Iterative High-Resolution Site Investigation and Remediation

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Traditional Investigation & Remediation

- Traditional Soil Borings/Monitoring Well Investigation
  - Typical gas station site investigation completed in multiple phases over years
  - Incentive to limit the number of borings and wells
  - Horizontal & vertical extent rarely adequately delineated
  - Thin but significant permeable units & impacted clay lenses often missed or ignored
  - Changes in plume direction often masked
- Remediation Using Traditional Soil Borings/Monitoring Wells
  - Access limitations to areas of investigation
  - Transport horizons and stored mass zones often ignored or not targeted
  - Well spacing is pushed to the limits of the zone of influence
  - Pilot testing based on few well points
  - Can take months to expand to full system

Hollow Stem Auger or Mud Rotary Investigation/Remediation

- Time-consuming
- Large boreholes
- Waste generation
- Limited site access
- Limited ability to collect discrete groundwater samples (averaged groundwater concentrations)

Direct Push Technology Investigation & Remediation

- Direct Push Technology (DPT) Investigation
  - Enables high resolution site characterization (HRSC)
  - Budgetary incentive to maximize daily production of push points
  - Horizontal & vertical extent delineation in single mobilization
  - Thin permeable units & impacted clay lenses recognized
  - Changes in plume direction recognized
- DPT Remediation Systems
  - Greater access to areas of remediation
  - Targeted injection
  - Injection point spacing chosen to maximize cost-effectiveness
  - Pilot test area typically becomes first phase of remediation
  - Timely implementation

DPT Investigation/Remediation

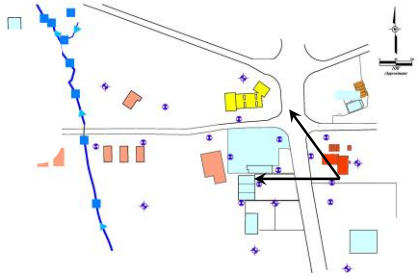
- Greater access to areas of investigation
- Rapid deployment & sample acquisition
- Less waste generation
- Better suited for HRSC
- More flexible to collect discrete soil & groundwater samples (not averaged concentrations)

Chronology of UST Release & Response

1. Station opened in 1960s
2. Undocumented Release occurred in 1970s (Pre-UST Trust Fund)
3. 1994 Off-site investigations discovered PSH
4. Source determined to be 3-6,000 gallon USTs
5. 2001 Gasoline constituents detected in stream
6. 2003 Site investigation completed
7. 2007 DPVE system began operation
8. 2012 DPVE system deactivated having recovered 2,073 gallons of PSH
9. 2016 ISCO injection conducted to target Benzene exceedances in one monitor well and stream

UST Site Setting

- Source is approximately 700 ft up-gradient of a stream
- Additional UST sites also up-gradient of stream
- The gradient is ≈ 0.02 toward the W to NW



Elements of HRSC & Conceptual Site Model (CSM)

Hydrogeologic Elements
- Vadose Zone Soils
- Capillary Fringe
- Phreatic Zone
- Utility Lines
- Permeable Horizons & Lenses
- Clay-rich Facies
- Slickensides, Bioturbation

Contaminant Distribution Elements
- NAPL & Soil Vapor
- Hydrocarbon Smear Zone
- NAPL Pools, Residual, Dissolved
- Preferential Pathways
- Horizontal Plume Expansion
- Mass Storage & Back-Diffusion
- Vertical Migration

Revisit & Refine CSM With Each Phase of Project

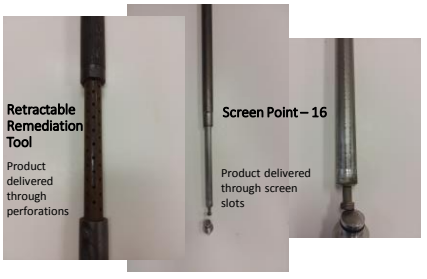
Major Historical Site Activities

- UST Removal (Source Removal)
- Site Investigation Monitoring Well Installation
- First Remediation Phase – DPVE
- Second Remediation Phase – ISCO

DPT Remediation Tools

ISCO Delivery Methods

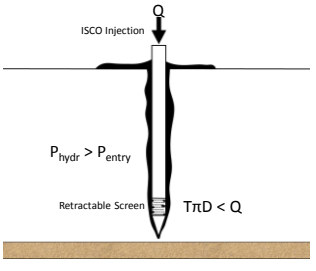
- Evolved from DPT methods
- Parallel evolution with HRSC
- HRSC created the need for discrete injection capability



ISCO Undesired Delivery

Surfacing

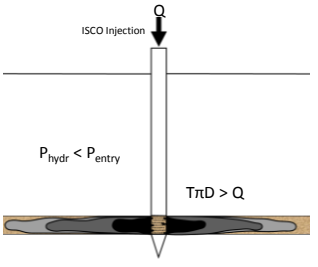
- If the transmissivity of the formation at the targeted interval does not allow steady-state passage of injected fluid, pressure head increases until entry pressure into the annular space is exceeded
- Injected fluid escapes to the ground surface instead of entering the formation
- Preferential pathway to ground surface is likely irreversible



ISCO Desired Delivery

Successful Injection

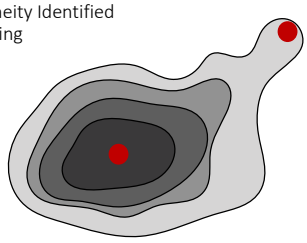
- Flow rate does not exceed steady-state flow rate allowed by screen dimensions and formation transmissivity
- Entry pressure of annular space is not exceeded
- Steady state flow rate may increase as injected volume increases
- ISCO solution becomes diluted towards migration front, controlled by hydraulic conductivity



Localized Facies Heterogeneity Identified Through Injection Monitoring

Interaction Among Injection Points

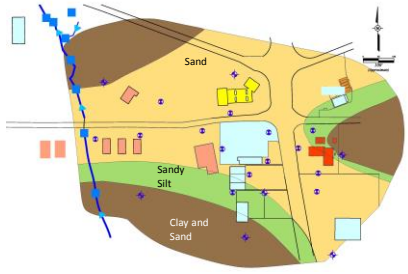
- Controlled by formation heterogeneity
- Develops over time
- Affects the steady-state flow rate at affected injection points
- Preferential pathways become irreversible



CSM Refinement

Heterogeneity vs Data Density

- Conventional monitoring well network inadequate to characterize lateral facies changes
- Gradational changes in clay and silt content affect hydraulic conductivity
- Clay content affects contaminant storage capacity and potential back-diffusion



CSM Refinement

Injection Strategies Depends on Soil Characteristics

- Sand and Clay: Grid Pattern
  - Closely spaced low volume injection locations
  - Expect surfacing; monitor closely and abort immediately
  - Prepare pre-cleared grid
- Poorly Sorted Sand: Sweet Spot Path
  - Irregularly distributed sweet spot high volume locations
  - Avoid surfacing with gradual pressure buildup
  - Flexible treatment area
  - Multiple simultaneous injection points possible

Injection Method Reflects Soil Properties

Grid Injection in Clay-Rich Facies

Sweet Spot Injection in Sands and Silts

- **Anticipate surfacing – mobile injection**
- **Injection responses give clues to facies changes (refine CSM)**
- **Potentially use multiple injection points simultaneously or alternating sequentially or cyclically**

Conclusions