Large Scale Experiments: Performance, Upscaling and Lessons Learned for Application in the Field

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NanoRem Final Conference

Nanoremediation for Soil and Groundwater Clean-up - Possibilities and Future Trends

Main Purpose of Large Scale Experiments

Lab scale
1D, 2D

Large Scale Experiments
3D + homogeneity

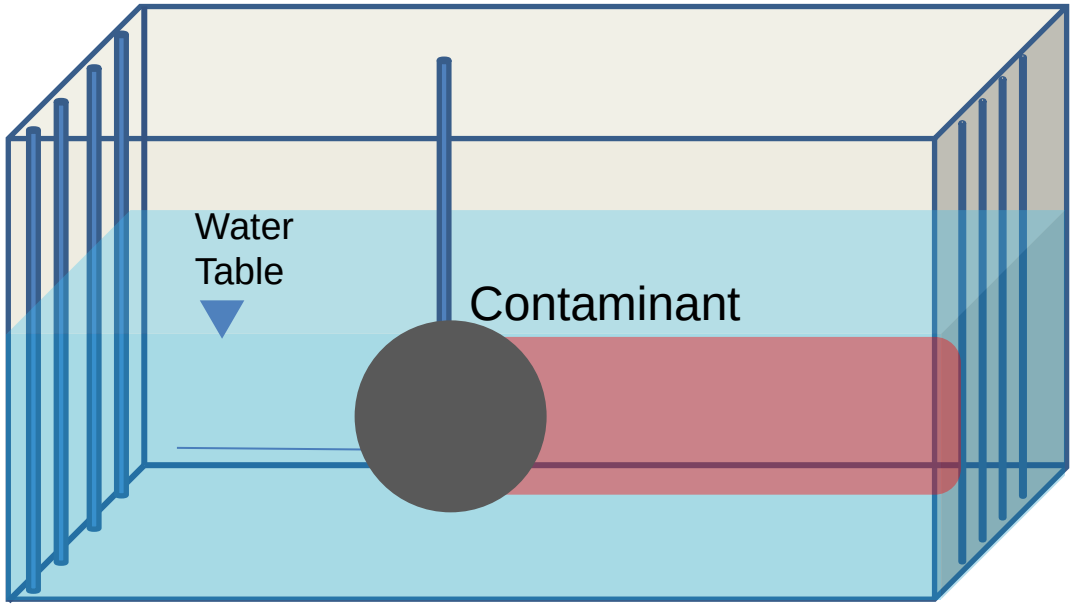
Field Application
3D + heterogeneity

Injecting NPs in field relevant scale experiments

- Bulk volume: 20 m³ ~ 300 m³
- Homogeneous aquifer
- usage of tap water for groundwater

Standard of NPs mobility and reactivity in 3D system

Principle of LSE



Artificial aquifer

Emplacement of contaminants

NP injection

Particle mobility in 3D injection

Particle reactivity in aquifer

Advantages:

Closed system and controlled boundary conditions

→ **Mass balance of NPs and contaminants**

Dense monitoring system

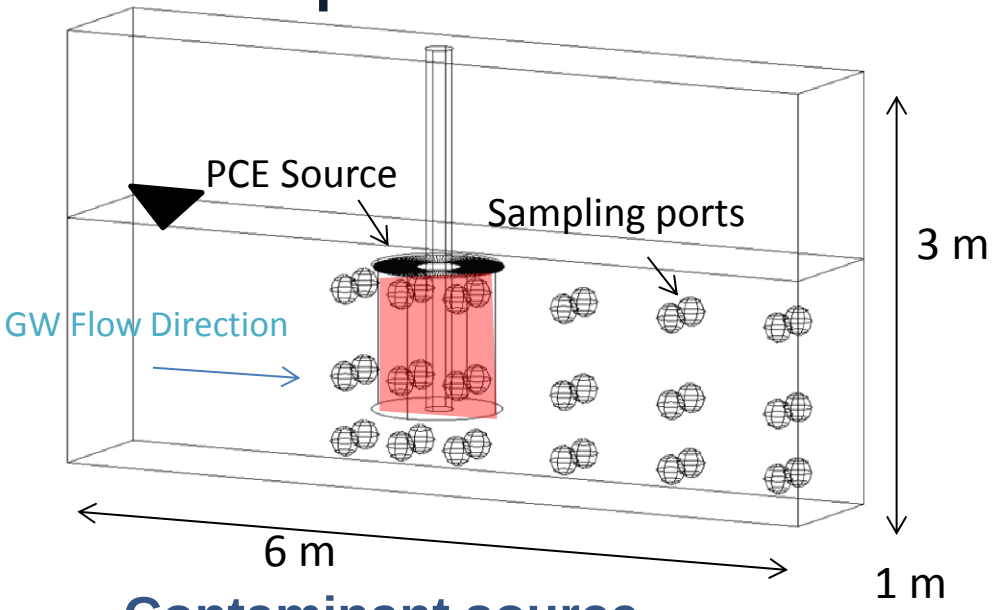
→ **Detail investigation of NP transport and reaction**

3 Large Scale Experiments

- Large scale flume experiments (LSF) for the remediation of a chlorinated hydrocarbon (CHC) source in a saturated aquifer
  - LSF 1: nano-ZVI (nZVI) particles (NANOFER STAR)
  - LSF 2: composite nZVI particles (Carbo-Iron®)

- Large scale container experiment (LSC) to test application of iron-oxides Goethite particles for the removal of a BTEX plume

Large Scale Flume Experiments



Artificial aquifers in large glass flumes

- L/W/H = 6.0/ 1.0/ 3.0 m
- Homogeneous sandy aquifer
  $K = 4 \times 10^{-4}$ m/s
- Water table: 1.7 m
- Groundwater flow v: 0.2 m/d

Contaminant source

- 2~3 kg chlorinated solvents (PCE)
  in r = 0.45 m,
  z = 0.3 – 1.3 m BWT
- Plume concentration: ~150 mg/L
- 38 sampling ports:
  36 in Aquifer, 2 in In/Outflow

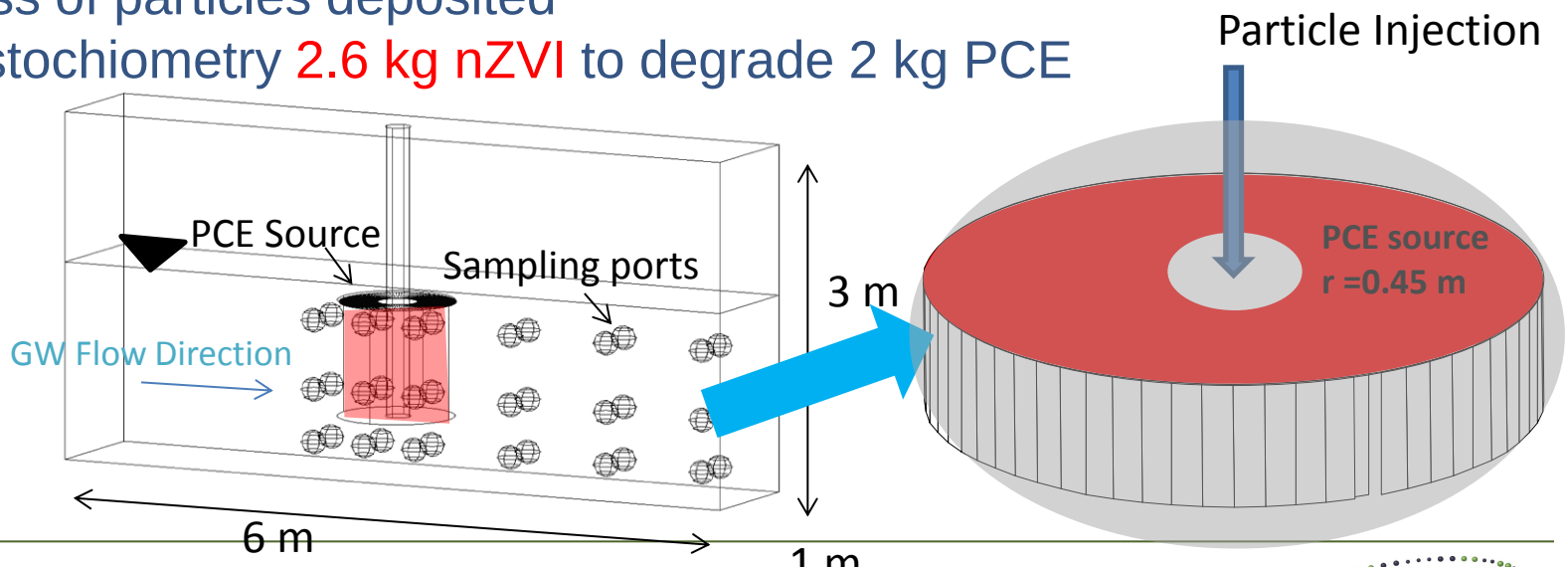
Goal of the Flume Experiments

Investigation of particle reactivity in 3D system

- Degradation of 2~3 kg PCE source zone (r = 0.45m , h = 1m) by nanoparticles

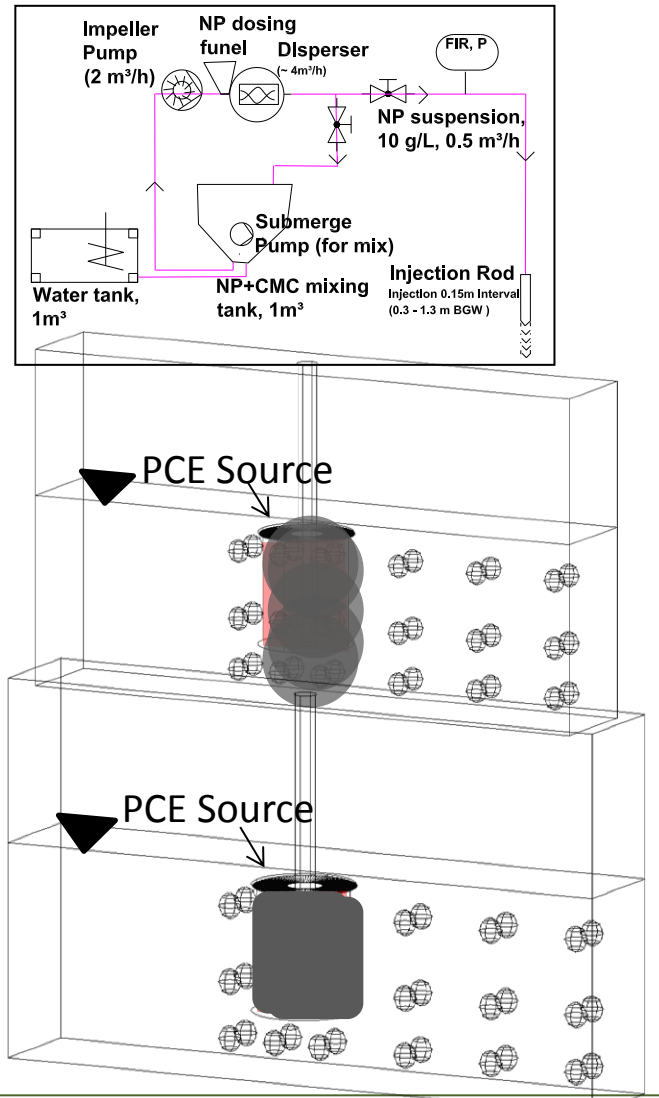
Investigation of particle mobility in 3D injection system (in radial flow field)

- Distance of deposition of particles→ r = 0.5 m
- Mass of particles deposited
  → stochiometry 2.6 kg nZVI to degrade 2 kg PCE



Injection Boundary Conditions

	LSF 1	LSF 2
	nZVI (NANOFER STAR)	Composite nZVI (Carbo-Iron®)
Injection Method	Sequential injection at 5 different depths	Intermittent injections at one injection depth
Injection Rod	Direct push rod with 1" ID with 4 small injection nozzles	Injection well with 1¼" ID and 1m filter screen
Injection position	In the middle of the source zone	In the middle of the source zone
Injection Depth	5 depths (from 1.7 to 2.3 bgl at 0.15 m interval)	As source zone (from 1.5 to 2.5 bgl)
$Vol._{Injection}$	(5 x 0.2 m³) total **1 m³**	(2 x 0.35 m³) **total 0.7 m³**
$Mass_{NP}$	**10 kg**	**14 kg (Fe mass ~ 3.5 kg)**
C_{NP}	**10 g/L**	**20 g/L**
Stabiliser	5 g/L of CMC	1 and 2 g/L of CMC
$Q_{injection}$	**0.5 m³/h**	**0.22 and 0.15 m³/h**
$P_{injection}$	**Constant as 2.5 bar**	**Changing between 0.5 and 1.7 bar**

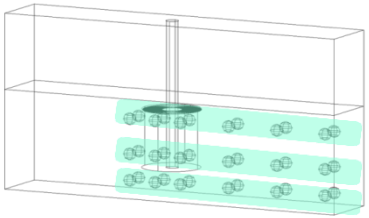


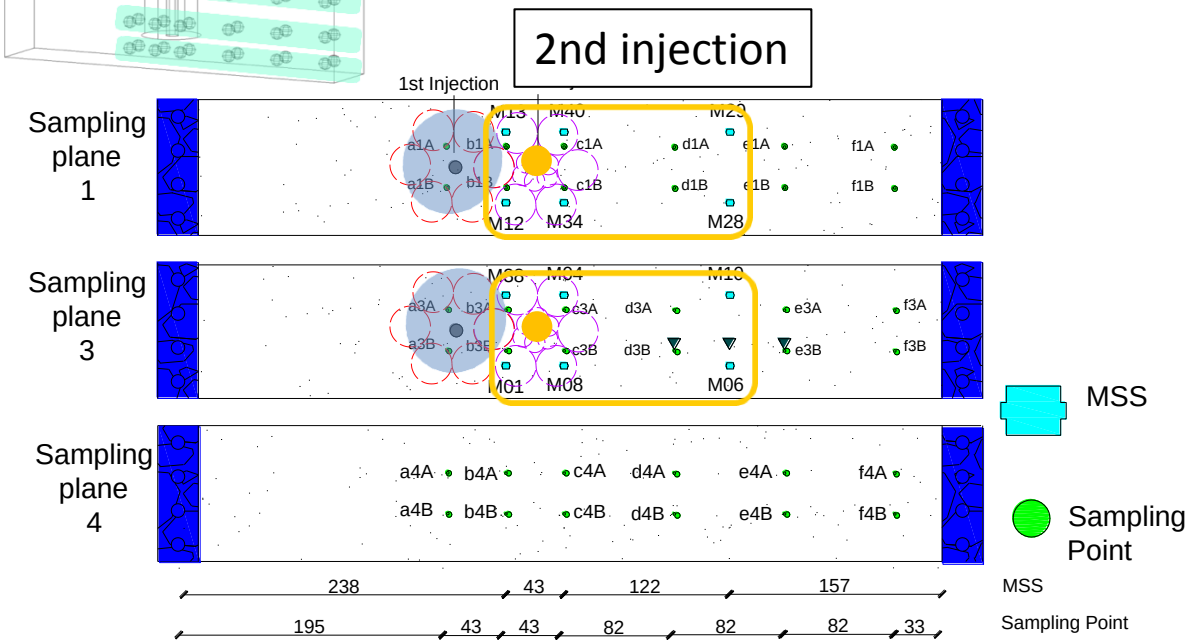
Particle Mobility NANOFER STAR

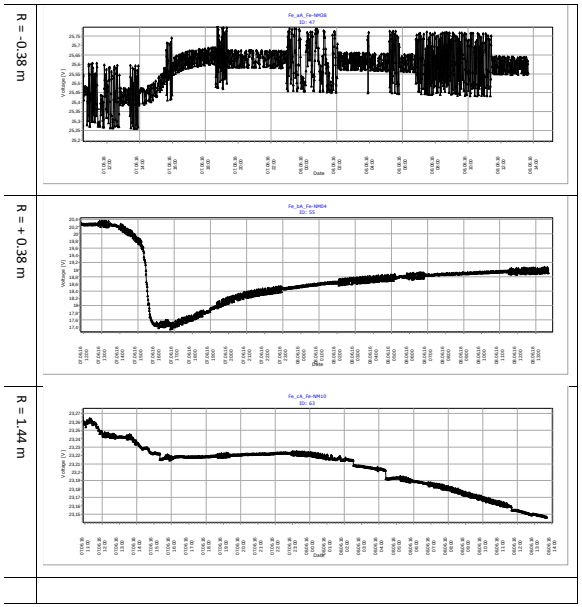
Particles transport: > 0.4 m in all dimension

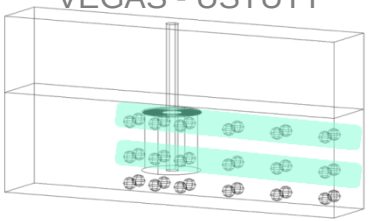
Maximum travel distance: ~1.4 m.

A reactive zone was established with a distribution of particles extending over the whole contaminant source zone.









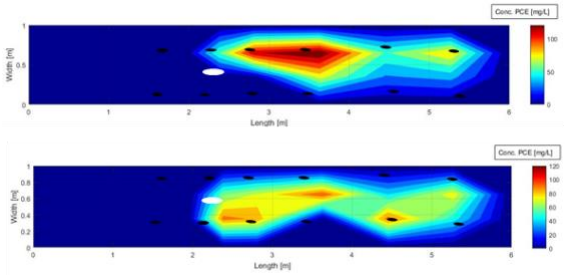
Particle Reactivity
NANOFER STAR

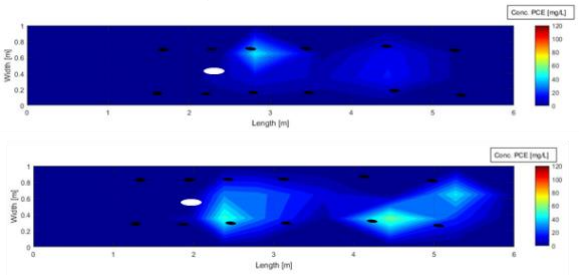
1 week before

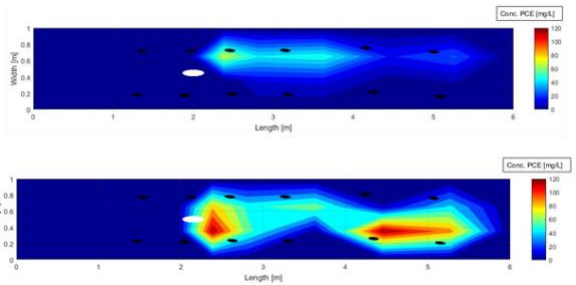
After 1 week

After 4 weeks

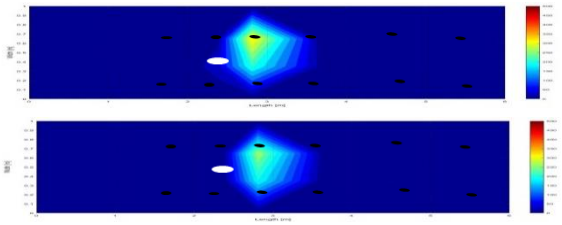
PCE

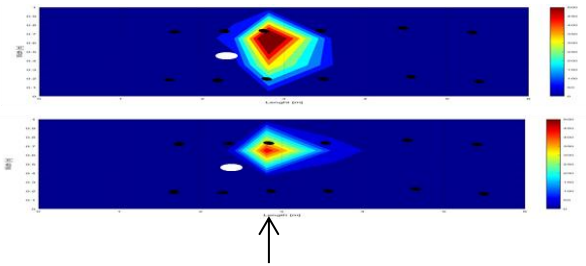






Chloride





Everywhere background concentration ~ 7 mg/L

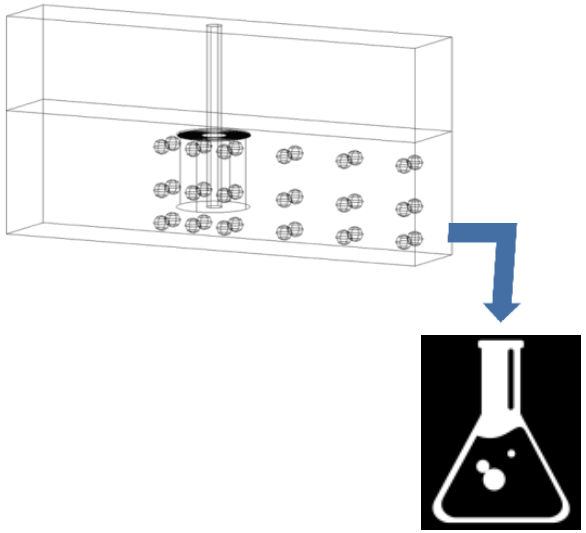
- Sampling ports
- Injection position

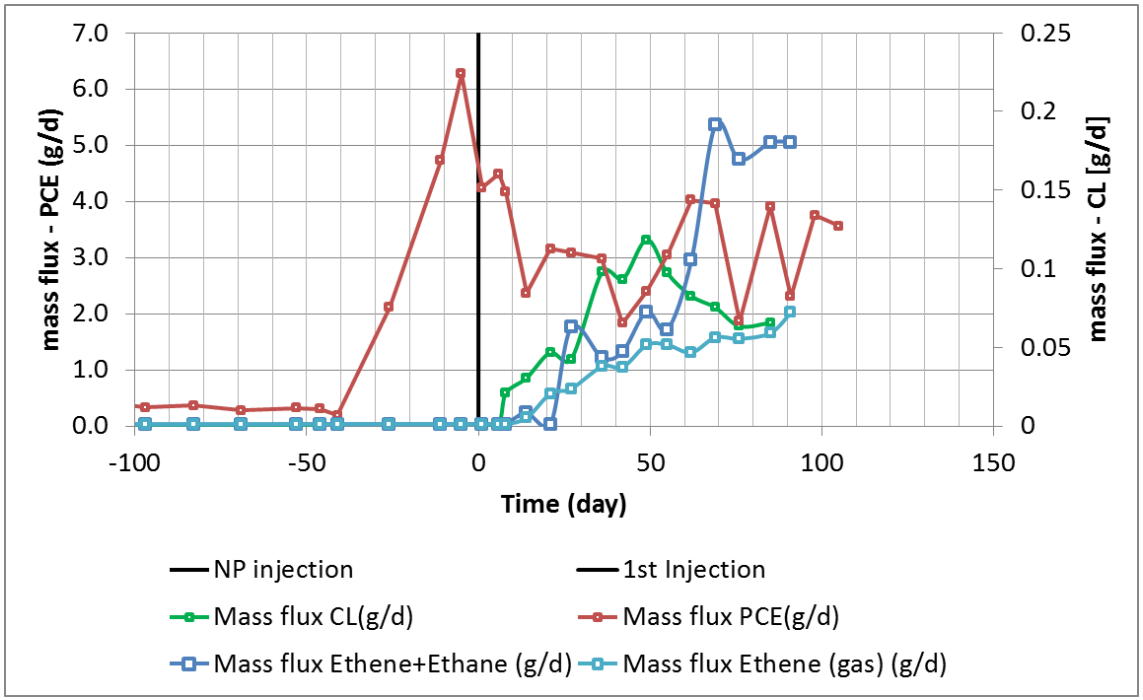
Sampling ports clogged
No data available

Aquifer Remediation by NANOFER STAR

PCE degradation is still in progress 90 days after injection.

STAR particles had degraded 190 g of PCE.





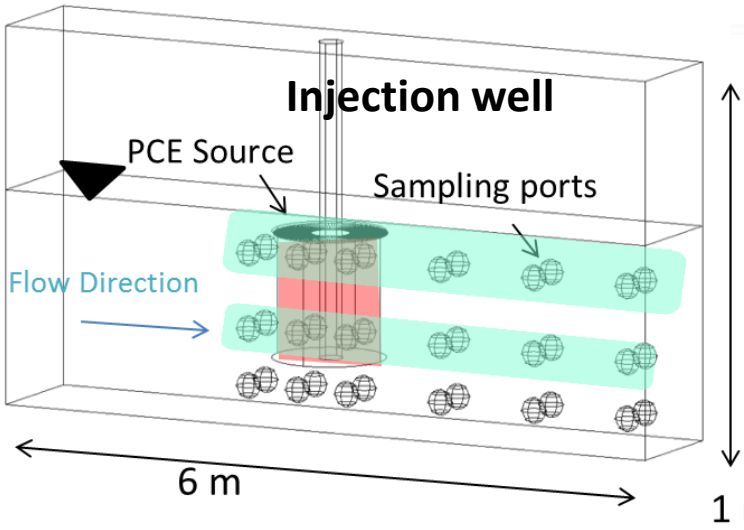
Particle Mobility Carbo-Iron®

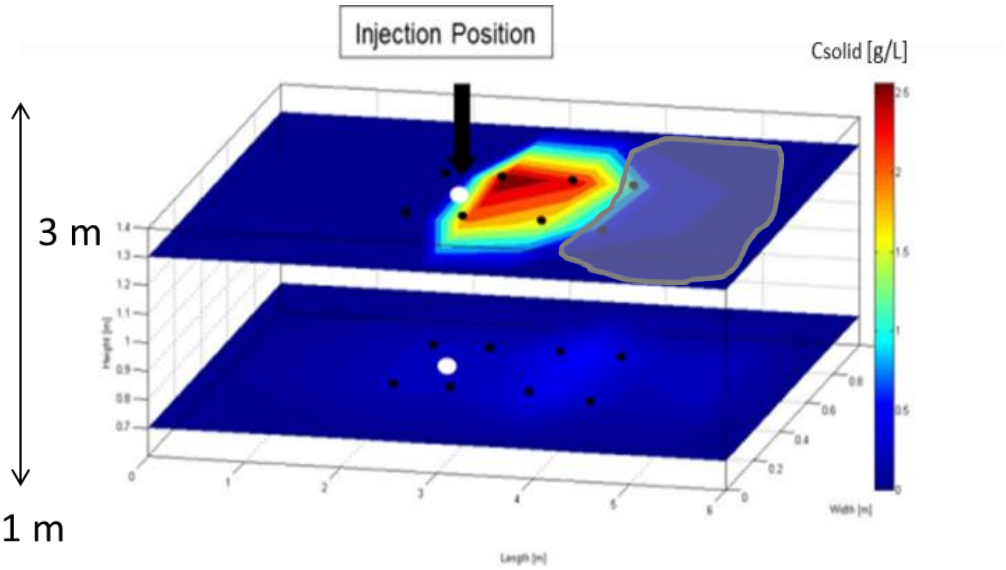
Particles transport: > 0.5 m downstream in upper plane

Maximum travel distance: ~1.0 m

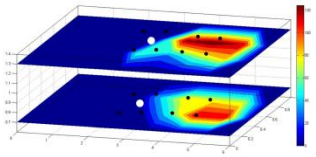
Particle distribution not uniform: Contaminant source zone was partially covered by NPs.

(some) NP migration by base flow was observed for 50 days.



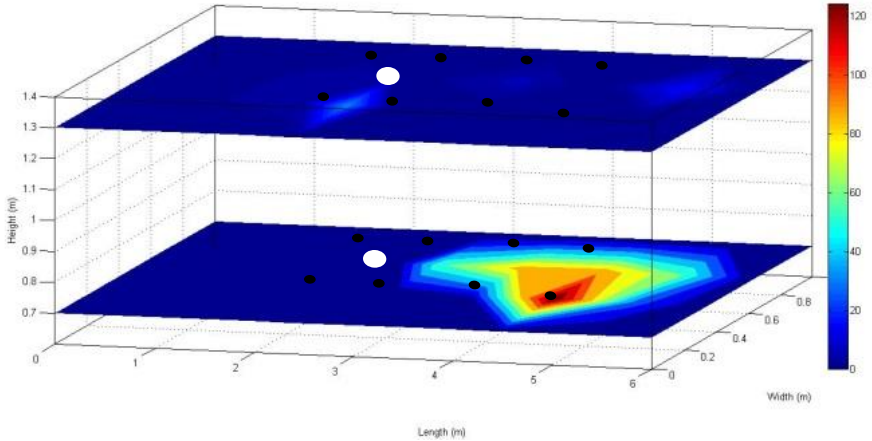


Particle Reactivity Carbo-Iron®

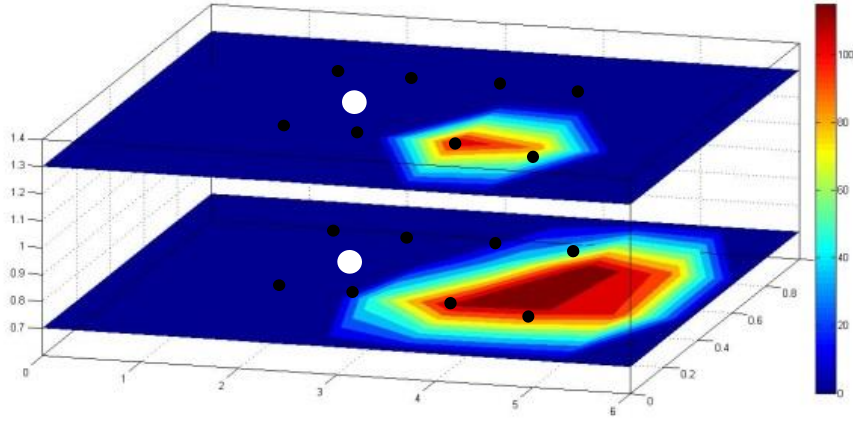


PCE

After 2 weeks

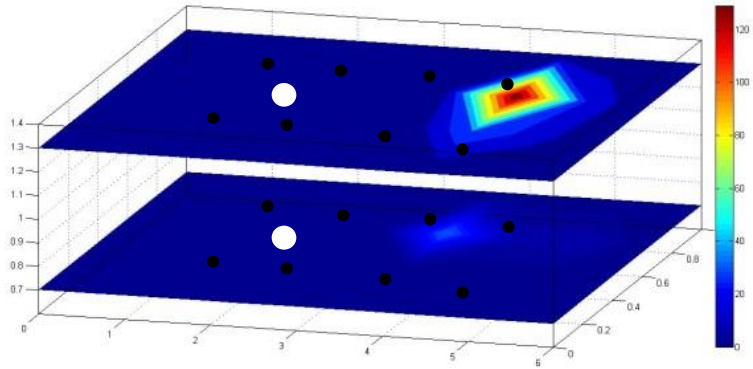


After 4 weeks

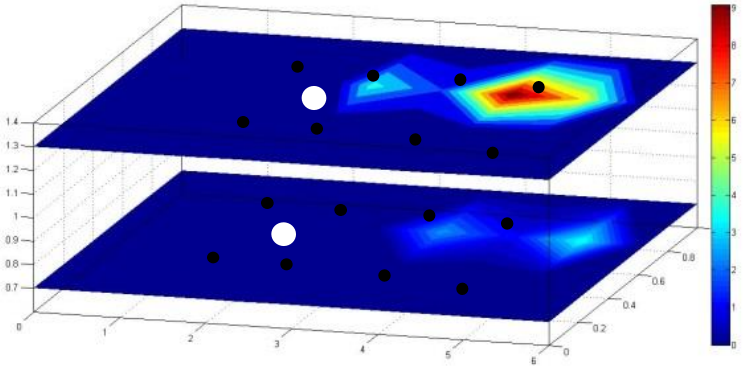


Chloride

After 2 weeks



After 4 weeks

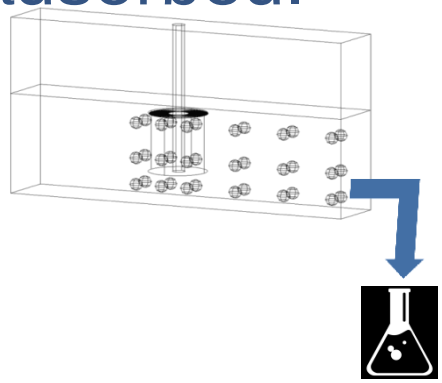


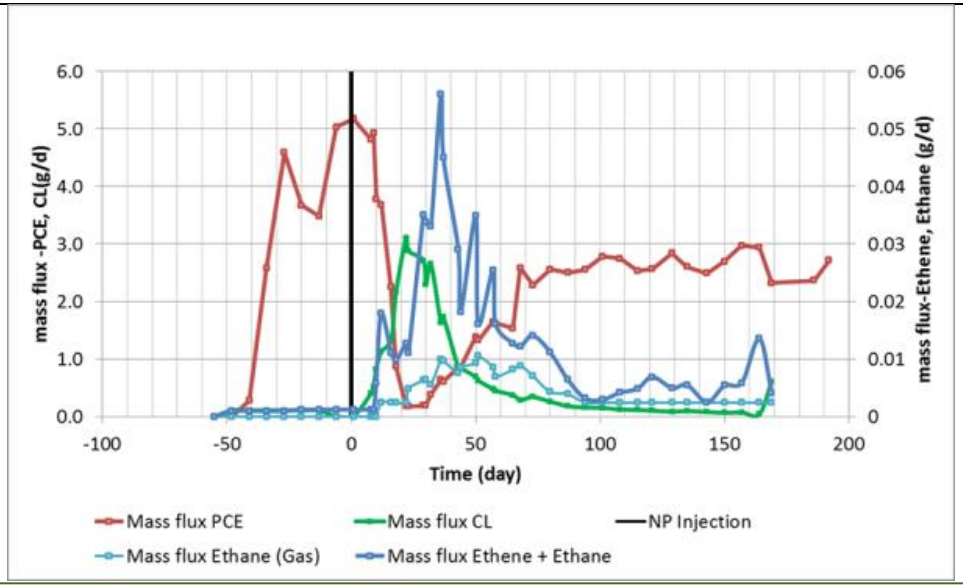
- Sampling ports
- Injection position

Aquifer Remediation by Carbo-Iron®

Active nZVI particles were depleted after 100 days. However this did not yield an increase of PCE mass flux due to the adsorption of PCE on the activated carbon.

120 g of PCE were degraded and 280 g were adsorbed.





Carbo-Iron® Injection with DP

Carbo-Iron® with DP injection at 2.4 m bgs

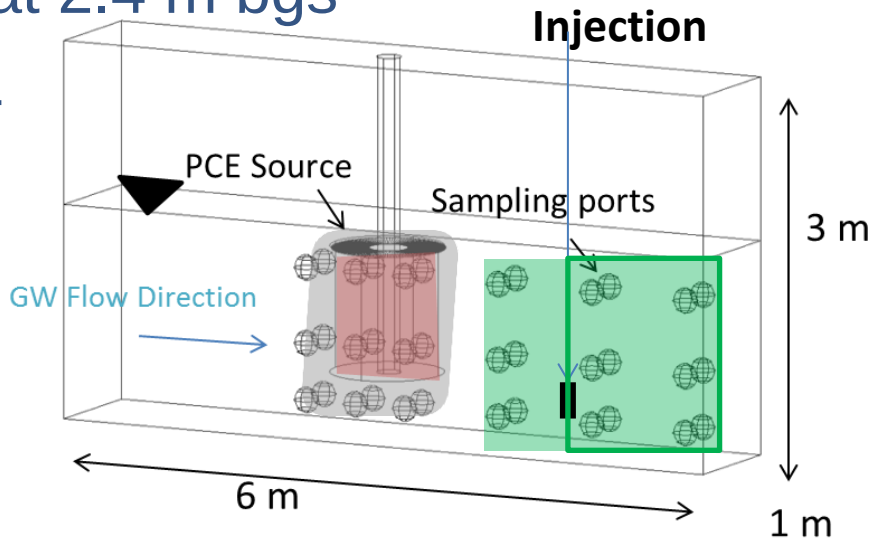
$c_{Carbo\text{-}Iron}$ = 5 g/L, c_{CMC} = 0.5 g/L

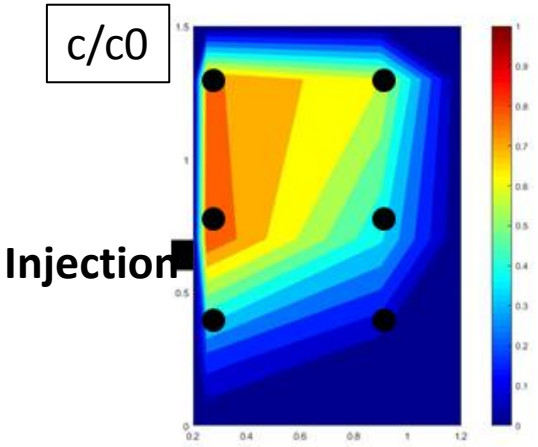
Vol pre-/post flush 100 L CMC

Volume suspension: 200 L

Q: 0.25 m³/h

Transport distance: > 1 m





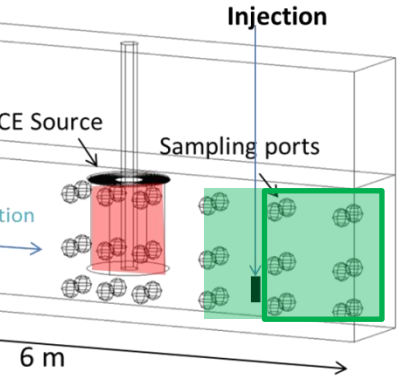
Carbo-Iron® Injection with DP

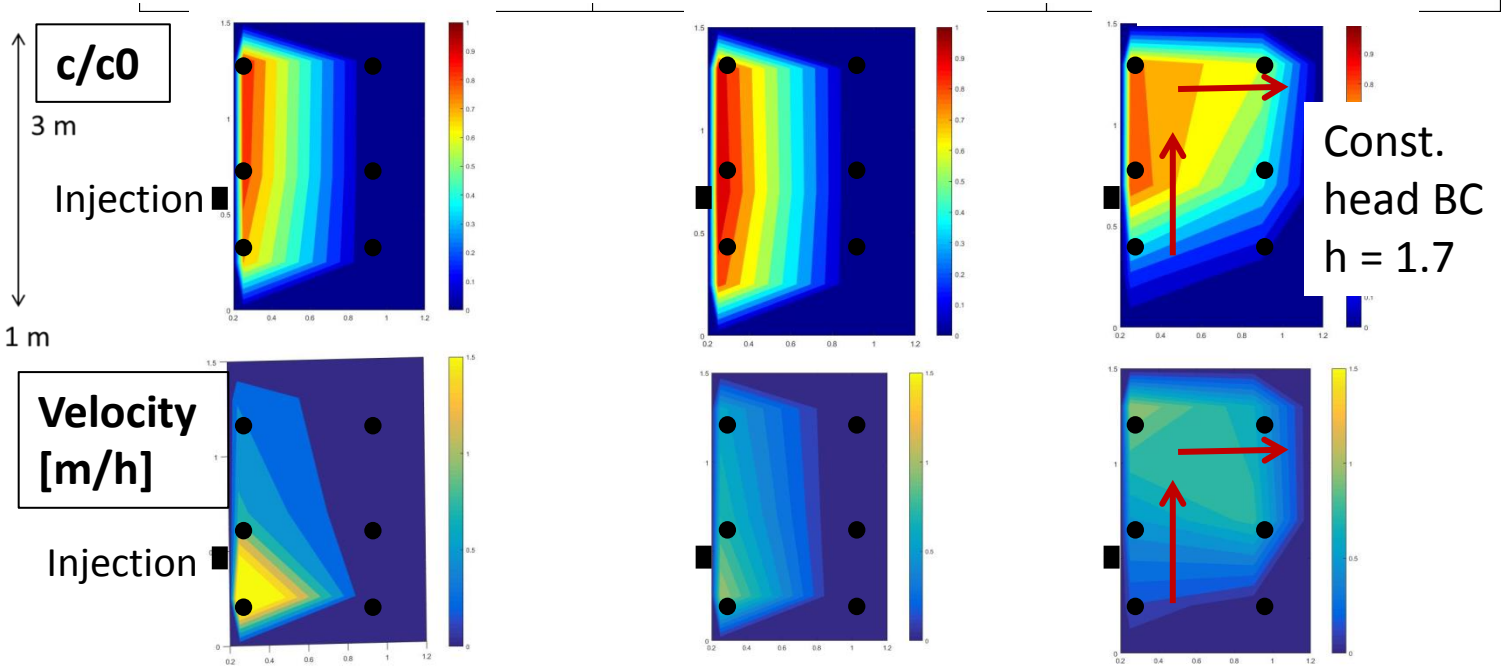
Tracer in water | Tracer in CMC 0.5 g/l | Suspension 5 g/L

Inject

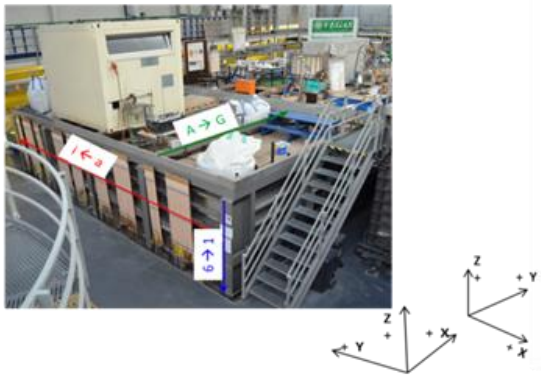
Particles move towards low hydraulic head (or pressure) zone much more than water or CMC due to higher injection pressure.
→ non-uniform distribution.

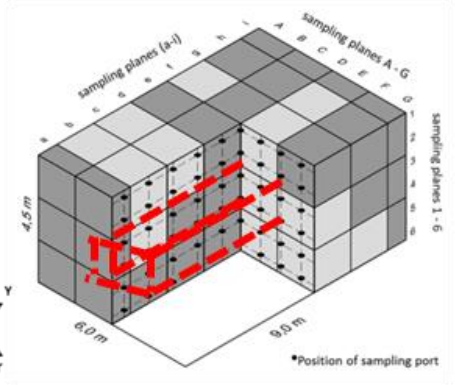
Vol.: 0.3 m³
Q: 0.25 m³/h

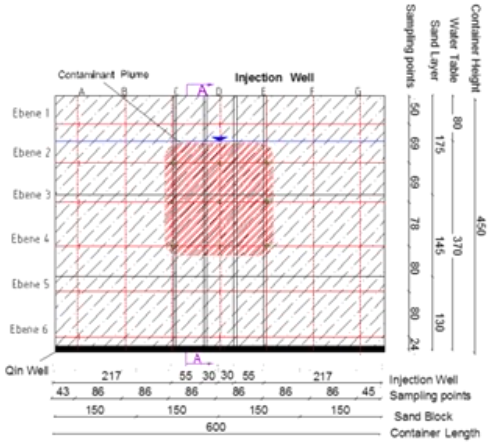




Large Scale Container Experiment







Artificial Aquifer in the Large Scale VEGAS Container

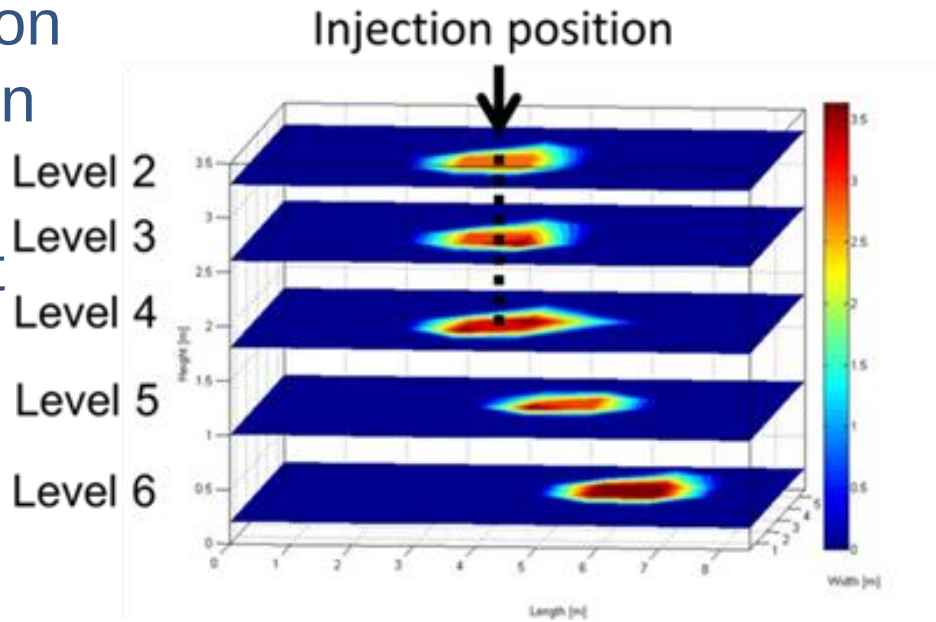
- Size: L/B/H = 9.0/ 6.0/ 4.5 m
- Layered heterogeneous sand aquifer ($K = 4 \times 10^{-4}$ and 4×10^{-3} m/s)
- Water table: 3.7 m
- Seepage velocity: 0.42 m/d
- 380 Sampling ports: 378 in the aquifer, 2 in/outflow

LNAPL Plume Zone (Toluene)

- Plume cross-sectional area: 4.0 m² in the center of the aquifer (red colored area of right schematic image)
- Toluene dosing rate ≈ 1.6 g/h (~400 mg/L x 4 L/h)
- Toluene concentration in plume ≈ 70.0 mg/L

Particle Mobility Goethite NP

- In the upper reaches of the aquifer (level 2, 3 and 4) Transport distance > 1.5 m
- At lower levels (5 and 6), very little NP were observed during the injection, 1 day after the injection a relative high NP concentration was observed.
- Maximum transport distance at level 6 was confirmed at 4.3 m from the injection well.



Summary

- Particle mobility and reactivity in 3D injection system (radial flow field) was well investigated.
- Due to injection pressure (> 2 bar), increased depth of injection increases performance.
- nZVI transport cannot be predicted directly based on tracer results.
- Heterogeneities greatly affect NP distribution. →Numerical model necessary

Thank you for your attention

This project received funding from the European Union Seventh Framework Programme (FP7 / 2007-2013) under Grant Agreement No. 309517.

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