Managing Water Quality for Public Health

Department of Agriculture, Forest and Food Sciences University of Torino

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Nanoscale iron particles for groundwater remediation

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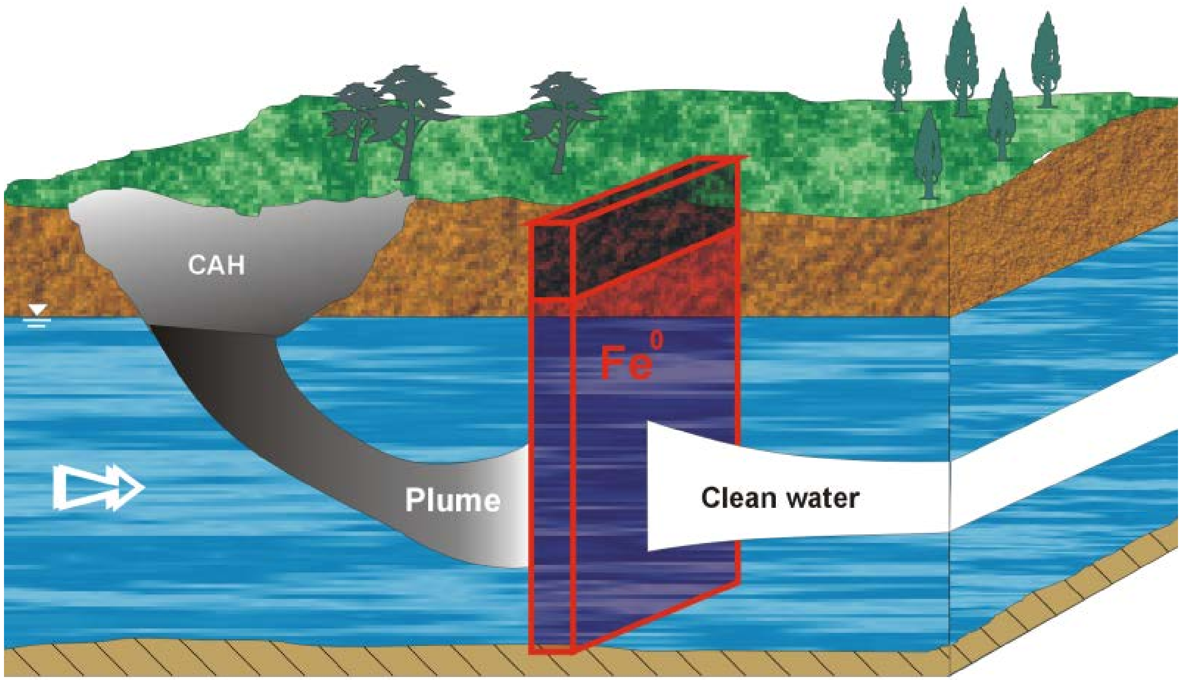
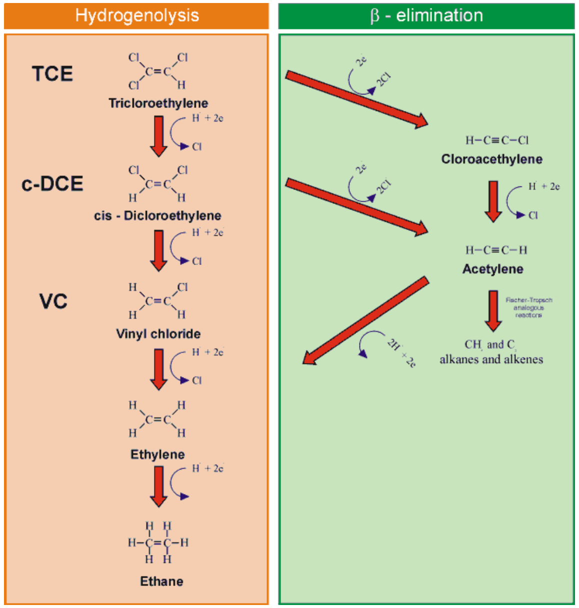
Ingegneria degli Acquiferi
Groundwater Engineering

Zerovalent iron permeable reactive barriers

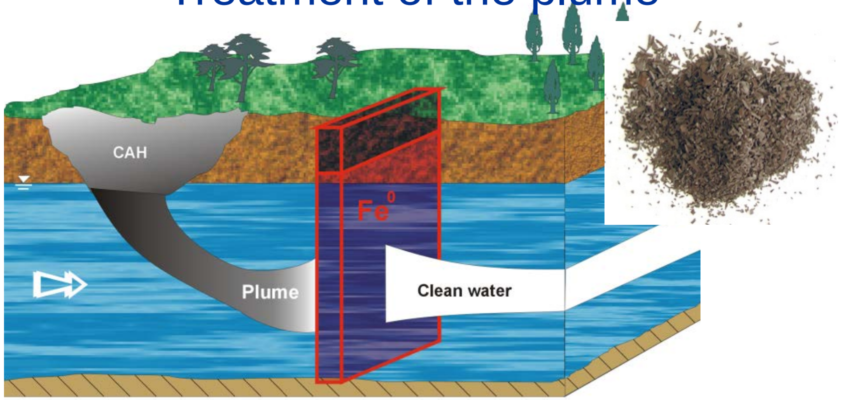




Millimetric vs Nanoscale zerovalent iron

Millimetric iron (PRB)

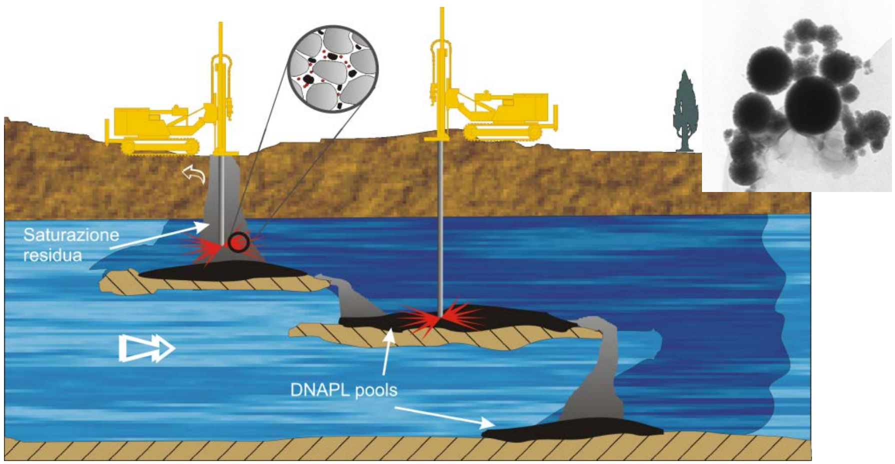
Treatment of the plume



Installation:
-high costs
-technical problems
-maximum depth
<30m

Nanoscale iron injection

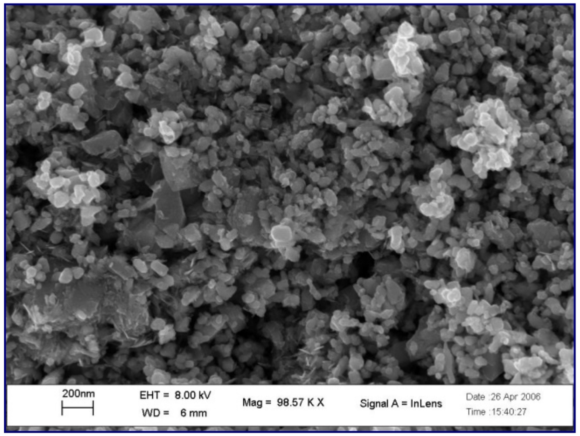
Treatment close to the source



Installation:
-lower costs
-easily injectable
-maximum depth
<70m

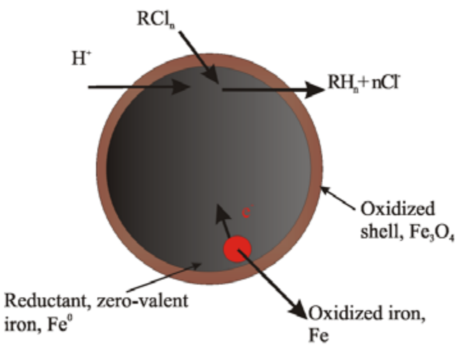
Reactivity

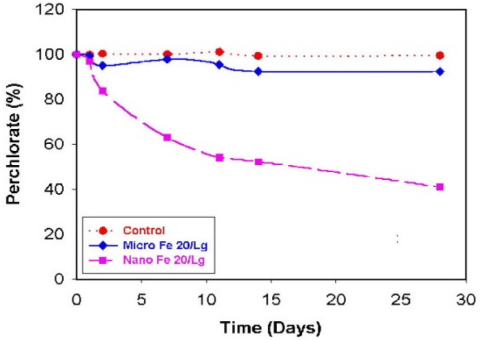
1 kg of nanoscale iron = 2 x Stadio Olimpico (Roma)



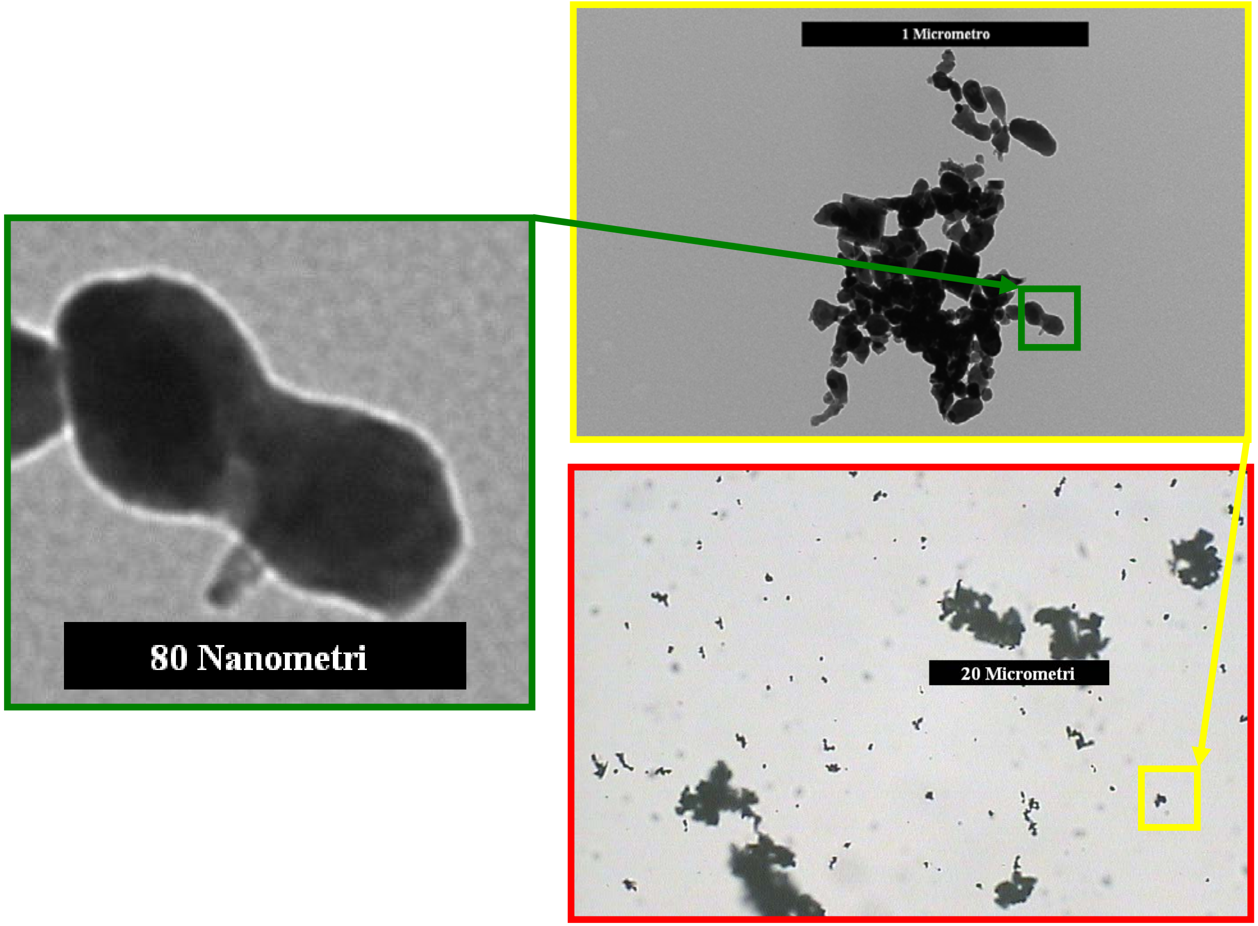
~30000 m^2

$$\frac{dc_{TCE}}{dt} = -kc_{TCE} = -\left(k_M \cdot c_{Fe}\right) \cdot c_{TCE} = -\left(k_{SA} \cdot SSA \cdot c_{Fe}\right) \cdot c_{TCE}$$



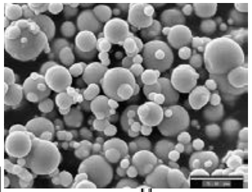


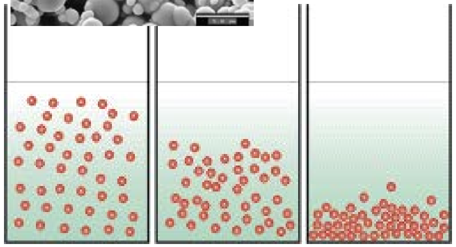
Agglomeration NZVI



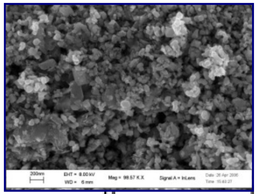
MZVI & NZVI: suspension stability

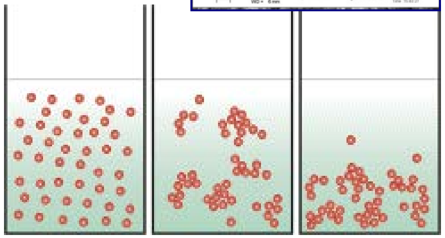
MZVI





NZVI





(0.1-100 μm)

(15–100 nm)

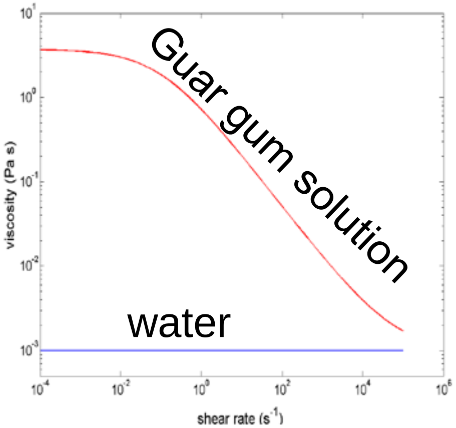
relevant specific weight, high density

particle – particle attraction

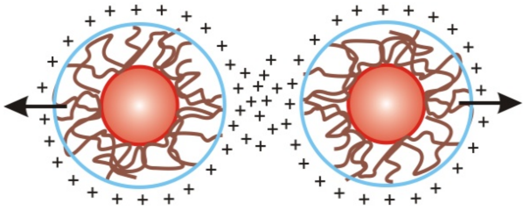
sedimentation & aggregation

STABILIZATION

- KINETIC: polymers to increase viscosity of the suspensions (high concentration)



- THERMODYNAMIC: salts and polymers to increase the repulsion among particles (low concentration)



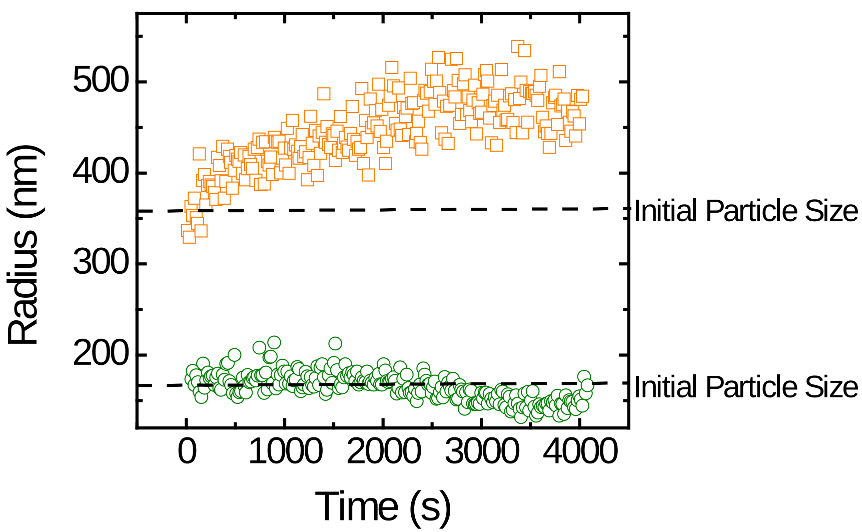
Guar Gum

1. GREEN: natural origin, extracted from guar plant
2. CHEAP: Sigma-Aldrich: 44.60 €/kg
   Commercial: ~2 €/kg
3. COMMERCIALLY AVAILABLE: used in food industry
   → non toxic

Stabilization of ZVI

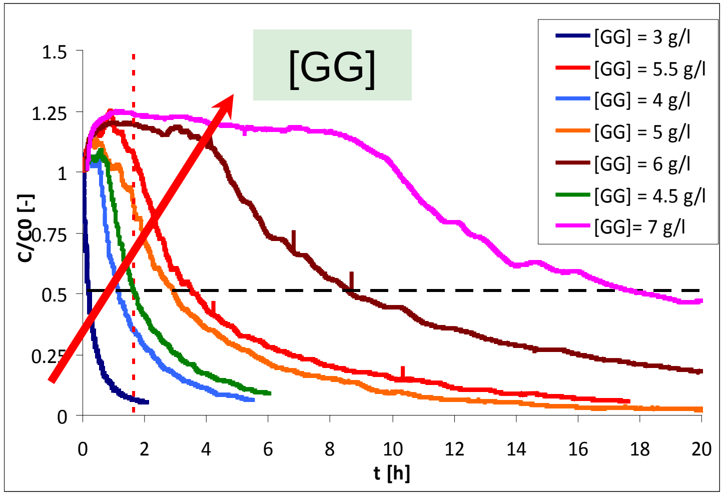
- Thermodynamic stabilization
- DLS analysis: NZVI and GG @ 0.5 g/l

10mM NaCl



□ Bare Particles
○ Particles in solution of Guar Gum 0.5 g/L

- Kinetic stabilization
- Sedimentation tests: MZVI & NZVI 20 g/l, GG 6 g/l

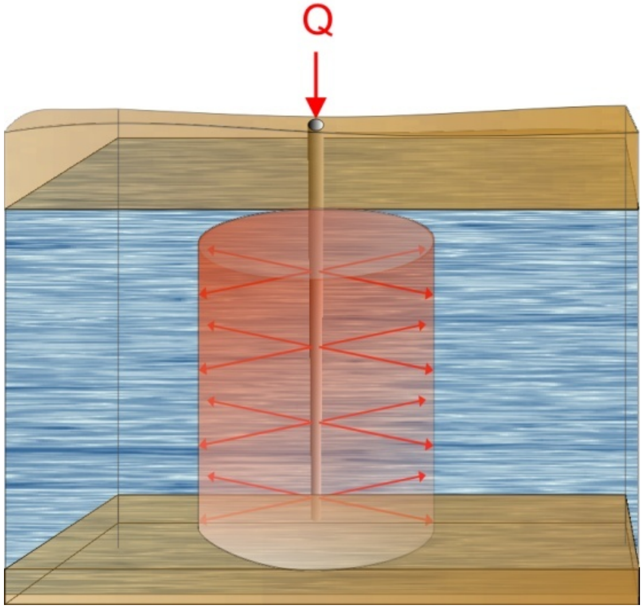


Gastone, F., T. Tosco, and R. Sethi (2014), J Colloid Interf Sci, 421, 33-43.

Delivery in the subsurface

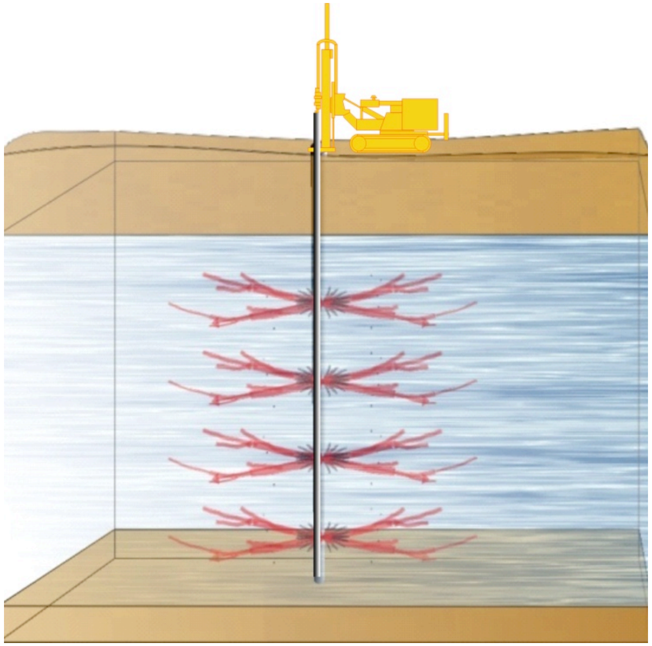
Permeation

- Homogeneous iron distribution
- Small injection pressure
- Well or piezometer



Fracturing

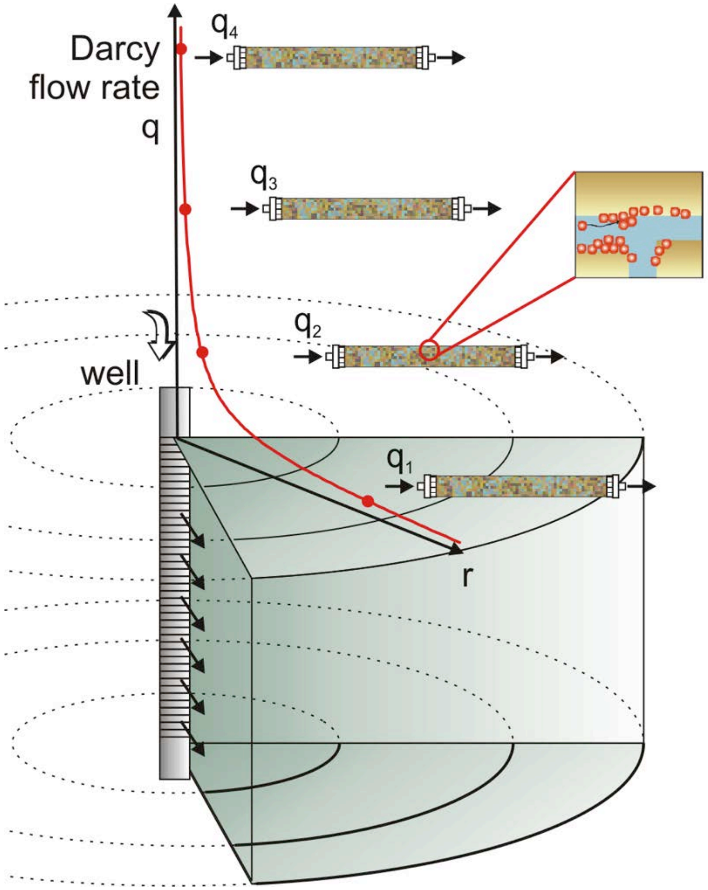
- Heterogeneous distribution
- High injection pressure
- Direct push system



Modeling

- AIM:
  - develop a radial model to simulate the transport of non-Newtonian slurries of iron nanoparticles and clogging of the media

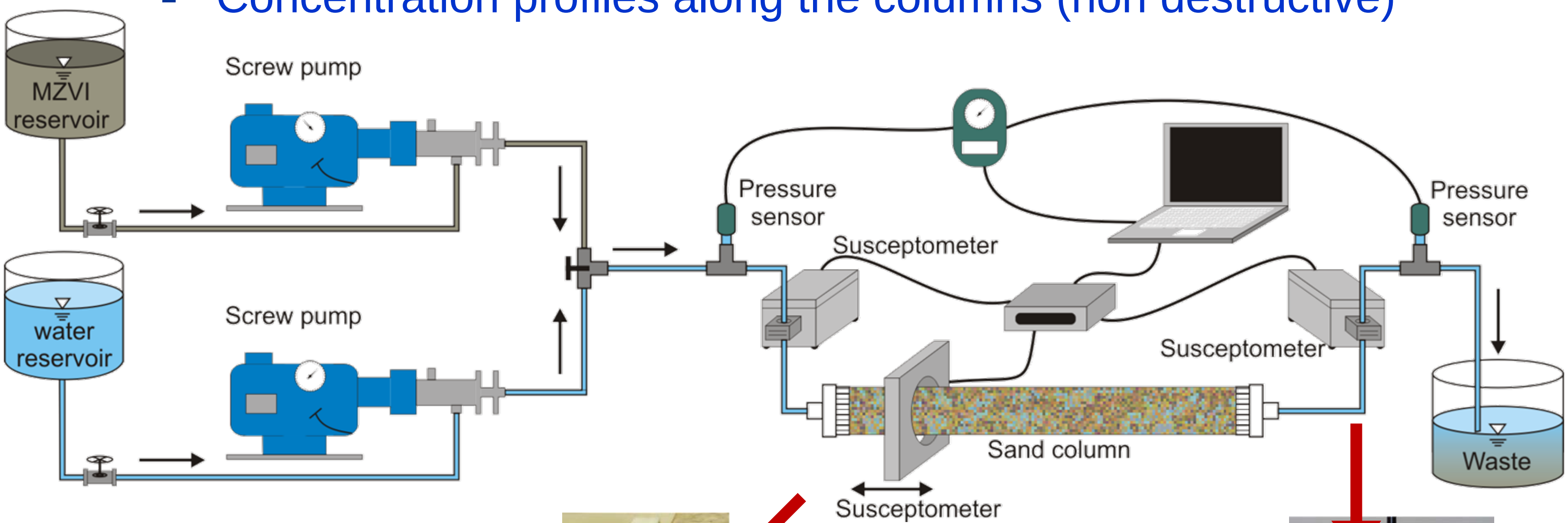
- OUTLINE:
  - Lab tests
  - 1D cartesian model (E-MNM1D)
  - radial model (E-MNM)

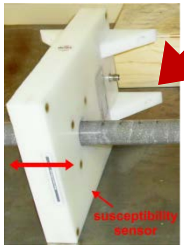


Gastone, F., T. Tosco, and R. Sethi (2014), *Submitted*

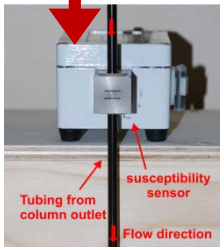
Laboratory tests: Column transport tests

- Monitored data:
  - Pressure drop at column ends (continuous)
  - Breakthrough iron concentration (continuous)
  - Concentration profiles along the columns (non destructive)

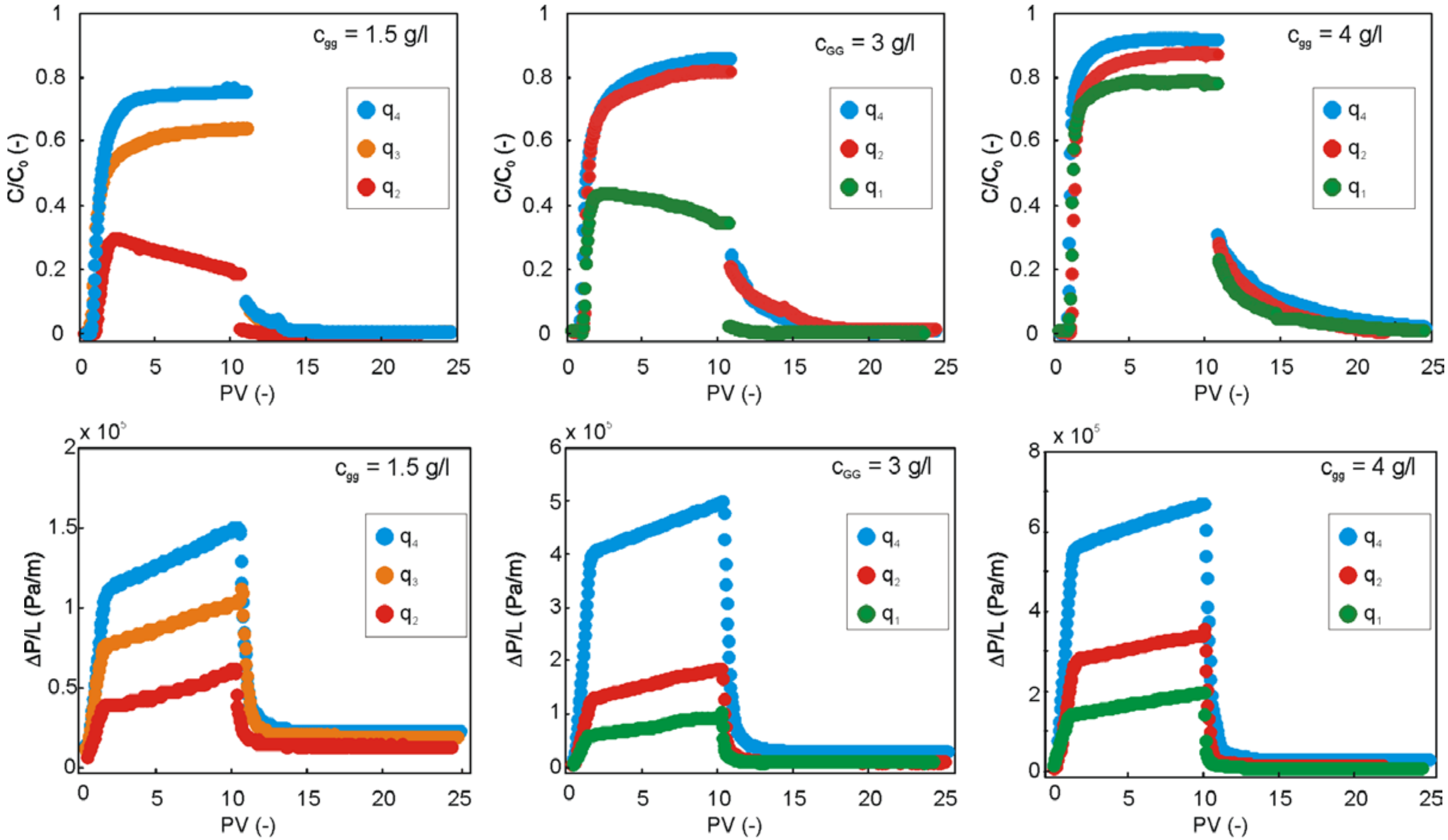




Magnetic susceptibility sensors (MS2 series, Bartington, UK)



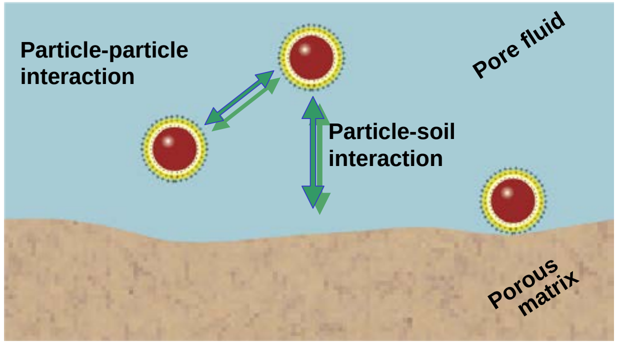
Laboratory tests: Column transport tests

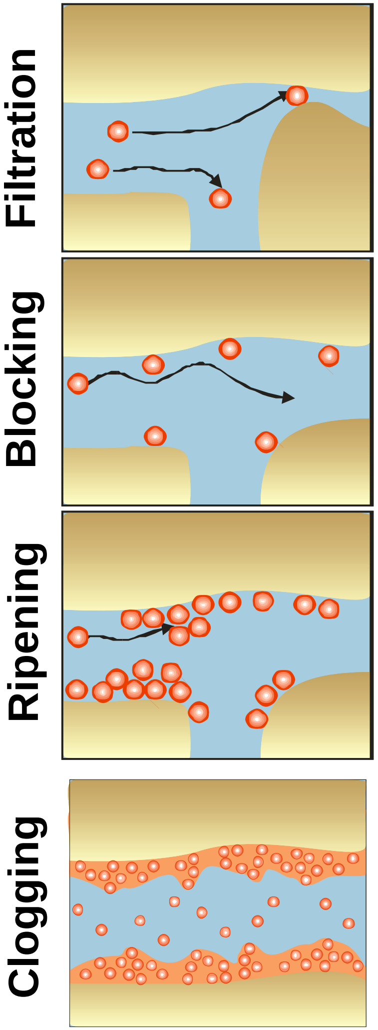


[Tosco et al., 2014, Journal of Contaminant Hydrology 166, 34-51]

Modeling approach: key aspects

- Key aspects:
  1. **Particle interactions with the porous matrix**
     - Physico-chemical interactions: blocking, ripening
     - Physical filtration/straining
  2. **Clogging**:
     - Influence of particle deposits on porous medium properties
     - Coupled problem
  3. **Viscosity** of the dispersant fluid
     - Shear-thinning behavior
     - Darcy's law for non-Newtonian fluids





MNMs: coupled model for 1D simulation

Darcy's law:

$$q_m = -\frac{K(s)}{\mu_m(\dot{\gamma}_m, c, c_x)}\frac{\partial p}{\partial x}$$

Transport equations:

$$\begin{cases} \frac{\partial}{\partial t}(\varepsilon_m c_x) + \frac{\partial}{\partial x}(q_m c_x) - \frac{\partial}{\partial x}\left(\varepsilon_m D \frac{\partial c_x}{\partial x}\right) = 0 \\ \frac{\partial}{\partial t}(\varepsilon_m c) + \frac{\partial(\rho_b s_1)}{\partial t} + \frac{\partial(\rho_b s_2)}{\partial t} + \frac{\partial}{\partial x}(q_m c) - \frac{\partial}{\partial x}\left(\varepsilon_m D \frac{\partial c}{\partial x}\right) = 0 \\ \frac{\partial(\rho_b s_1)}{\partial t} = \varepsilon_m k_{a,1}\left(1 + A_1 s_1^{\beta_1}\right)c - \rho_b k_{d,1} s_1 \\ \frac{\partial(\rho_b s_2)}{\partial t} = \varepsilon_m k_{a,2}\left(1 + \frac{x}{d_{50}}\right)^{\beta_1} c - \rho_b k_{d,2} s_2 \end{cases}$$

Porosity:

$$\varepsilon_m(s) = n - \frac{\rho_b}{\rho_s} s$$

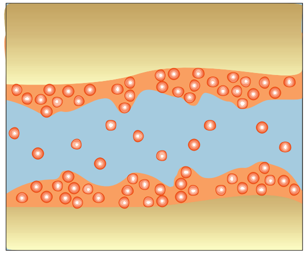
Fluid viscosity:

$$\mu_m(\dot{\gamma}_m, c, c_x) = \mu_{m,\infty} + \frac{\mu_{m,0}(c, c_x) - \mu_{m,\infty}}{1 + \left[\lambda_m(c)\cdot\dot{\gamma}_m\right]^{\chi_m(c)}}$$

$$\dot{\gamma}_m = \alpha_\gamma \frac{q_m}{\sqrt{K(s)\varepsilon_m(s)}}$$

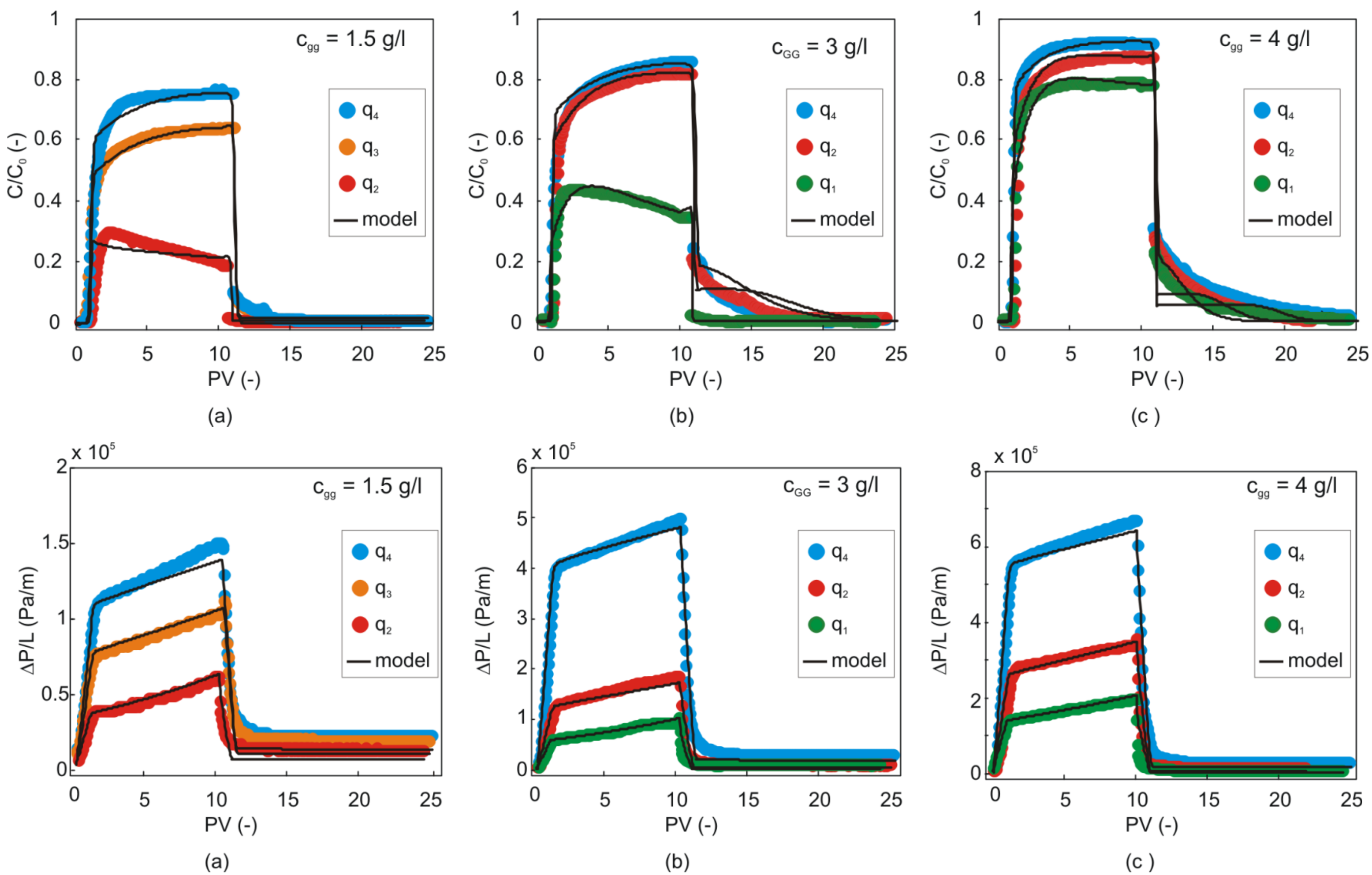
Permeability:

$$K(s) = \left[\frac{\varepsilon_m(s)}{n}\right]^3 \left(\frac{A_0}{A_0 + \vartheta A_c \frac{\rho_b}{\rho_c} s}\right)^2 K_0$$



http://www.polito.it/groundwater/software/MNMs.html

Modeling results: 1D

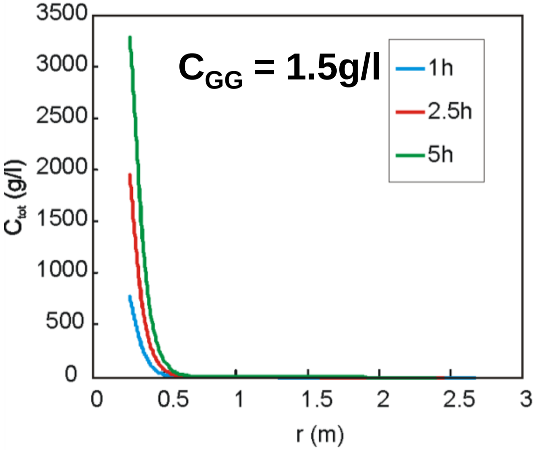


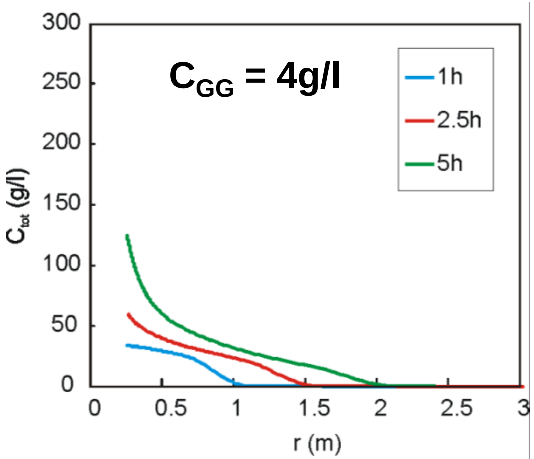
Gastone, F., T. Tosco, and R. Sethi (2014), J Colloid Interf Sci, 421, 33-43.

Model results: 1D radial transport of MZVI

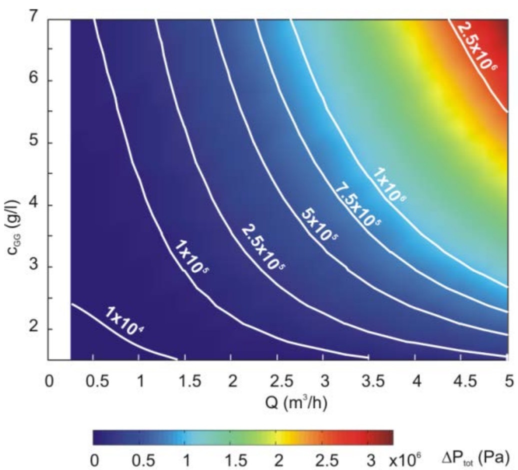
- Example of model output:
  - MZVI in guar gum
  - C_{GG} = 1.5 and 4 g/l
  - 1 m^3/h per unit length of the well screen
  - Up to 5 hours of injection

MZVI concentration

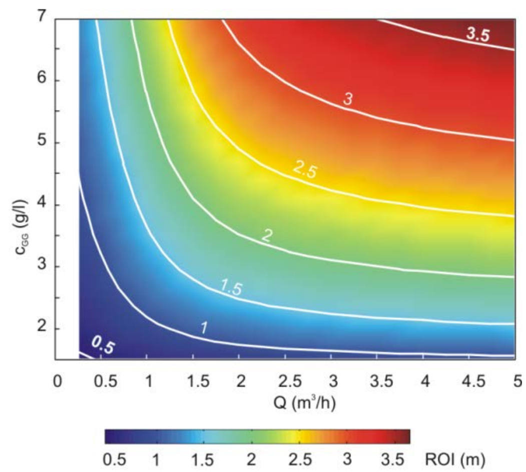




Pressure drop



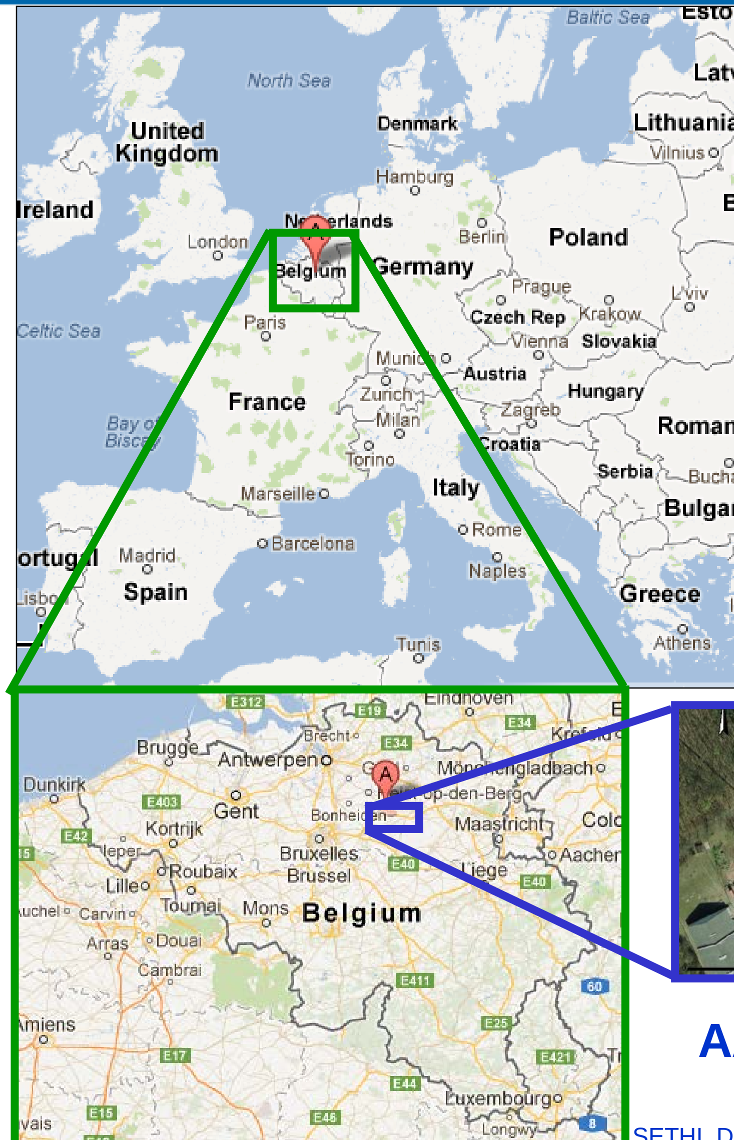
Radius of influence



[Tosco et al., 2014, Journal of Contaminant Hydrology 166, 34-51]

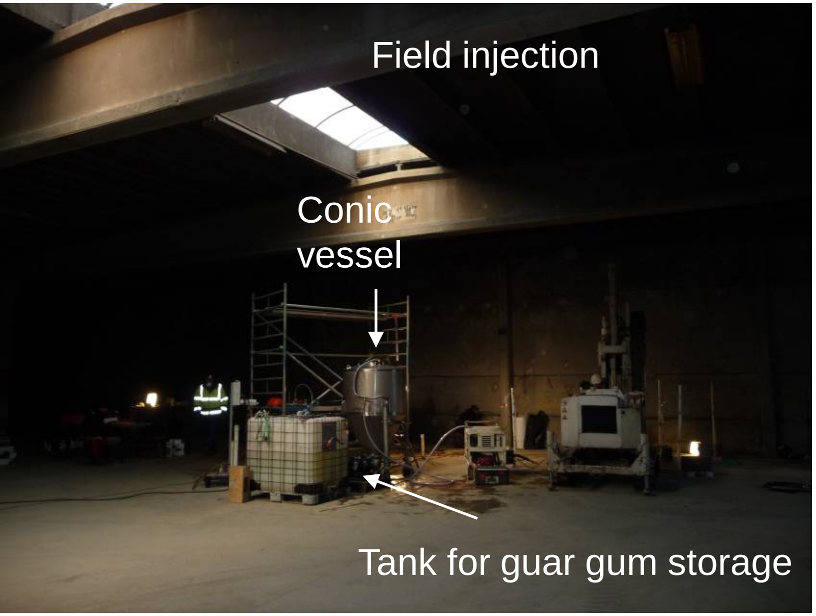
Pilot Test 1- Aarschot site (Belgium)

- Aarschot site
  - 1975-1980: wet painting production
  - 1980: Powder coatings
- Indoor Contamination
  - Chlorinated ethanes (1,1-DCA and 1,1,1-TCA)
  - Chlorinated ethenes (TCE, cis-1,2-DCE)



AARSCHOT

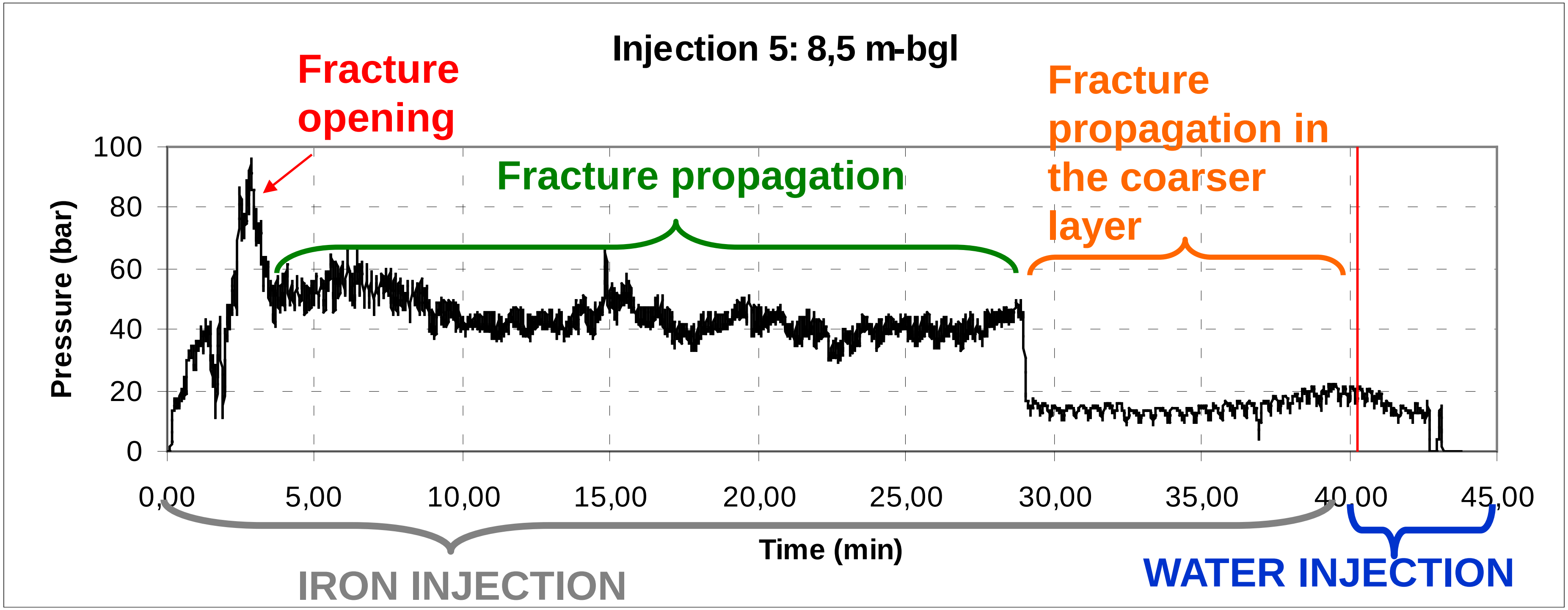
Injection @ Aarschot site November 2011



High-shear mixing iron particles dispersion

Injection level	Depth (m-bgl)	Volume (l)	Injection time Ti (min)	Average Flow Rate (l/min)
1	10,5	300	34,53	8,69
2	10	300	31,15	9,63
3	9,5	300	33,583	8,93
4	9	300	35,7	8,40
5	8,5	300	40,283	7,45

Monitoring: Pressure during injection



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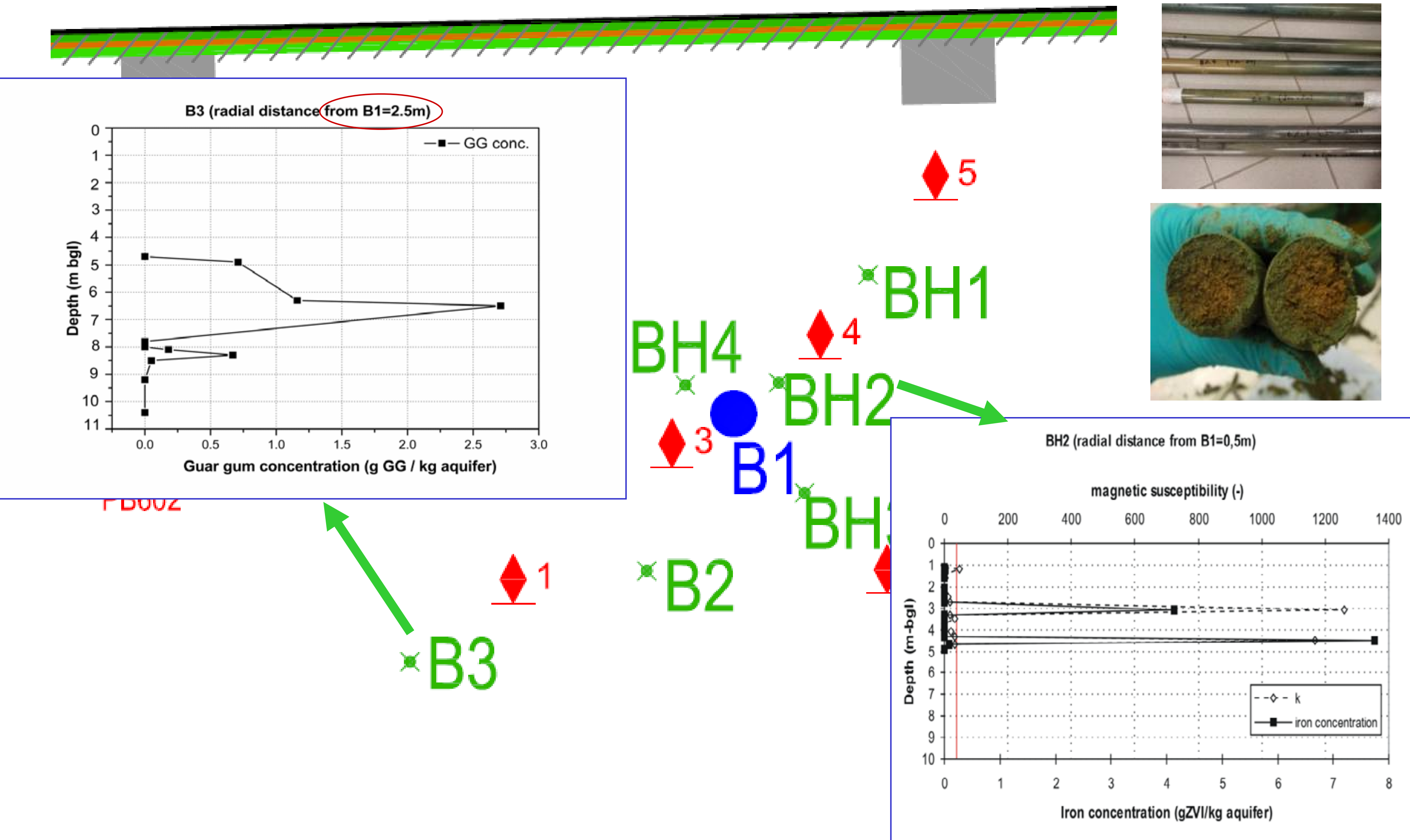
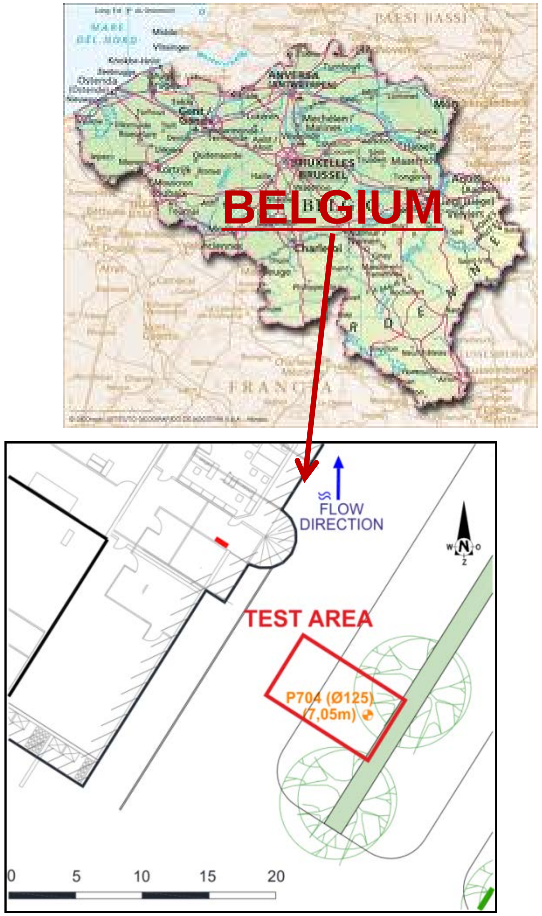
Iron distribution:chemical and susceptibility analysis

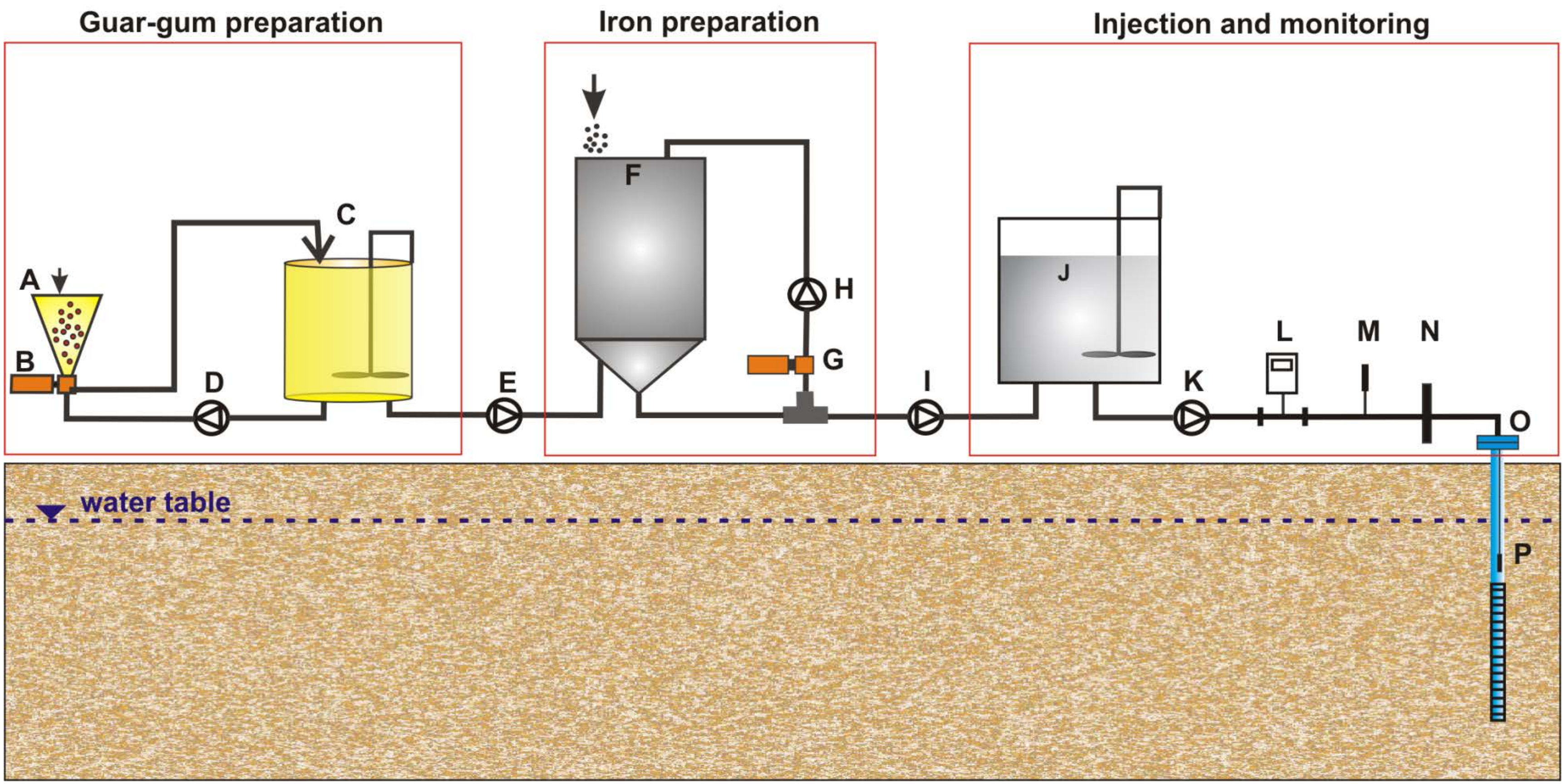


Pilot Test 2- Site P (Belgium)

- Site P (Belgium)
  - Active industrial site
- Contaminants conc.
  - PCE: C = 35 mg/l
- Geology
  - Medium K
  - Layers with fine sand
  - water table depth = 1.5 m;

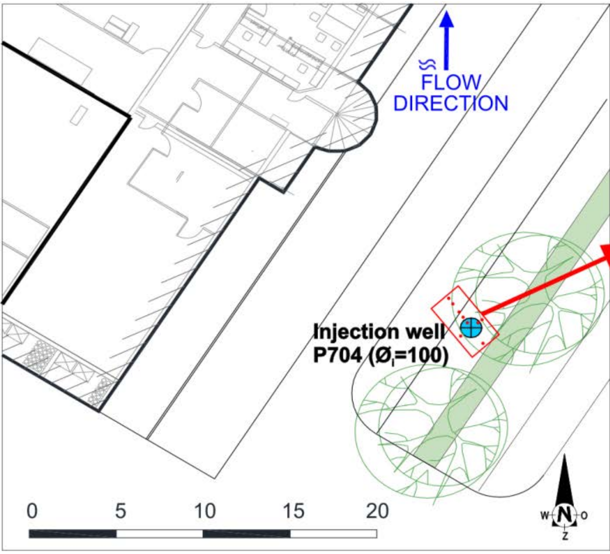


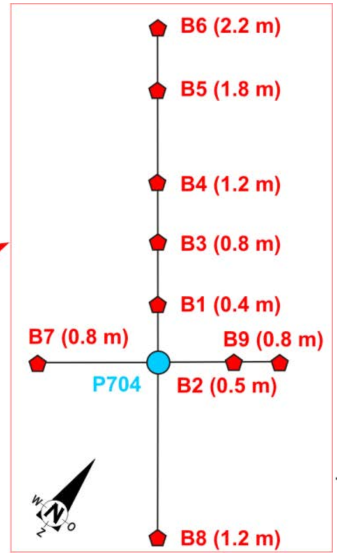
Injection set-up

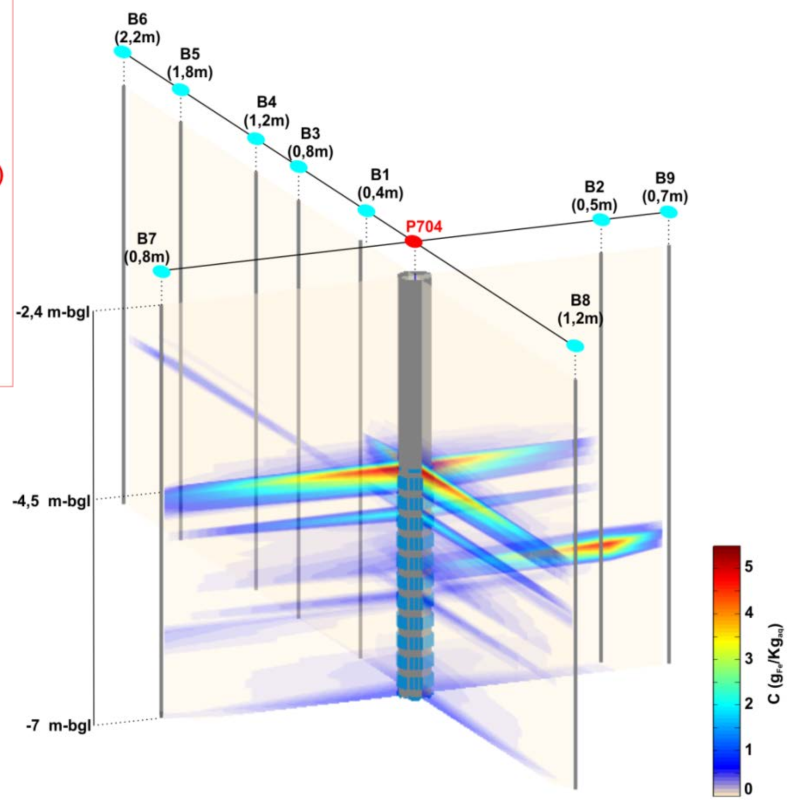


Field injection

Iron distribution after injection







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  - Master Students at Politecnico di Torino

Publications

- Tosco T., Petrangeli Papini M., Cruz Viggi C., Sethi R. (**2014**) Nanoscale zerovalent iron particles for groundwater remediation: a review. Journal of Cleaner Production
- Gastone, F., T. Tosco, and R. Sethi (**2014**), Green stabilization of microscale iron particles using guar gum: bulk rheology, sedimentation rate and enzymatic degradation, *J Colloid Interf Sci, 421, 33-43.*
- Gastone F., Tosco T., Sethi R., Guar gum solutions for improved delivery of iron particles in porous media (Part 1): porous medium rheology and guar gum-induced clogging*, submitted*
- Tosco T., Gastone F., Sethi R., Guar gum solutions for improved delivery of iron particles in porous media (Part 2): iron transport tests and modelling in radial geometry*, submitted*
- Luna M., Gastone F., Tosco T., Sethi R., Velimirovic M., Bastiaen L., Gemoets J., Muyshond R., Sapion H. and Klaas N. Low pressure pilot scale injection of guar gum stabilized microscale iron particles*, submitted*
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