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# **Analyse expérimentale de l'érosion essais et interprétation**

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# L'Atelier International de 2005 sur l'Erosion Interne (Aussois, France)

**Une description simplifiée  
en 4 phénomènes, bien adaptée  
aux expérimentations de laboratoire :**

- suffusion
- érosion par écoulement localisé ( fissure, trou...)
- érosion de contact (entre deux sols)
- érosion régressive



## **Internal Erosion of Dams and their Foundations**

Robin Fell & Jean-Jacques Fry - editors

## Florence (1997)

- 8 phénomènes
- Entraînement
- Erosion régressive
- Débouillage
- Bouillonnement
- Défloculation
- Renard
- Suffusion

## Aussois (2005)

- 4 phénomènes
- Erosion de conduit
- Erosion régressive
- Erosion de contact
- Suffusion

## Projet ERINOH 2005-2008 3 mécanismes élémentaires

- **érosion**  
(détachement des particules de sol)
- **transport** des particules de sol
- **accrétion**  
(attachement des particules de sol)

*chaque mécanisme est caractérisé par :*

- *un seuil*

*Il y a érosion ou pas*

- *une cinétique*

*L'érosion peut être lente ou rapide*

# La loi d'érosion

Quantité  
de sol  
érodé

=

Coefficient  
de  
cinétique  
d'érosion

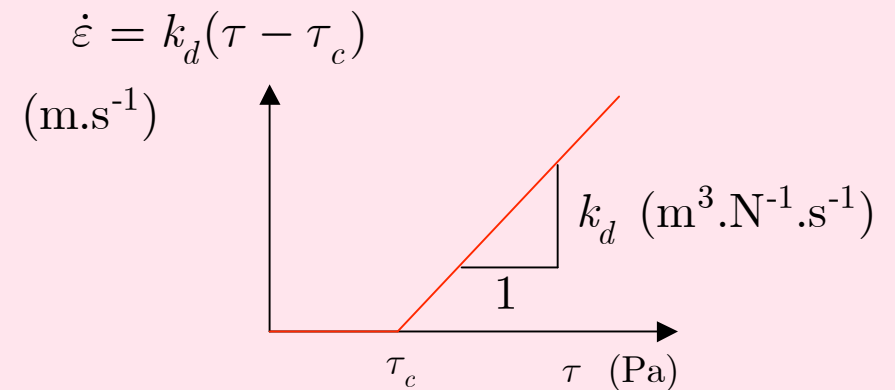
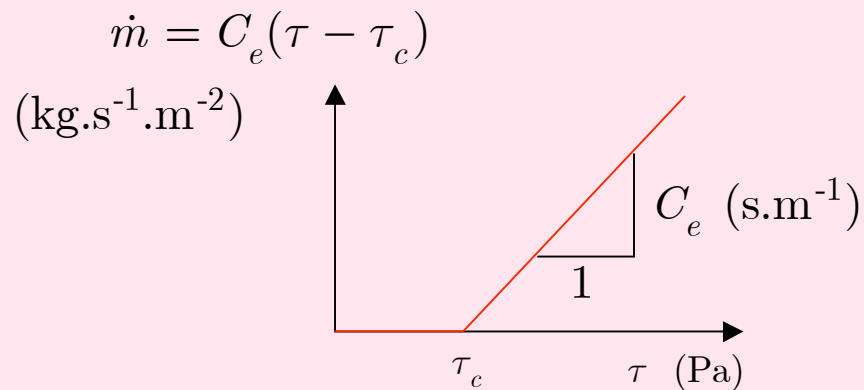
x

Action  
de  
l'eau

-

Seuil  
d'érosion

Deux écritures équivalentes d'usage courant



Equivalences :  $\dot{\varepsilon} = \frac{\dot{m}}{\rho_d}$        $k_d = \frac{C_e}{\rho_d}$        $\rho_d$  (kg.m<sup>-3</sup>) est la masse volumique sèche du sol

# Principe d'une expérimentation

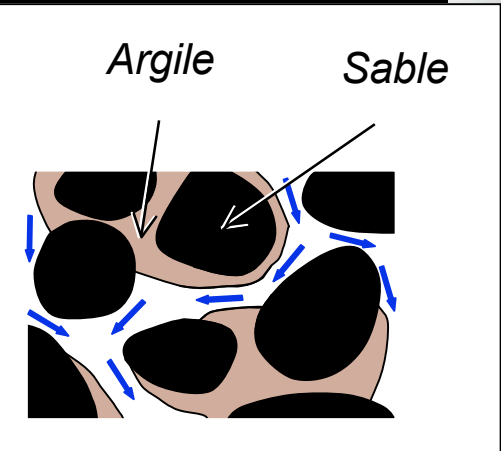
Réaliser une expérimentation physique au laboratoire, c'est :

- imposer l'action de l'eau
- évaluer la quantité de sol érodée
- en déduire les valeurs des paramètres d'érosion (le seuil et le coefficient de cinétique)

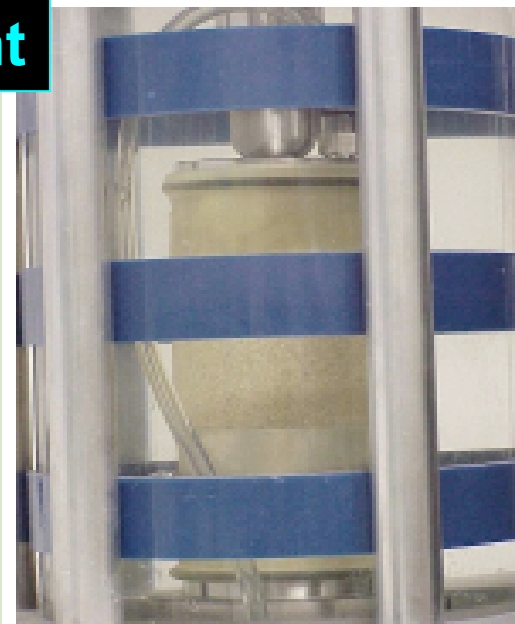
$$\text{Quantité de sol érodé} = \text{Coefficient de cinétique d'érosion} \times \left( \text{Action de l'eau} - \text{Seuil d'érosion} \right)$$

# Suffusion

La suffusion est le détachement des fines et le transport de ces fines à travers la matrice granulaire



écoulement



Circulation d'eau au sein d'un sable argileux



**Suffusion**

L'argile est détachée  
Le sable reste



**Erosion régressive**

L'argile et le sable  
s'en vont

Suffusion (or suffosion) is an internal erosion process by which finer soil particles are detached from the solid matrix, and transported through pore constrictions by seepage flow.

(L. *suffossio*, from *suffodere*, « to dig under », introduced in 1898 by Pavlov.)

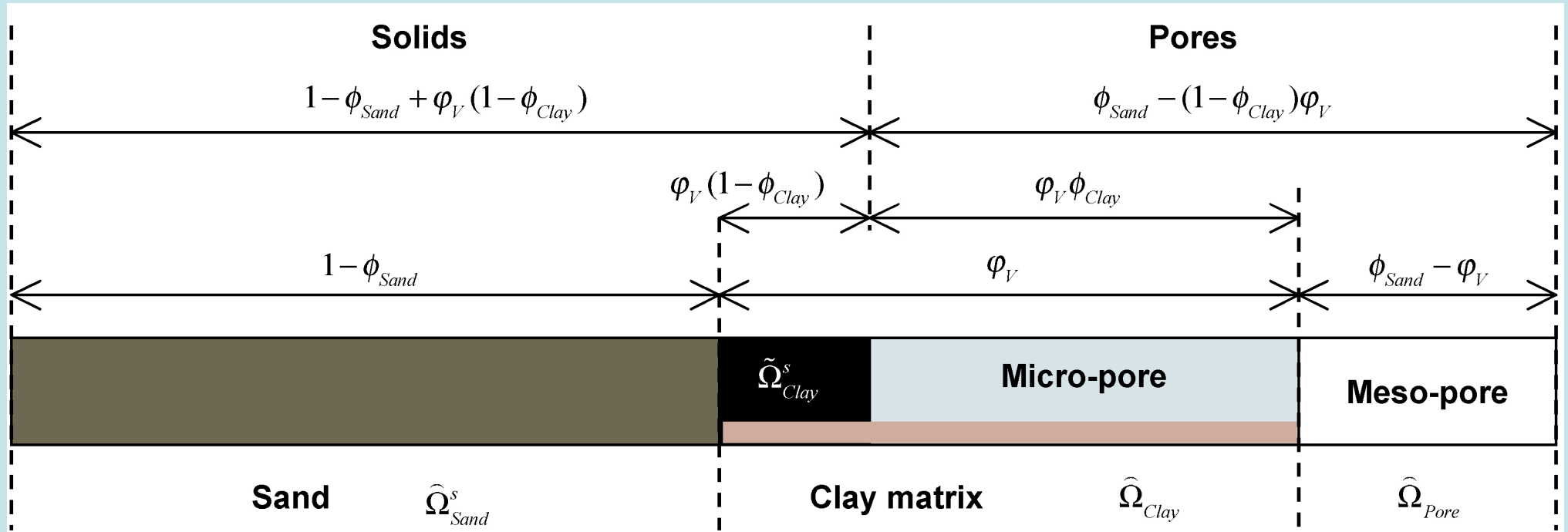
Modelling is well-established (e.g. Vardoulakis & Papamichos, 1996)

Balance equations		Constitutive laws	
Eroded mass	$\frac{\partial \phi}{\partial t} = \frac{r}{\rho_s}$	<span style="border: 1px solid red; padding: 2px;">? (<i>Bulk erosion</i>)</span>	This system describes the increase of porosity $\phi$ induced by the bulk erosion process at the macro-scale (REV)
Fluid mass	$\frac{\partial q}{\partial x} = 0$	Incompressibility	
Fluid momentum	$-\frac{\partial p}{\partial x} = F$	$F = \frac{\eta_w}{\lambda} q$ ( <i>Darcy law</i> )	

$r \propto  q $	(Einstein, 1937; Vardoulakis & Papamichos, 1996; ...)	<b>This choice is not without consequences due to the increase of permeability with bulk erosion</b>
$r \propto \left  \frac{\partial p}{\partial x} \right $	(Papamichos, 2004)	
$r \propto q^2$	(Steeb <i>et al.</i> , 2007)	

$$\lambda = \lambda_0 \frac{\phi^3}{(1 - \phi^2)} \quad (\text{Kozeny-Carman})$$



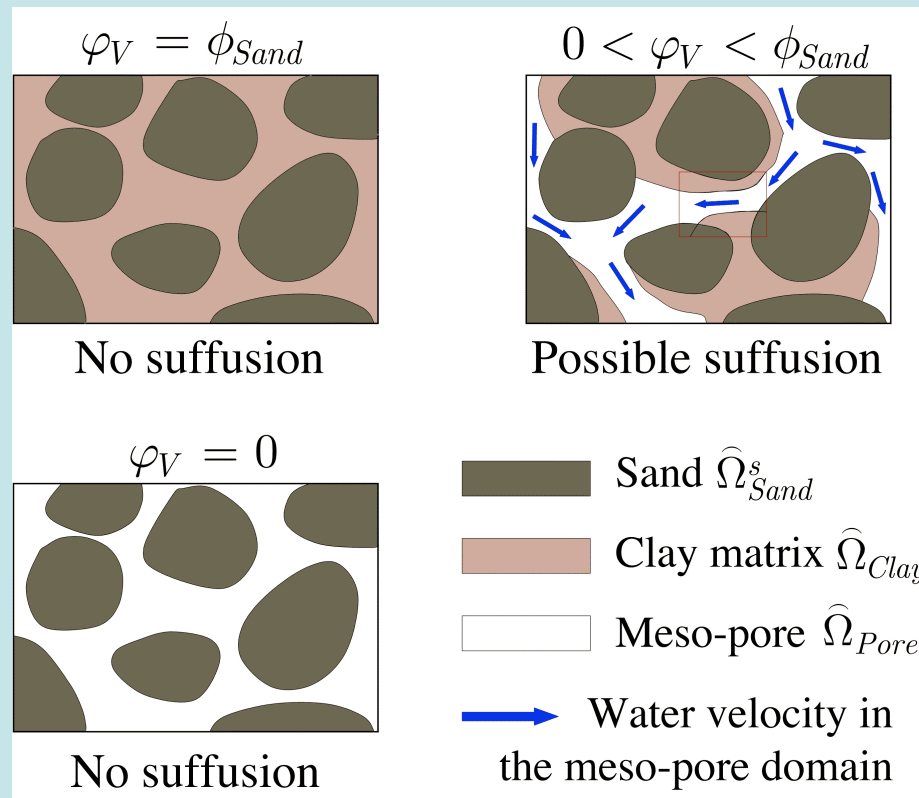


Proportions relatives de chaque constituant

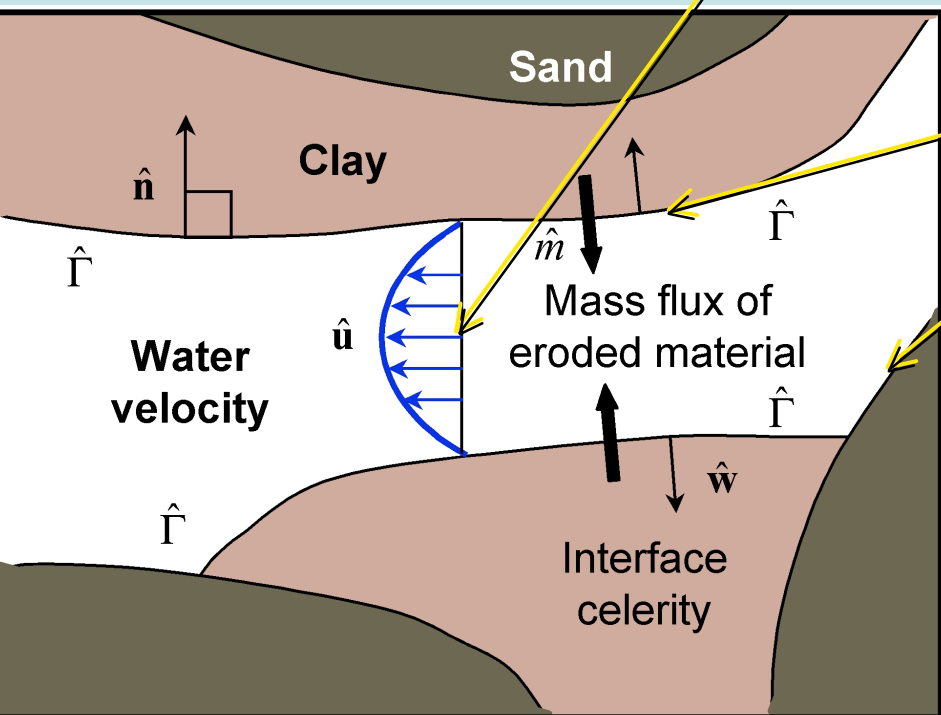
$$\varphi_V = \frac{V_{\text{argile}}}{V_{\text{total}}} \quad (\text{fraction volumique d'argile})$$

$$\phi_{\text{sand}} = 1 - \frac{V_{\text{sable}}}{V_{\text{total}}} \quad (\text{porosit  de la matrice granulaire})$$

$$\varphi_V = \phi_{\text{sand}} - \phi$$



	Volume (meso-pore) Stokes dilute flow		Interface	
			Sand/water	Clay/water
Balance laws	Mass	$\widehat{\nabla} \cdot \widehat{\mathbf{u}} = 0$	$\widehat{\mathbf{u}} \cdot \widehat{\mathbf{n}} = 0$	$[[\widehat{m}]] = 0$
	Momentum	$\widehat{\nabla} \cdot \widehat{\mathbf{T}} = 0$	$[[\widehat{\mathbf{T}} \cdot \widehat{\mathbf{n}}]] = 0$	$[[\widehat{\mathbf{T}} \cdot \widehat{\mathbf{n}}]] = -\widehat{m} [[\widehat{\mathbf{u}}]]$
Behaviour laws	(Viscosity law)	$\widehat{\mathbf{T}} = -\widehat{p}\mathbf{I} + 2\eta_w(\widehat{\nabla}\widehat{\mathbf{u}})_{\text{sym}}$	Continuity of tangential velocities	(Surface erosion law)
	Incompressibility			$\widehat{m} = \begin{cases} \widehat{k}_{er}(\widehat{\tau} - \widehat{\tau}_c) & \text{if } \widehat{\tau} > \widehat{\tau}_c \\ 0 & \text{otherwise} \end{cases}$ + Cont. of tang. velocities



**At micro-scale, erosion is due to the tangential stress vector**

$$\widehat{\tau} = || \widehat{\boldsymbol{\tau}} ||$$

$$\widehat{\boldsymbol{\tau}} = [\mathbf{I} - \widehat{\mathbf{n}} \otimes \widehat{\mathbf{n}}] \cdot \widehat{\mathbf{T}} \cdot \widehat{\mathbf{n}}$$

Mass flux crossing the interface

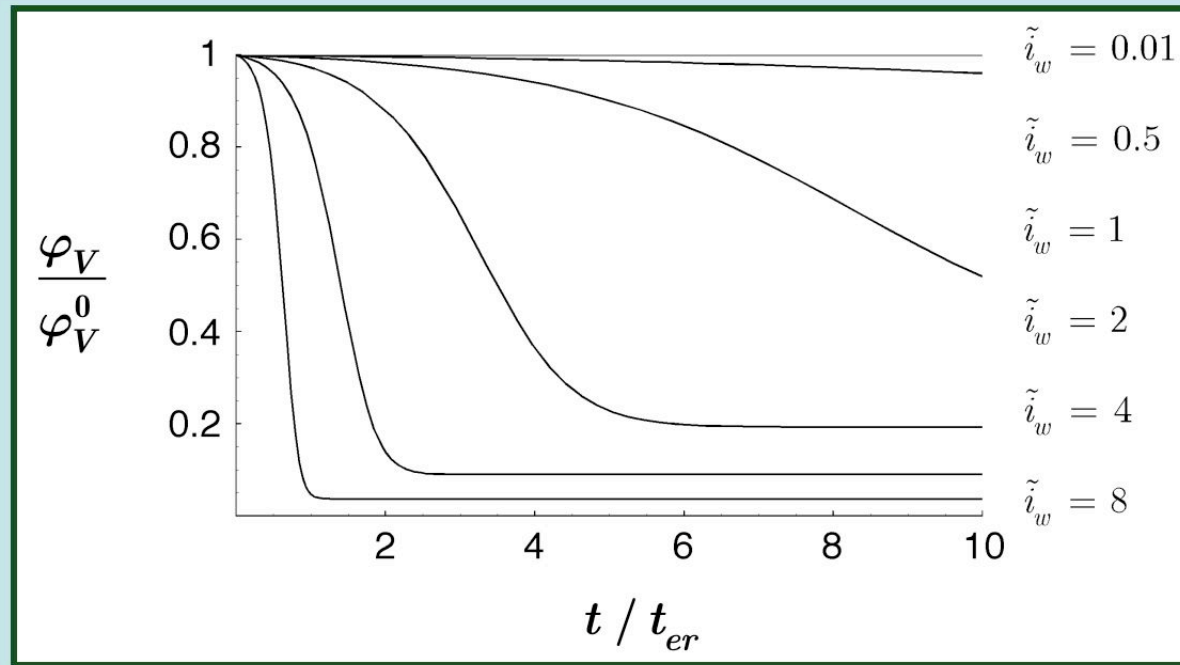
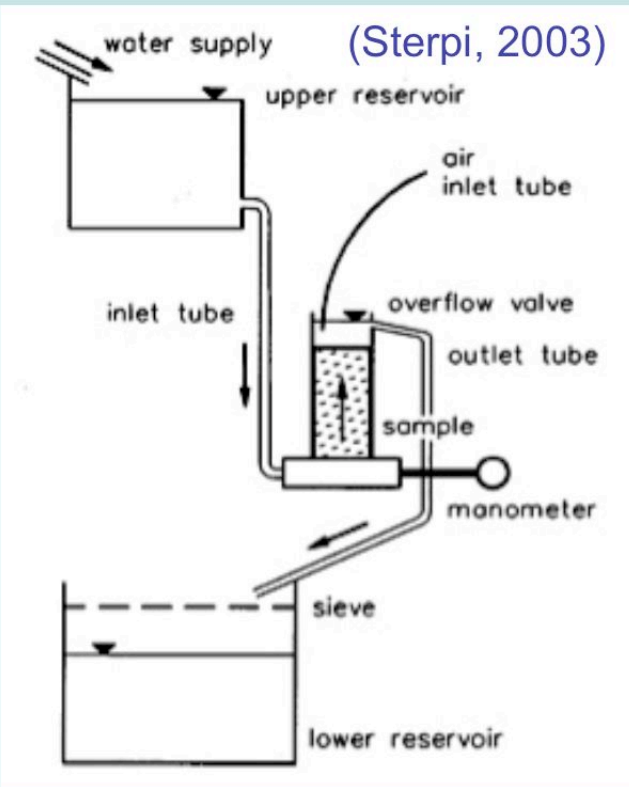
$$\widehat{m} = \widehat{\rho}(\widehat{\mathbf{w}} - \widehat{\mathbf{u}}) \cdot \widehat{\mathbf{n}} = \widehat{\rho}_{Clay} \widehat{\mathbf{w}} \cdot \widehat{\mathbf{n}}$$

**1. Le terme source « d'érosion de volume » est une moyenne volumique du flux dérosion d'interface argile/eau**

$$r = \frac{1}{|\hat{\Omega}|} \int_{\hat{\Gamma}} \hat{m} d\hat{\Gamma} \quad \hat{m} = \begin{cases} \hat{k}_{er} (\hat{\tau} - \hat{\tau}_c) & \text{si } \hat{\tau} > \hat{\tau}_c \\ 0 & \text{sinon} \end{cases}$$

**2. C'est le gradient global de pression qui est pertinent pour la loi d'érosion et non la vitesse de Darcy**

$$\frac{1}{|\hat{\Omega}|} \int_{\hat{\Gamma}} \hat{\tau} d\hat{\Gamma} = \phi_{\zeta} \left| \frac{\partial p}{\partial x} \right| \quad \left( \text{donc } r \propto \left| \frac{\partial p}{\partial x} \right| \right)$$



$$i_w = \frac{1}{\gamma_w} \left| \frac{\partial p}{\partial x} \right|$$

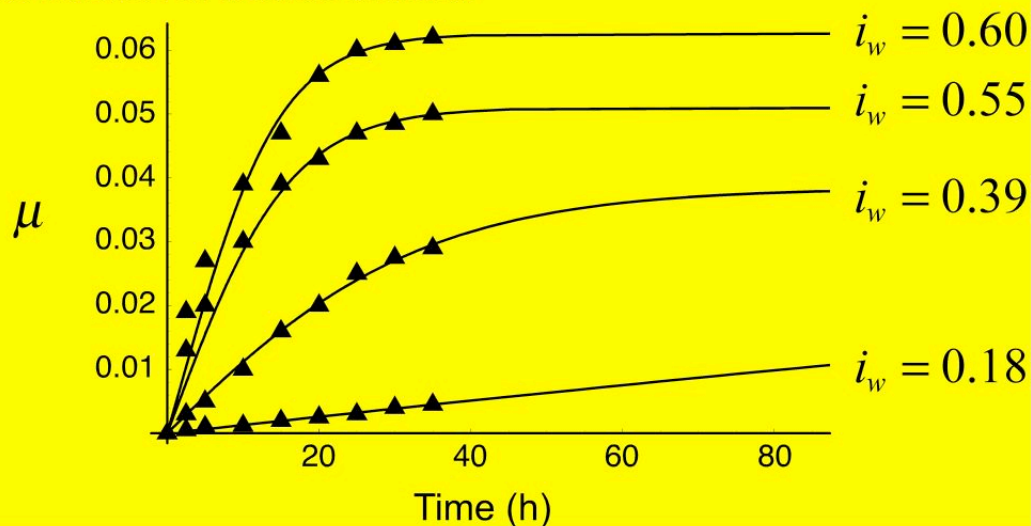
Dimensional analysis of the system shows that the characteristic time of bulk erosion is

$$t_{er} = \frac{\rho_{Clay}}{\gamma_w \widehat{k}_{er}}$$

A fit to the experimental data obtained by Sterpi (2003) yields a relevant value of the coefficient of surface erosion

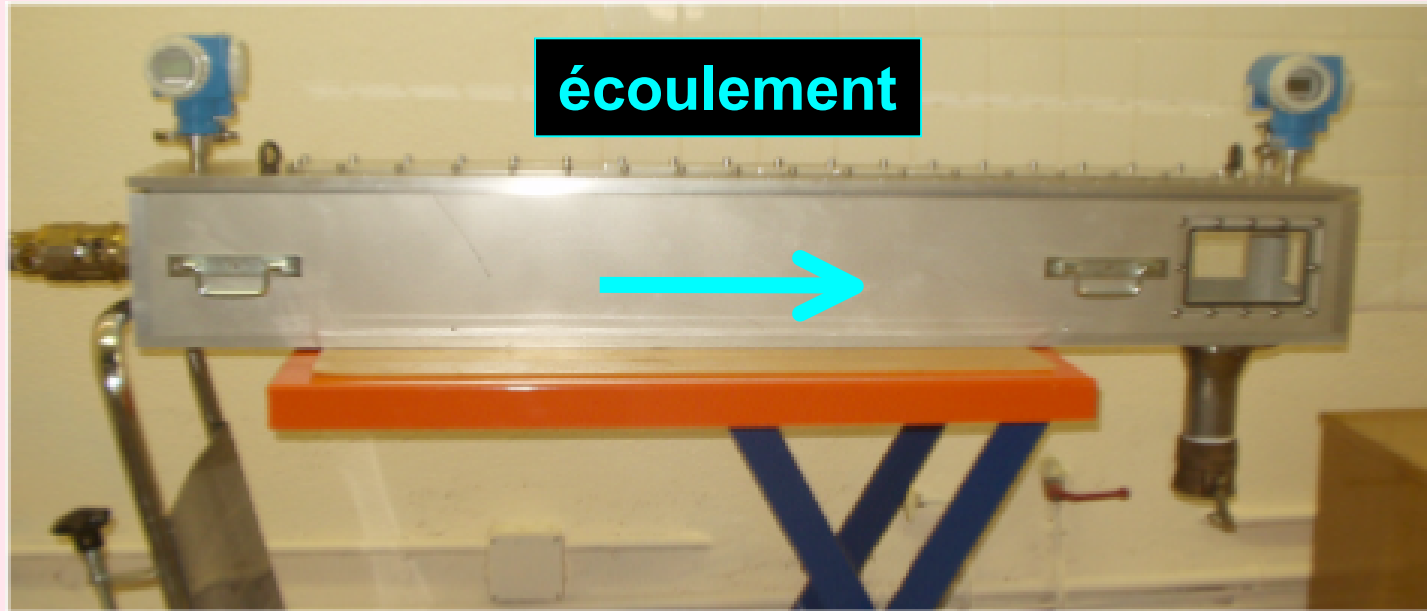
$$\widehat{k}_{er} \approx 10^{-5} \text{ s/m}$$

Mass fraction of eroded material

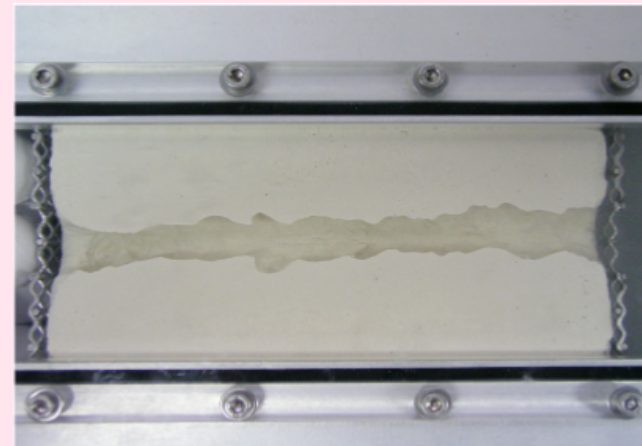
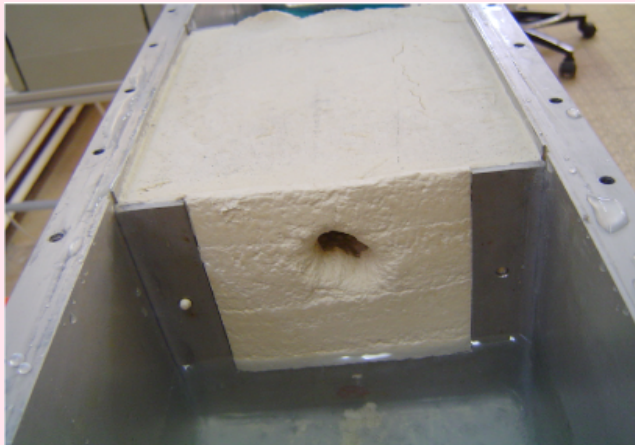


Experimental data : Sterpi (2003)

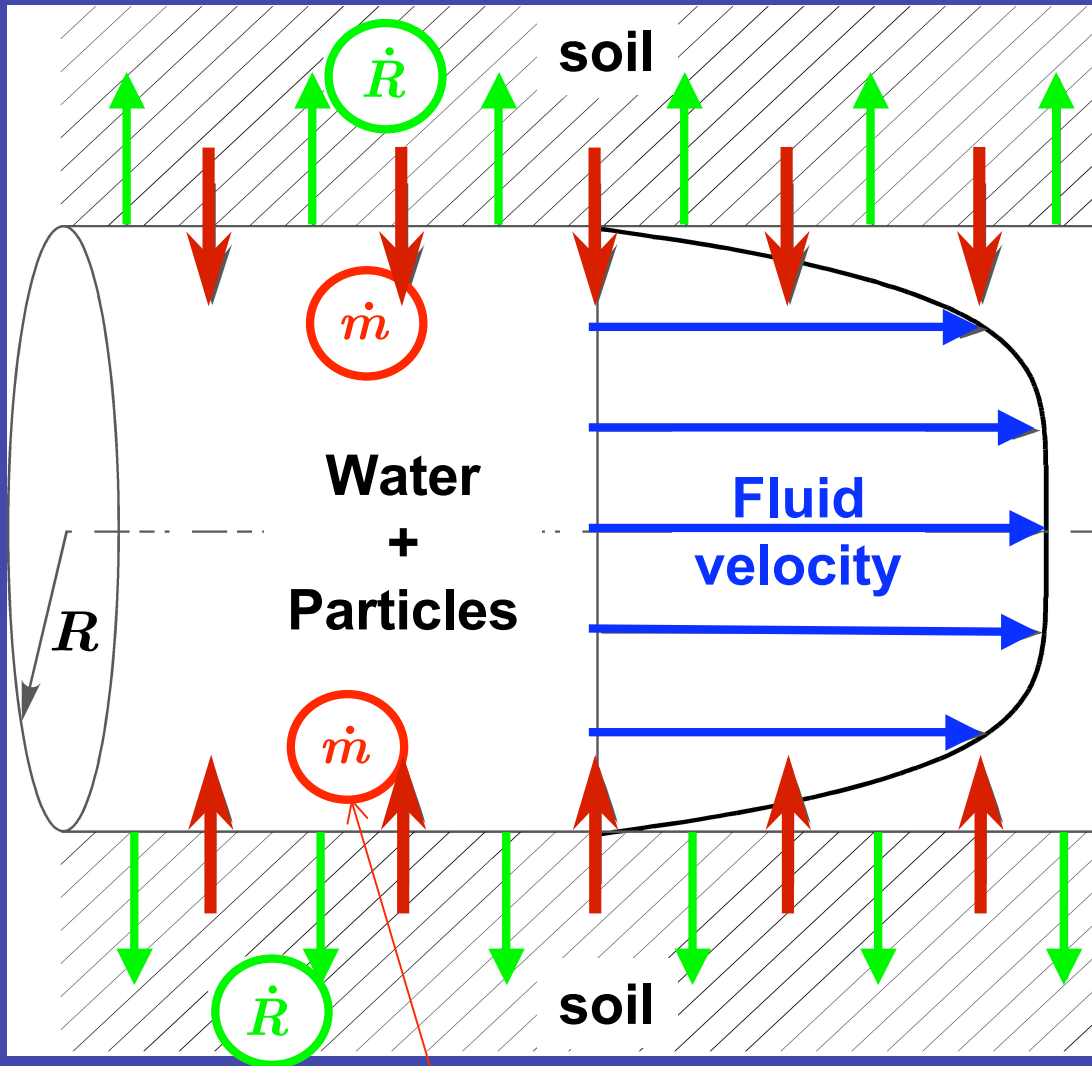
# Érosion de conduit



Pressions  
(entrée et sortie)  
Débitmètre  
Turbidimètre



Radius velocity



Mass flux of eroded material

Equations for turbulent two-phase flow

+

Jump equations for fluid/soil interface

+

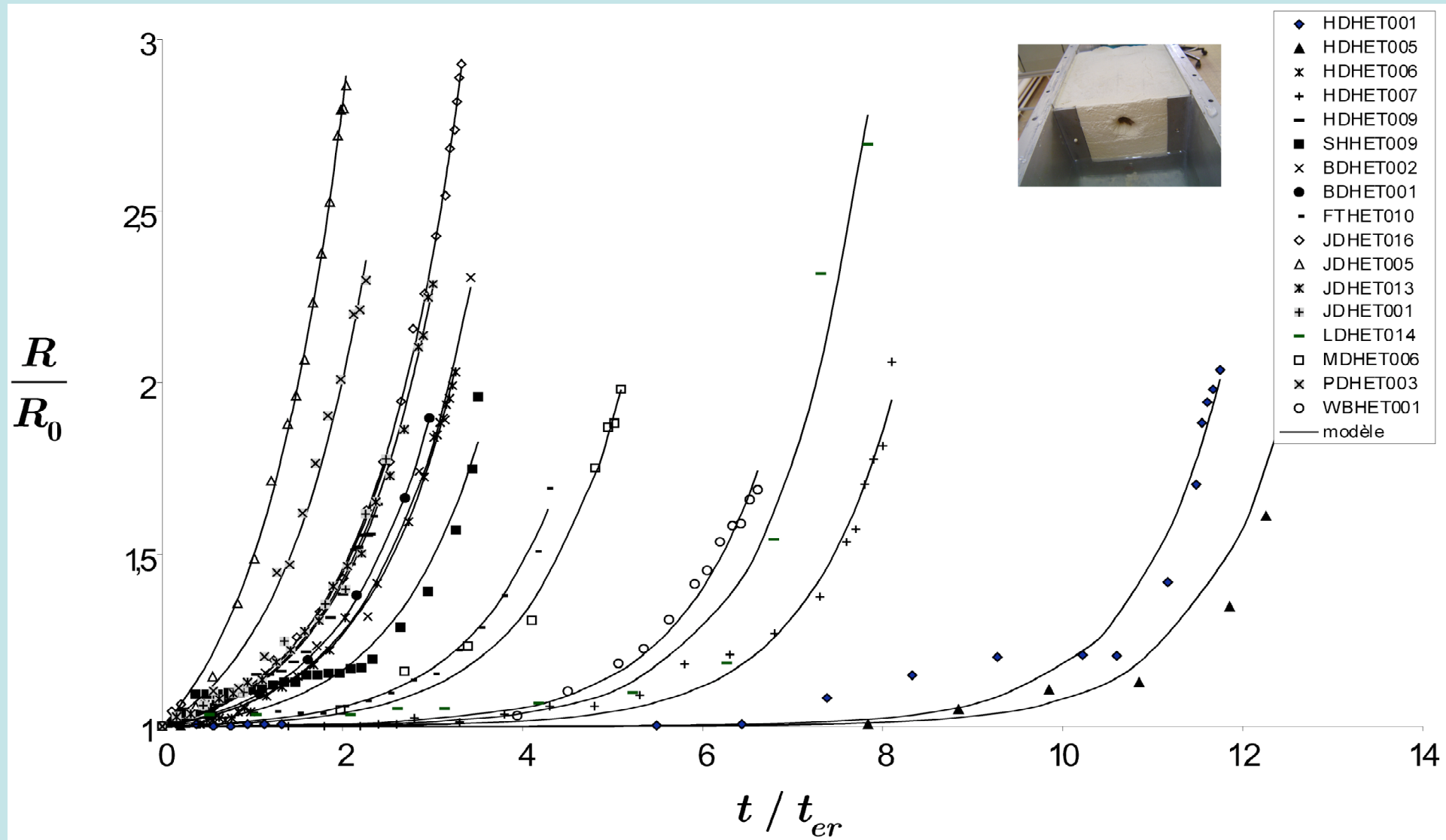
Erosion law of the soil

Mass jump equation

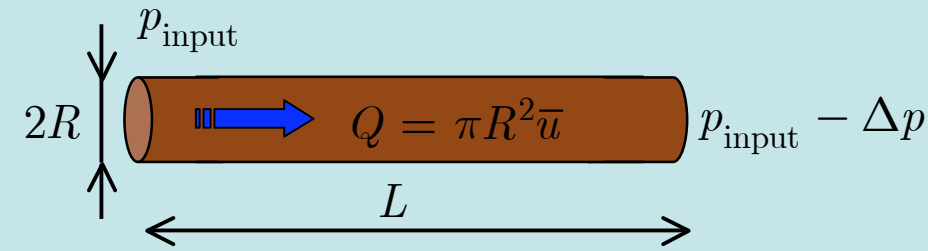
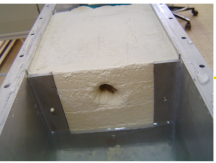
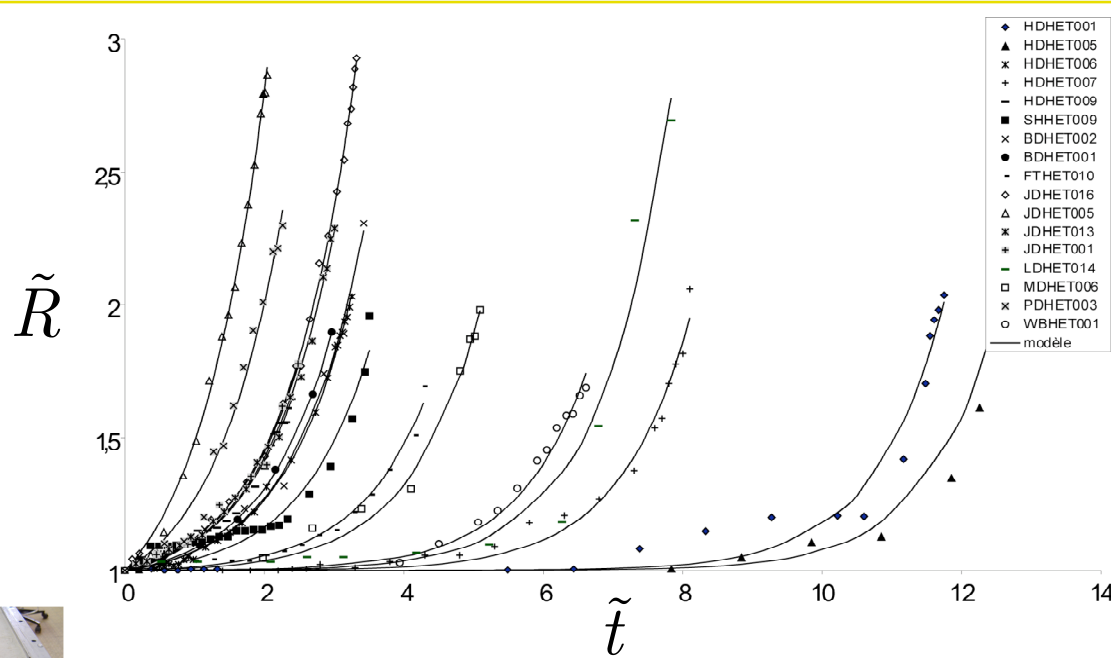
$$\frac{\partial R}{\partial t} = \frac{\dot{m}}{\rho_{soil}} \sqrt{1 + \left(\frac{\partial R}{\partial x}\right)^2}$$

Erosion constitutive law for cohesive soil

$$\dot{m} = \begin{cases} k_{er} (|\tau_b| - \tau_c) & \text{if } |\tau_b| > \tau_c \\ 0 & \text{otherwise} \end{cases}$$







Driving pressure  $P_0 = \frac{R_0 \Delta p_0}{2L}$

Characteristic time  $t_{er} = \left( \frac{\rho_{soil}}{k_{er}} \right) \frac{2L}{\Delta p_0}$

Dimensionless quantities

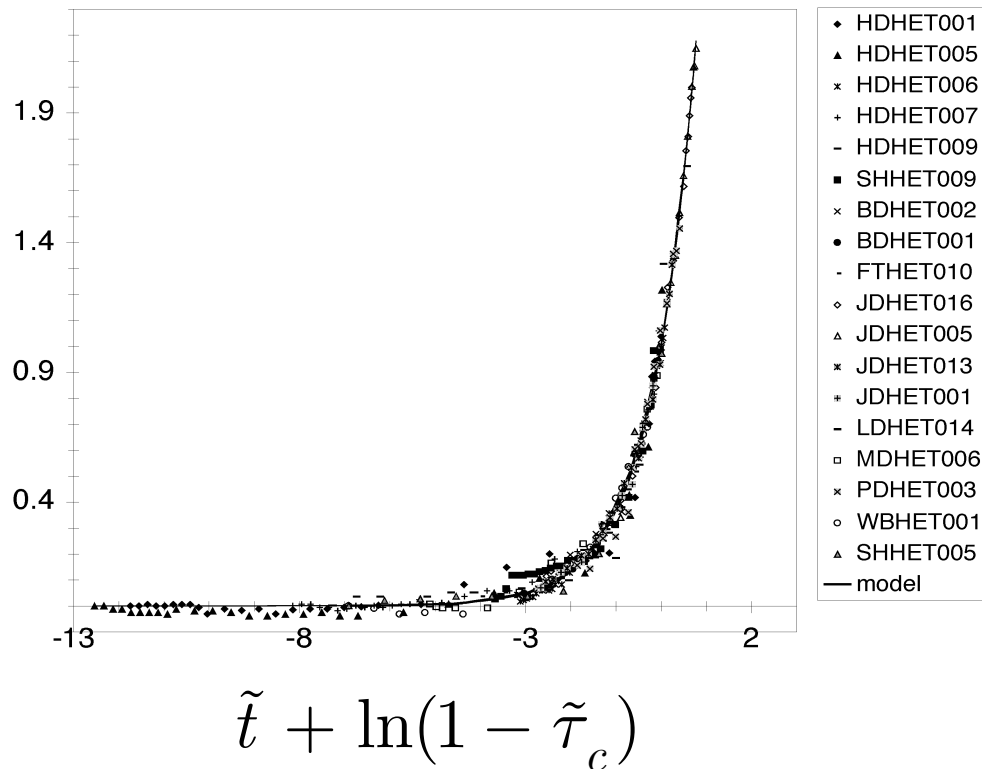
$$\tilde{R} = \frac{R(t)}{R_0} \quad \tilde{\tau}_c = \frac{\tau_c}{P_0} \quad \tilde{t} = \frac{t}{t_{er}}$$

Closed-form solution ( $\Delta p = \text{cste}$ )

$$\frac{R(t)}{R_0} = \left( \frac{Q(t)}{Q_0} \right)^{2/5} = \left( \frac{\bar{u}(t)}{\bar{u}_0} \right)^2$$

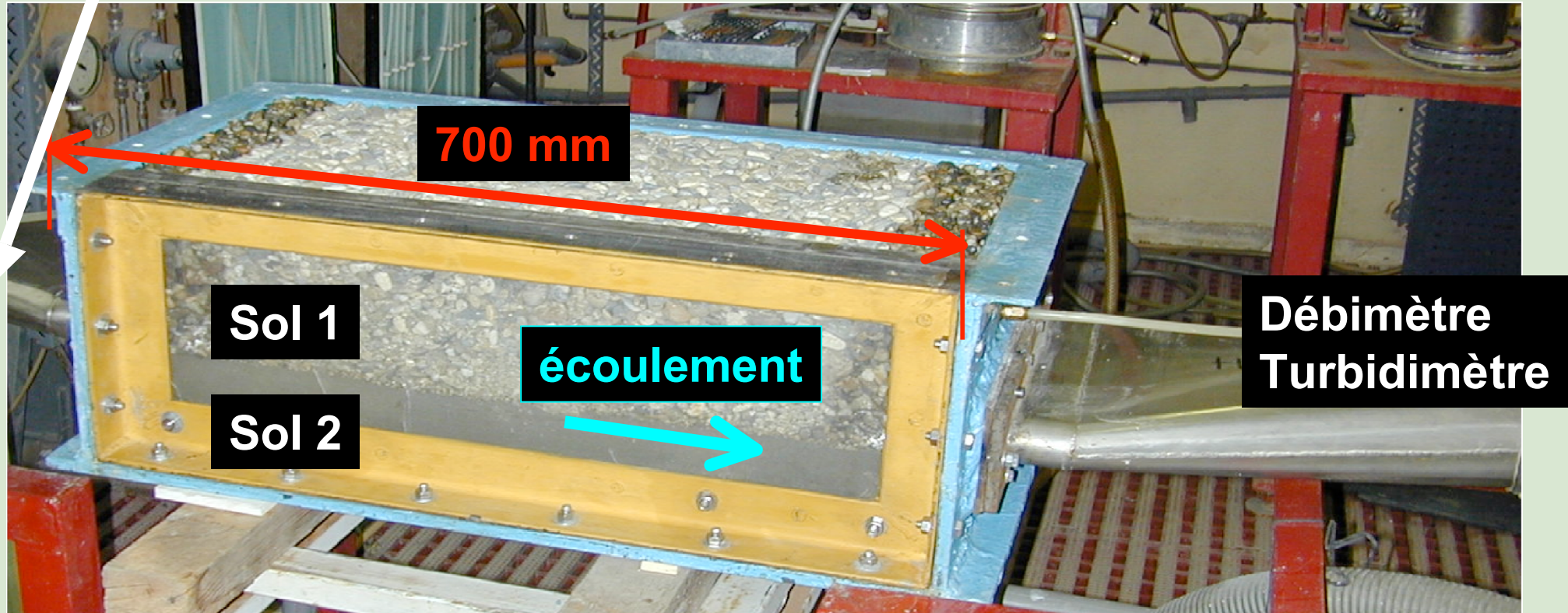
$$\tilde{R}(t) - \tilde{\tau}_c = \exp \left[ \tilde{t} + \ln(1 - \tilde{\tau}_c) \right]$$

$\tilde{R} - \tilde{\tau}_c$

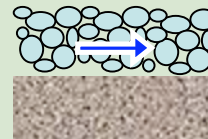
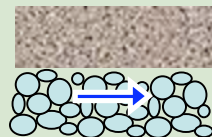


# Érosion de contact

Alimentation par un réservoir à niveau constant avec mesure du débit

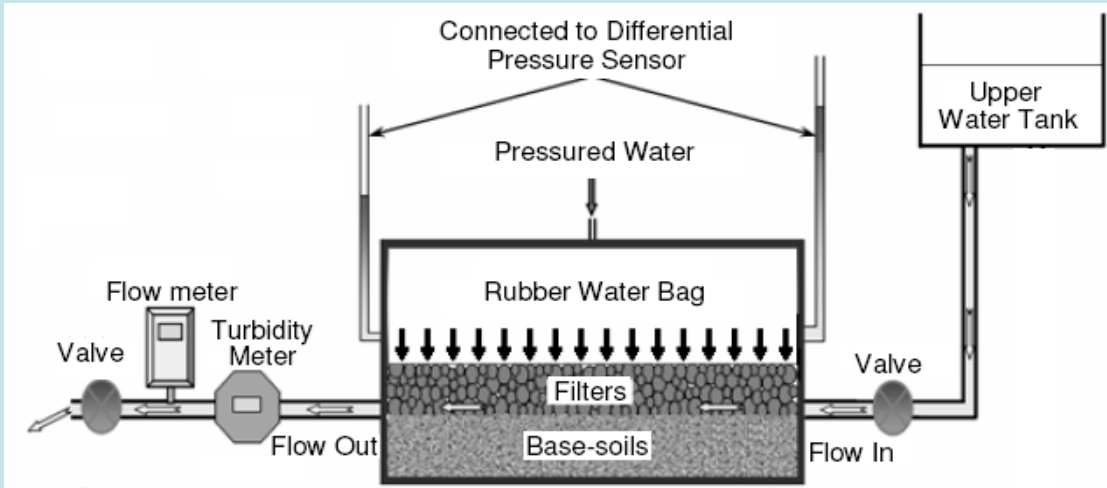


SABLON SUR GRAVIER



GRAVIER SUR SABLON





**Banc d'érosion de contact**

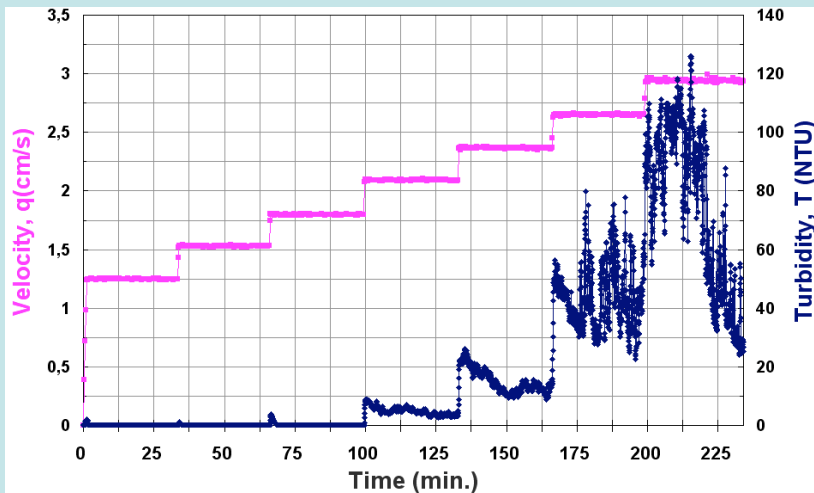


Avant

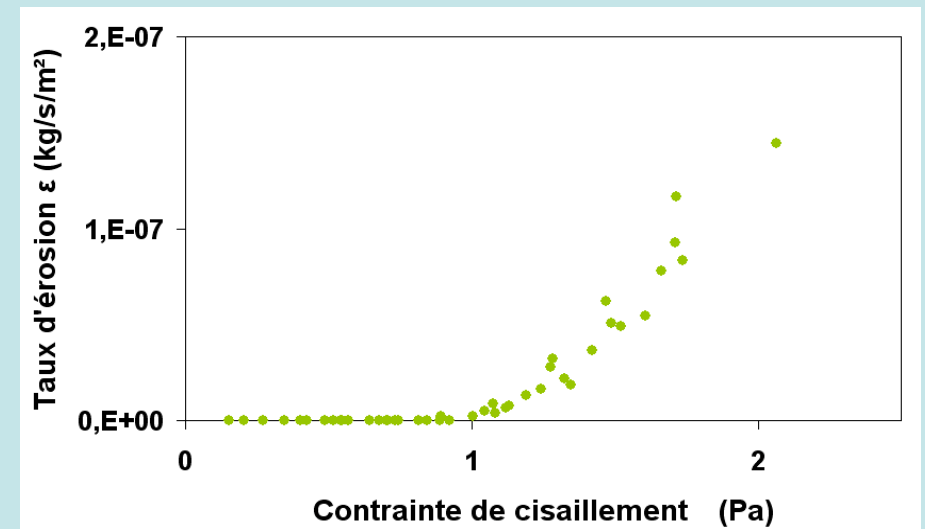


Après

**Observations**



**Données expérimentales**



**Lois d'érosion**

**Merci**