EQUIPMENT AND SCALE-UP CONSIDERATIONS FOR IN-SITU SOLIDIFICATION OF MGP SITES

This paper illustrates the many factors that affect implementation of in-situ stabilization and solidification (ISS) at manufactured gas plant (MGP) sites, as well as the important scale-up issues that are commonly encountered when transitioning from the bench-scale treatability work to the field pilot demonstration, through full-scale treatment. Flexibility in adapting to changing field conditions and adjusting construction methods and mix designs is critical to a successful project that remains on budget. This paper also describes the types of construction equipment used to implement ISS for various field conditions. *In-situ* solidification can be performed utilizing various techniques, including single-auger mixing, patented rake injectors, high-speed rotating mixing devices and excavators.

Equipment and Scale-Up Considerations for *In-Situ* Solidification of MGP Sites

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In-situ solidification (ISS) is becoming an important technology for the remediation of source areas through containment and treatment at former manufactured gas plant (MGP) sites as the fate and transport mechanisms of solidified materials are better understood, and as more sites are successfully remediated with this technology. This technology is also compatible with redevelopment of former MGP sites for productive reuse. As with many remedial technologies, no one technology is suitable for all sites. The suitability assessment of ISS begins with bench-scale treatability testing to determine whether it can be implemented cost effectively to achieve the site-specific remedial objectives. Site physical conditions can also affect the suitability of the technology as well as its feasibility. Important considerations include water content of soils, coal tar saturations and distributions, site heterogeneity of geologic strata, surface and subsurface infrastructure and debris, and proposed site reuse, among others. This paper illustrates the many factors that affect implementation of ISS at MGP sites, as well as the important scale-up issues that are commonly encountered when transitioning from the bench-scale treatability work to the field pilot demonstration, through full-scale treatment. Flexibility in adapting to changing field conditions and adjusting construction methods and mix designs is critical to a successful project that remains on budget. This paper also describes the types of construction equipment used to implement ISS for various field conditions. *In-situ* solidification can be performed utilizing various techniques, including single-auger mixing, patented rake injectors, high-speed rotating mixing devices and excavators. The characteristics of each project are reviewed to determine the most effective method of ISS application.

1. Introduction

A typical MGP was dismantled after ceasing operations and the subsurface structures were abandoned in place, often with significant volumes of coal tar remaining in these structures. During operations and in the ensuing 50 to 100 years that these abandoned structures have been left idle, coal tar (typically in the form of a dense non-aqueous phase liquid [DNAPL]) leaked or was released from these structures into surrounding soils. By its nature, DNAPL sinks through vadose zone soils and water saturated soils until it reaches a lower permeability zone. The DNAPL can then migrate horizontally. This release and migration process can cover large areas and result in significant volumes of soil being impacted by coal tar well below the water table.

The depth of DNAPL impacts presents challenges for conventional excavation approaches. The physical and chemical characteristics (e.g., viscosity, range of compound solubilities, and hydrophobicity) of coal tar DNAPL also present challenges for many *in-situ* treatment technologies relying on physical contact, chemical destruction, or solubilization. *In-situ* solidification has emerged as a cost-effective remediation technology to address coal tar sites with significant DNAPL impacts. As the technology matures, the equipment and procedures to implement ISS are broadening and the scale-up considerations, based on data and observations at numerous sites, are becoming better understood.

2. Technology Description

In-situ solidification involves *in-situ* mixing of DNAPL-containing soils with cementitious reagents (e.g., portland cement) and possibly additives (e.g., fly ash, ground granulated blast furnace slag) to lower the soil hydraulic conductivity, encapsulate the soils, and blend the DNAPL more uniformly throughout the soil mass to below its residual saturation point, thereby eliminating the non-aqueous phase. The lowered hydraulic conductivity contains the impacted soils within a solidified monolith, significantly reducing the contact of the source with groundwater and the leaching of contaminants. A conceptual model of ISS is illustrated in Figure1.

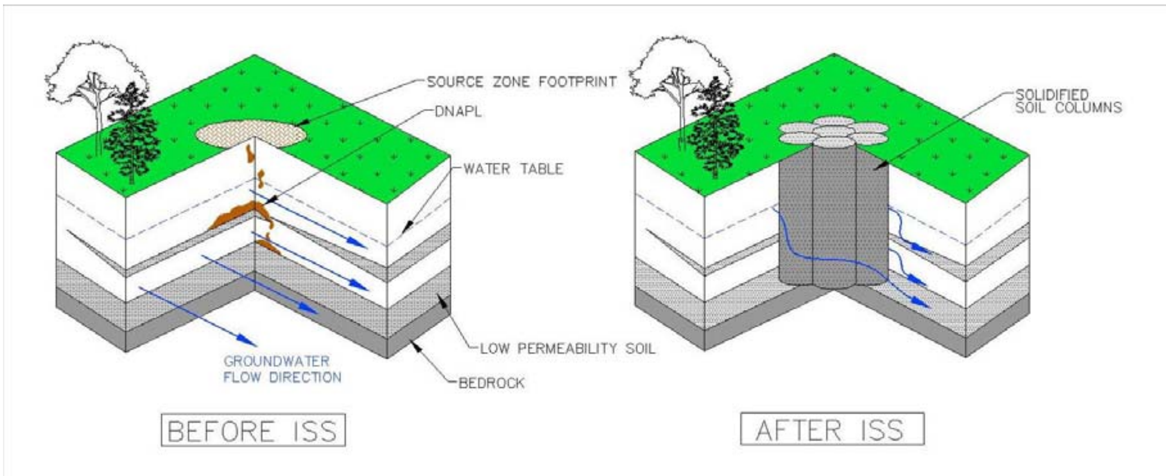

Figure 1. Conceptual model of *in-situ* solidification

Some of the benefits of ISS include:

- Source control through encapsulation and soil hydraulic conductivity reduction;
- Minimization of long-term impacts to groundwater;
- No long-term operation, maintenance and disposal;
- Potential lower cost than excavation and off-site treatment;
- Transformation of mobile DNAPL to below residual saturation by blending with cement and site soils;
- Greatly reduced source release to groundwater due to low hydraulic conductivity of the solidified soil monolith which minimizes groundwater flow; and
- Little to no dewatering is required to accomplish treatment.

2.1 ISS Mixing Equipment

The selection of equipment is based on several factors, including depth of stabilization, amount of debris present, and the solids content of the material to be stabilized. ISS can be performed utilizing various techniques, including single-auger mixing, patented rake injectors, high-speed rotating mixing devices and excavators.

2.1.1 Large Diameter Vertical Mixing Augers

In-situ large-diameter vertical auger mixing involves the use of a crane-mounted turntable or a track-mounted drill rig to rotate a 4- to 12-foot-diameter auger for *in-situ* soil treatment up to 60-foot depths, as shown in Figure 2. A liquefied cementitious grout is injected through the crane or drill rig’s hollow Kelly bar and the auger’s injection ports. As the auger rotates with upward or downward movement, the grout is injected. When the mixing and treatment cycles are complete, an *in-situ* column of treated soil and groundwater is created. The process is repeated by installing a series of overlapping columns across the desired treatment area’s surface until the entire project area is treated. Subsurface debris and foundations must be removed prior to using this type of equipment.

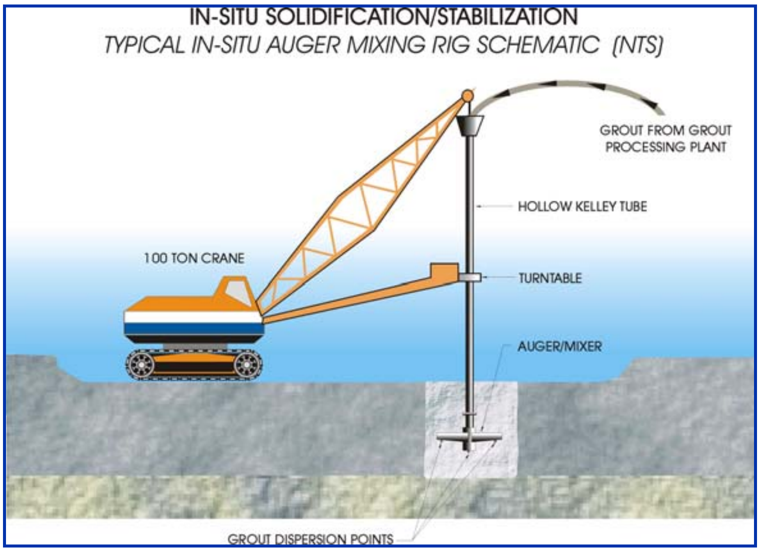

Figure 2. Vertical mixing auger equipment

Benefits of using the *in-situ* large-diameter vertical auger mixing technology include the following:

- Soil and/or sludge excavation to facilitate treatment is not required;
- The need for sheeting, shoring, and/or dewatering is eliminated because no excavation is required to perform the treatment;
- The technology accurately controls treatment depth and reagent application rates;
- Auger mixing produces a uniform, homogenous blend of *in-situ* material; and
- Minimal fugitive emissions are generated during treatment. This can be further controlled through the use of a containment shroud.

2.1.2 Excavator-Mounted Rake Injectors

In-situ soil mixing with excavator-mounted injectors involves the use of a set of hollow “forks” or “rake” attachments to treat contaminated soil and/or sediments, as shown in Figure 3. The rake is mounted on a conventional hydraulic excavator for *in-situ* mixing and treatment of soil and/or sludge at depths up to 10 feet. Liquid grout is injected through the hollow “forks” and mixed *in-situ* with soil or sediments through the rake motion of the excavator. This technology is well suited for shallow treatment of soft sediment, sludge, or soils.

Figure 3. Injector rake attachment

Benefits of *in-situ* soil mixing using excavator-mounted injectors include the following:

- Because treatment is done *in-situ*, soil or sediment excavation for treatment is not required, effectively eliminating the need to double handle contaminated materials;
- The *in-situ* treatment eliminates the need for sheeting, shoring, or dewatering because excavation is not required; and
- Rake-injector mixing provides an economical alternative for shallow, *in-situ* treatment with rapid construction progress.

2.1.3 Excavator-Mounted Rotary Blender

High-speed rotary stabilization equipment is also available. This type of ISS is applicable to soils and sludges with a moderate to high solids content and involves processing wastes in controlled layers. Processing steps typically include excavation, layering, conditioning, and stabilization. Mixing solidification/stabilization reagents into the soil or sludge is accomplished through the rotating action of the bladed equipment. A typical rotary blender is illustrated in Figure 4.

Figure 4. Rotary blender attachment

2.1.4 Excavator Mixing

Mixing of soils, sludges, or sediments with an excavator bucket is applicable to shallow depths, generally less than 20 feet, depending on the equipment size. This approach requires no specialty mixing equipment, but does require a skilled operator. Generally, the solidification area is gridded off into cells. At each cell, clean overburden is first stripped away to create a shallow containment excavation. Cementitious reagents are added as a liquid grout or dry with the addition of supplemental water. The excavator mixes the soil with the grout in layers to liquefy and blend the soil and grout together. This approach is illustrated in Figure 5. Use of excavators for ISS is applicable to areas where significant debris may be encountered and can be used to blend size-reduced demolition debris with the treated soil to reduce the need for off-site demolition debris disposal.

Figure 5. Excavator mixing

3. Bench-Scale Treatability Testing

Evaluation of the suitability of ISS for a particular site begins with a bench-scale treatability test in which various reagent combinations and strengths are mixed with site soil samples to determine the most cost-effective mix design to achieve performance standards. Typically strength, permeability, and leachability are the primary performance parameters. Other factors such as grout viscosity, volume increase, vapor emissions, strength gain rate, durability, slump, and moisture content variation effects may also need to be considered. Sample collection from a site for bench-scale testing may be performed with an excavator or a drill rig, depending on the depth of impacted material. Several 5-gallon buckets of material are typically required, depending on the complexity of the treatability study. Collected samples should represent both worst-case and average conditions of DNAPL impacts. Variability of soil types, moisture content, and *in-situ* hydraulic conductivities should also be identified. Treatability testing should consider the type of equipment, reagent application method, and equipment limitations (e.g., minimum grout water content to be pumpable). Treatability studies for ISS, which typically include a solidified soil leachability evaluation, can take four to eight months or more to complete. Once a mix design is determined to be acceptable, it should be tested with a few replicates to assess repeatability and reliability of the mix design, as this mix design will often be the basis for contractor bidding.

4. Performance Criteria

Performance criteria can vary widely from state-to-state and site-to-site, but generally include strength and permeability. Leachability is generally assessed in the lab and correlated to a target strength and permeability. Due to the timeframe required to perform leaching tests that mimic a solidification scenario, leachability is not typically a construction quality assurance criteria. However, some sites have utilized a short term destructive leaching test such as the Toxicity Characteristic Leaching Procedure (EPA Method 1311) or the Synthetic Precipitation Leaching Procedure (EPA Method 1312), although the suitability of these destructive tests for ISS has been in question for some time.

The project's performance criteria need to be set to account for some variability in field conditions and differences between lab bench-scale testing results and full-scale results. An example of performance criteria that account for some variability is as follows:

- Unconfined Compressive Strength
    - 50 psi average of all
    - 40 psi minimum
    - No more than 20% of samples < 50 psi

- Hydraulic Conductivity
  - $1x10^{-6}$ cm/sec average
  - $1x10^{-5}$ cm/sec maximum
  - No more than 20% of samples > $1x10^{-6}$ cm/sec

5. Scale-Up Considerations

Following the bench-scale treatability testing, the selected mix design is ready for application at field scale. Typically, a pilot scale treatability evaluation is conducted at the site to determine if the mix design requires any adjustment for full-scale application and to evaluate the selected mixing equipment for its ability to achieve the desired solidified product. Depending on the size of the project and the construction timeframe, the pilot test may be conducted as a distinct phase of the overall project, or it may be performed as an initial phase of the full-scale construction. Performance of the pilot test as a distinct phase of the project allows for the test area samples to be cured at varying durations and tested, and the results can be compared to typical 28-day performance criteria. While this approach is more costly (it requires equipment mobilization solely for a limited area pilot test), it presents the least amount of construction risk during full-scale treatment. Conducting the pilot test as the first phase of full-scale treatment allows cost savings in equipment remobilization or downtime, and a tighter project schedule; however, it relies on early testing results (e.g., 7 or 14-day) to indicate the ability to meet 28-day performance criteria, presenting more construction risk with continued solidification. This additional risk can be mitigated by evaluating the 7 or 14-day test results in the bench-scale treatability study or by planning for additional reagent above what the bench-scale testing indicated was necessary.

In scaling up from the bench-scale to full-scale, a number of factors can influence results including one or more of the following:

- *In-situ* mixing and curing differs from *ex-situ*;
- Curing conditions for small cylinders is different than in the ground;
- There will be variability in soil characteristics, moisture content and DNAPL saturations; and
- The potential to “under-treat” or “over-treat” exists, and can be influenced by:
  - Soil dry density variability
  - Moisture content variability
  - Soil/fill/debris – ability to homogenize thoroughly
  - Reagent delivery equipment calibration
  - Field quality control procedures
  - Reagent density

Field quality control and quality assurance procedures are critical to a successful project outcome. Field observations and screening tests can be a useful real-time tool to assess the quality of mixing and curing progress and may include:

- A slump test, which can be useful for consistency (especially with dry mix);
- A penetrometer, used as a gross indicator of curing progress;
- Extra samples to observe on site (see Figure 6); and
- Visual observation – if it doesn’t look right, it probably isn’t.

Figure 6. Left photo of a properly prepared test cylinder. Right photo of a poorly prepared cylinder that will result in poor test results for strength and permeability.

Full-scale implementation should allow for field adjustments which may include one or more of the following:

- Additional reagent for excessively oily areas;
- Modification of grout water content;
- Addition of dry reagent for excessively wet shallow areas;
- Re-mixing if necessary, but before too much strength gain; and
- Installation of a perimeter wall to “enclose” the solidification area to control water conditions and encapsulate the treatment area

Variability in soil and contaminant characteristics across a site cannot be avoided, therefore the full-scale implementation needs to have the flexibility to account for these variations in order to meet established performance criteria. The selected mix design for the project should allow for some buffer between bench-scale results and performance criteria. For example, if the bench-scale test indicated that a 5×10^{-8} cm/sec permeability could be achieved, consideration should be given to establishing the performance criteria somewhat higher (e.g., 1×10^{-7} cm/sec), or to utilizing a higher reagent percentage to account for field variability. It should also be recognized that the solidified mass behaves as a large monolith and that some variation in results in individual mix cells will have little bearing on the overall performance of the remedy. Other elements of the remediation should also be factored into the assessment of results such as use of a geomembrane cover, remedial goal (i.e., source control or groundwater remediation), contaminant conditions outside the treatment area, and regulatory requirements.

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