Modélisation numérique de la propagation des fractures sous sollicitations hydromécaniques

Ahmad Pouya
Van Linh Nguyen, Siavash Ghabezloo

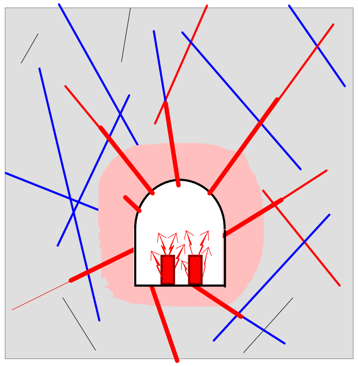
Laboratoire Navier/CERMES (IFSTTAR-ENPC-CNRS)
Project ANR FISIC

CFMR, le 16 octobre 2014

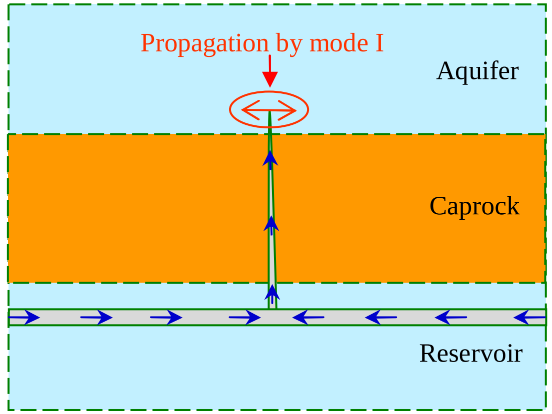
Hydromécanique des milieux poreux fracturés

Propagation des fractures sous sollicitations hydromécaniques:

Réservoirs non conventionnels, géothermie, stockage de déchets radioactifs et du CO2 …

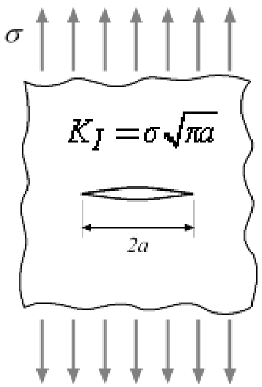


Stockage dans les massifs granitiques

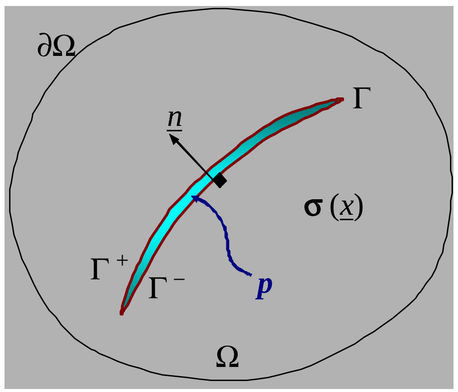


Stockage du CO_2

Mécanique de la rupture
+ Effets hydrauliques



Facteurs d'intensité des contraintes



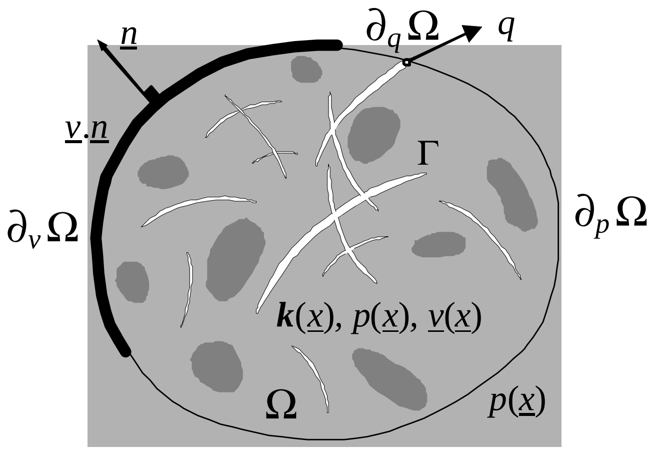
Effets de pression de fluide dans les fractures

Complexités:

Ecoulement transitoire dans un milieu poreux fracturé non saturé,
Echanges de masse matrice/fractures,
Couplage avec la mécanique,
Propagation des fractures (mécanique de la rupture),
Difficultés numériques…

Problème de diffusion hydraulique

- Milieu poreux hétérogène fracturé
- Fractures multiples avec intersections internes et avec la frontière
- Echanges de mass de fluide fracture/matrice et fracture/fracture

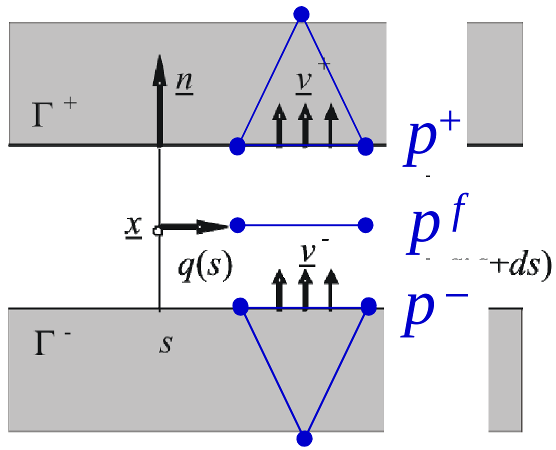


Le point clé: maîtriser les échanges de fluide entre la matrice et la fracture:

Matrice: $div\,\underline{v} = 0$

Fractures: $\nabla_s.\left[\rho \underline{q}\right] + \rho [\![\underline{v}]\!].\underline{n} = 0$

Barenblatt 1960,…

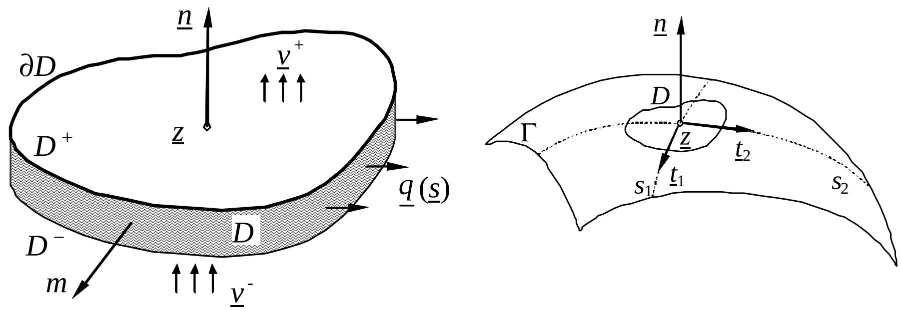


Pouya et Ghabezloo 2010

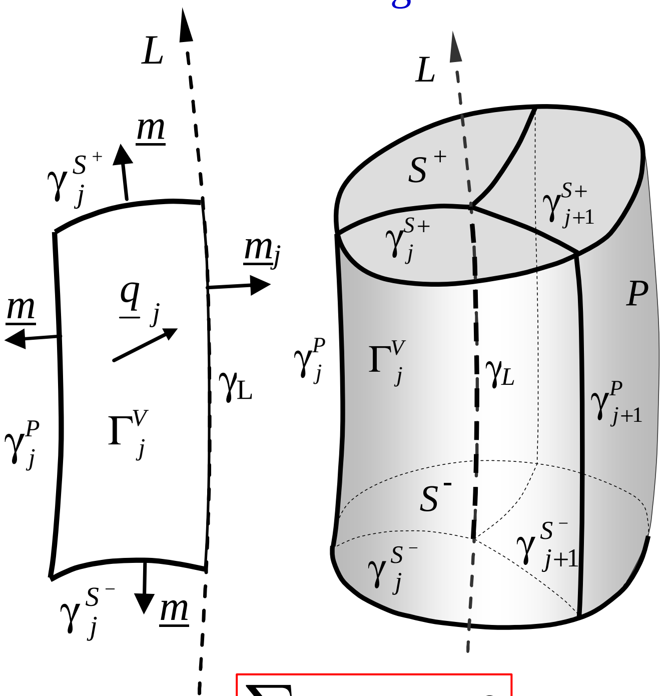
Wu Y.S et al., AWR, 2004: (Tough2)
«modeling fracture–matrix interaction, which is a key issue… serious flaw …*unphysical solutions or significant numerical errors* ».

Lois d'échanges et de conservation de mass

$$\boxed{\frac{\partial(\rho e)}{\partial t} + \rho [\![\underline{v}]\!] . \underline{n} + \nabla_s . \left[\rho \underline{q}\right] = 0}$$



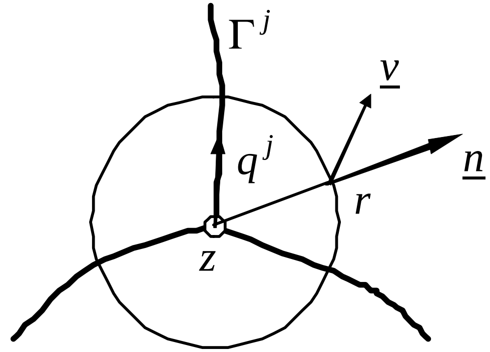
Echanges matrice/fracture en un point courant de surface de fracture



$$\boxed{\sum_j \underline{q}_j \cdot \underline{m}_j = 0}$$

Ligne d'intersection de fractures (3D)

Pouya (AWR, 2012)



$$\boxed{\sum_j q_j = 0}$$

Point d'intersection de fractures (2D)

Les lois de conservation sur les lignes et points d'intersection de fractures sont les mêmes que pour un réseau de fractures dans une matrice imperméable!

Formulation Faible, Eléments Finis

Equations locales:

Matrice: $$C_m \frac{\partial p_f}{\partial t} = div\left[k\nabla p_f\right] - b\frac{\partial \varepsilon_V}{\partial t}$$

Fractures: $$C_f \frac{\partial p_f}{\partial t} = div\left[c\nabla p_f\right] - \left\|[\underline{v}]\right\| \cdot \underline{n} - \frac{\partial e}{\partial t}$$

$$[M]\left[\frac{\partial p}{\partial t}\right] = -[K][p]-[V]$$

$$M_{ij} = \sum_n C^n \int_{\Omega_n} N_i^n(\underline{x}) N_j^n(\underline{x})\, d\omega + \sum_J C_J^f \int_{H_J} h_i^J(\underline{s}) h_j^J(\underline{s})\, ds$$

$$K_{ij} = \sum_n \int_{\Omega_n} \boldsymbol{B}_i^n(\underline{x}).\boldsymbol{K}^n.\boldsymbol{B}_j^n(\underline{x})\, d\omega + \sum_J \int_{H_J} \boldsymbol{b}_i^J(\underline{s}).\boldsymbol{c}^J.\boldsymbol{b}_j^J(\underline{s})\, ds$$

$$V_i = \sum_n r^n \int_{\Omega_n} N_i^n(\underline{x})\, d\omega + \sum_J r_J^f \int_{\Gamma_J} h_i^J(\underline{s})\, ds + \sum_K \int_{H_K} h_i^K(\underline{s}) V_K^g\, ds + \sum_m \int_{H_K} \lambda_i^m(l) Q_m^g\, dl$$

$$-b\frac{\partial \varepsilon_V}{\partial t} \qquad -\frac{\partial e}{\partial t}$$

Termes sources

Matrice

Fractures

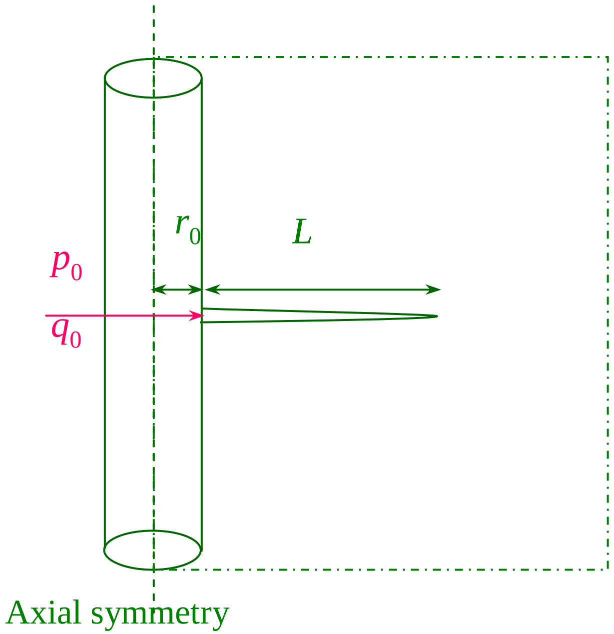
Conditions aux limites de flux

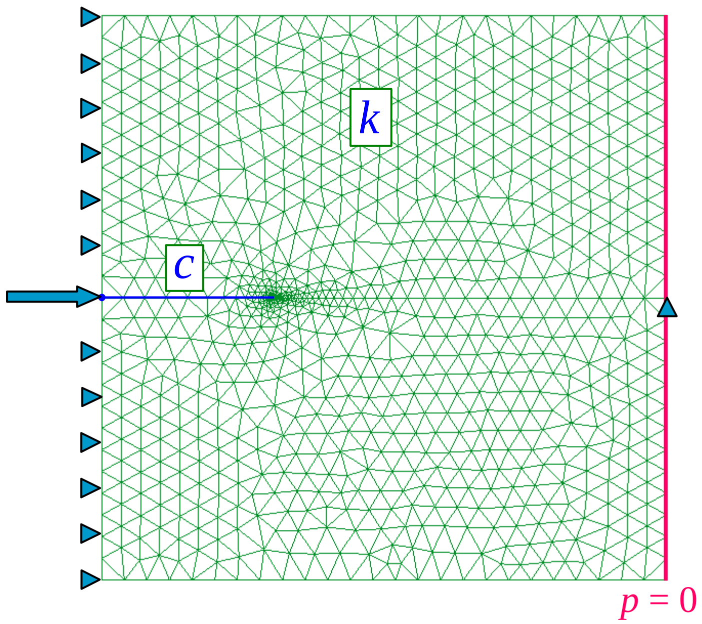
⇩

Code *Porofis* : milieux Poreux Fissurés

Pouya (IJNAMG, 2014)

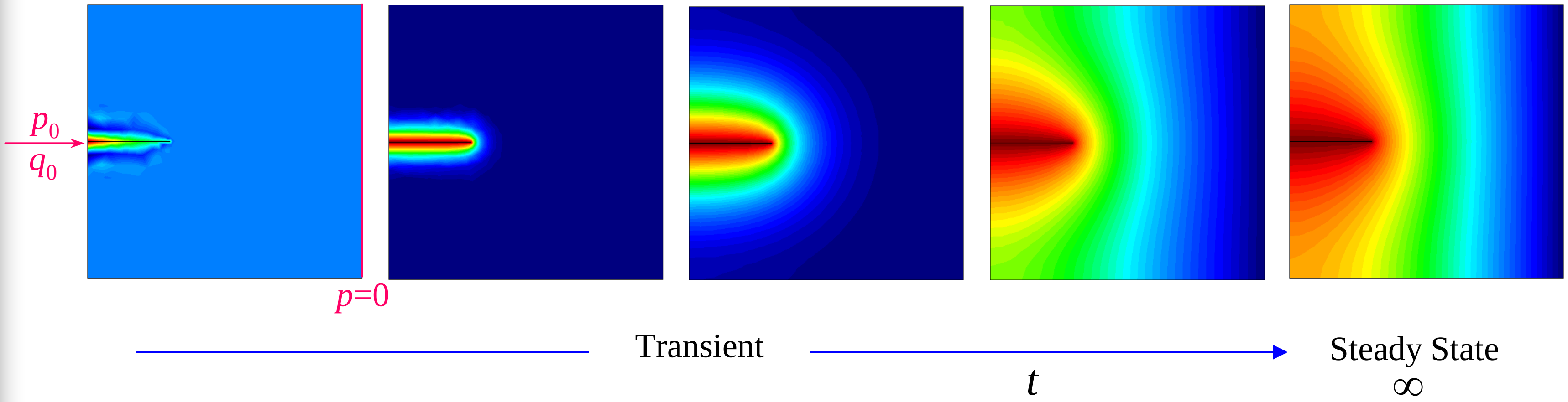
Fluid injection in a fracture

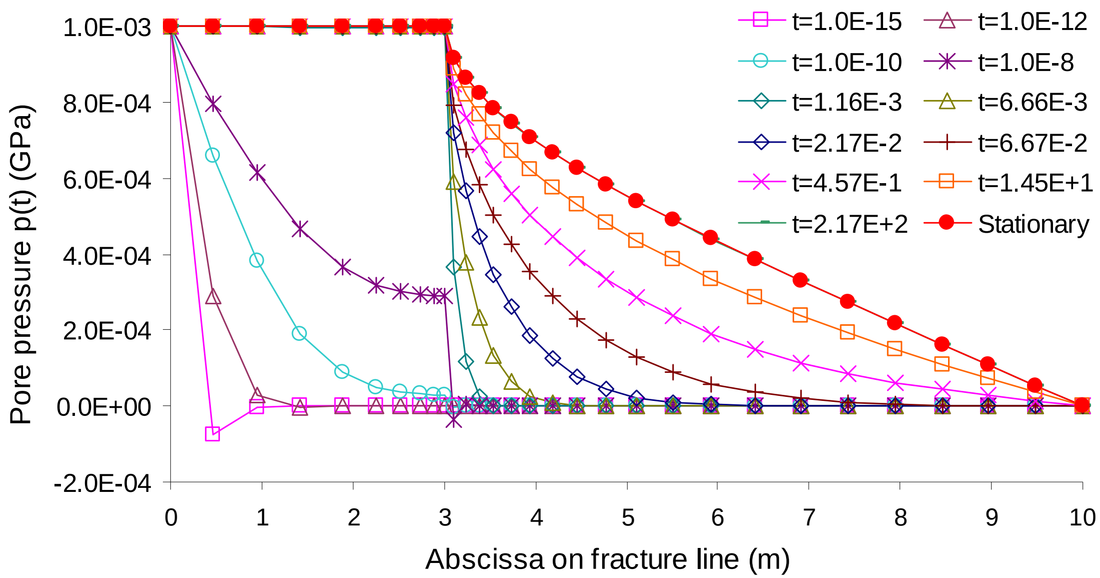




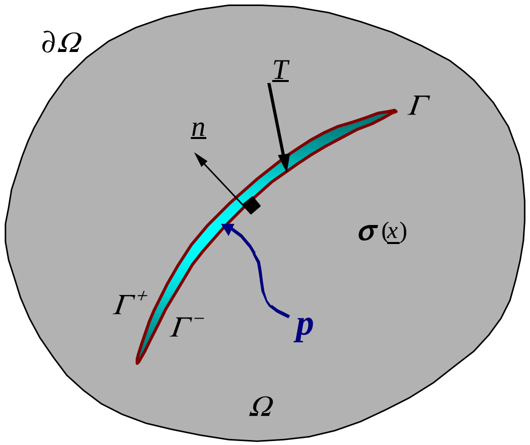
Fluid injection in a fracture

- Transient fluid flow for constant pressure or flow rate injection





Couplage avec la Mécanique de la Rupture



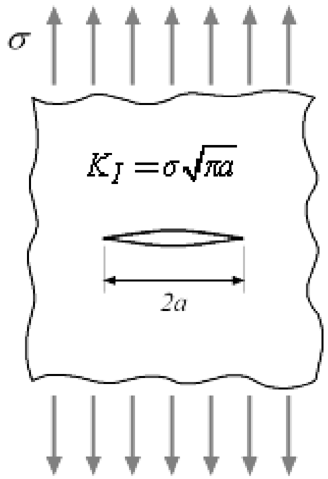
Modèle poromécanique avec la contrainte effective de Biot.

$$\sigma' = C : \varepsilon, \qquad \sigma' = \sigma + b\, p\mathbf{I}$$

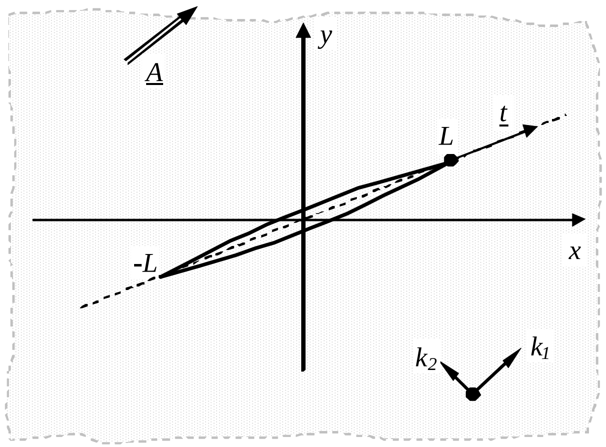
Critère de propagation:
Facteur d'intensité de contraintes effectives ?

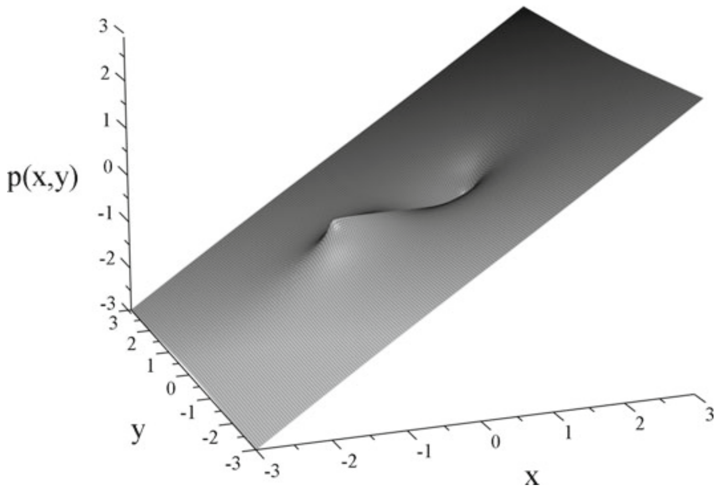
$$K_I = \sigma' \sqrt{\pi a}$$

$$\sigma' = \sigma + bp$$



Singularité des vitesses de fluide aux extrémités des fractures

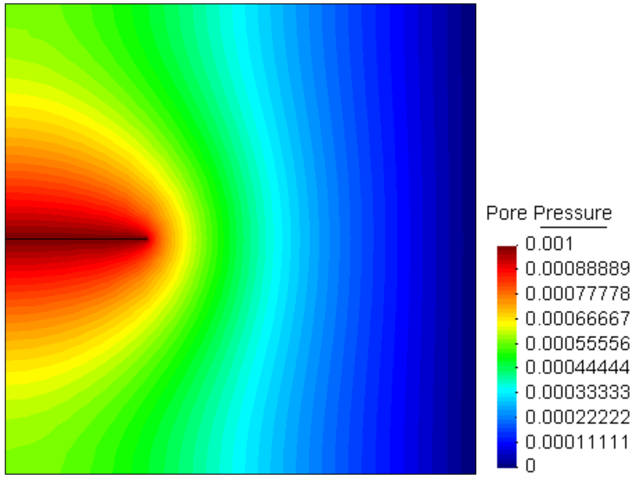




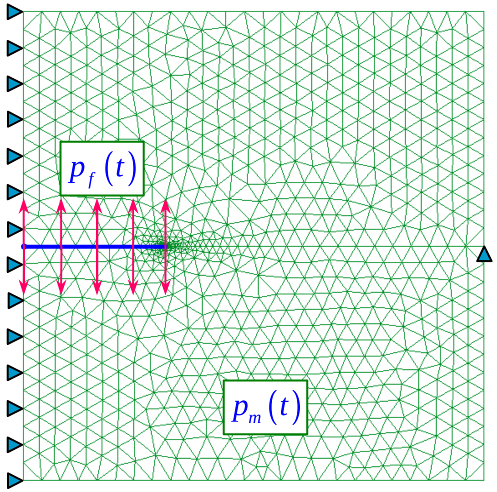
Champ de pression autour d'une fissure dans une matrice soumise à un gradient de pression lointain (Pouya et Ghabezloo 2010)

Determination of Stress Intensity Factor

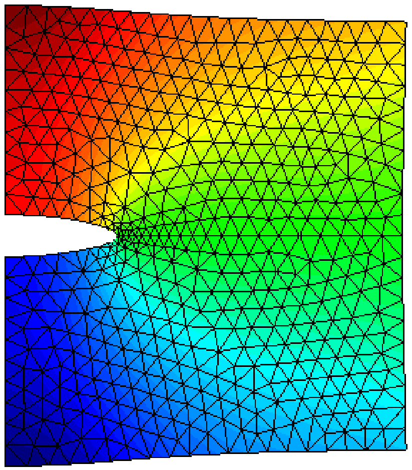
→ Extrapolation of displacement field at fracture tip



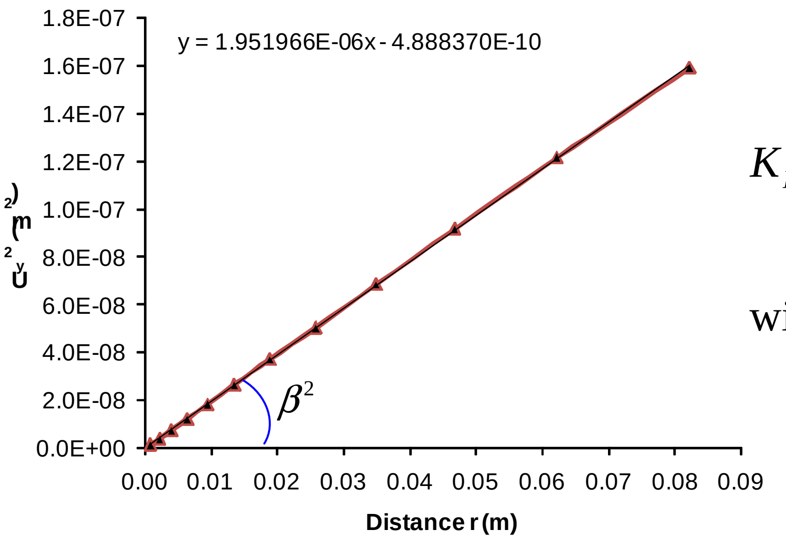
Transient pore pressure field



Mechanical problem



Displacement field

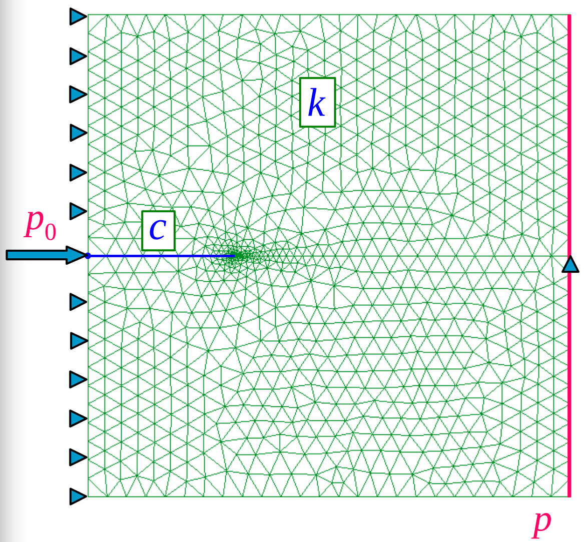


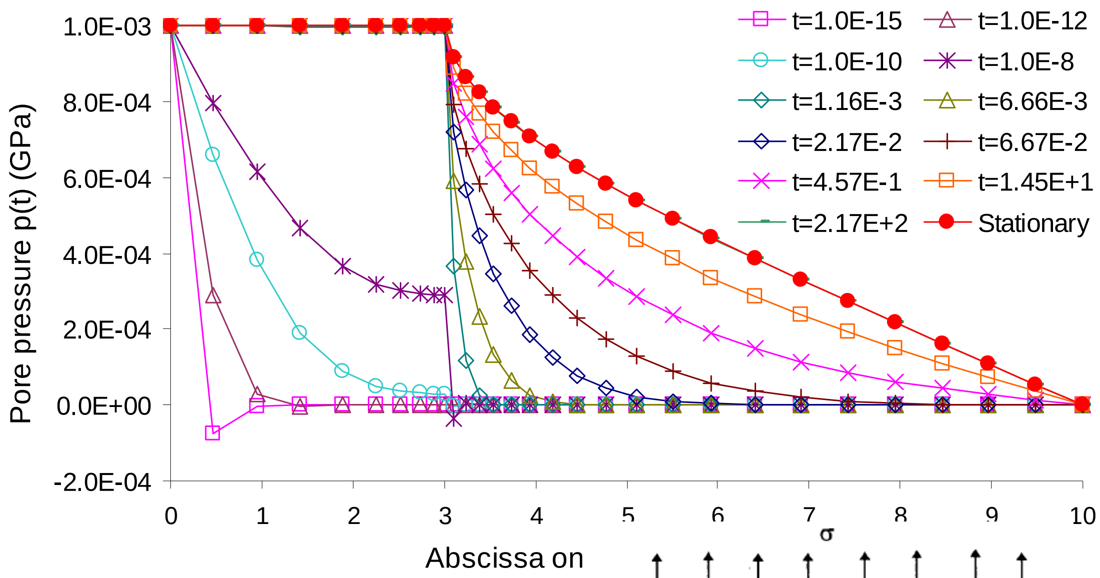
Plane strain or axial symmetry

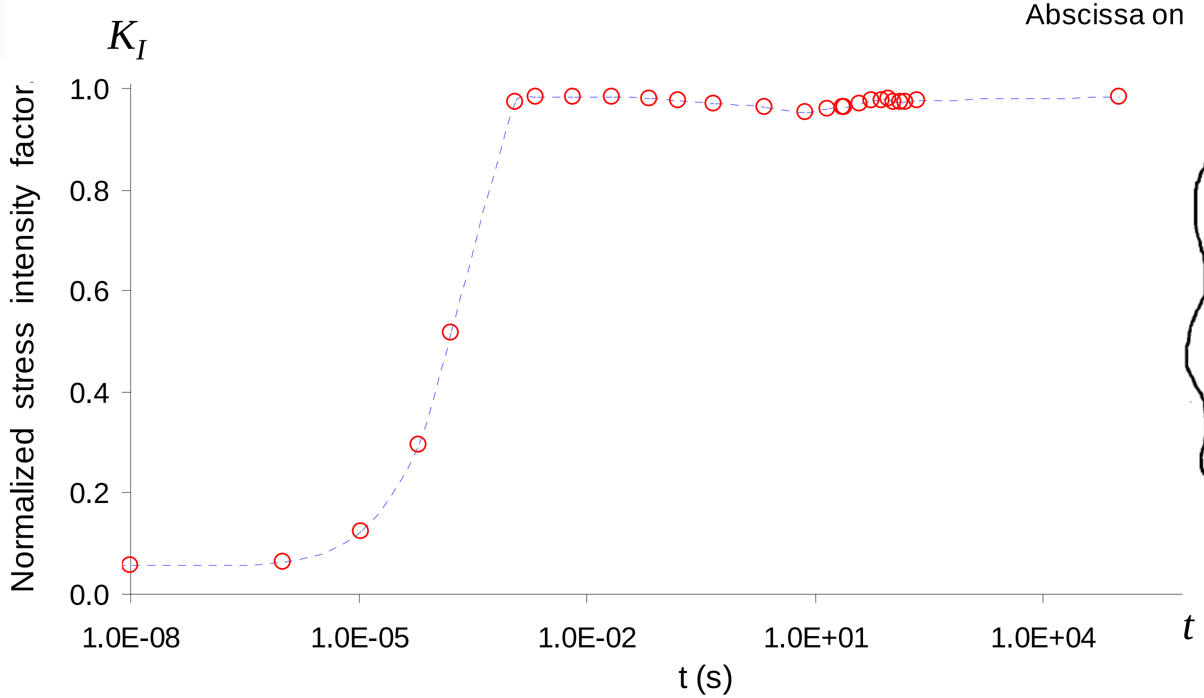
$$K_I = \frac{E\sqrt{2\pi}}{8(1-\nu^2)}\beta$$

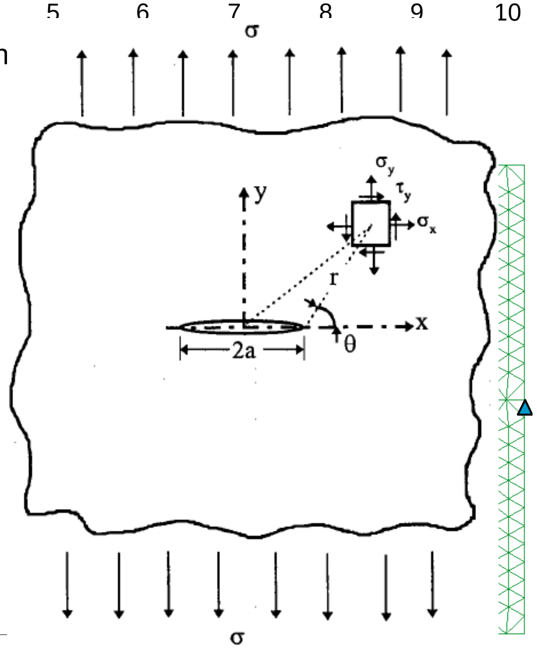
with $\beta = \lim_{r\to 0} \frac{[\![u_y(r)]\!]}{\sqrt{r}}$

Fluid injection at constant pressure



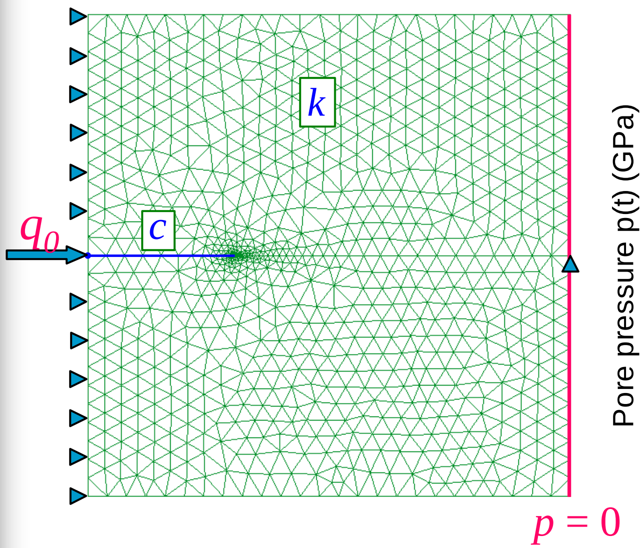


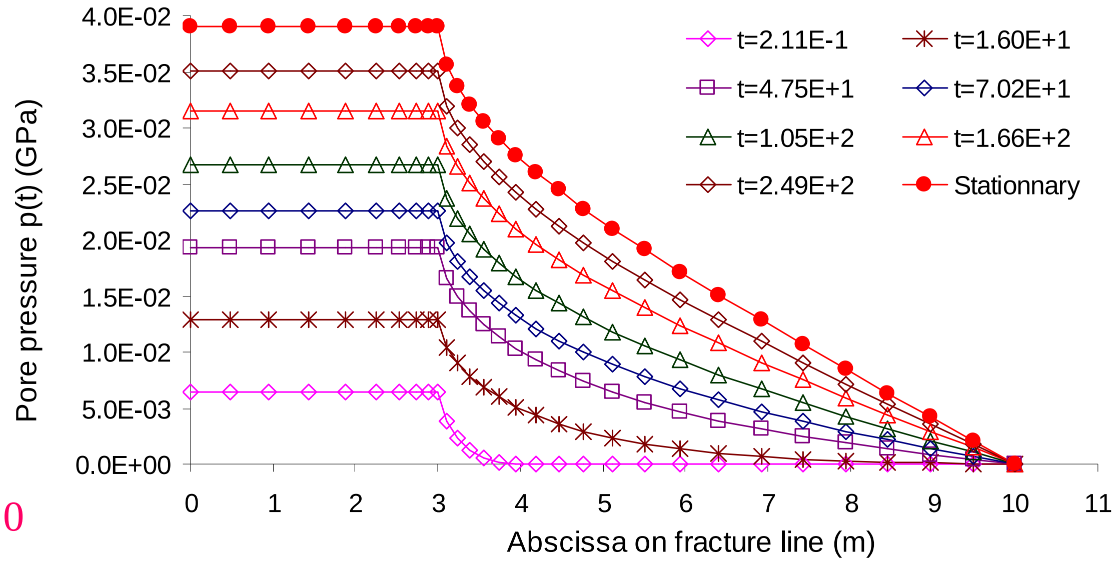


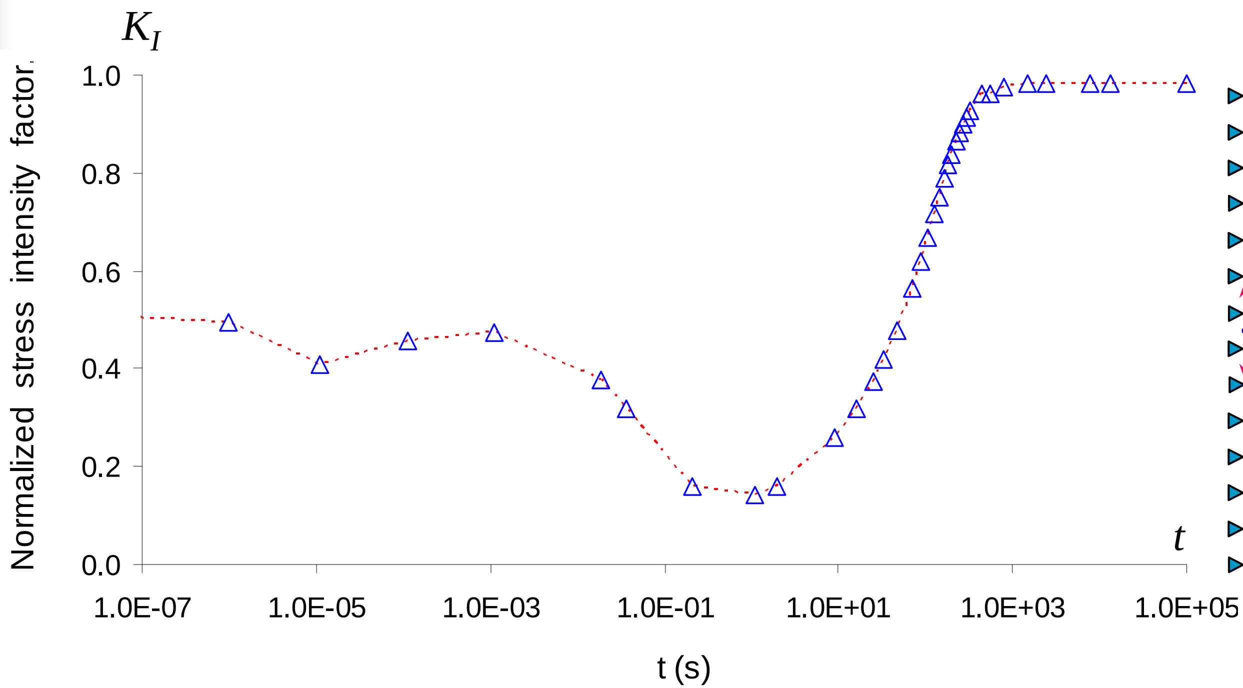


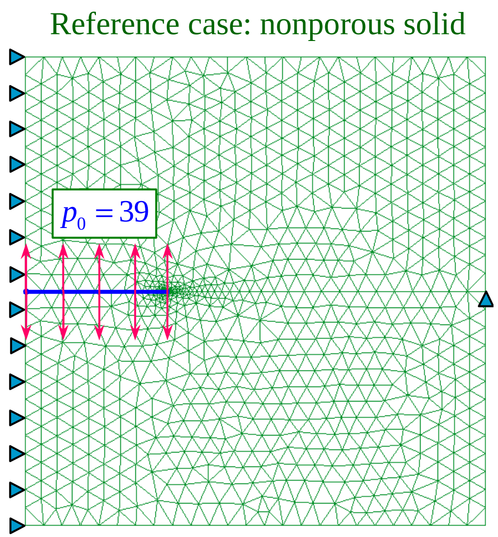
$$K_I = \alpha p_0 \sqrt{\pi L}$$

Fluid injection at constant flow rate



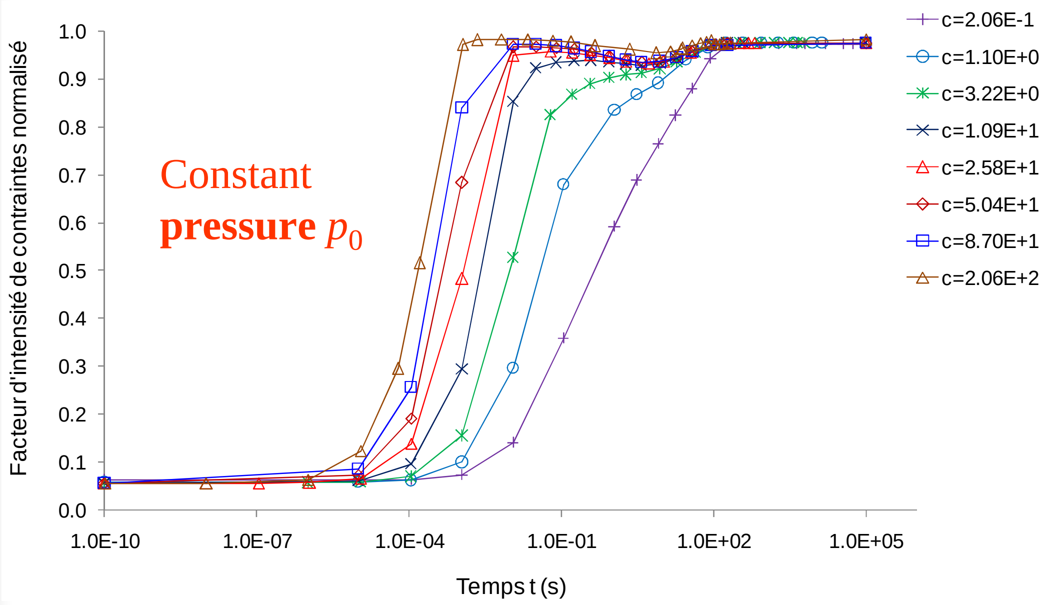


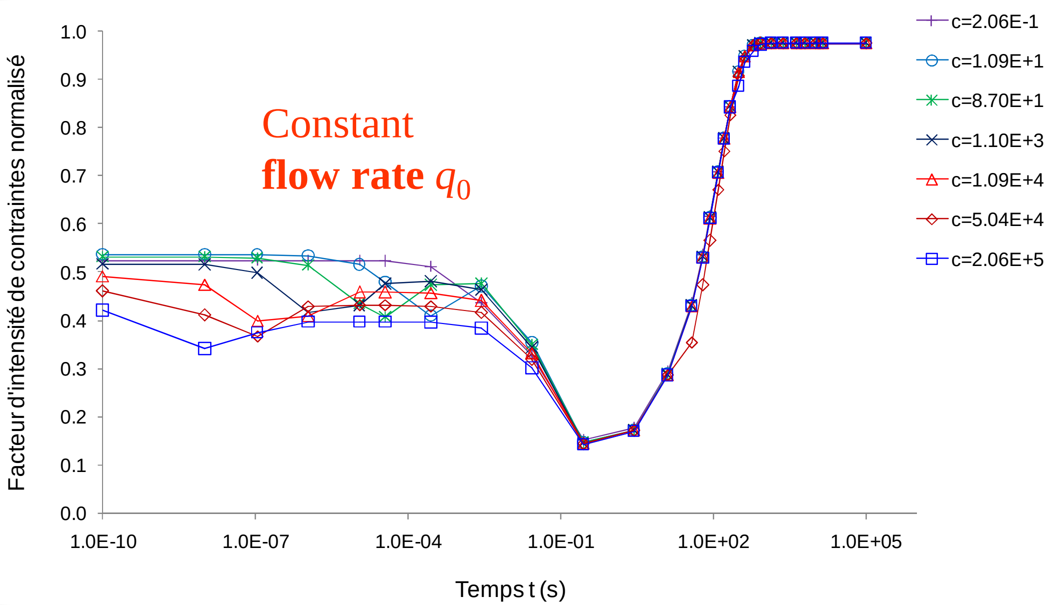




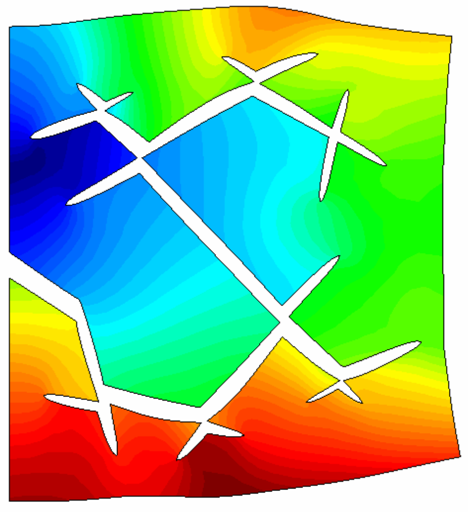
$$K_I = \alpha p_0 \sqrt{\pi L}$$

Steady state K_I as the maximum value





The steady state K_I as a maximum value is a valuable information to discuss the fracture propagation conditions.



Constant fracture geometry →
Limit of steady state flow

⇓

Lower bounds of fracture propagation

Problem simplification for steady state flow

Under steady state flow some couplings between mechanical and hydraulic phenomena disappear : time derivative terms vanish.

Matrix: $$\cancel{C_m \frac{\partial p_f}{\partial t}} = div\left[k \nabla p_f\right] - b\cancel{\frac{\partial \varepsilon_V}{\partial t}} \quad \text{avec} \quad C_m = \left(\frac{\phi}{K_f} + \frac{b-\phi_0}{K_S}\right)$$

Fractures: $$\cancel{\frac{e}{K_f}\frac{\partial p_f}{\partial t}} = div\left[c \nabla p_f\right] - \left[\!\left[\underline{v}\right]\!\right] \cdot \underline{n} - \cancel{\frac{\partial e}{\partial t}}$$

This simplifies a lot theoretical and numerical modeling and allows to establish semi-numerical solutions.

Mechanical problem decomposition (plan strain)

Decomposition of the mechanical problem in two basic problems

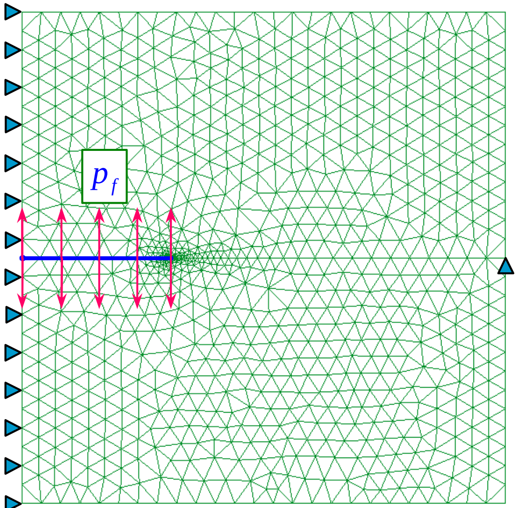
Fracture pressure

$$\begin{cases} \forall \underline{x} \in \Omega; & C_{ijkl}\partial_{jk} u_l^{(1)}(\underline{x}) = 0 \\ \forall \underline{x} \in \partial_f \Omega; & n_j C_{ijkl}\partial_k u_l^{(1)}(\underline{x}) = -p(\underline{x})\, n_i \\ \forall \underline{x} \in \partial_u \Omega; & u_x^{(1)}(\underline{x}) = 0, \quad \lim_{\|\underline{x}\|\to\infty} \underline{u}^{(1)}(\underline{x}) = 0 \end{cases}$$

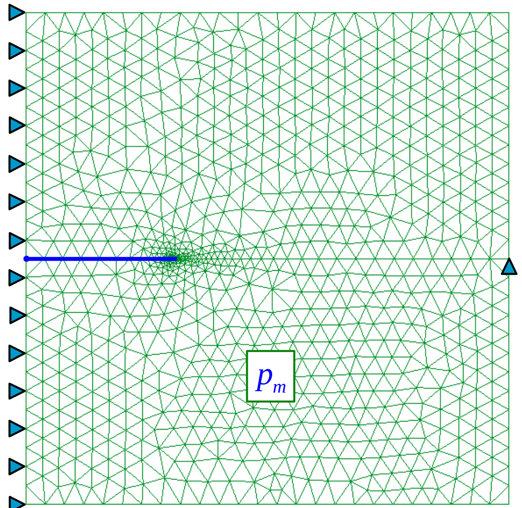
Matrix poroelasticity

$$\begin{cases} \forall \underline{x} \in \Omega; & C_{ijkl}\partial_{jk} u_l^{(2)}(\underline{x}) = b\partial_i p(\underline{x}) \\ \forall \underline{x} \in \partial_f \Omega; & n_j C_{ijkl}\partial_k u_l^{(2)}(\underline{x}) = 0 \\ \forall \underline{x} \in \partial_u \Omega; & u_x^{(2)}(\underline{x}) = 0, \quad \lim_{\|\underline{x}\|\to\infty} \underline{u}^{(2)}(\underline{x}) = 0 \end{cases}$$

Effect of the fluid pressure in the fracture



Effect of the pore pressure in the matrix and poroelastic deformation



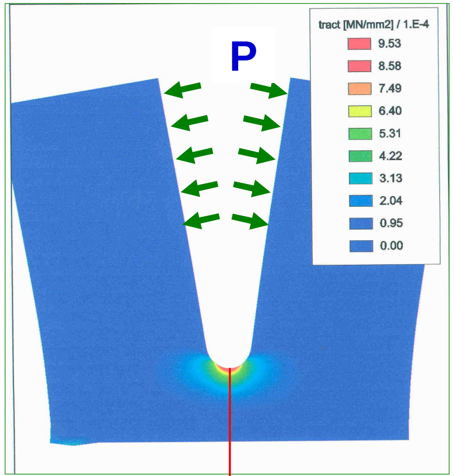
$\Psi_1(\nu,\eta)$ $\quad$ $\Psi_2(\nu,\eta)$

$K_I^{(1)}$ $\rightarrow$ $K_I = K_I^{(1)} + K_I^{(2)}$ $\leftarrow$ $K_I^{(2)}$

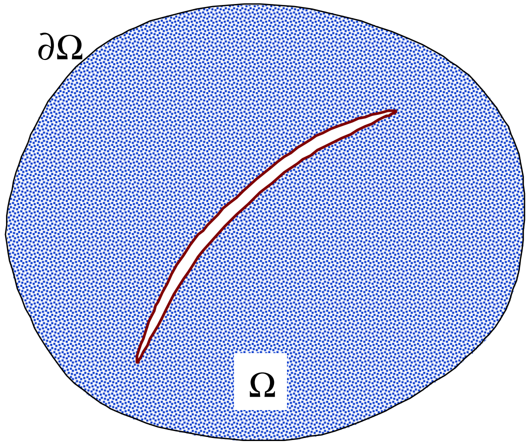
- Dimensionless analysis of SIF $\boxed{K_I = p_0\sqrt{L}\left[\Psi_1(\nu,\eta) + b\Psi_2(\nu,\eta)\right] \quad \text{with } \eta = c/kL}$

Double rôle du fluide

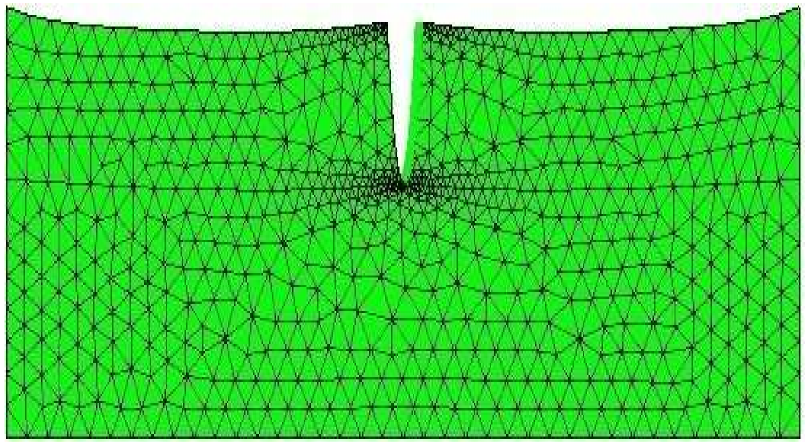
Force agissant sur les parois de la fracture



Pression de pore induisant des déformations « poroélastiques »



Phénomène inverse: fissuration de retrait des sols



Mechanical problem decomposition (plan strain)

Decomposition of the mechanical problem in two basic problems

Fracture pressure

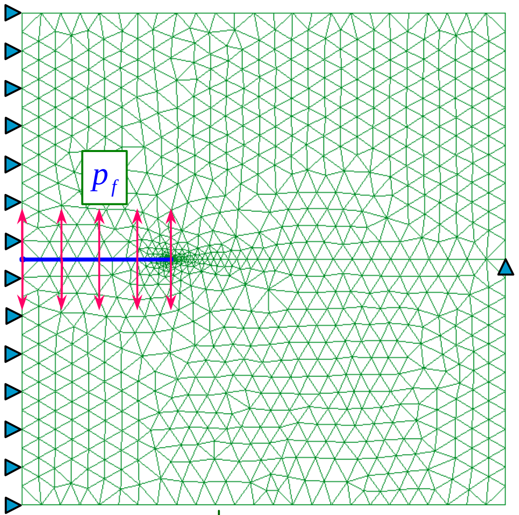
$$\begin{cases} \forall \underline{x} \in \Omega; & C_{ijkl}\partial_{jk} u_l^{(1)}(\underline{x}) = 0 \\ \forall \underline{x} \in \partial_f \Omega; & n_j C_{ijkl}\partial_k u_l^{(1)}(\underline{x}) = -p(\underline{x})\, n_i \\ \forall \underline{x} \in \partial_u \Omega; & u_x^{(1)}(\underline{x}) = 0, \quad \lim_{\|\underline{x}\| \to \infty} \underline{u}^{(1)}(\underline{x}) = 0 \end{cases}$$

Effect of the fluid pressure in the fracture

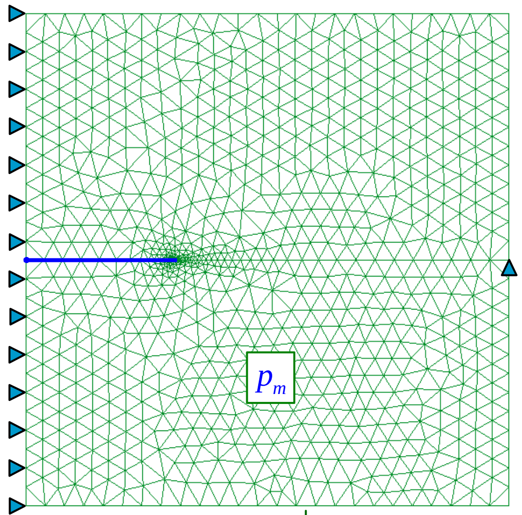
Matrix poroelasticity

$$\begin{cases} \forall \underline{x} \in \Omega; & C_{ijkl}\partial_{jk} u_l^{(2)}(\underline{x}) = b\partial_i p(\underline{x}) \\ \forall \underline{x} \in \partial_f \Omega; & n_j C_{ijkl}\partial_k u_l^{(2)}(\underline{x}) = 0 \\ \forall \underline{x} \in \partial_u \Omega; & u_x^{(2)}(\underline{x}) = 0, \quad \lim_{\|\underline{x}\| \to \infty} \underline{u}^{(2)}(\underline{x}) = 0 \end{cases}$$

Effect of the pore pressure in the matrix and poroelastic deformation



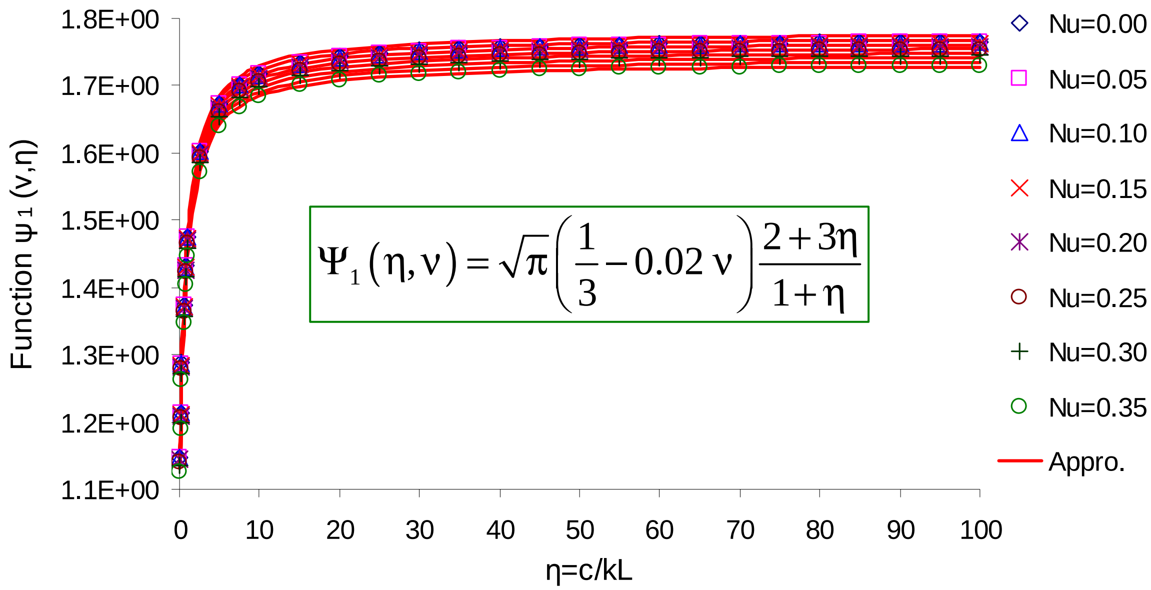
$\rightarrow \Psi_1(\nu,\eta)$ $\quad$ $\Psi_2(\nu,\eta) \leftarrow$

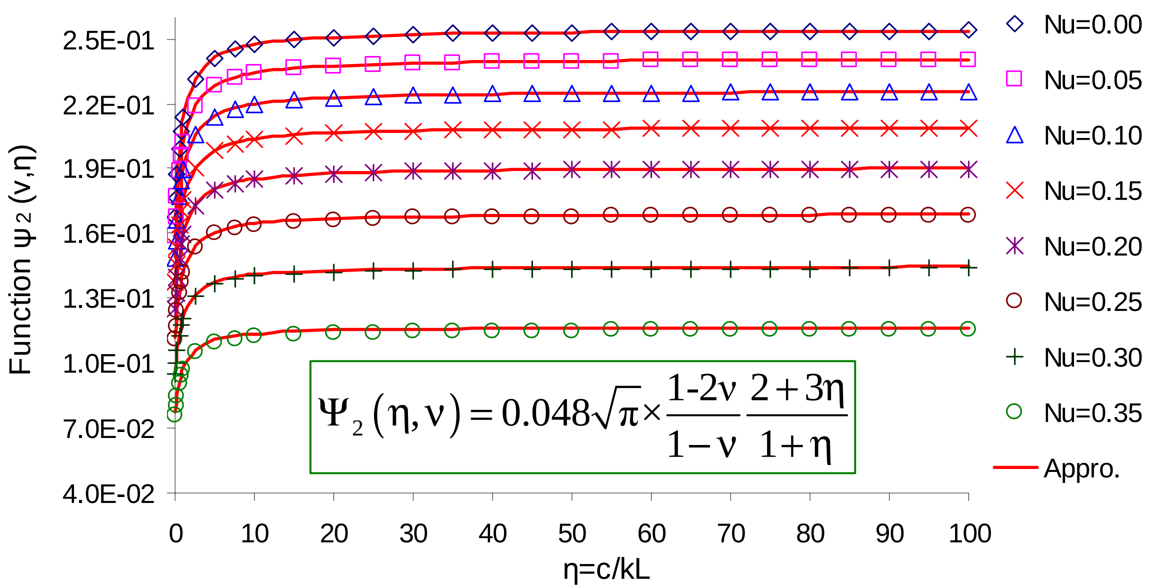


$$\boxed{K_I^{(1)}} \rightarrow \boxed{K_I = K_I^{(1)} + K_I^{(2)}} \leftarrow \boxed{K_I^{(2)}}$$

- Dimensionless analysis of SIF $\boxed{K_I = p_0\sqrt{L}\,[\Psi_1(\nu,\eta) + b\Psi_2(\nu,\eta)] \quad \text{with } \eta = c/kL}$

Ψ_1 and Ψ_2 determination by curve fitting (plane strain)





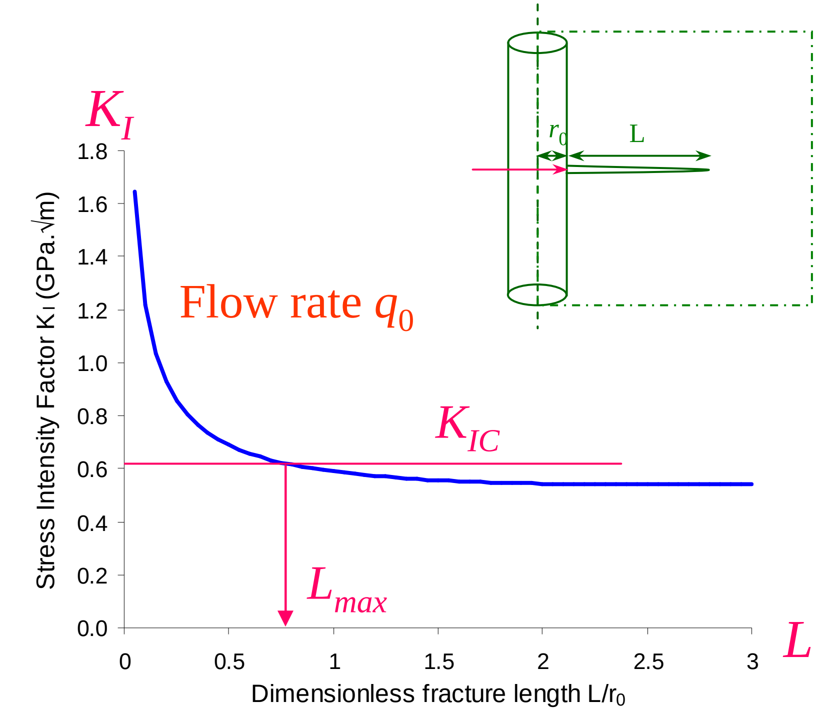
Application

- The general expression of the SIF is then the following (function of q_0)

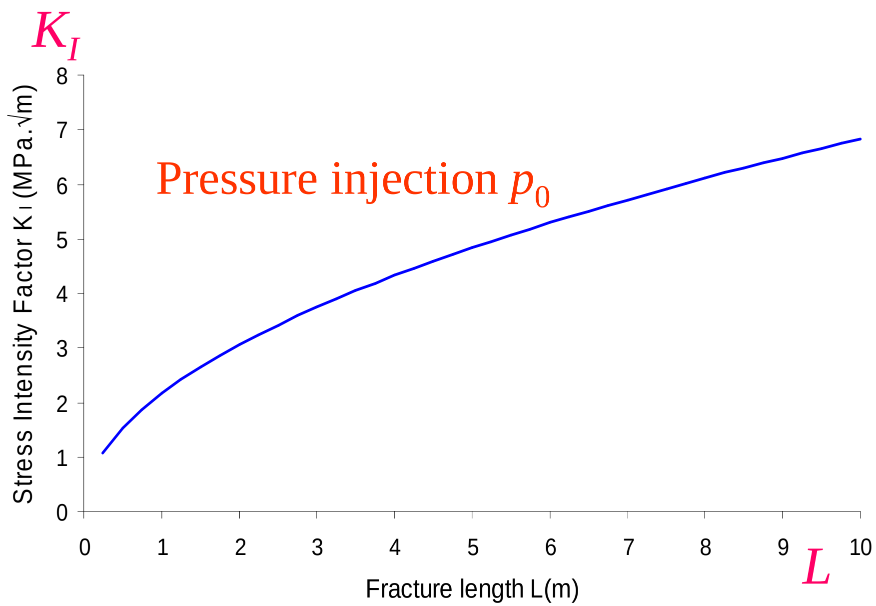
$$K_I = p_0\sqrt{r_0}\,\left[\Psi_1(\nu,\eta,L/r_0)+b\Psi_2(\nu,\eta,L/r_0)\right]$$

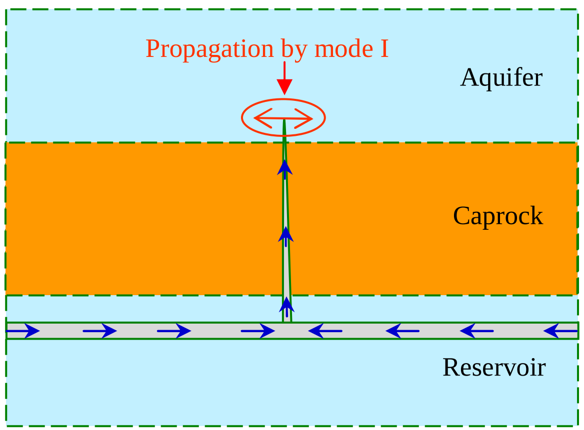
with $p_0 = f\left(q_0\right)$ expressed above

- So it shows that for a given q_0 what is the maximum extension of the fracture



For injection under constant pressure the propagation is instable.



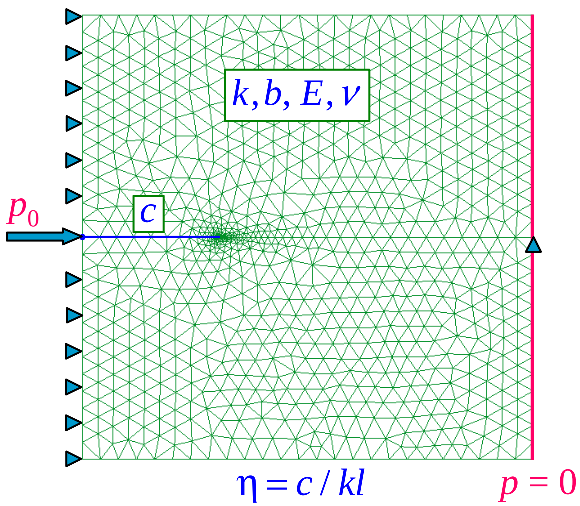


Closed-form expressions for hydromechanical K_I

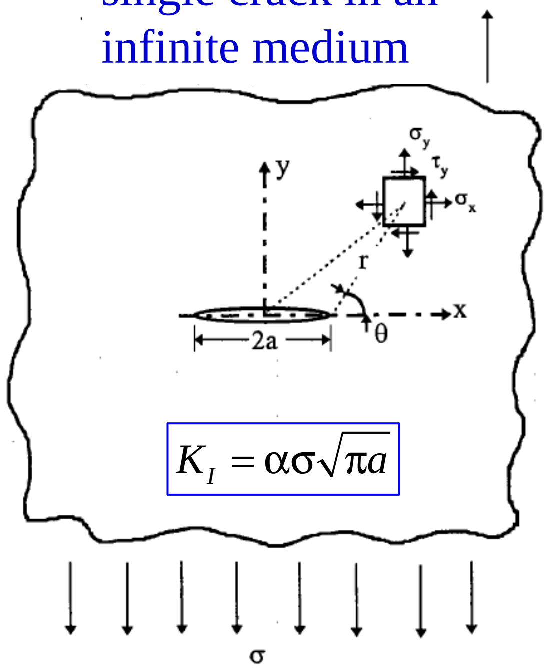
K_I around a crack tip subjected to fluid injection: infinite half-space + linear poroelasticity + steady state flow

$$K_I = p_0\sqrt{L}\,[\Psi_1(\nu,\eta)+b\Psi_2(\nu,\eta)] \qquad \text{Plane Strain}$$

$$K_I = p_0\sqrt{r_0}\,[\Psi_1(\nu,\eta,L/r_0)+b\Psi_2(\nu,\eta,L/r_0)] \qquad \text{Axial Symmetry}$$



single crack in an infinite medium



Linear Fracture Mechanics

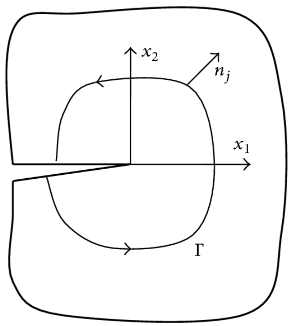
Simple configurations and simplified models

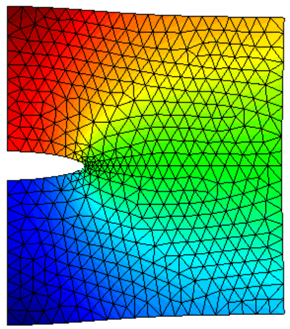
→ **rough estimations / theoretical investigations**

Difficultés de modélisation de la propagation par la mécanique de la rupture

• **Numériques**

- Calcul non local pour déterminer le facteur d'intensité de contraintes :
- Nécessité de remaillage
- Appliquer pression de fluide : problème à frontière variable.

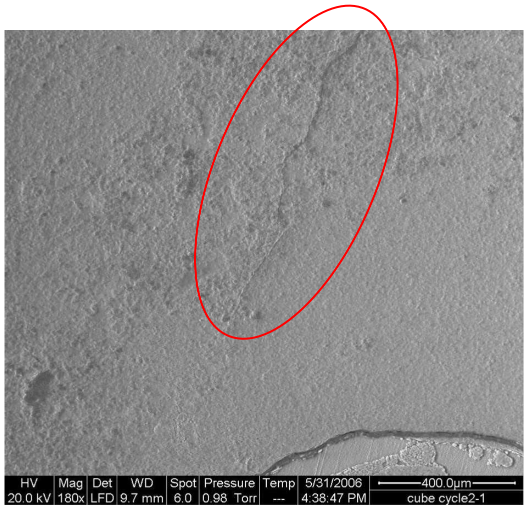


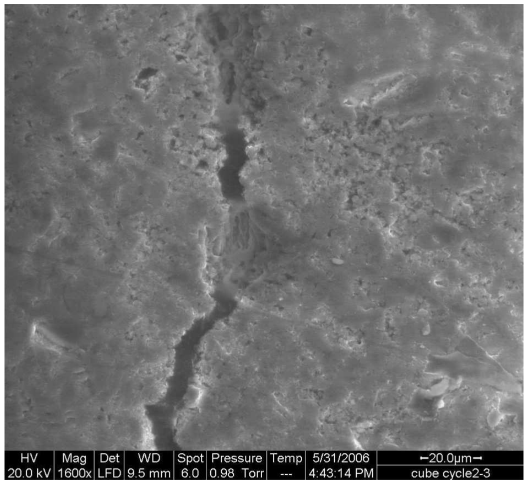


• **Pertinence physique**

- Pertinence pour les matériaux autres qu'élastique-fragile (poreux, plastiques, endommageables…)?

- Pertinence pour des failles ou fractures avec matériaux de remplissage?

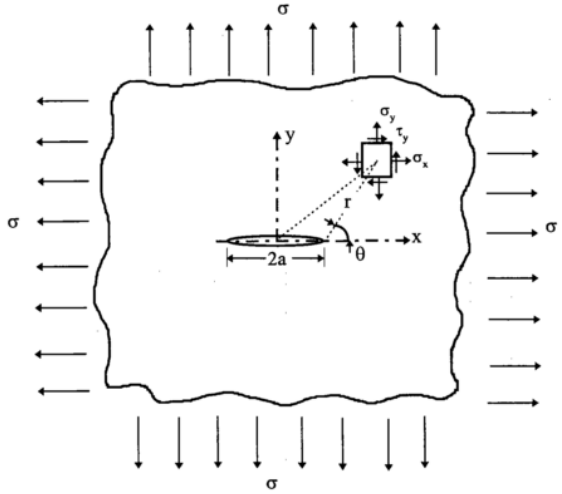




Ponts rocheux sur la ligne de fracture

M. Bost (2008)

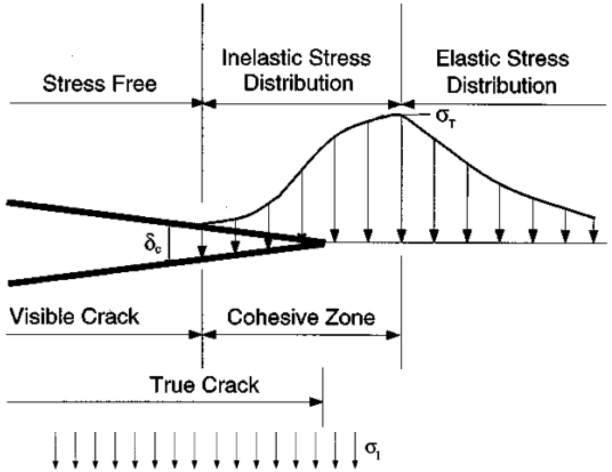
Modèles « Cohesive crack » ou « Cohesive zone »

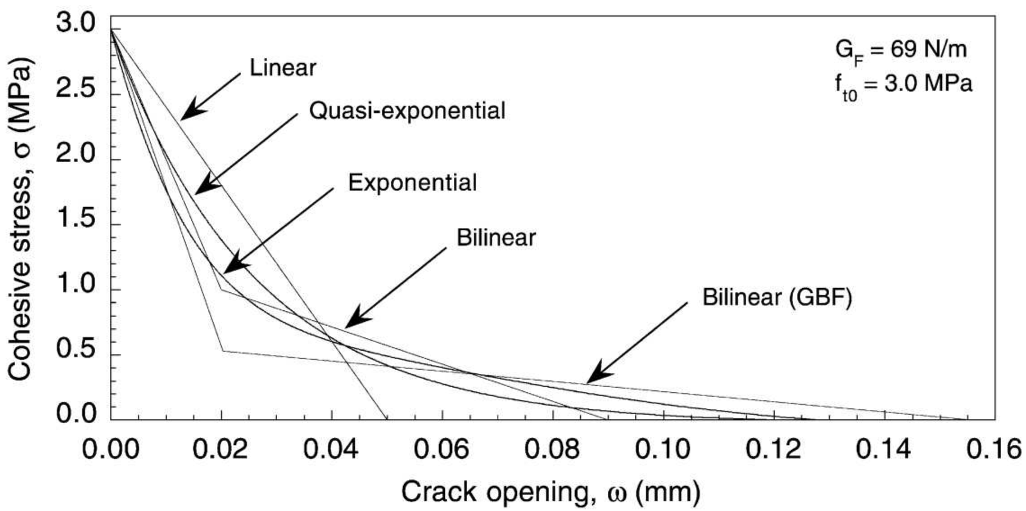


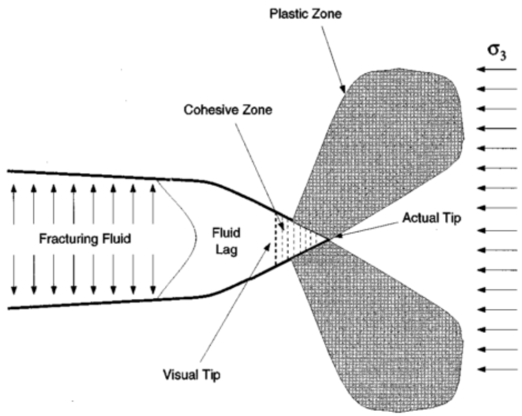
La décohésion progressive dans une zone prolongeant l'extrémité de la fracture *(Barenblatt (1959, 1962), Dugdale (1960)…,*

Application fracturation hydraulique:

Carrier et Granet 2012, Sarris et Papanastasiou, 2013)…





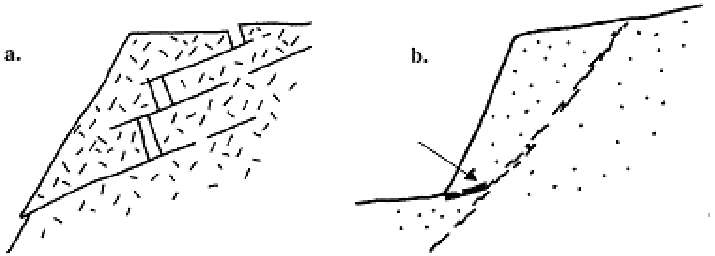


Diminution de la cohésion avec le déplacement d'ouverture de la fissure

Modèle de fracture cohésive

Endommagement des joints rocheux

(Pouya & Bemani 2010)

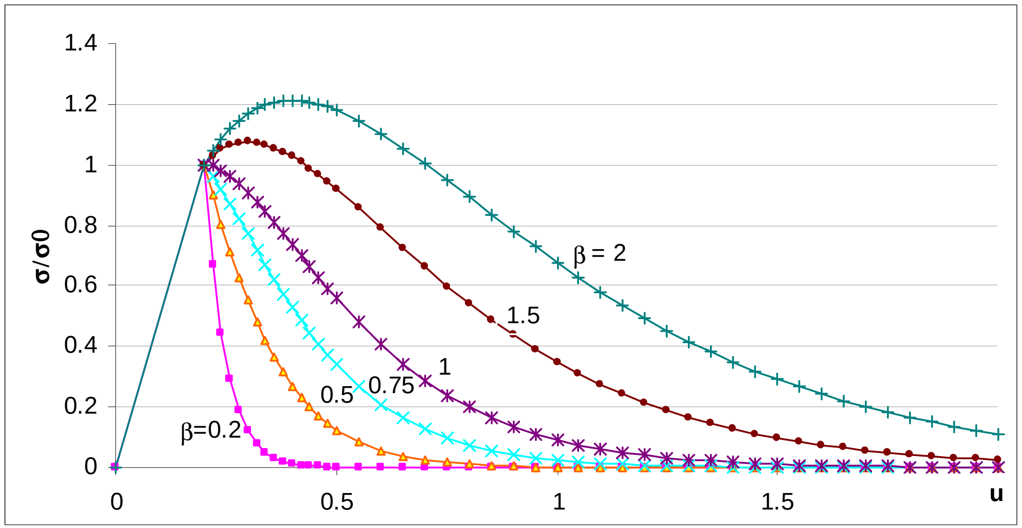


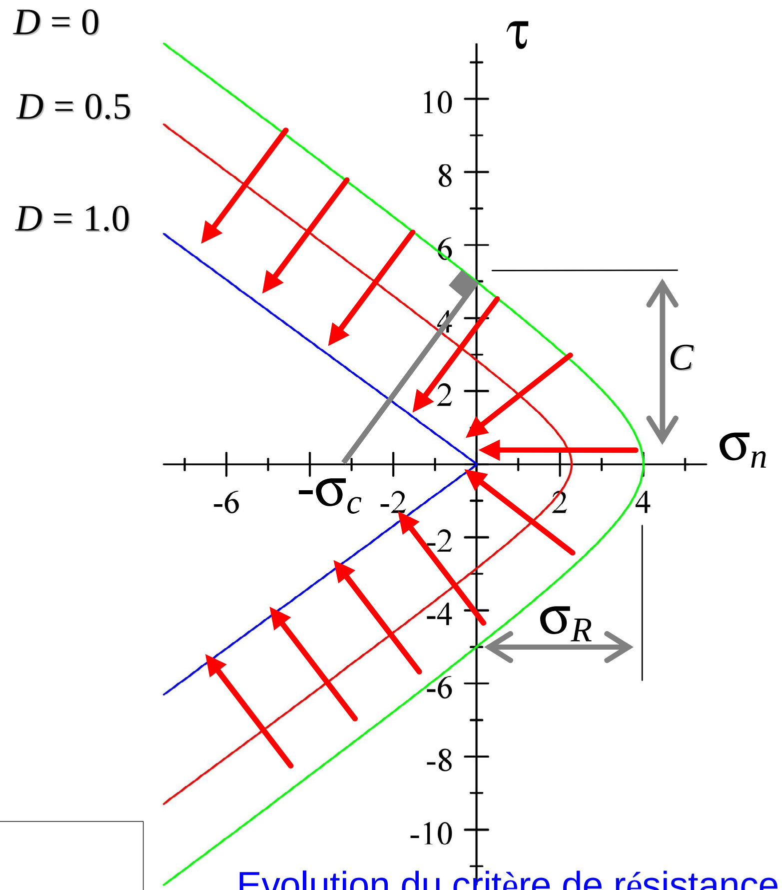
$$\underline{\sigma} = (1-D)\,\boldsymbol{k}\,(\underline{u} - \underline{u}^{p})$$

Critère d'endommagement et de plasticité:

$$F(\underline{\sigma}, D) = \tau^2 - \sigma_n^2 \tan^2\varphi + 2g(D)\sigma_c\sigma_n - g^2(D)C^2$$

$$g(D) = (1-D)\big(1 - \beta\, ln(1-D)\big)$$



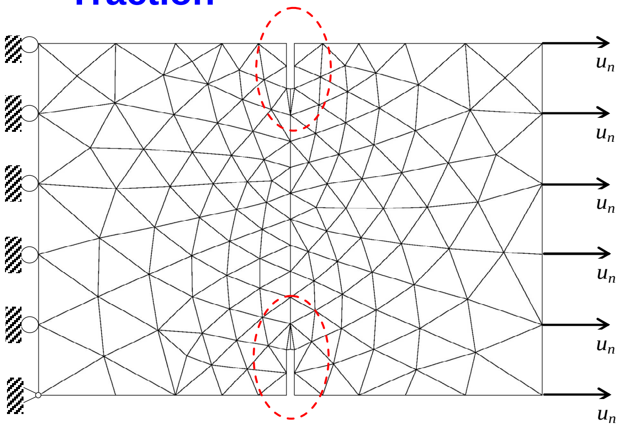


Evolution du critère de résistance avec l'endommagement
(Pouya et Bemani 2014)

Courbes de contrainte normale / ouverture de la fracture cohésive

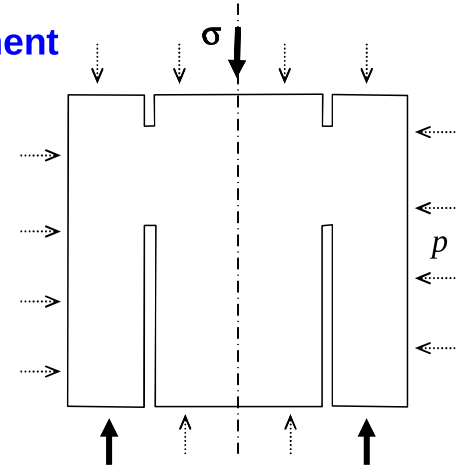
Modèle de fracture cohésive : comparaison modèle/expérience

Traction

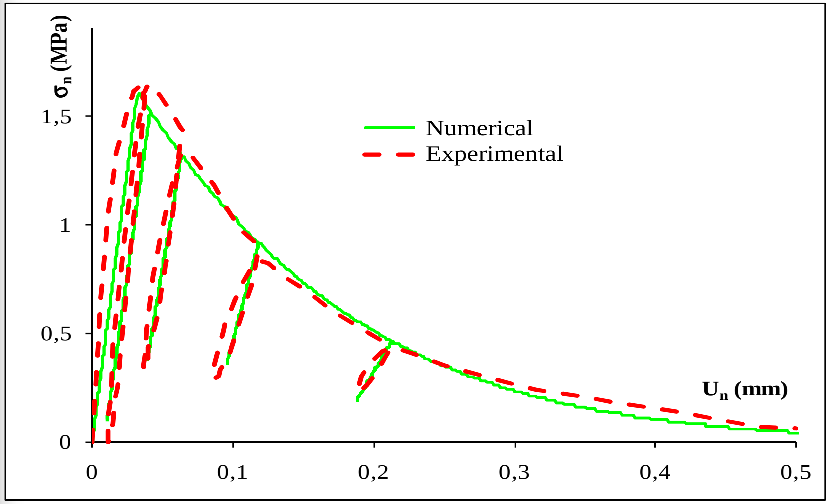


Essais de traction sur une éprouvette avec une entaille (*Slowik et al.* 1996)

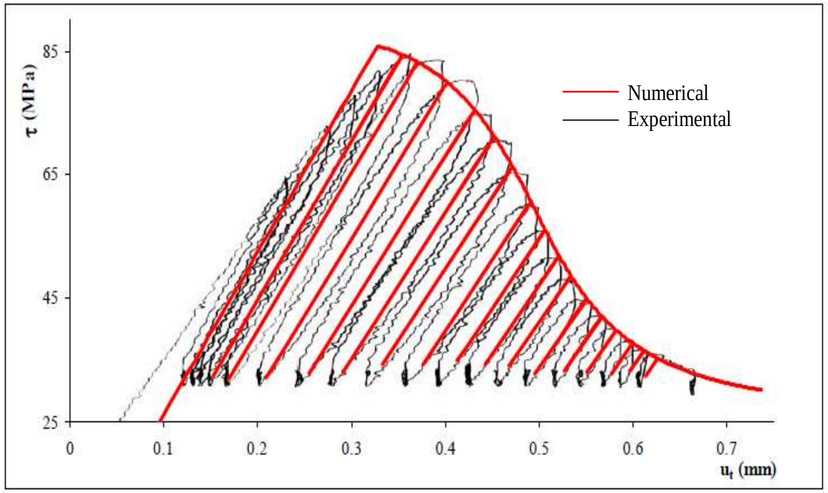
Cisaillement



Essais de cisaillement sur du Marbre sous 40 MPa de contrainte normale (*Backers* 2004)



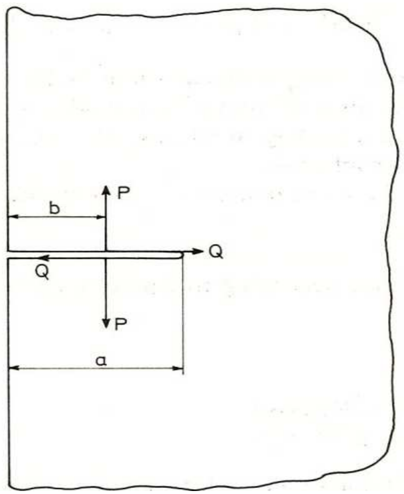
Comparaison modèle/expérience pour des essais de traction



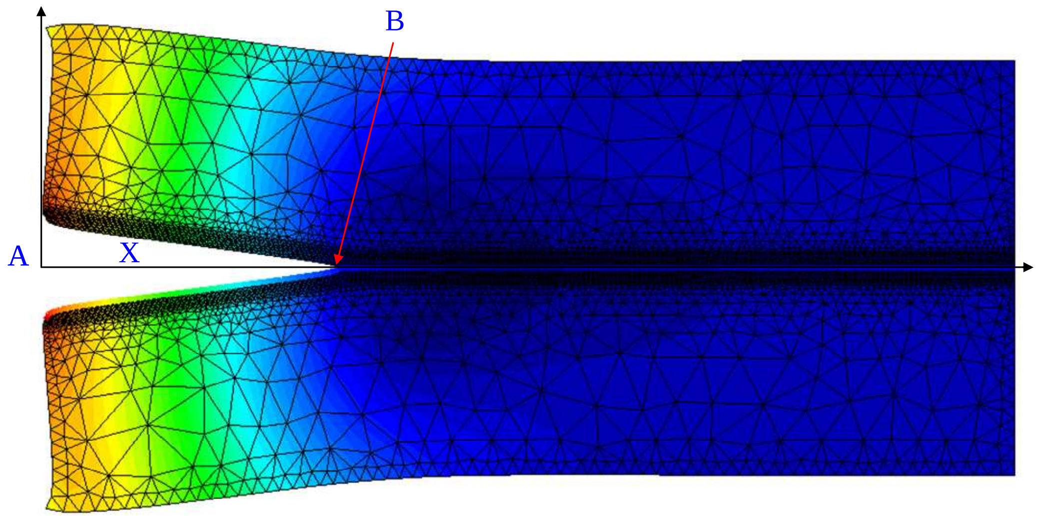
Comparaison modèle/expérience pour des essais de cisaillement

Comparaison des propagations prédites par:
Modèle de fracture cohésive / Mécanique de la rupture

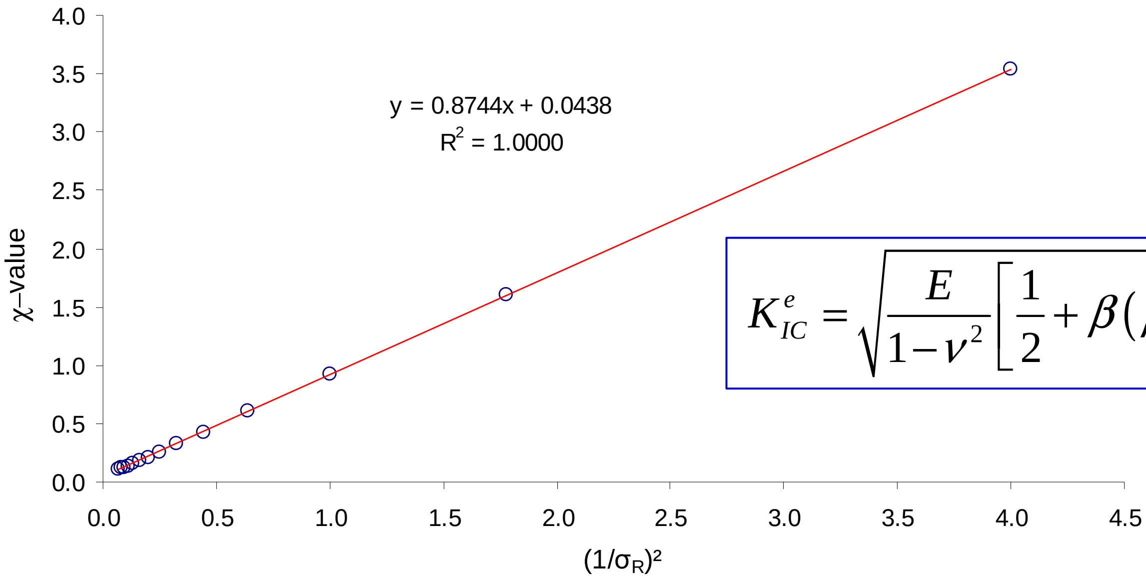
Linh Van Nguyen *et al.* 2014



Mécanique de la Rupture

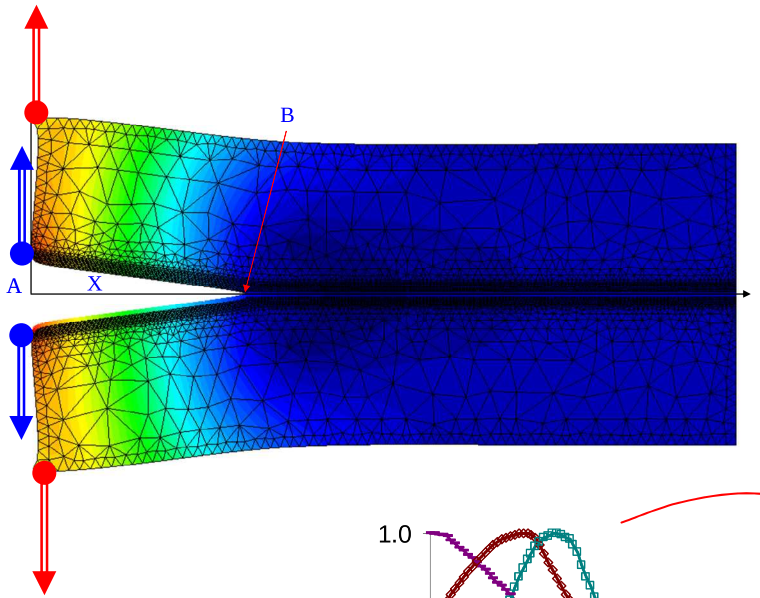


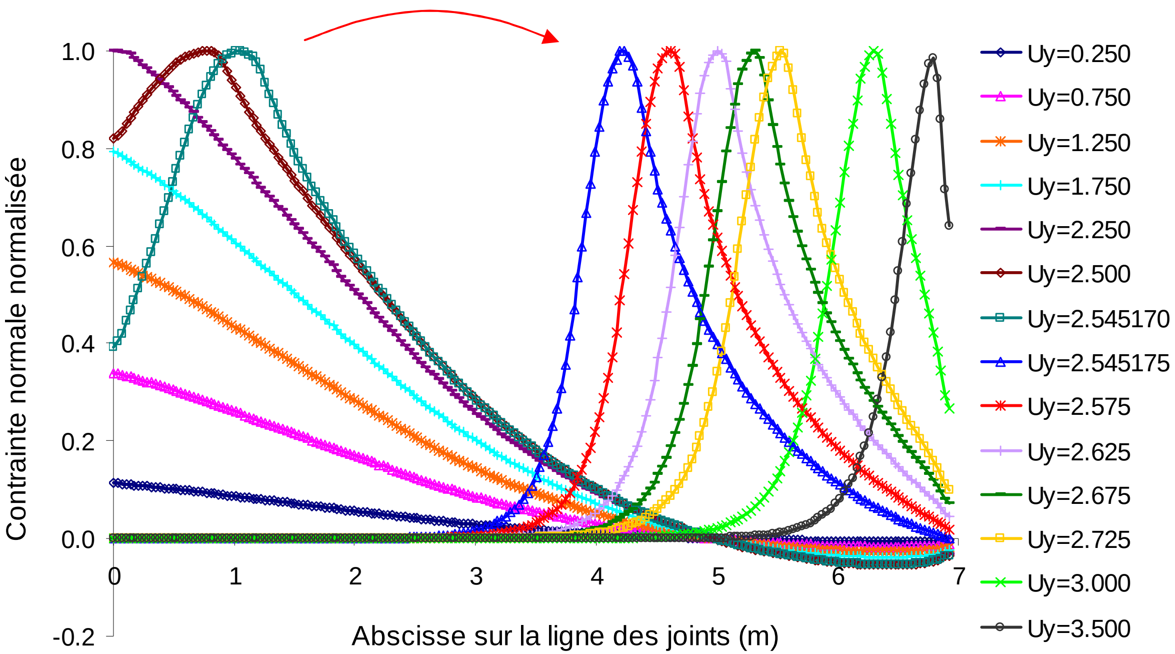
Fractures cohésive



$$K_{IC}^{e}=\sqrt{\frac{E}{1-\nu^2}\left[\frac{1}{2}+\beta(\beta+1)\right]\frac{\sigma_R^2}{k_n}}$$

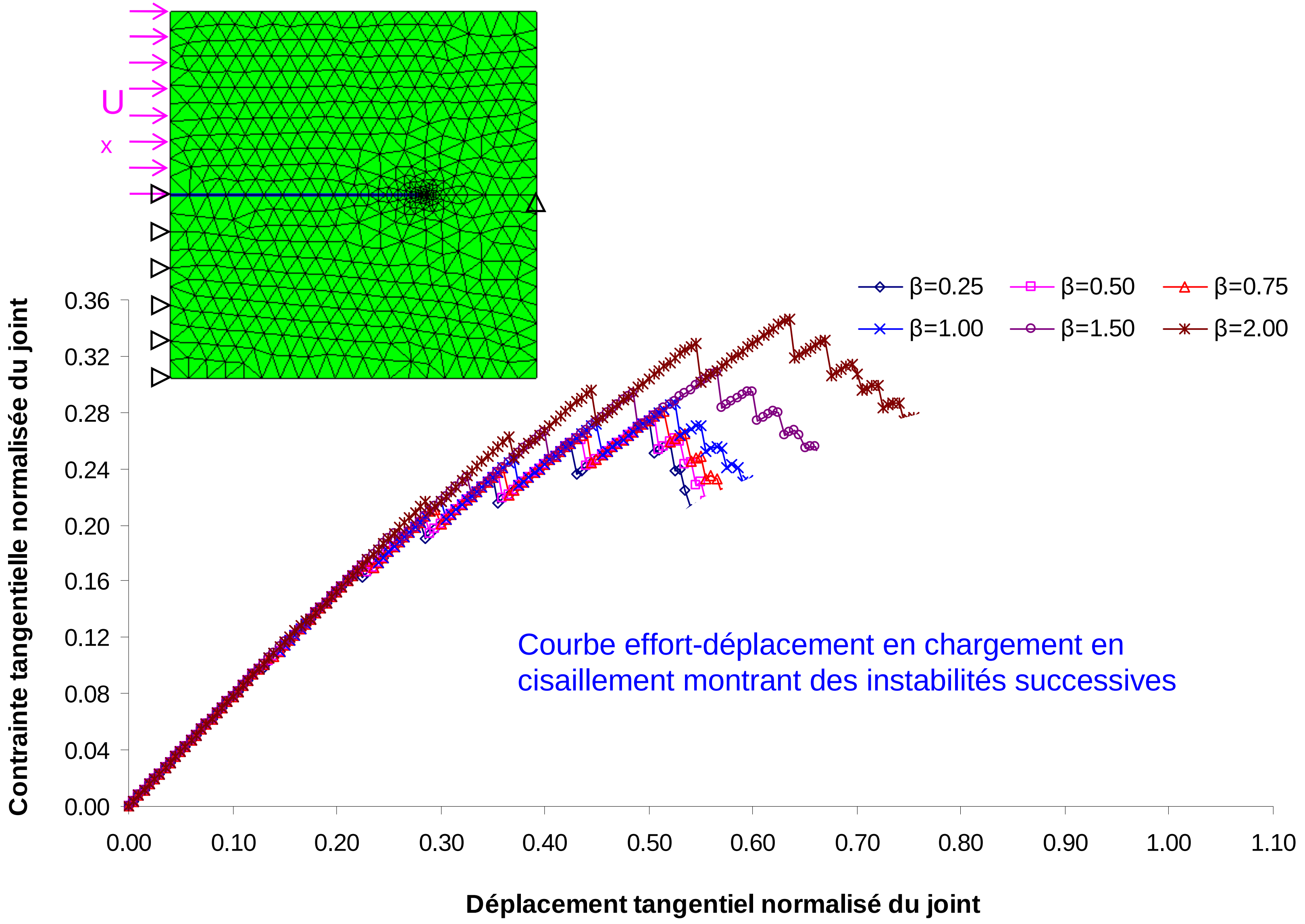
Instabilité de propagation de la fracture (mode I)



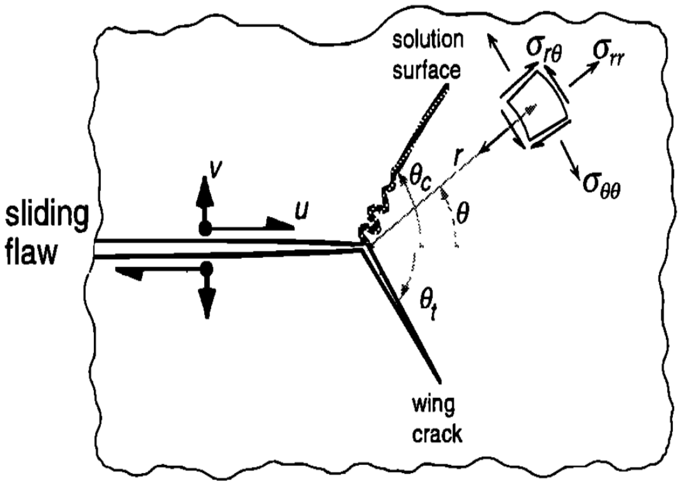


Déplacement du point d'extrémité de la fracture (σ_n max) pour un chargement monotone graduel

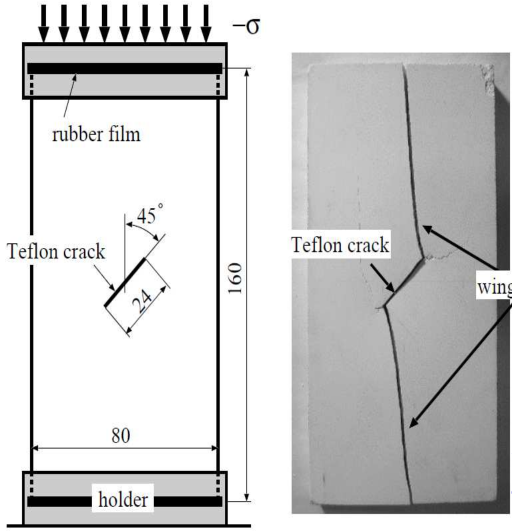
Instabilité de propagation de la fracture (mode II)



Instabilité de direction de propagation sous mode II: Bifurcation

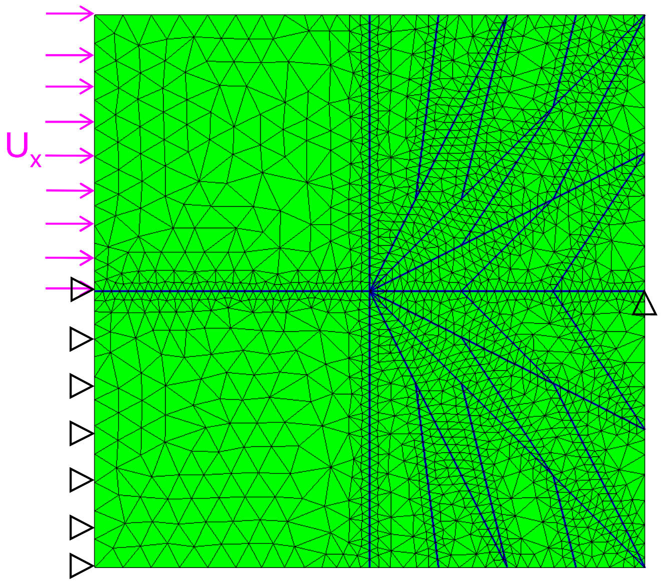


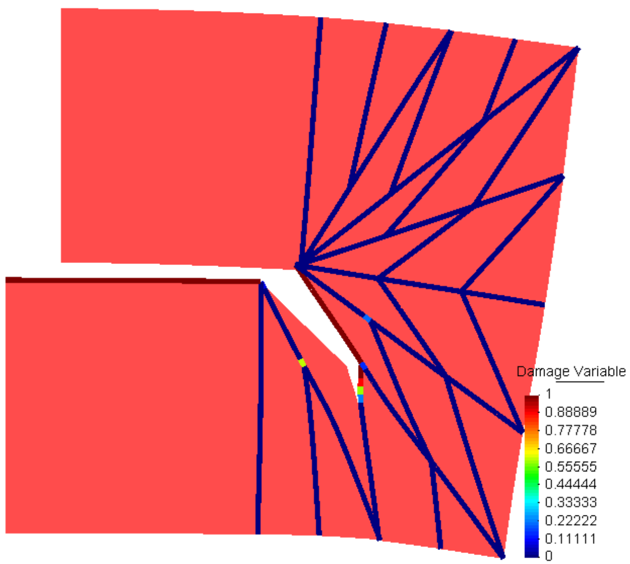
Willemse et Pollard (1998)



Saimoto et al. (2009)

Fig. 1. Observed wing crack growth in Mortar specimen under uniaxial compression test[6].

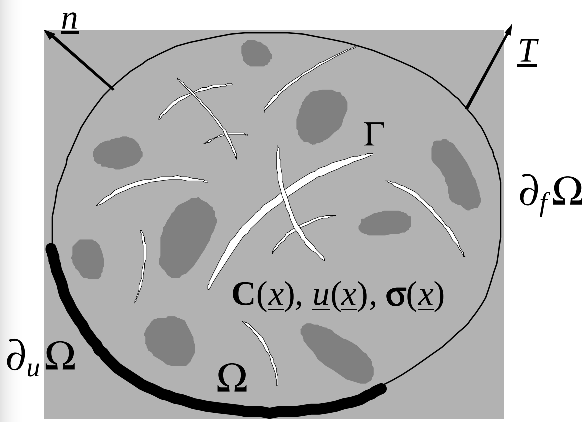


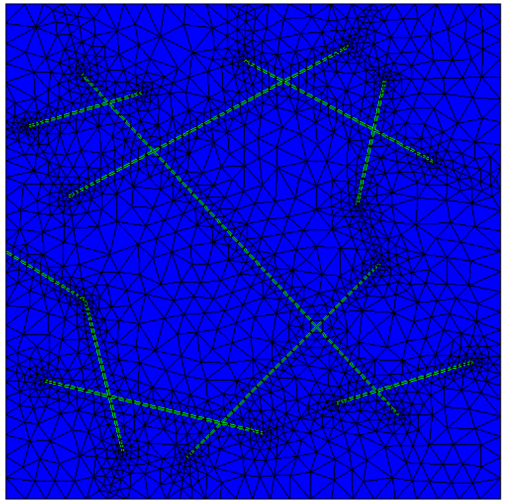


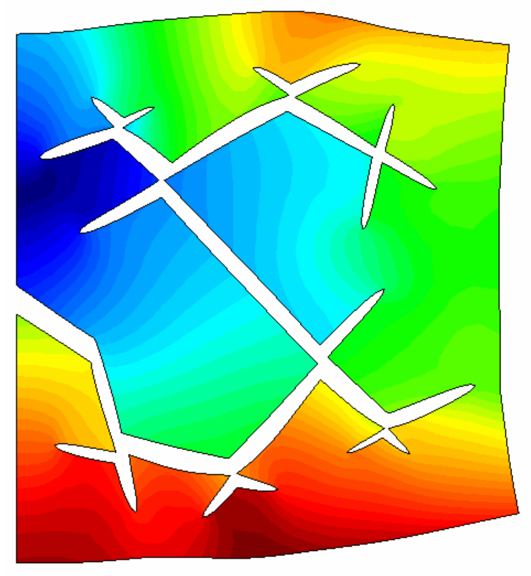
Bifurcation de la fracture sur un angle θ≈76° pour une valeur théorique de θ ≈ 70 à 80°

POROFIS : FEM code for Porous Fissured media (A. Pouya, 2014)

Coupled transient flow and deformation processes in porous multi-fractured media







Mechanical problem

Elasticity-plasticity,

Poroelasticity (Matrix)

Elasticity/damage (Joints)

Coupling
(Iteration)

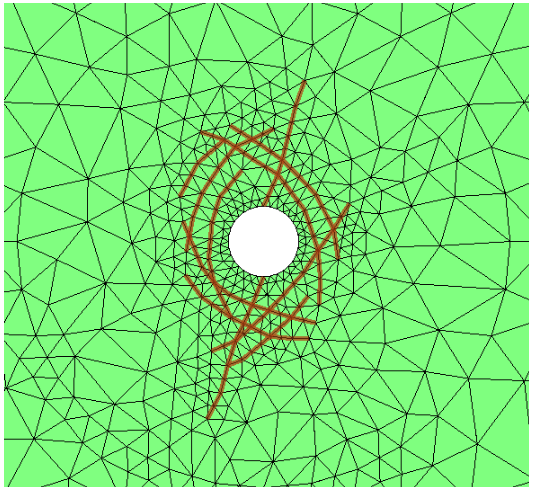
Hydraulic problem

Darcy’s flow saturated/
unsaturated (Matrix)

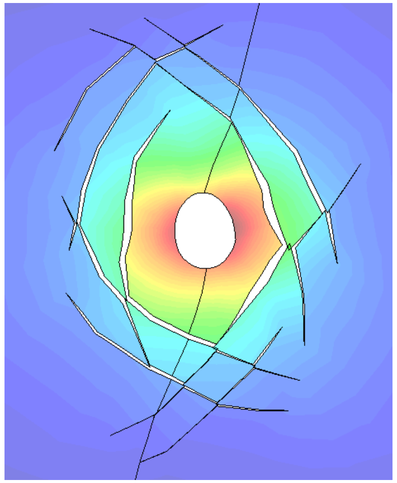
Lubrication model (Fractures)

Applications

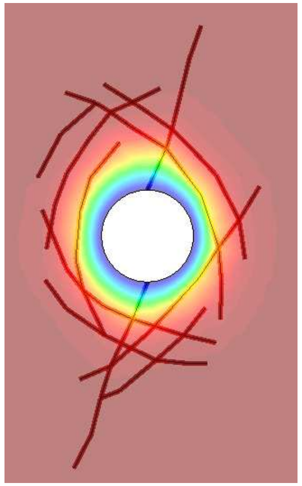
Effet de la fracturation autour des puits pétroliers sur la production



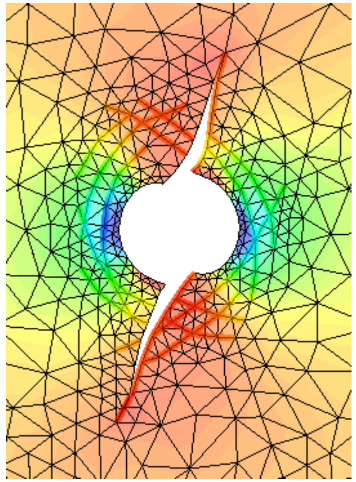
Puits entouré de fractures



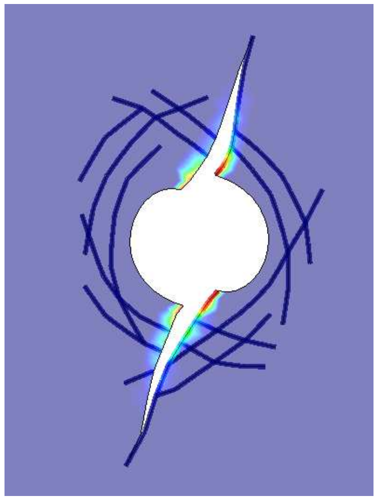
EDZ



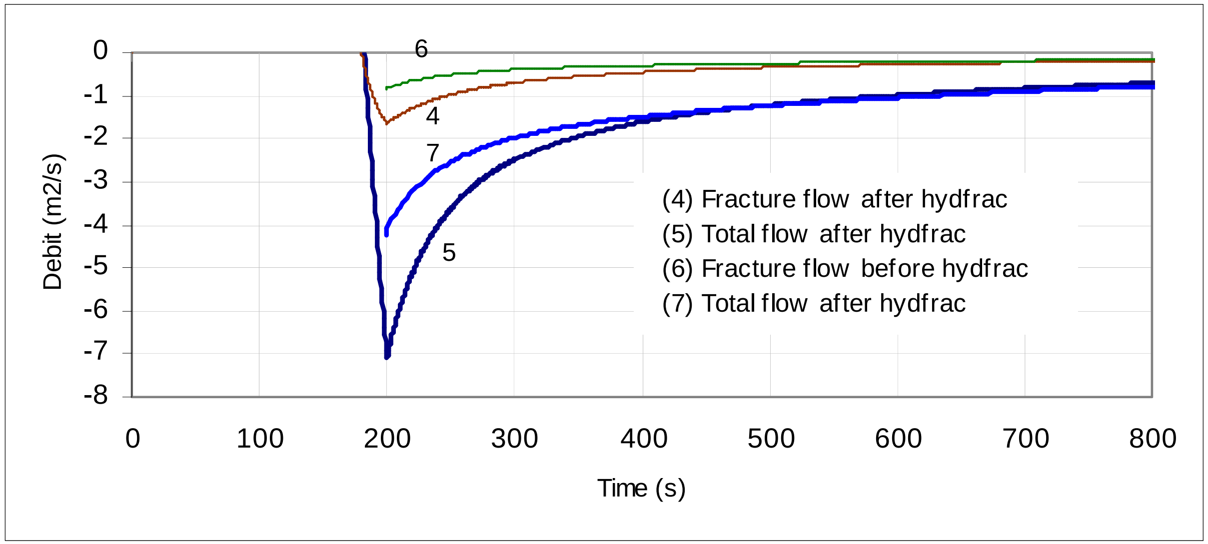
Pression



Contraintes σ_{xx}



Ouverture plastique u^p



Courbes de production du puits et la contributions des fractures avant et après la fracturation hydraulique

Applications

- Propagation des failles dans des réservoirs de stockage du CO2
  (Thèse L.V. Nguyen, S. Ghabezloo, ANR Fisic)

- Mécanismes de fracturation dans les bassins sédimentaires (l'effet des surpressions)
  (Thèse Z. Ouraga, N. Gyu, IFPEN)

- Fissuration (hydrique) des sols non saturés
  (Thèse T.D. VO, S. Hemmati, IFSTTAR)

Conclusions

- La méthode des éléments finis complété des éléments joints et de modèle de fracture cohésive permet la simulation de la propagation des fractures sous sollicitations hydromécaniques.

- Les outils existants permettent de modéliser la propagation sur des trajets prédéfinis, mais comme on peut mettre des joints partout, cela ne constitue pas une grande limitation.

- Les couplages et non linéarités et les configurations de fracturation complexes (intersections multiples) peuvent être pleinement pris en compte avec les éléments finis enrichis d'éléments joints.

Perspectives

- Non saturé et multiphasé: fluide d'injection différent du fluide des pores
- Multiphysique (thermique et chimique)
- Remaillage pour suivre la propagation
- 3D

- Fin