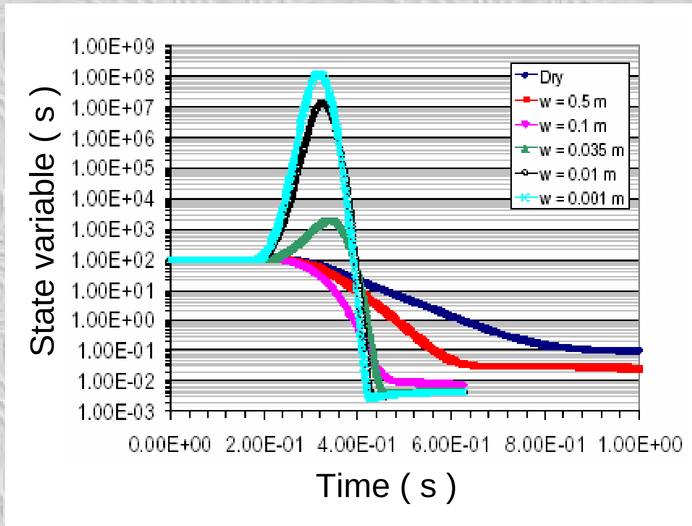


The breakdown zone

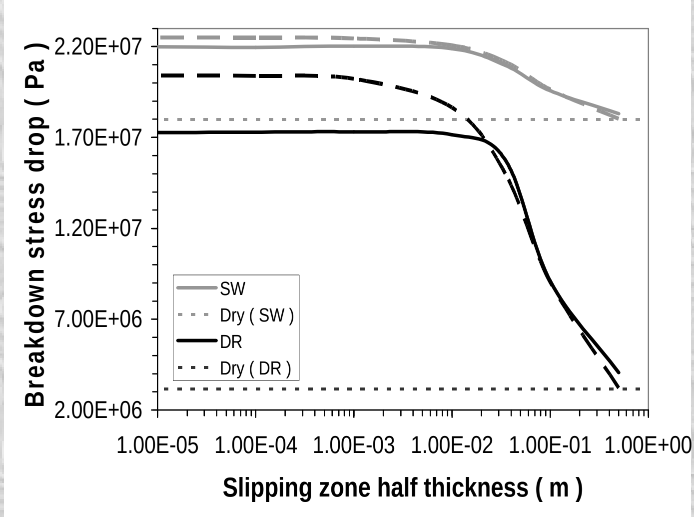








Scaling laws #1

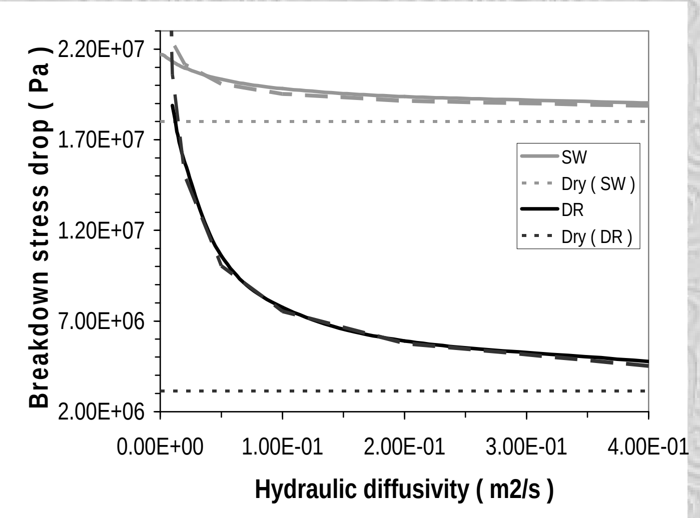


$$Dt_b = Dt_b^{(dry)} \left(1 + a_2 \, e^{-\frac{w}{d}} \right) \left(a_3 + a_4 \sqrt{\frac{w_*}{w}} \right)$$

where $w_* = 0.02$ m²/s and

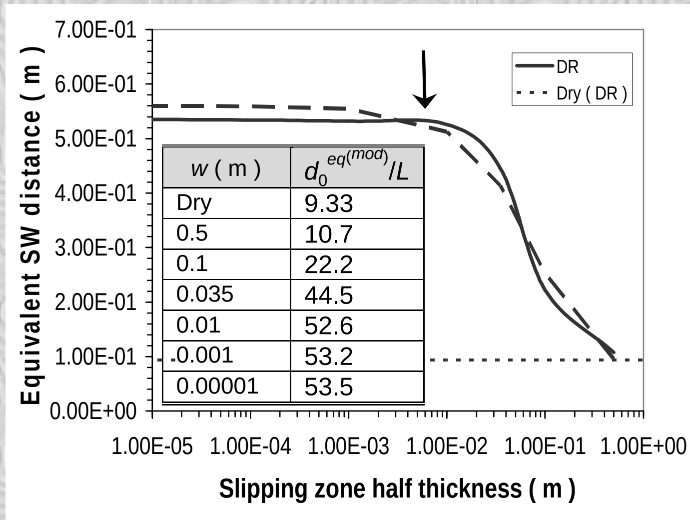
for SW: $a_2 = 0.25$, $a_3 = 0.86$, $a_4 = 0.14$, $d = d_0^{(dry)}$

for RS: $a_2 = 5.5$, $a_3 = 0.1$, $a_4 = 0.9$, $d = d_0^{eq(dry)}$



Bizzarri and Cocco (2006a, 2006b, *JGR*, 111, B05303 and B05304)

Scaling laws #2

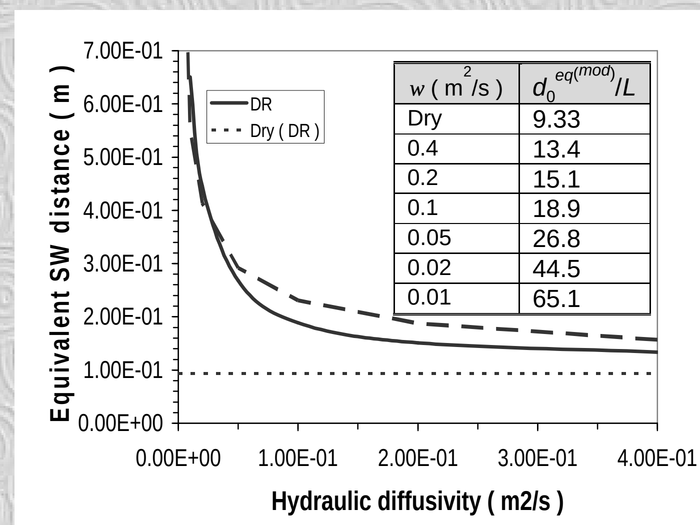


w (m)	$d_0^{eq(mod)}/L$
Dry	9.33
0.5	10.7
0.1	22.2
0.035	44.5
0.01	52.6
0.001	53.2
0.00001	53.5

$$d_0^{\,eq} = d_0^{\,eq(dry)} \left(1 + b_2\, e^{-\frac{w}{d}}\right)\left(b_3 + b_4 \sqrt{\frac{w_*}{w}}\right)$$

where $w_* = 0.02$ m²/s and

$b_2 = 5$, $b_3 = 0.2$, $b_4 = 0.8$; $d = d_0^{eq(dry)}$



w (m^2/s)	$d_0^{eq(mod)}/L$
Dry	9.33
0.4	13.4
0.2	15.1
0.1	18.9
0.05	26.8
0.02	44.5
0.01	65.1

Bizzarri and Cocco (2006a, 2006b, *JGR*, 111, B05303 and B05304)

Effects of porosity evolution #1

If porosity F evolves through time the heat source function for the elementary solution is:

$$\tilde{q}(x_1,z,x_3,t)=\begin{cases}\dfrac{t(x_1,x_3,t)\,v(x_1,x_3,t)}{2\,w(x_1,x_3)}\ \text{Constant}\ F & ,t>0,|z|\le w(x_1,x_3)\\ 0 & ,|z|>w(x_1,x_3)\end{cases}$$

The solution for the pore fluid pressure is (erf(.) is the error function):

$$\tilde{p}_{fluid}^{\,w}(x_1,z,x_3,t)=p_{fluid_0}+\frac{g}{4\,w(x_1,x_3)}\int_0^{t-e}\mathrm{d}t'\,\Big\{-\frac{c}{w-c}\Big[\mathrm{erf}\Big(\frac{z+w(x_1,x_3)}{2\sqrt{c(t-t')}}\Big)-\mathrm{erf}\Big(\frac{z-w(x_1,x_3)}{2\sqrt{c(t-t')}}\Big)\Big]+$$

$$+\frac{w}{w-c}\Big[\mathrm{erf}\Big(\frac{z+w(x_1,x_3)}{2\sqrt{w(t-t')}}\Big)-\mathrm{erf}\Big(\frac{z-w(x_1,x_3)}{2\sqrt{w(t-t')}}\Big)\Big]\Big\}\Big\{t(x_1,x_3,t')\,v(x_1,x_3,t')+\text{Constant}\ F\Big\}$$

On the fault plane (i. e. in the limit $z\to 0$) the pore fluid pressure change is

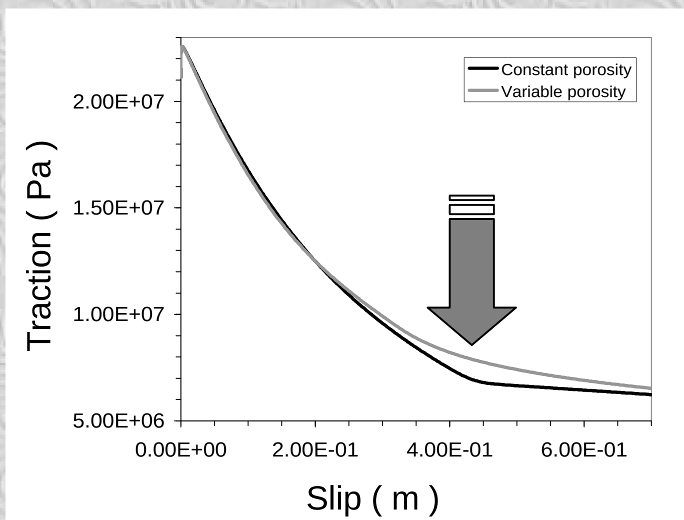
$$\tilde{p}_{fluid}^{\,wf}(x_1,x_3,t)=p_{fluid_0}^{\,f}+\frac{g}{2\,w(x_1,x_3)}\int_0^{t-e}\mathrm{d}t'\,\Big\{-\frac{c}{w-c}\,\mathrm{erf}\Big(\frac{w(x_1,x_3)}{2\sqrt{c(t-t')}}\Big)+$$

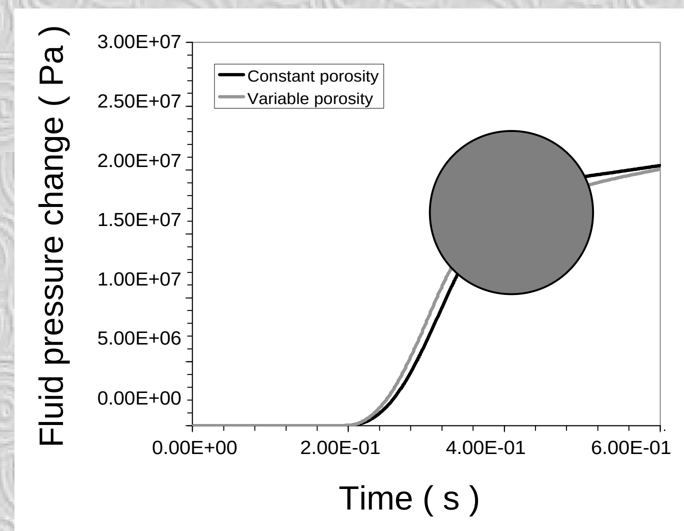
$$+\frac{w}{w-c}\,\mathrm{erf}\Big(\frac{w(x_1,x_3)}{2\sqrt{w(t-t')}}\Big)\Big\}\Big\{t(x_1,x_3,t')\,v(x_1,x_3,t')+\text{Constant}\ F\Big\}$$

Effects of porosity evolution #2

Assuming that porosity evolves accordingly to the law proposed by Segall and Rice (1995), and assuming $L_{SR} = L$

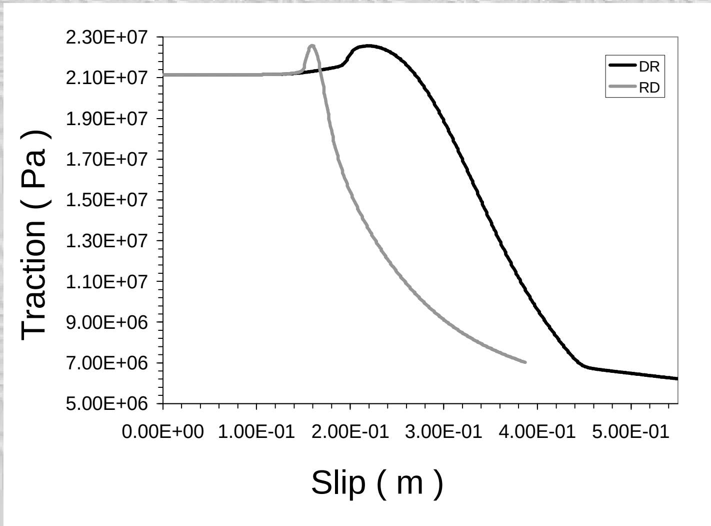
$$F\left(x_1, z, x_3, t\right) = F_* - e_{SR} \ln\left(\frac{Y \;\; v_*}{L_{SR}}\right)$$

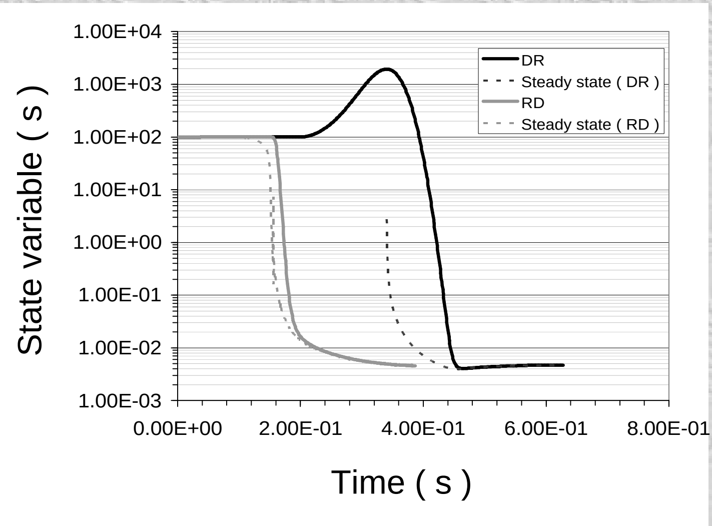




Bizzarri and Cocco (2006a, 2006b, *JGR*, 111, B05303 and B05304)

Importance of the evolution law





DR (ageing evolution law)

$$t = \left[m_* + a \ln\left(\frac{v}{v_*}\right) + b \ln\left(\frac{Y\, v_*}{L}\right) \right] s_n$$

$$\frac{\mathrm{d}}{\mathrm{d}t} Y = 1 - \frac{Y\, v}{L}$$

Dry fault

RD (slip evolution law)

$$t = \left[m_* + a \ln\left(\frac{v}{v_*}\right) + b \ln\left(\frac{Y\, v_*}{L}\right) \right] s_n$$

$$\frac{\mathrm{d}}{\mathrm{d}t} Y = -\frac{Y\, v}{L} \ln\left(\frac{Y\, v}{L}\right)$$

Dry fault

Conclusioni

- ✓ L' inclusione della pressurizzazione termica dei fluidi cambia la forma del fronte di rottura e l' evoluzione della trazione all' interno della zona coesiva;
- ✓ L' andamento della trazione mostra una continua diminuzione per crescenti valori dello slip su faglia;
- ✓ L' equazione evolutiva della variabile di stato influenza la dipendenza della trazione dallo slip e dal tempo;
- ✓ La lunghezza caratteristica di slip – weakening equivalente d_0^{eq} può perdere significato (e. g. per porosità temporalmente variabile);
- ✓ La caduta di sforzo di breakdown e d_0^{eq} sono inversamente proporzionali al fault thickness ed alla diffusività idraulica.

Grazie!

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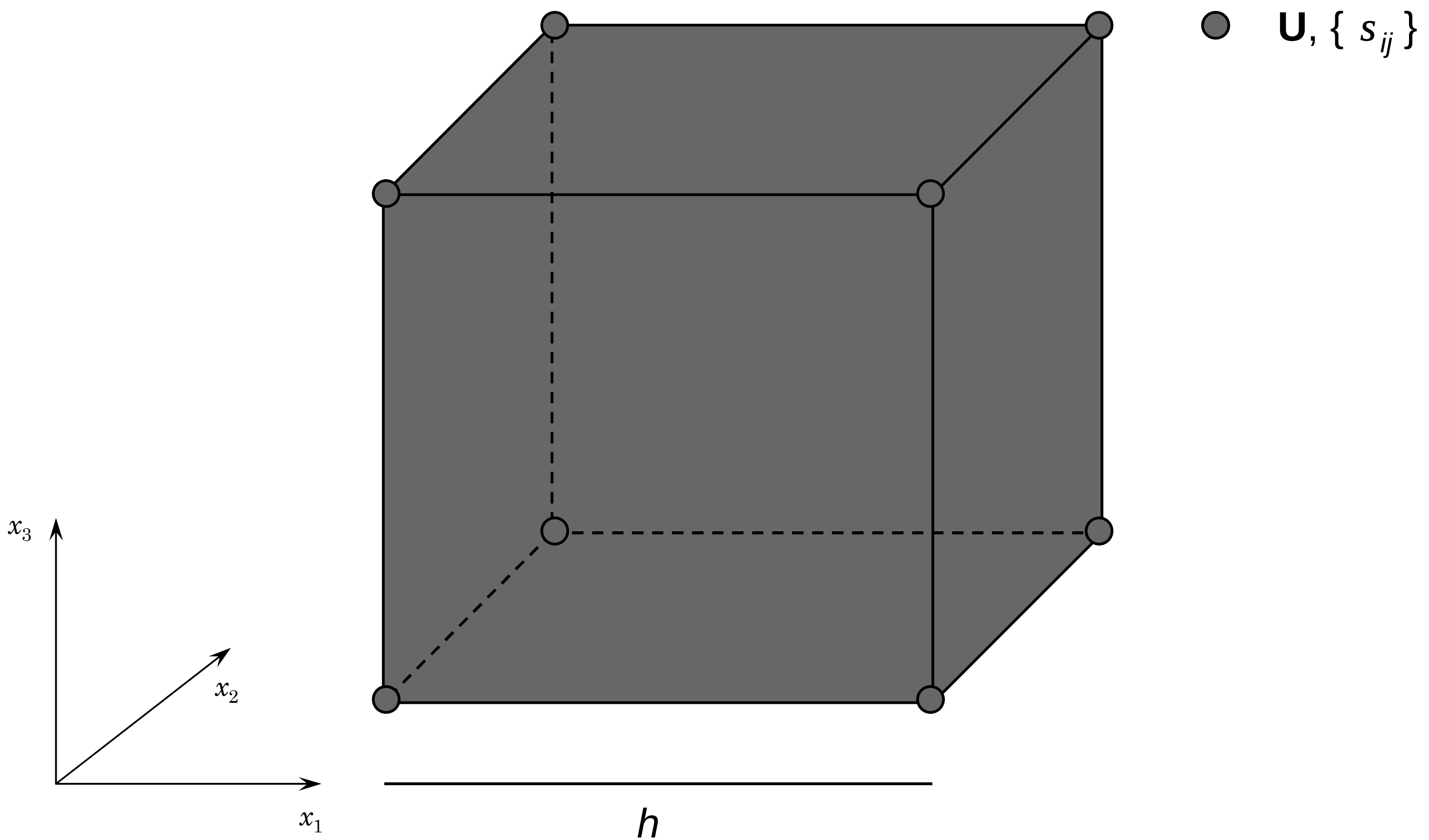
Why " *truly* " 3 – D ?

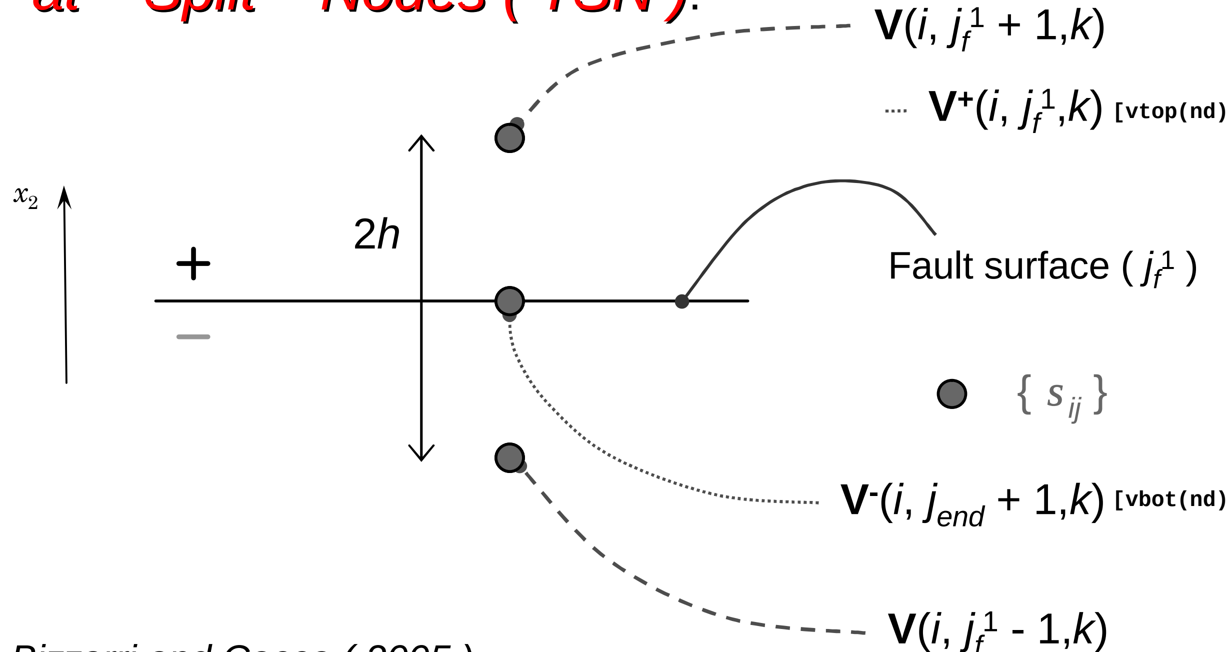
Remembering the dimensionality of the problem:

2 – D Mode II (pure in – plane):	$\mathbf{u} = (u_1(x_1,t), 0, 0)$
2 – D Mode III (pure anti – plane):	$\mathbf{u} = (0, u_2(x_1,t), 0)$
3 – D Mixed mode:	$\mathbf{u} = (u_1(x_1,t), u_2(x_1,t), 0)$
3 – D having only one non null component:	$\mathbf{u} = (u_1(x_1,x_2,t), 0, 0)$
Truly 3 – D:	$\mathbf{u} = (u_1(x_1,x_2,t), u_2(x_1,x_2,t), 0)$

- ***Conventional - grid (CG)***:



- ***Traction – at – Split – Nodes (TSN)*:**

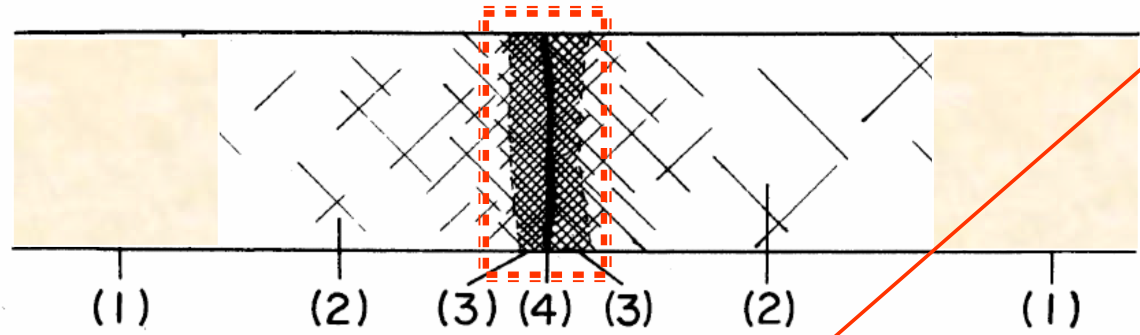


Andrews (1999), *Bizzarri and Cocco (2005)*

* **Discontinuum medium** (continuum mechanics equations of motion are applied to each half - space individually; the fault is an explicit discontinuity in displacement)

Non – laminar fault model

Internal Structure of Principal Faults of the North Branch San Gabriel Fault



1) Undeformed Host Rock

Fault Zone {
2) Damaged Host Rock
3) Foliated Zone
4) Central ultracataclasite layer
} Fault Core

Fig. 2. Schematic section across the North Branch San Gabriel fault zone illustrating position of the structural zones of the fault. The diagram is not to scale.

30- 100 m (Damage ˜ *highly cracked rock*)

1- 10 m (*foliated gouge* or *gouge*)

10s- 100s mm (containing the ***principal slipping zone***, *which* is *much thinner*, typically < 5 mm)

Chester, Evans and Biegel, *JGR,*1993
Sibson, BSSA, 2003
Chester and Chester, SSA, SCEC meetings 2004

Parameter	*Value*
Medium and discretization parameters	
$\lambda = G$	27 GPa
v_P	5196 m/s
v_S	3000 m/s
$\Delta x_1 = \Delta x_3$	25 m
Δx_2	100 m
Δt	0.83671×10^{-3} s
$\sigma_n - p^f_{fluid_0}$	30 MPa
Slip–weakening model parameters	
τ_0	20 MPa
μ_u	0.93333
μ_f	0.33333
S (at $t = 0$; reference)	0.8
d_0	0.1 m
Rate– and state–dependent models parameters	
τ_0	$\tau^{ss}(v_{init})$
a	0.007
b	0.016
L	0.01 m
v_{init}	1×10^{-4} m/s
μ_*	0.56
Ψ_{nucl}	1×10^{-4} s
$\Psi_{outside\ the\ nucleation}$	$\Psi^{ss}(v_{init})$
α_{LD} (reference)	0.53
Thermal pressurization parameters	
T_0^f	100 °C
k (reference)	5×10^{-17} m^2
η_{fluid}	1×10^{-4} Pa s
c	3×10^{6} J/(m^3 °C)
χ	1×10^{-6} m^2/s
Φ_0	0.025
α_{fluid}	1.5×10^{-3} °C^{-1}
β_{fluid}	1×10^{-9} Pa^{-1}
w (reference)	0.035 m