Seepage Induced Geotechnical Instability

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Internal erosion processes: experimental characterizations and energy based interpretative method

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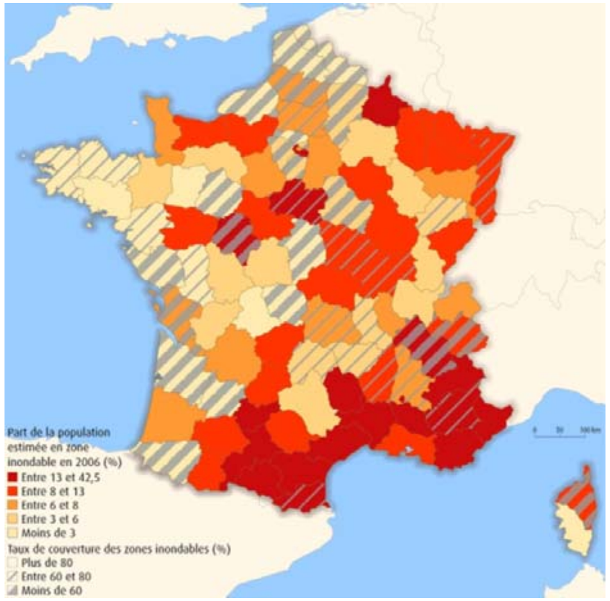
Background

Between 1998 and 2002, Europe suffered over 100 major damaging **floods**,
Between 1998 and 2004, floods caused some **700 fatalities**, the displacement of about half a **million people** and at least **€ 25 billion** in insured economic losses

Among 36 000 French communes
17 000 are exposed

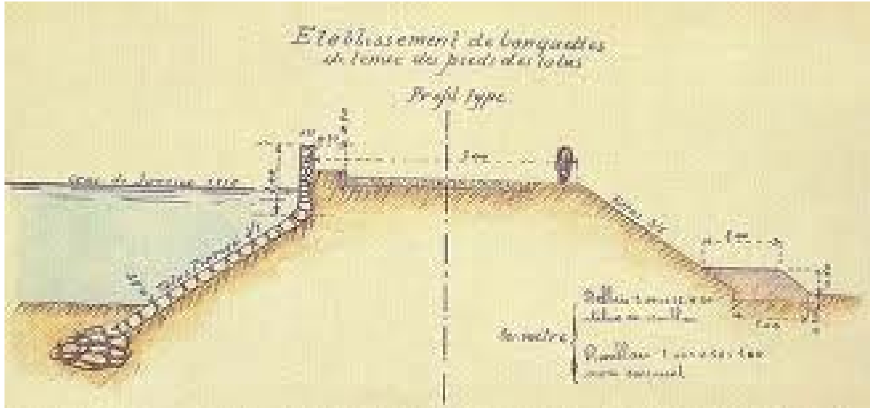


Quimperlé, 2014

Sydney, 2012 & 2013

Katrina, New Orléans, 2005

Dikes for flood protection

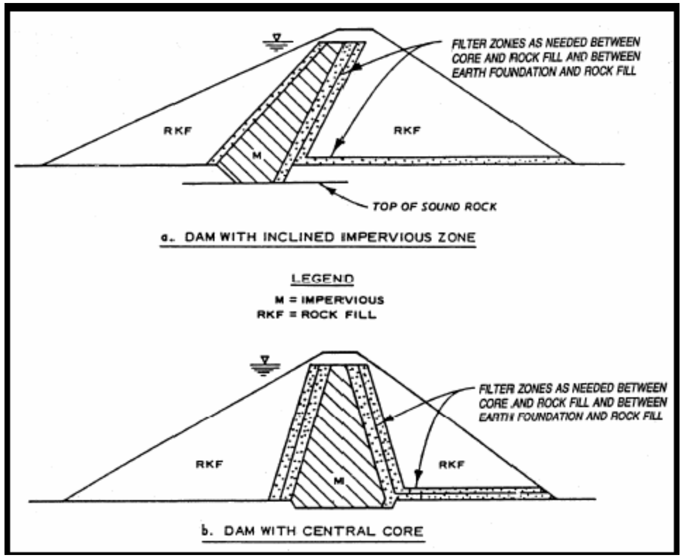


Along Loire river, France

Dikes of canals

Along Rhin river, France-Allemagne

Dams



Incidents and failures in dams

Mécanisme	Total	érosion interne	érosion externe	érosion int. & ext.	glissement	indéterminé
nombre	49	36	6	4	2	1
%	100 %	74 %	12 %	8 %	4 %	2 %

94%

Fry et al. (2015)

Incidents and failures in dikes

Mécanisme	Total	érosion interne	érosion externe	érosion interne & ext.	indéterminé
nombre	207	59	77	6	65
%	100 %	29 %	37 %	3 %	31 %

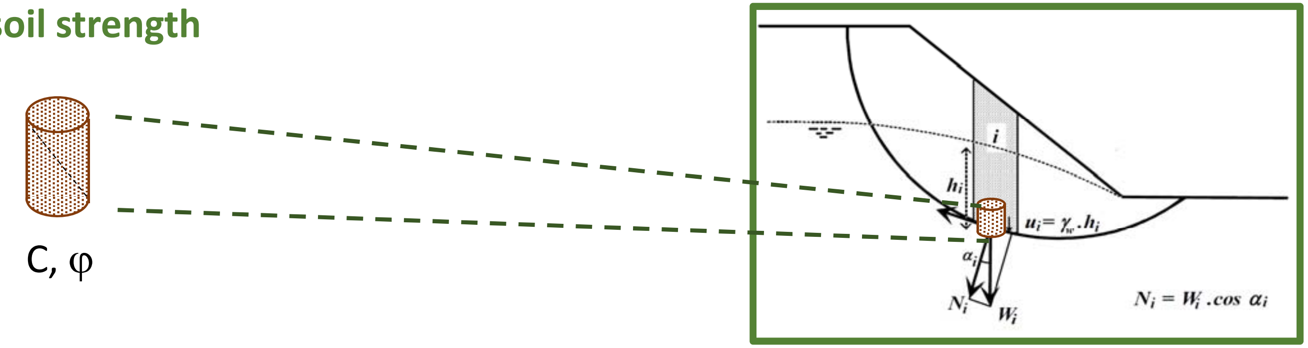
Fry et al. (2015)

69%

Instabilities by sliding process

At laboratory scale, soil strength

At real scale, instability by sliding

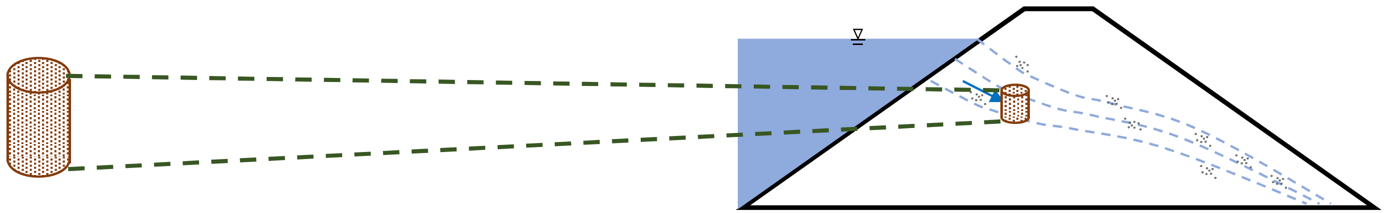


C, φ

Instabilities by erosion processes

At laboratory scale

At real scale?



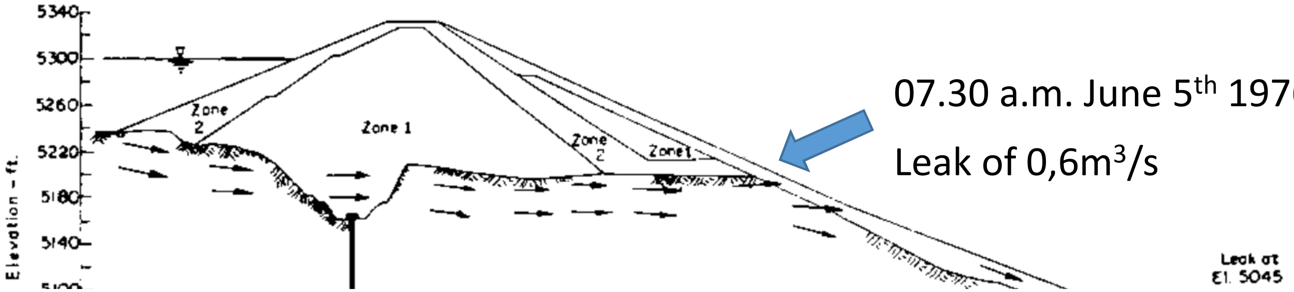
GSD, i_{cr}, v_{cr}, τ_c, k_d,

➔ **Spatial scale effect?**

➔ **Time scale effect?**

Dam Les Ouches (200 years)

Teton Dam (1st reservoir filling) h = 93m, L = 950m



07.30 a.m. June 5th 1976,

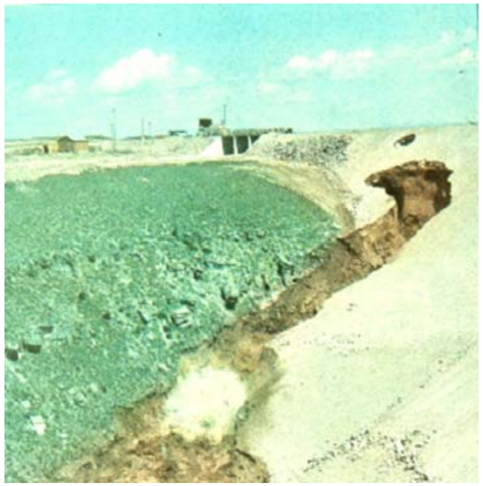
Leak of 0,6m³/s

Deaths: 11 people and 13 000 cattles

Construction cost: 100 million $ compensations: 300 million $

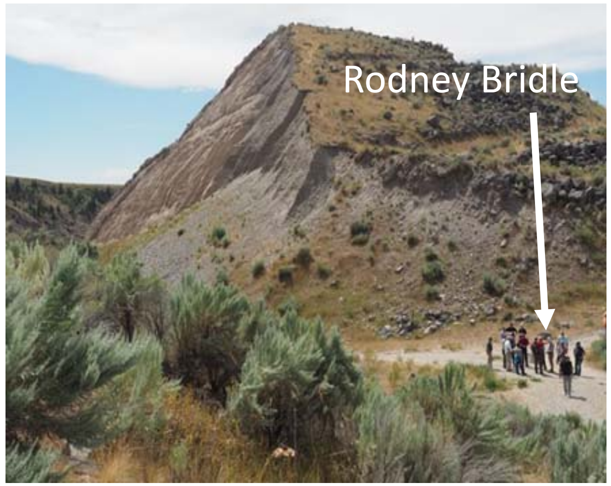
10.30 a.m.

11.00 a.m.



11.57 a.m.

Now



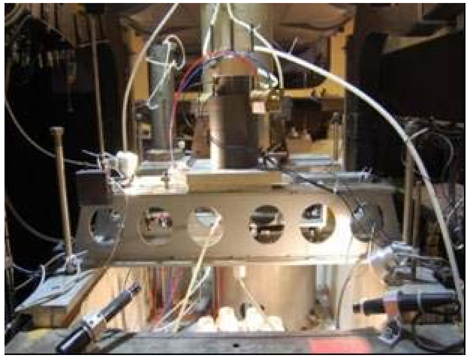
Methodology

- Development of **specific benchs**

Triaxial erodimeter

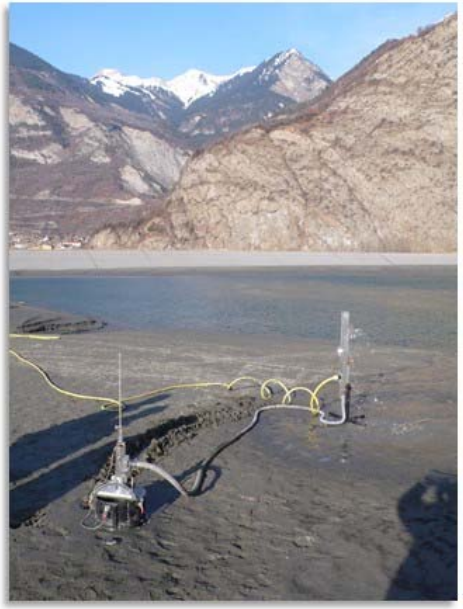
Oedopermeameter

Centrifuge erodimeter



In partnership with IFSTTAR

Jet Erosion Test



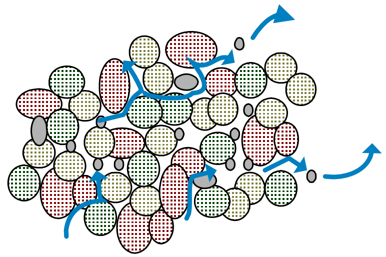
- **Parametric** studies
- Interpretation of tests by **energy approach**

- **Numerical modelling** by DEM and by FEM methods
- **Comparison** numerical results and measurements

Characterization of suffusion

Suffusion: complex and coupling phenomena

Detachment of finest fraction



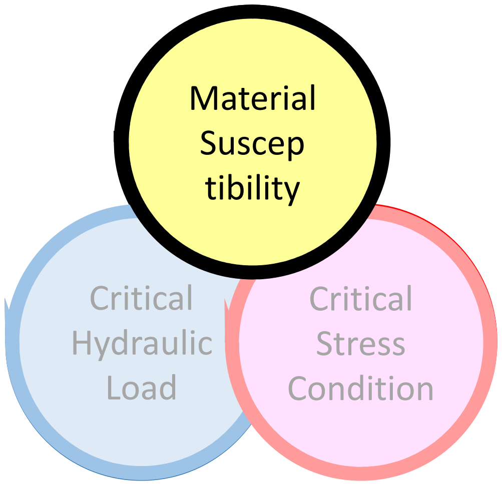
Some detached particles can re-settle or be filtered

➔ Hydraulic loading and soil responses are **coupled**

Transport within the poral network

Main initiation conditions

Venn diagram
(Garner & Fannin, 2010)

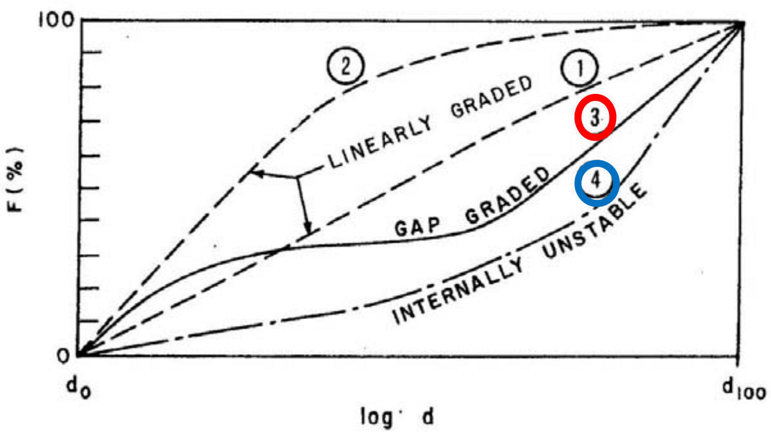


- Geometric criterion,
- Stress criterion,
- Hydraulic criterion

3 criteria related to
- the size of the constriction
- the percentage of fine particles and
- the flow velocity.

(Fell & Fry, 2013)

Grain size distribution criteria



The soils that are likely to **suffer from suffusion** have a grain size distribution: either discontinuous (**curve 3**) or upwardly concave (**curve 4**) *(Fell & Fry, 2007)*

Likelihood of suffusion **initiation**: criteria based on the study of grain size distribution *(Kenney & Lau, 1985, etc…)*

The most widely used criteria are **conservative** *Li & Fannin (2008)*
Wan & Fell (2008)

- Influence of **porosity**, or size of **constrictions ?**
- Influence of **physicochemical characteristics** of medium and interstitial fluid **?**

➔ rate of erosion decreases when the concentration in **sodium chlorate** increases
(Reddi et al., 2000)

influence of sodium chlorate on the flocculation of the soil
(Arulanandan & Perry, 1983)

- Influence of grain **angularity ?**

➔ effect of **grain shape**: increase of resistance by a factor of 5
(Marot et al., 2012, Influence of angularity of coarse fraction grains on internal erosion process, La Houille Blanche, International Water Journal)

Potential susceptibility of suffusion

Comparison of criteria *by Li & Fannin (2008)*, by *Wan & Fell (2008) and by Chang and Zhang (2013)*

- **Gap graded soils**
  - Percentage of fine particles **> 35 %** → stable
  - Percentage of fine particles **< 35 %** → Chang & Zhang's criterion
- **Widely graded soils**

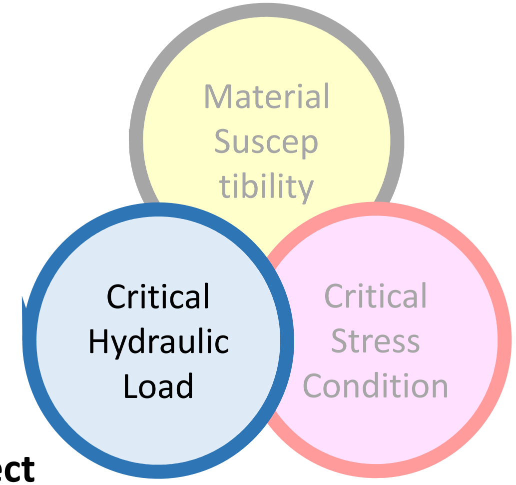
  fine fraction: identified within the granular distribution
  by the minimum value of *Kenney & Lau (1985)* ratio H/F

  - Percentage of fine particles **< 15%** → criterion of *Kenney & Lau (1985)*
  - Percentage of fine particles **> 15%** → criterion of *Wan & Fell (2008)* or criterion of *Chang & Zhang (2013)*

→ **Potential susceptibility** of suffusion

If **potential instability**, the erodibility characterisation needs **suffusion tests**

Hydraulic criteria



Hydraulic conditions have to be studied (*Kovacs,1981*)

Onset & development of suffusion related to:

- critical value of **hydraulic gradient** (*Li, 2008*)

$$i_{cr} = \alpha \left(\frac{\sigma'_{vm0}}{\rho_w \, g \, L} + 0.5 \, \frac{\rho'}{\rho_w} \right)$$

But i_{cr} decreases with seapage length: **scale effect**

(Marot et al., 2012, Study of scale effect in an internal erosion mechanism. European Journal of Environmental and Civil Engineering)

- **Power expended** by interstitial seepage flow which can induce suffusion
  power transferred from fluid to solid particles: negligible

(Sibille et al., 2015, Internal erosion in granular media: direct numerical simulations and energy interpretation. Hydrological Processes, Vol. 29, Issue 9, 2149-2163)

$$P_{flow} = \left(\gamma_w \, \Delta z + \Delta P \right) \, Q$$

Expended energy

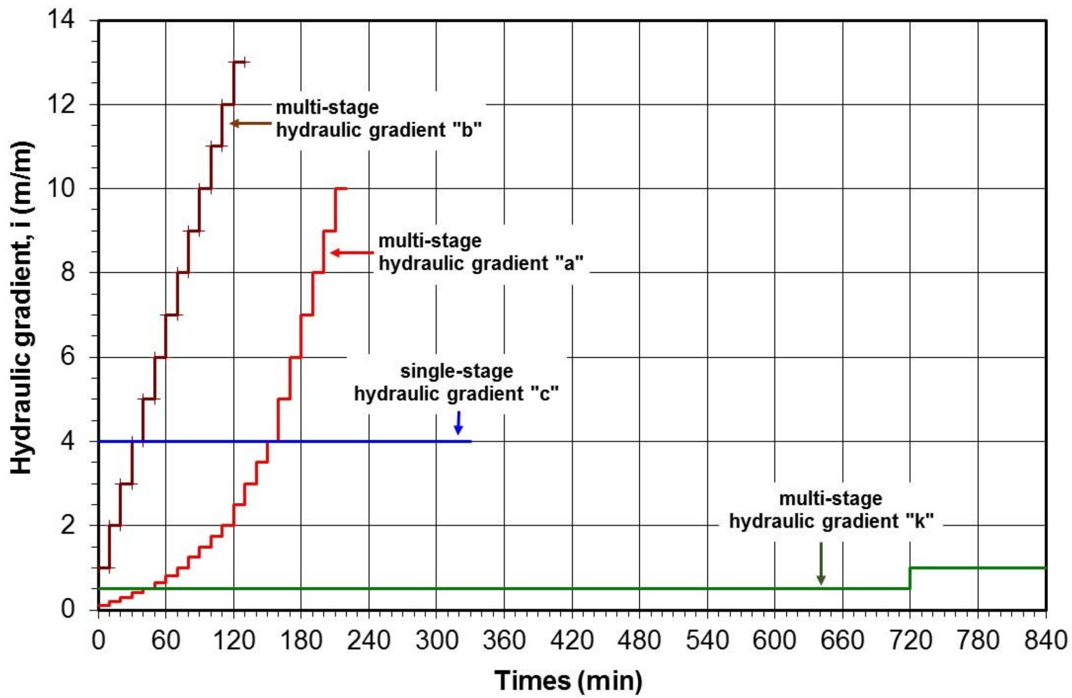
$$E_{flow} = \sum P(t) \, \Delta t$$

Erosion resistance index

$$I_\alpha = -\log_{10} \left(\frac{\text{Eroded dry mass}}{E_{flow}} \right)$$

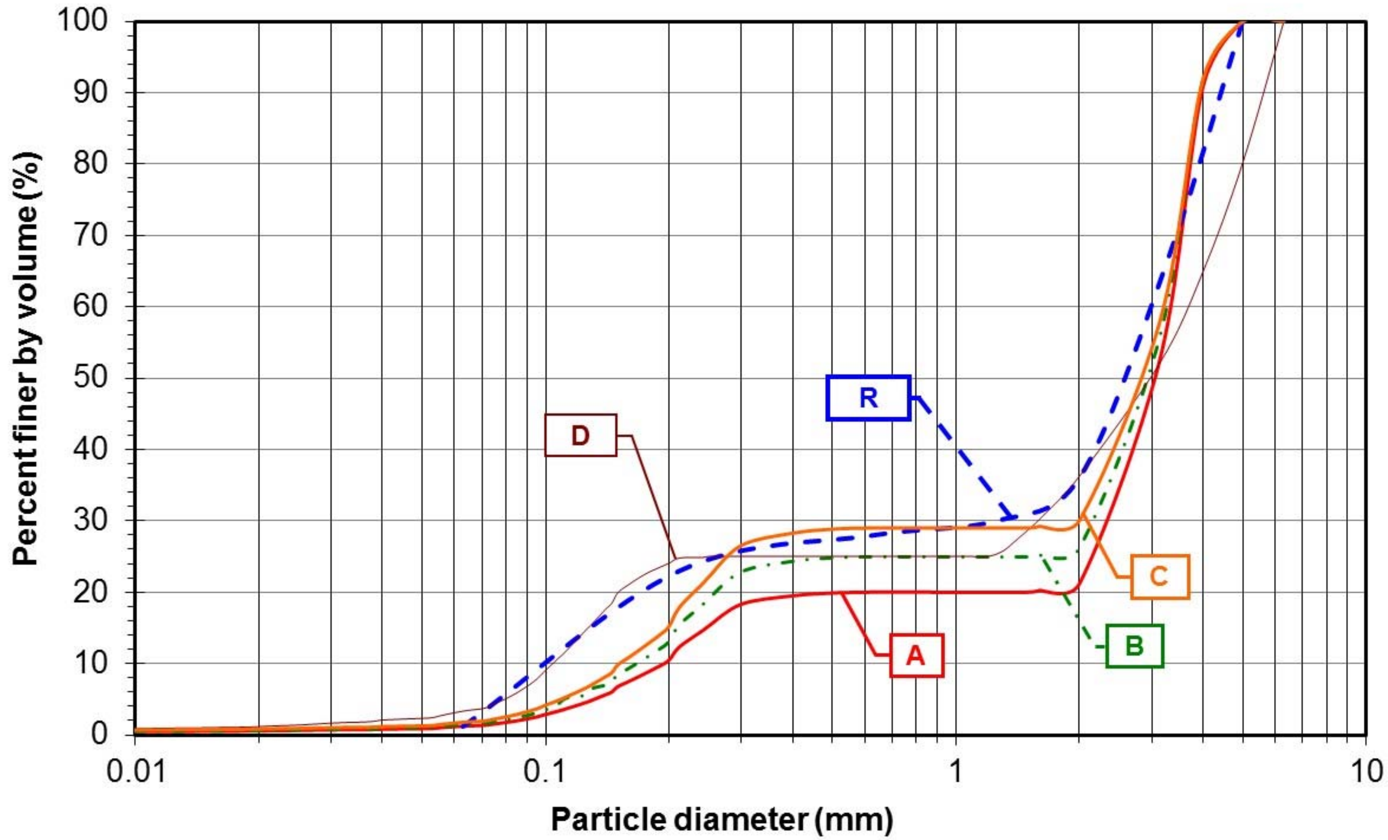
Histories of hydraulic loading

- Hydraulic gradient controlled conditions:



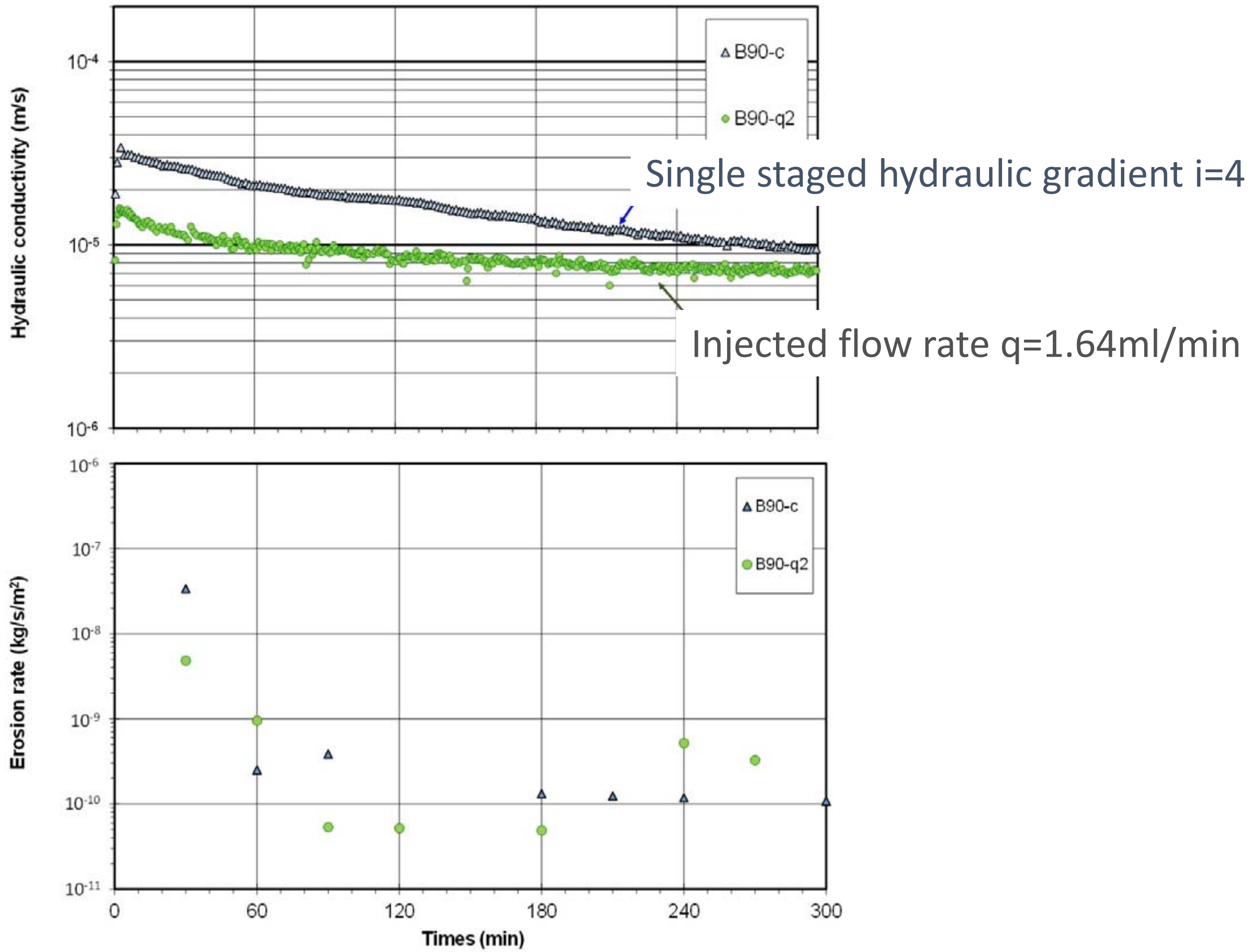
- Flow rate controlled conditions: q_1=1.247 ml/min q_2=1,641 ml/min

Grain size distribution of tested cohesionless soils



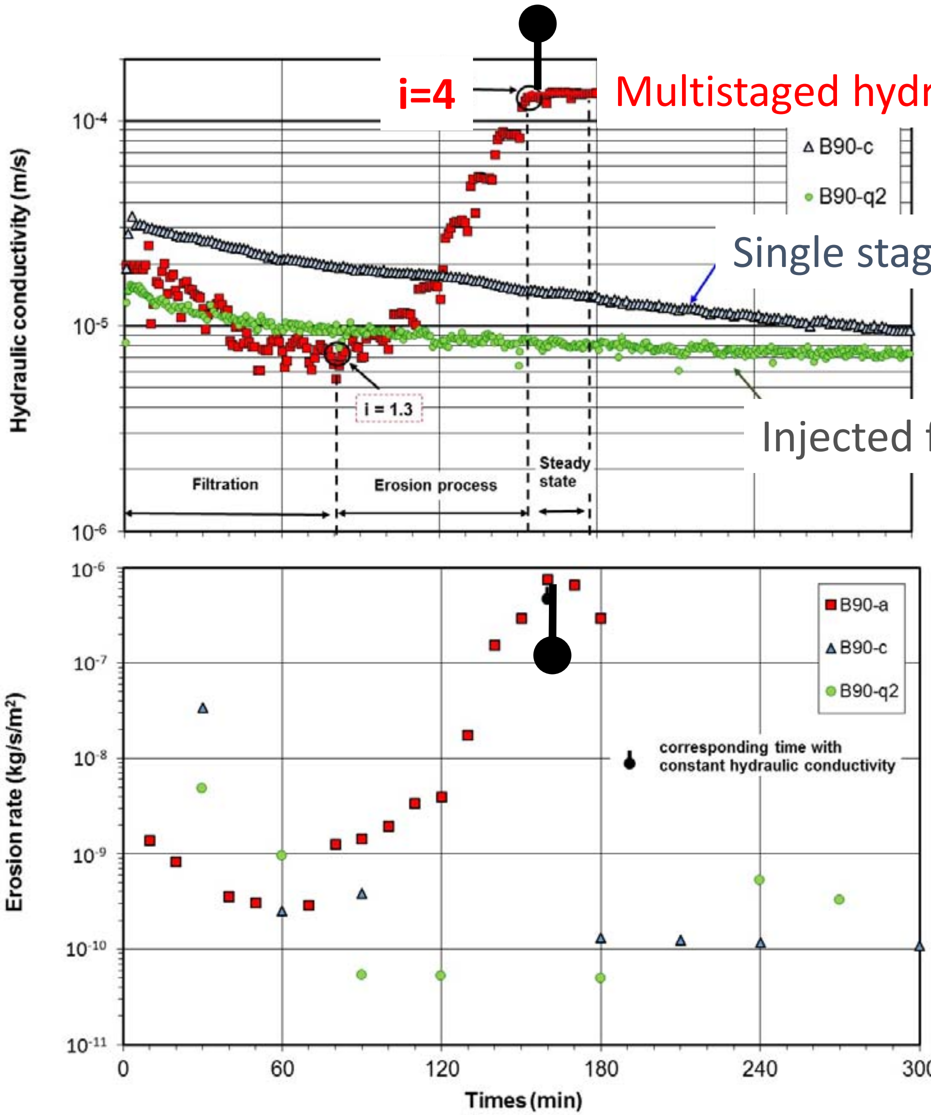
Hydraulic conductivity

Rate of erosion



Hydraulic conductivity

Rate of erosion

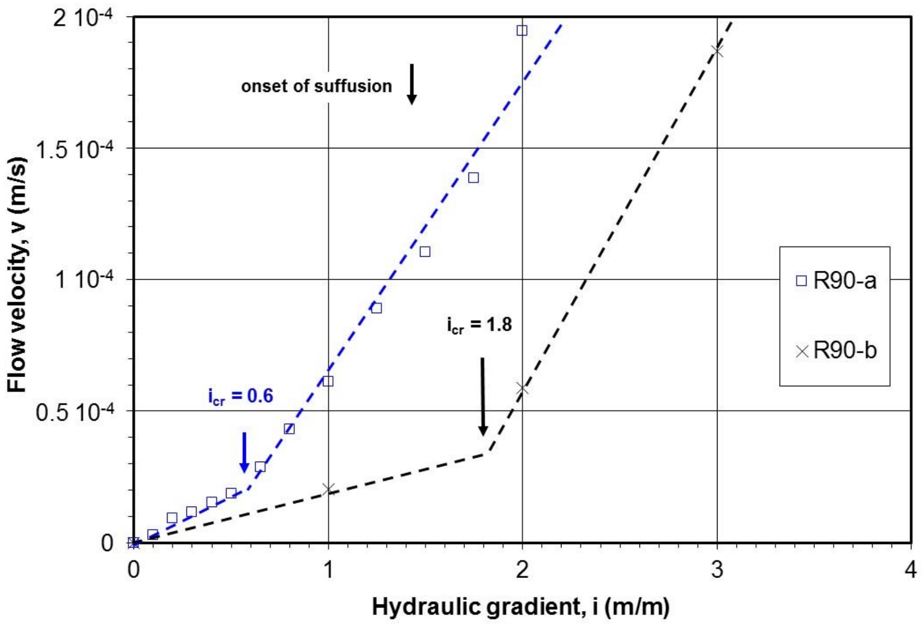


same soil,
same device and operator
same hydraulic gradient
but **different** processes according to the **history of hydraulic loading**

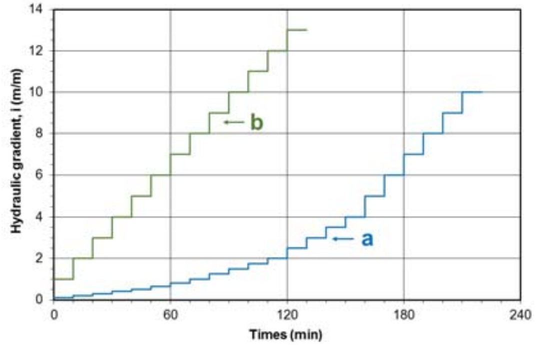
Steady state

Onset of suffusion

Skempton & Brogan ‘s approach

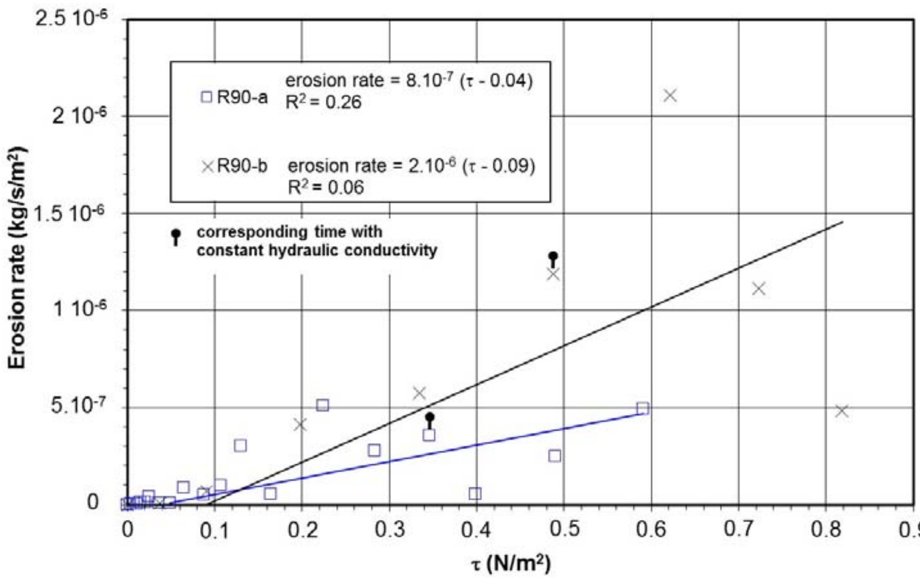


i_{cr}-a < i_{cr}-b



Development of suffusion

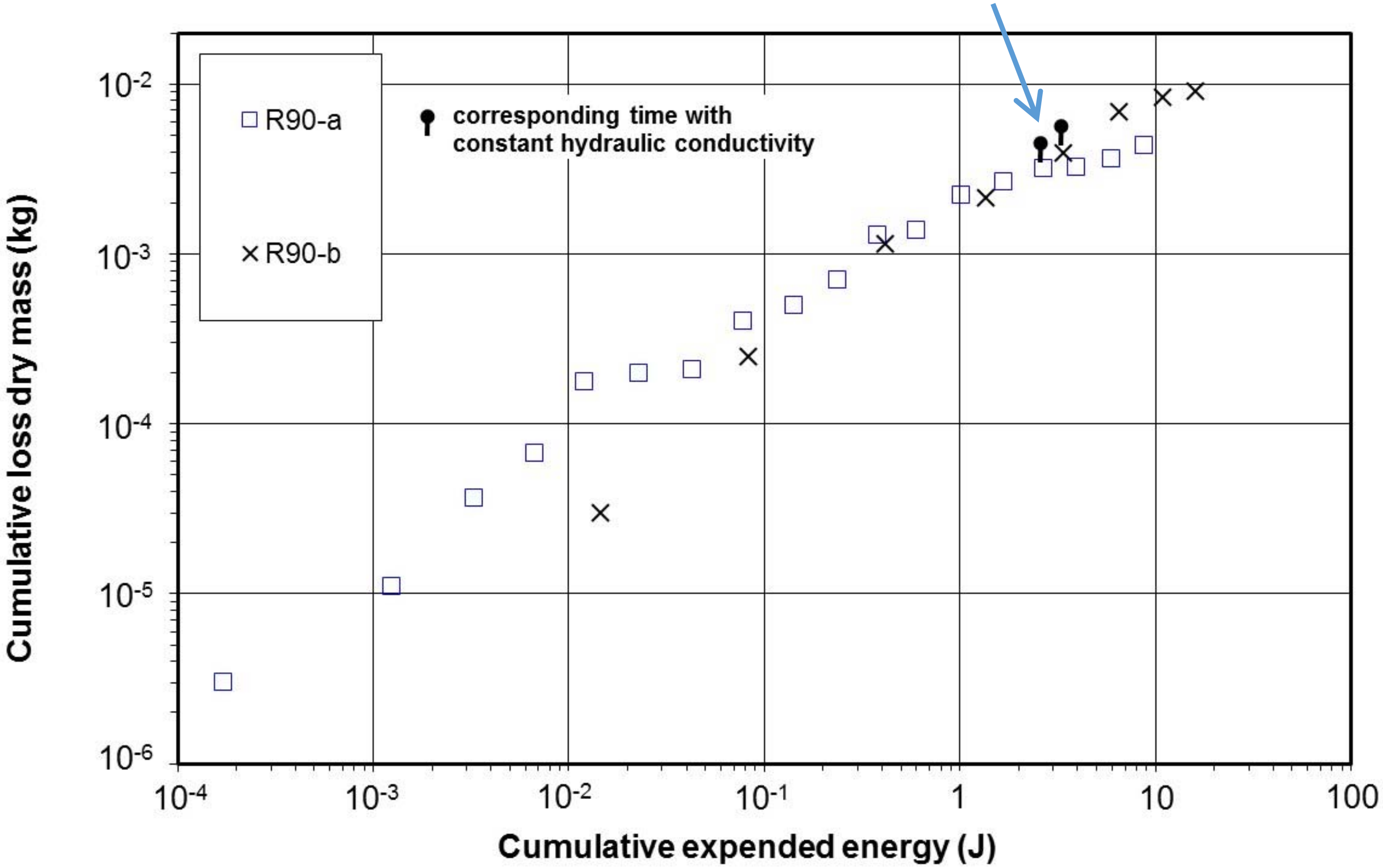
k_d-a < k_d-b



Not possible under single stage hydraulic gradient or under flow rate controlled conditions

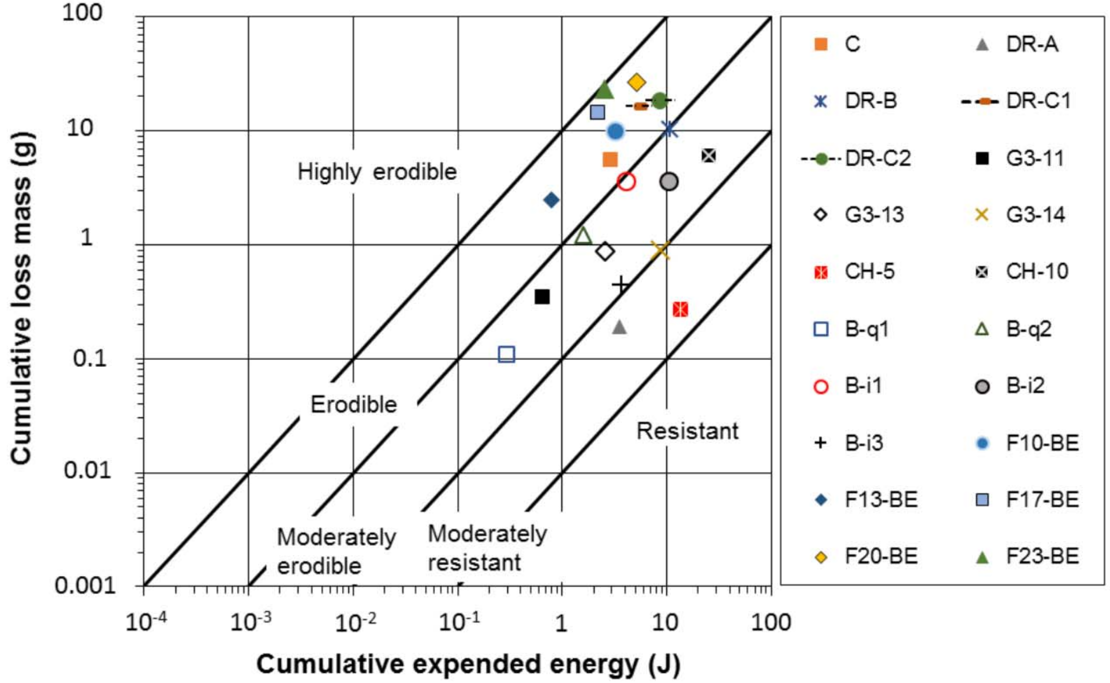
Energy based method

At steady state $I_{\alpha} = 2.94$



Rochim A., Marot D., Sibille L., Le V.T. Effect of hydraulic loading history on the characterization of suffusion susceptibility of cohesionless soils. Journal of Geotechnical and Geoenvironmental Engineering (ASCE), in press

Suffusion susceptibility classification



Marot D., Rochim A., Nguyen H.H., Bendahmane F., Sibille L. (2016). Assessing the susceptibility of gap graded soils to internal erosion: proposition of a new experimental methodology. Natural Hazards

Le V.T., Marot D., Rochim A., Bendahmane F., Nguyen H.H. Suffusion susceptibility investigation by energy based method and statistical analysis. Canadian Geotechnical Journal. Accepted, in press.

Density Grain shape Plasticity GSD

Estimation for gap-graded soils

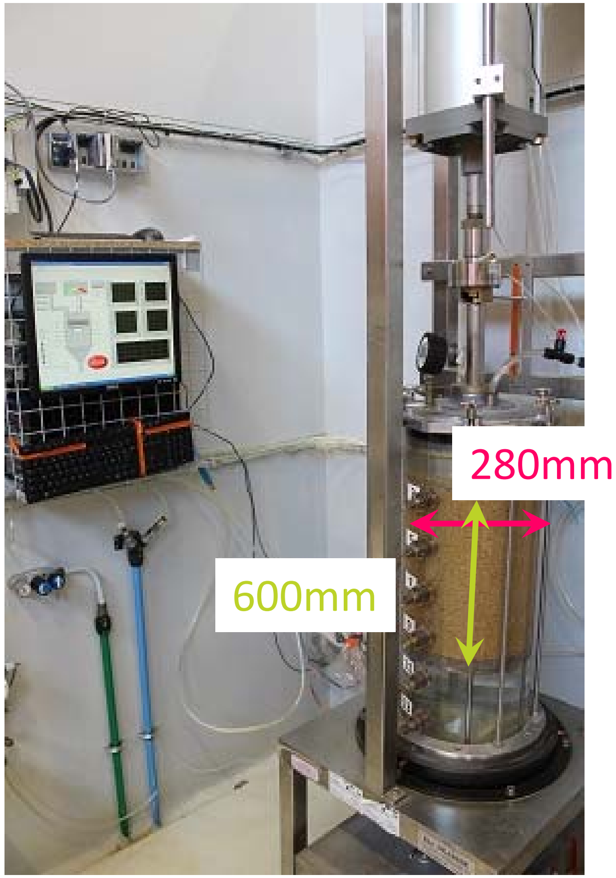
$$I_\alpha = -37.62 + 0.67\,\gamma_d + 0.64\,\varphi - 0.03 V_{BS} + 0.09 \text{Finer KL} - 1.43P + 0.63 G_r + 0.76 d_5 - 0.97 d_{60} + 0.61 d_{90}$$

Estimation for widely-graded soils

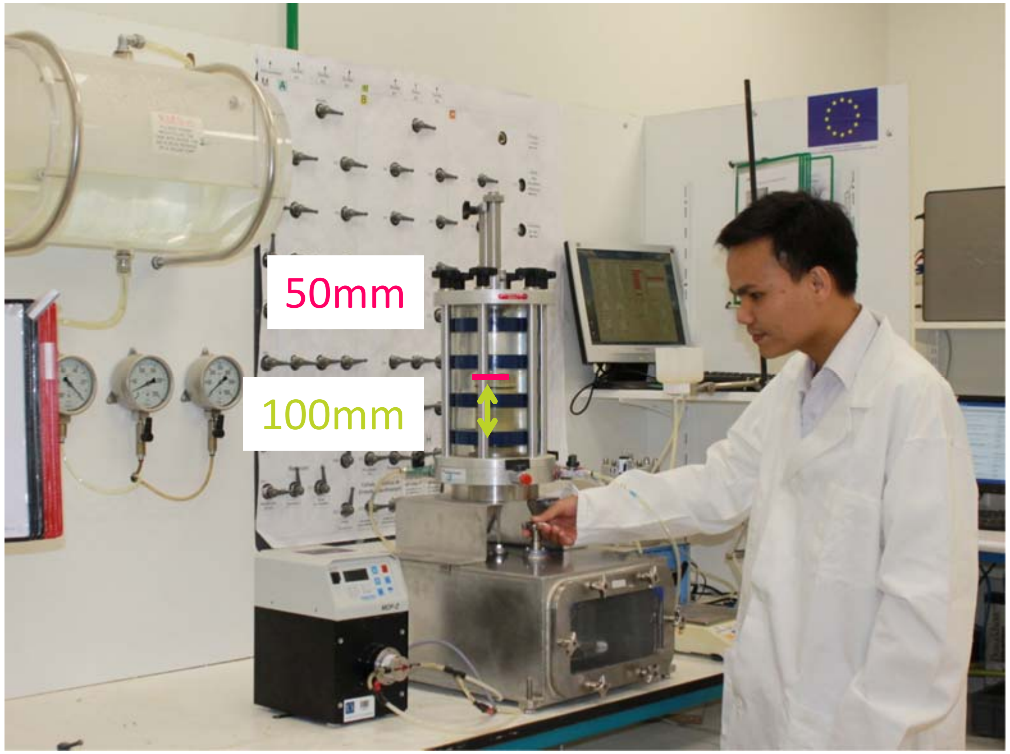
$$I_\alpha = -26.34 + 0.43\gamma_d + 0.66\,\varphi + 1.15 V_{BS} - 0.16 \text{Finer KL} + 0.37P + 6.82 d_5 - 1.26\, d_{60}$$

Testing devices

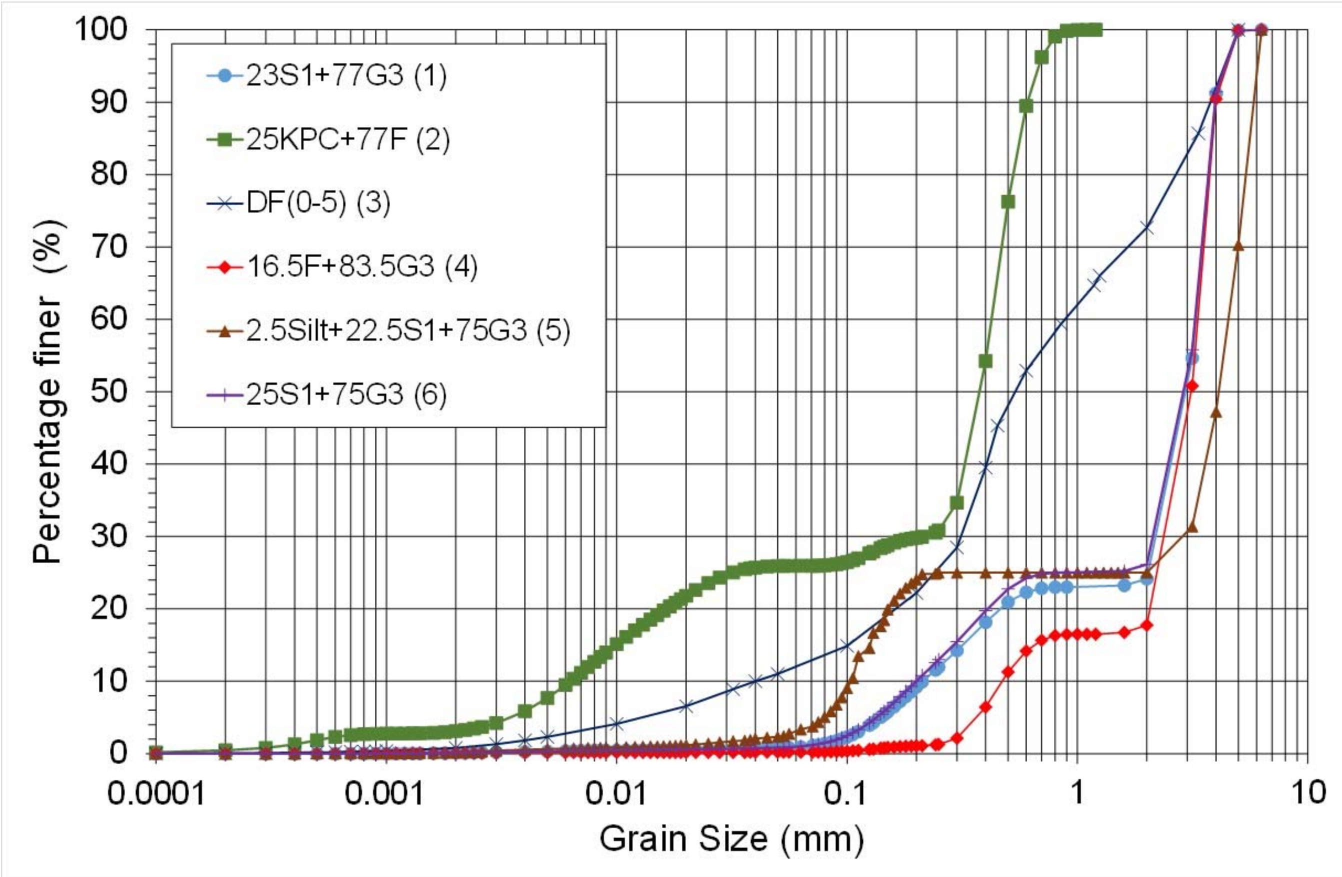
Oedopermeameter



Triaxial erodimeter



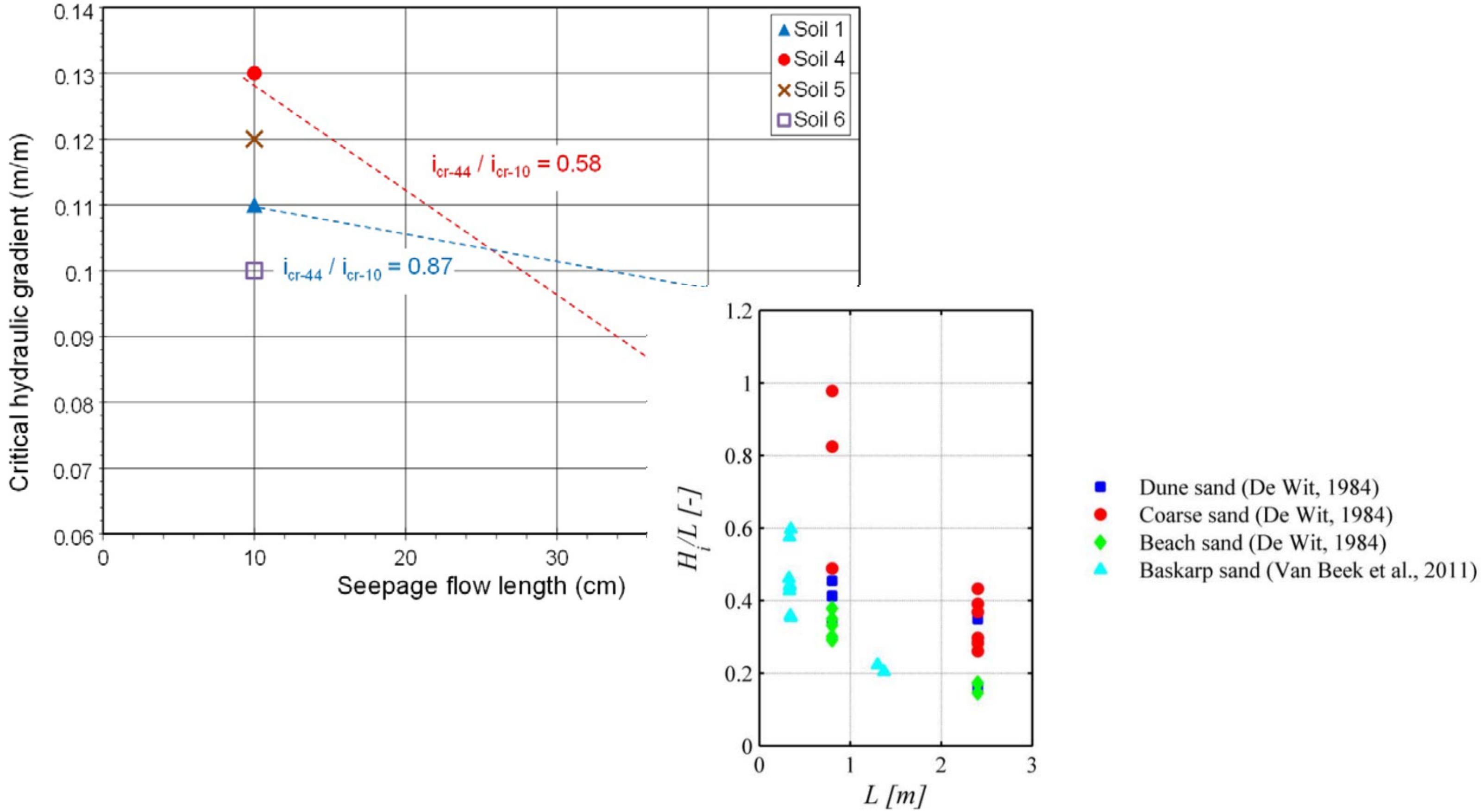
Grain size distribution of tested soils



Tests under multistaged hydraulic gradients

Onset of suffusion

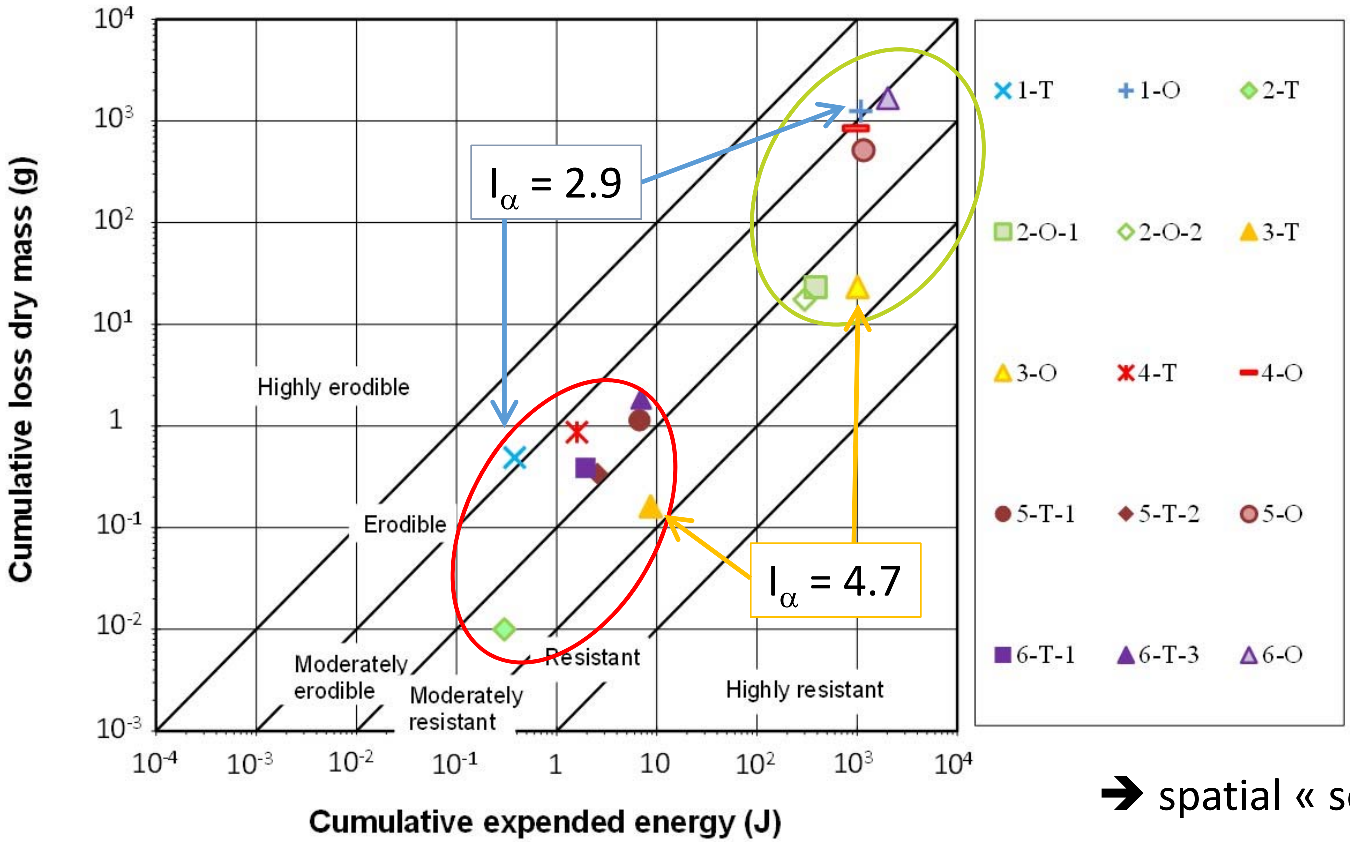
➔ contradictory to safety assessment



van Beek (2015). Backward erosion piping, initiation and progression. PhD Thesis TUDelft

Energy based method

Triaxial erodimeter tests Oedopermeameter tests



Zhong C. et al.
Comparison of erodimeters and interpretative methods for suffusion susceptibility characterization.
Under review Journal of Geotechnical and Geoenvironmental Engineering (ASCE)

➔ spatial « scale effect » **not** intrinsic

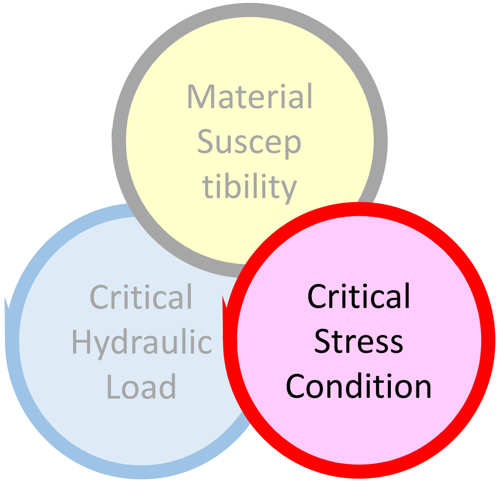
Selection of the most successful **criterion** between criteria from Kenney & Lau, Chang & Zhang or Wan & Fell.

If **potential instability**, the erodibility characterisation needs **suffusion tests**,

Computation of energy dissipated the water seepage, E_{flow}
(by temporal integration of the erosion power) and measurement of the cumulative **eroded dry mass**

Finally the **erosion sensibility classification** can be evaluated by the **erosion resistance index** I_{α}

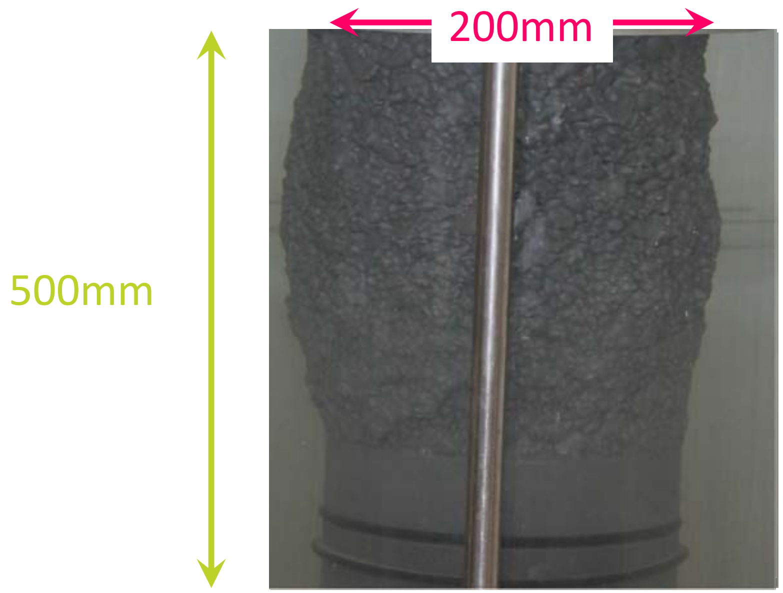
Perspectives



In partnership with EDF

Large triaxial erodimeter

Undisturbed cohesionless soils



➔ Characterization of **suffusion development**

➔ Characterization of induced variation of **soil mechanical behavior**

Large triaxial device for suffusion erodibility and mechanical behavior characterization of coarse soils, 25th Meeting of the European Working Group on internal erosion in embankment dams & their foundations

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Thank you for your attention

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