Generalized Guideline for Nanoremediation Application

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NanoRem Final Conference
Nanoremediation for Soil and Groundwater Clean-up
- Possibilities and Future Trends

Frankfurt am Main, 21st November 2016
How to nano?

Successful Site Remediation

- Conceptual Site Model
- Particle Information
- Field/ Pilot Test
- Monitoring
- Laboratory Tests
- Legal/ Regulatory Issues
- Finances
- Numerical Model
- Field Injection

Generalized Guideline for Nanoremediation Application

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Flowchart of Guideline

Generalized Guideline for Nanoremediation Application

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Prerequisites

- Detailed Site Investigation
- Conceptual Site Model (what we know + what we don’t know)

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Prerequisites

- Particle List
  - Reaction type
  - Reaction mode
  - Recommended site conditions
  - Stabilizer
  - Application rules
  - Reactivity data for typical target contaminants
  - …
Prerequisites

- Operating Window
- Requirements/ limitations
- Process/ Synergies
- Deployment
- Operational boundaries
- Treatable contaminants
- Hydrogeology
- Hydrochemistry
- Additional info
Pre-Screening Tool

- “Simple” Excel based tool
- Combines NP-information, CSM, OW, site specific contaminants, hydro-geochemical conditions, injection technology etc. to give

→ Indication on potential of nanoremediation

→ List of critical parameters
Site Specific Particle Tests

Use MSDS and producer claims on reactivity and transport??

Reactivity

Mobility

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Site Specific Reactivity Tests

- For specific site conditions and/or specific contaminants
  - Batch tests for yes/no decisions
  - Column tests for mass balance and longevity
Site Specific Mobility Tests

Goal:
- homogeneous particle distribution in reactive zone
- Safe NP deposit → Renegades?

• Cascading column experiments
  - Experimental reproduction of radial flow field (hyperbolically decreasing $v$)
  - High resolution in time and space
    - Direct indication of travel distance and of homogeneity of NP distribution
    - Input for numerical model to predict particle placement in radial flow field
Site Specific Mobility Tests

- Small column experiments based on filtration theory
  - Particle breakthrough and particle deposition
    - calculate attachment efficiency, particle deposition rate coefficient
      → Prediction of travel distance for base flow → Renegades
    - Input for numerical model
      → use MNMs or MNM3D to predict particle placement in radial flow field
Experimental Upscaling

\[ v_{a1}, c_1, V_1 \]
\[ v_{a2}, c_2, V_2 \]
\[ v_{a3}, c_3, V_3 \]
Model Assisted Upscaling

Porous medium properties → Identification of transport kinetics/mechanisms → Slurry properties

Inverse fitting of column transport tests

Simulated breakthrough curves, concentration profile, pressure drop at column ends

Experimental breakthrough curves, concentration profile, pressure drop at column ends

Determination of transport parameters

Model-assisted design of pilot injection
  → Radius of influence
  → NP injected mass and concentration

In situ monitoring of NP concentration during/after injection

3D full scale modelling
Pilot Tests

- Selection of nanomaterial, evaluation of efficiency and longevity
- Particle distribution (ROT) → distance of application wells
- Effects on aquifer properties
- Reactivity and reaction kinetics, formation of intermediate products
- Verification of application method and performance of proposed equipment
- Cost estimation for a full scale remediation
Full Scale Design

• Based on monitoring, site specific particle tests, numerical model, remediation goal and pilot test decide on
  – NP to be used (pure / modified / composite / …)
  – Composition of slurry (NP concentration, surfactants, additives, stabilizers, …)
  – Injection technology (direct push injection, well infiltration, …) and well spacing
  – Target NP concentration in subsurface and total NP mass to be injected
  – Injection monitoring
  – Health and safety measures
Site Installation and NP Deployment

• Drilling/DP equipment
  – Installing of wells prior to injection, use packers to focus injection
  – Use direct push technology

• Preparation of slurry
  – Dispersers, vessels, inert gases, dosing equipment, injection pumps, water supply, …

• Deployment of slurry
  – Injection pumps, packers, direct push rods,

• Monitoring

• Health and safety
Monitoring

• Pre-Injection Monitoring
  – Qualitative and quantitative delineation of contamination
  – Characterization of hydrochemical milieu
  – Determination of aquifer properties
    → direct push / depth oriented soil and water sampling

• Monitoring during NP injection
  – Particle transport and distribution
    → direct measurement via susceptibility sensors or water samples
    → indirect measurement via temperature or tracers
    (caution: ROI is not necessarily equal to ROT)
Monitoring

• Monitoring during system recovery phase
  – Determination of natural flow conditions
  – Confirmation of NP distribution (renegades?)
    ➔ Monitoring of head (water table)
    ➔ Evaluation of soil samples

• Long term monitoring
  – Determination of success
    ➔ Analysis of water samples for daughter products, metabolites and end products of reaction
    ➔ Analysis of soil samples
    ➔ Final data analysis
Long Term Performance “Success?”

- Reduction of concentration
  - Based on ground water samples
  - Point type information
  - High spatial and temporal uncertainty
  - No information on inventory or emission

- Reduction of emission
  - Based on ground water samples
  - Integrative approach necessary (e.g. pumping test)
  - High certainty, but only snapshot (“rebound effect”)
  - No (little) information on inventory

- Reduction of inventory
  - Based on soil samples
  - Only point type information possible
  - High uncertainty due to heterogeneity
  - Comparison before – after uncertain
  - No (little) information on emission

Costs

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Regulatory Issues

• Description of technology
  – General mode of operation
  – Site installations
  – NP deployment / injection technology to be applied
  – Necessity of pilot test
  – Detailed description of monitoring system

• Description of suspension
  – Particles
  – Additives
  – Stabilizers
Regulatory Issues

• Description of chemical processes
  – Applicability to given contaminants
  – Reaction kinetics, degradation products

• Risk / Risk Management
  – to ecology
  – to humans
  – Options for risk mitigation
  – Stakeholder involvement
Regulatory Issues

• Alternative Technologies
  – Technical aspects
  – Combination with other technologies / treatment trains

• Financial aspects

• Long Term Risk
  – Stability of NP in subsurface
  – Change of land use (zoning) due to nanoremediation?
  – Stakeholder involvement

• Best Practice
  – Well documented sites with comparable NP application
Financial Issues / Cost Drivers

- Regulatory Aspects
  - Injection permit, monitoring, reporting

- Remediation Goal

- Time Horizon / Time Limitations

- Site Installation and Mobilization of Equipment

- Additional Site Investigation
Financial Issues / Cost Drivers

- Cost for NP and Suspension
- Hydrogeological Conditions
  - Injection system and operation
  - Aquifer pre-treatment
- Geometry, Inventory and Accessibility of Contaminants
- Miscellaneous
  - Shipping costs, customs
  - Compensation of land owners
### Examples of Nanoremediation

<table>
<thead>
<tr>
<th>Site</th>
<th>Country</th>
<th>Site Primary Investigator</th>
<th>Target Cont.</th>
<th>NP-Type</th>
<th>Reaction Principle</th>
<th>Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvay</td>
<td>CH</td>
<td>Solvay</td>
<td>CHC</td>
<td>FerMEG12 (milled nZVI)</td>
<td>Reduction</td>
<td>porous / unconfined</td>
</tr>
<tr>
<td>Spolchemie 1</td>
<td>CZ</td>
<td>Aquatest</td>
<td>CHC</td>
<td>NANOFER 25S / NANOFER STAR</td>
<td>Reduction</td>
<td>porous / unconfined</td>
</tr>
<tr>
<td>Spolchemie 2</td>
<td>CZ</td>
<td>Aquatest</td>
<td>BTEX</td>
<td>Nano-Goethite (Iron-Oxide)</td>
<td>Oxidation / microbial enhancement</td>
<td>porous / unconfined</td>
</tr>
<tr>
<td>Neot Hovav</td>
<td>IS</td>
<td>Negev, BGU</td>
<td>TCE, cis-DCE, toluene</td>
<td>Carbo-Iron®</td>
<td>Adsorption / Reduction</td>
<td>fractured</td>
</tr>
<tr>
<td>Balassagyarmat</td>
<td>HU</td>
<td>Golder</td>
<td>PCE, TCE, DCE</td>
<td>Carbo-Iron®</td>
<td>Adsorption / Reduction</td>
<td>porous / unconfined</td>
</tr>
<tr>
<td>Nitrastur</td>
<td>ES</td>
<td>Tecnalia</td>
<td>As, Pb, Zn, Cu, Ba, Cd</td>
<td>NANOFER STAR</td>
<td>Reduction</td>
<td>porous / unconfined</td>
</tr>
</tbody>
</table>

→ see CLAI:RE NanoRem Bulletin for details
Thank you for your attention

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