Design and Construction of a Sediment Cap that Controls NAPL Migration, Sediment Fracturing, and Ebullitive Mixing by Manipulating Effective Stress and Air Entry Pressure

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Outline

• Evolving paradigm for EFNMFS
• Nature of sediment mixing
• Design
• Construction
• Monitoring
• Conclusion
**Initial Model**

Organic matter and wastewater containing NAPL are co-deposited in sediment

- **A.** Gas (CH₄, CO₂, N₂) produced in sediment column within or below tarry layer
- **B.** Gas migrating through tarry sediment entrains tarry skin
- **C.** Gas bubbles drag NAPL to water surface

*modified from McLinn & Stolzenburg 2009*
Site Description

Bangor Landing Site
- Former MGP discharged wastewater containing tar to Penobscot River for > 100 years
- Tar deposit in sediment in lee of bulkhead covers over 10 acres
- Abundant ebullition and 12-20 ft tide
- Hardened tar over about 6 acres; NAPL migration and ebullition over about 3 acres - intense migration in 1 acre PAZ, diffuse in 2 acre SAZ
- Cap in place over PAZ for 10 years
- Extensively monitored
PAZ Sediment Cap Performance

- Sediment cap controls NAPL migration in PAZ
- Uncapped SAZ EFNMFS also ceased immediately; elevated concentrations of PAHs persist in shallow sediment
- Isolated area of NAPL migration
- Performance evaluation based on direct observations by trained observers (note density of observations and trained observer on sand bar)
Conceptual Cross Section in SAZ

- Depositional area in lee of bulkhead
- Ebullition throughout SAZ at low tide
- PAHs remain elevated in shallow sediment column long after tar deposition stops, and after PAZ sediment cap installed
- Isolated area of NAPL migration in channel where sand overlying tar is thinnest
- Concentrations in sediment trap (5-20 mg/kg) are much lower than surface sediment (60-100) – persistent post-remediation PAHs not due to recent deposition

PAH concentrations at sediment surfaces remain elevated despite source cutoff in 2010. PAH mass being deposited not sufficient to cause surface concentrations.
Laboratory Sand Columns – Wrong but Useful

Representative Elementary Volume & Dynamic Similitude
- Fine sand, quartz arenite, highly sorted, subround – like glass beads
- Laboratory grade coal tar
- NAPL source layer at base of sand; air injection in underlying fine gravel
- Grain size fine enough to behave as fractured and porous media; finer and coarser materials exhibit phenomena on a continuum
- Gas $Q = 200 \text{ ml/min}$; fast; high end of “burping” behavior; time machine; different rates evaluated
- 8-inch dia column sufficient to avoid domination by wall effects at this scale; different sizes evaluated
- Scale prohibits vent spacing development
- No groundwater advection in model; gas only
- Depth of sediment

“All models are wrong, some are useful.”
George Box
Ebullition- Facilitated NAPL Migration in Sediment–Time Lapse (16 d/23 s)

- Horizontal to vertical fractures
- Fracturing is abundant, and more so at shallow depths
- NAPL carried upward to top of sand column
- Fracture zones migrate laterally in column
Laboratory Evaluation of Mechanisms of NAPL Migration – Ebullitive Mixing Is a Function of Gas Flow Rate

- Test whether sediment mixing = fn (gas flow rate)
- Fine white sand with fine black sand of similar grain size distribution
- Mechanical process of ebullition was the same for varying gas flow rates (tested from 2 to 200 ml/min) –
- Rhythmic build up and release - burping
- Amount of sediment mixing is fn (gas flow rate)
- NAPL transport to sediment column also a function of gas flow rate (Vater et al, 2012)
NAPL Migration through Sediment Is Commonly a Function of Gas Migration Rate

Data adapted from Vater and others, 2012

Tar migrates into sand column with migrating gas
Laboratory Evaluation of Mechanisms of NAPL Migration – Fracture Propagation Downwards over Time

- Column test to illustrate downward propagation of fractures in fine sand under ebullition
- Sediment mixing starts at the surface where effective stress is at a minimum; fractures propagate downward
- Gas flow mostly in pores at depth, fractures above
- Mixing and fracturing down to where effective stress is greater than air entry pressure
Laboratory Evaluation of Mechanisms of NAPL Migration - Ebullitive Fracturing Is a Function of Grain Size (Strength and Air Entry Pressure)

- **Silty sand** – fracturing and pistoning (v. lg fractures); high entry pressure, low strength; very difficult to work with at this scale in laboratory
- **Fine sand** – fracturing and ebullitive mixing; minor channeling; medium - high air entry pressure, medium strength
- **Medium sand** – Minor fracturing and channeling of gas flow; 2 grains wide; low air-entry pressure, medium strength
- **Medium-coarse sand** – channeling and channel migration; one grain wide very low air-entry pressure, medium strength
Laboratory Evaluation of Mechanisms of NAPL Migration – Effective Stress and Air Entry Pressure

- Sediment mixing prevented because initial surface fracture was not allowed to form by increasing effective stress at base of the column and decreasing air entry pressure at gravel layer.
Effective Pressure Cap
200 mL/min
Time Lapse
1 minute = 1 day
Evolving Paradigm of Ebullition and Transport – Ebullitive Mixing

- Organic matter and wastewater containing NAPL are co-deposited and/or NAPL has been re-deposited on sediment surface from elsewhere.
- Gas (CH4, CO2) produced in sediment column within or below tarry layer.
- Gas invades pores and migrates through pores until sufficient gas pressure accumulates to exceed the air entry pressure (gas forces water out of pores).
- Initially, sediment mixing starts at or near the sediment surface, where effective stress is at a minimum, and fracturing is easiest.
- The fracture propagates downward into the sediment column as ebullition continues.
- Below the rising bubble is a field of unbalanced low pressure; fluid and granular sediment rush into this area– micro-liquefaction facilitates sediment mixing.
- Fracturing in the field is often focused on vents in the field, esp in sand.
- Sediment mixes upward and downward as fracturing continues, redistributing new sediment downwards and older sediment upwards.
- Gas migrating through tarry sediment entrains tarry skin – rapid transport through fractures.
- Gas bubbles drag NAPL to water surface.
Conceptual Model for NAPL Migration and PAH Migration in Sediment in SAZ

Changes in depth of burial of tarry layer due to presence of channel yield different effective stress conditions. At tarry sediment layer, NAPL migration occurs when critical stress value is exceeded and fractures connect to tarry layer.
EFNMFS Testing of Various Cap Designs

PAH Migration Through Different Laboratory Caps during Ebullition

- Control - Sand Only
- Sand + 10% Organoclay
- Effective Stress and Filter
- Effective Stress Alone

Control - Sand
Organo-clay
Eff stress filter
Eff stress

PAH Concentration (ug/kg)

Distance from Source (in)
Conceptual Design

Design of effective stress cap is like a filter for dam construction to prevent piping failure, but instead of preventing water piping, it interrupts fracture propagation due to gas migration.
Construction

Construction November 2017
Monitoring

2010 - 2015

2018
Conclusion

- Ebullitive mixing of sediment is affected by a variety of factors, including gas migration rate, sediment texture, and effective stress conditions.
- Fracturing and mixing can extend into a sediment column at least to a distance of several feet.
- Ebullitive mixing can impede the progress of natural recovery of sediment by transporting old sediment upward (one of several factors).
- Cap design to control this mixture changed effective stress conditions and interrupted fracture propagation using earth materials, saving time and money.
CREATE AMAZING.