EXECUTIVE SUMMARY

New Application of Pre-Fabricated Vertical Drains To Remediate Low-Permeability Contaminated Media

ESTCP Project ER-201627

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ACRONYMS AND ABBREVIATIONS

bgs	Below ground surface
cis-1,2-DCE	*cis*-1,2-dichloroethene
CMT	Continuous Multichannel Tubing
CVOC	Chlorinated Volatile Organic Compound
ESTCP	Environmental Security Technology Certification Program
ft	Foot, feet
in	inch
low-k	Low permeability
MW	Monitoring Well
TCE	Trichloroethene
yd^3	Cubic yard
ZVI	Zero Valent Iron

1.0 INTRODUCTION

A critical challenge preventing many chlorinated solvent (or chlorinated volatile organic compound [CVOC]) sites from reaching groundwater cleanup goals is the long-term and persistent release of residual contaminants from low-permeability (low-k) media (e.g., clays/ silts). Sites dominated by matrix diffusion processes are very difficult to remediate and have the effect of significantly prolonging restoration timeframes and increasing long-term site management costs for the Department of Defense (SERDP/ESTCP, 2013; 2018). Currently, there are limited remediation options available to treat residual contamination trapped in low-k zones. For these long-lived, difficult to treat sites, inexpensive (in units of dollars per cubic yard or dollars per acre) technologies are needed that will: i) reliably address mass flux limitations of contaminants leaving low-k source zones and ii) increase the actual treatment of the contaminants leaving these low-k zones by enhancing natural attenuation processes.

The geotechnical industry offers a variety of well-established techniques for quickly and efficiently accessing the subsurface for the purposes of ground stabilization, foundation rehabilitation, porewater drainage, and structural support. The speed and efficiency of these techniques is advantageous to the field of environmental remediation, particularly for emplacement of remedial amendments (e.g., Zero Valent Iron (ZVI), vegetable oil, chemical oxidants) into the subsurface at contaminated sites. Two promising techniques with potential environmental applications were evaluated as part of this Environmental Security Technology Certification Program (ESTCP) project: i) prefabricated vertical drains (or "wick drains") and ii) cement grouting (the Grout Bomber or Bomber; **Figure ES-1**). Both technologies utilize specialized machinery to rapidly access the subsurface via a direct push technique, where hundreds of vertical drains or columns can be installed per day to depths greater than 80 feet (ft) below ground surface (bgs).

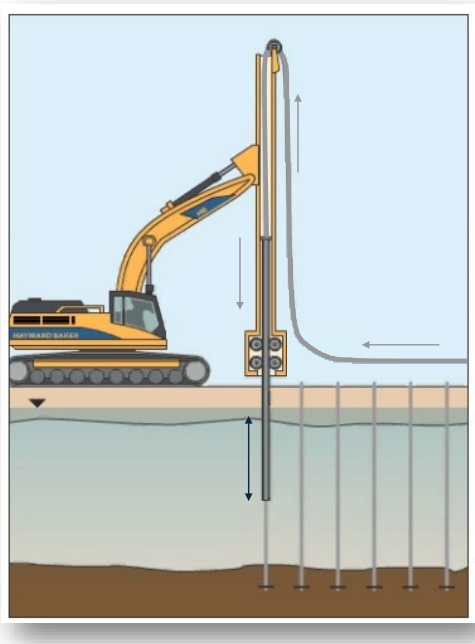

Figure ES-1. The Grout Bomber

This project initially focused on the application of wick drains as "reaction columns" for delivery of remediation amendments (e.g., ZVI, vegetable oil) to the subsurface where the wick drains would be installed first, followed by injection of the amendment into the wicks (in this scenario, the wicks serve as conduits for the emplaced remedial amendment). However, following discussions with the geotechnical contractor (Hayward Baker, now Keller), observations from site visits (to observe both the wick drain installation and the Bomber technology) and preliminary laboratory testing, the project team concluded that the Grout Bomber was the most viable method to achieve rapid and reliable amendment delivery into the subsurface for the field demonstration.

2.0 OBJECTIVES

The objective of the field demonstration was to test and validate an innovative application of a commercially available geotechnical technology, the Grout Bomber, to improve delivery of remediation amendments at sites with contaminants trapped in low-k zones (clays/silts). The following were proposed to demonstrate that:

- conventional geotechnical techniques could be used to efficiently install hundreds of closely spaced vertical reaction columns at contaminated sites;
- a remediation amendment (in this case, a "grout" mixture of ZVI, sand, and vegetable oil) could be delivered into the columns to serve as reactive zones for contaminated groundwater;
- the remediation amendment would stimulate abiotic and/or biotic degradation of CVOCs and generate concentration gradients to drive diffusion of contaminants into the reaction zones; and
- by having closely spaced (every 2 to 3 ft) vertical reaction zones, CVOC concentrations in low-k zones would be reduced, thus, significantly shortening the "long tail" of contaminant flux commonly observed at these sites.

3.0 TECHNOLOGY DESCRIPTION

The Grout Bomber is a subsurface stabilization technology that uses an excavator equipped with a specialized "stitcher" mast to quickly push a mandrel (3.5 inch [in] diameter hollow cylindrical rod) into the subsurface and subsequently fill the hole and subsurface voids with cement grout (from bottom to top) using an in-line grout delivery system. As shown in **Figure ES-2**, the typical arrangement of the Bomber includes the installation rig (excavator with the "stitcher" mast) and an on-site grout mixing and delivery unit (mixing hopper, pumps, hosing, power supply, etc.).

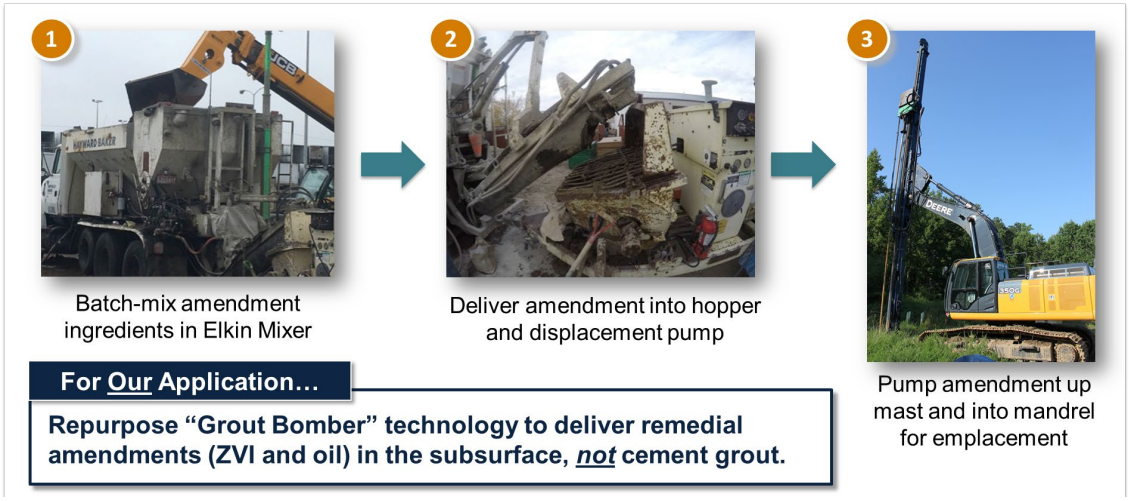

Figure ES-2. Grout Bomber Equipment Setup

Raw material (e.g., sand, cement, aggregate) is loaded into a volumetric mixer (e.g., Elkin mixer), where it is mixed to the appropriate consistency, unloaded into the hopper, and pumped to the top of the "stitcher" mast via flexible, reinforced hose at a rate of approximately 0.25 cubic feet per pump stroke. At the exit end of the Bomber mandrel, the "grout mixture" flows in a continuous and uniform manner, filling the column and surrounding voids with grout as the mandrel is lifted from the desired depth to the surface. Hundreds of grout columns can be installed per day.

For this ESTCP project, the proposed application of the Grout Bomber technology was to replace the cement grout with a remedial amendment mixture (ZVI, sand, and vegetable oil) without any modifications to the existing equipment and assess the capabilities of the technology for rapid delivery of amendments into low-k zones (clays/silts). Key features of the proposed application of the Grout Bomber include:

Rapid installation of reaction columns within the source area. Utilize the Grout Bomber equipment to quickly install hundreds of reaction columns (3.5 in diameter) per day, spaced 2-3 ft apart, to a depth of 30 ft bgs or greater.

Create amendment-filled reaction columns within the treatment zone. For the application, remediation amendment (mixture of ZVI/sand/water or oil/sand) was delivered into the subsurface (from bottom to top) to create vertical reaction columns. Minor amounts of neat soybean oil were used primarily to improve flow properties and pumpability of the ZVI amendment mixture and, secondarily, to serve as an electron donor to promote biotic reduction dechlorination of CVOCs.

Create hundreds of vertical reaction zones within the source area. Columns containing amendment serve as reactive interfaces (3.5 in diameter) with the surrounding subsurface media. These vertical reaction zones stimulate biotic and/or abiotic degradation processes and drive steep concentration gradients which, in turn, promote diffusion of contaminants entrapped in surrounding low-k units. In the presence of ZVI, CVOC degradation proceeds abiotically via a combination of reductive β-elimination reactions (generating chloroacetylene and acetylene as intermediate products) and hydrogenolysis reactions (producing *cis*-1,2-dichloroethene [*cis*-1,2-DCE] and vinyl chloride and ultimately ethene and other end products).

Not an injection technology but treats low-k clays/silts by reducing contaminant diffusion lengths. This application of the Bomber technology relies on diffusion to draw the contaminants from low-k zones to the reaction column. The diffusion of CVOCs is driven by steep concentration gradients between the pore water within the reaction column and the surrounding media (see **Figure ES-3**). The "long tail" of contaminant flux from low-k units can be significantly reduced if the diffusion lengths associated with matrix diffusion are reduced. The hypothesis is that reaction columns spaced every 2-3 ft within the plume center of mass would greatly reduce the back diffusion time as the contaminant only has to travel 1-1.5 ft to the nearest treatment zone.

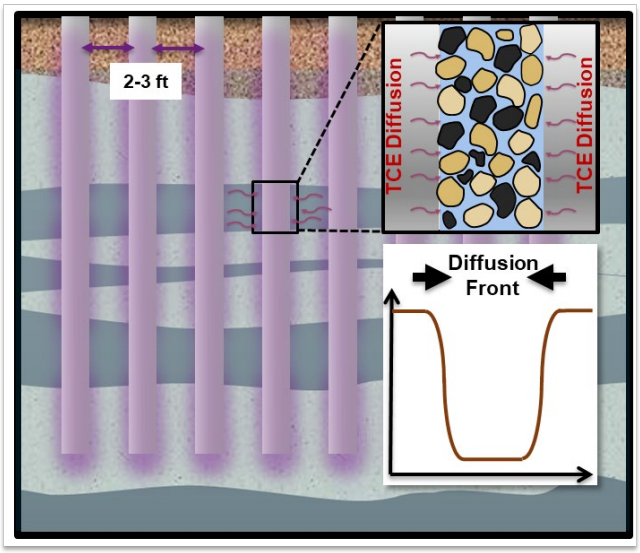

Figure ES-3. Illustration of Trichloroethene (TCE) Diffusion Towards the Closely Spaced Reaction Columns

4.0 PERFORMANCE ASSESSMENT

The Bomber technology successfully met the established performance objectives as follows:

Installation Speed and Efficiency: Considering only fully operational days (i.e., no weather or equipment related delays), an average of ~119 columns were installed per day, with a range of 82-180 columns per day. A total of 800 columns were installed over the course of 7.5 days (including half days due to weather or equipment related delays). This exceeded the goal of an average of 75 columns per day and confirms the technology's ability to install reaction columns quickly and efficiently. A total of 77,000 lbs (~39 tons) of ZVI was emplaced during the field demonstration into an approximately 5,200 cubic yard (yd^3) treatment zone.

Rate of Remediation Amendment Mixing: During the field demonstration, one operator was designated for replenishing the mixing truck bins with sand, ZVI, water, and oil as needed. This made material loading/mixing a continuous process and eliminated the need to prepare the amendment in batches. As result, material loading, and amendment preparation did not halt operation and continuous operation of the installation rig was maintained.

Distribution of Amendment to Treatment Depth: Based on field observations, all columns received amendment that filled >90% of total column length (~30 ft) based on mass estimates and number of pump strokes per column. Most of the magnetic separation test samples (7 of 10) resulted in ZVI content within ±30% of desired dosage (28%-52%). Three samples had ZVI content >52% (54%, 81%, and 88%).

Removal of Contaminant Mass: Groundwater data was collected at seven post-installation monitoring events over a period of 26 months and was compared to baseline sampling results prior to column installation. For the wells with detectable CVOC concentrations during the baseline event (IS17Monitoring Well [MW]04, MW12, MW14, and MW16), a greater than 70% reduction in TCE concentrations was observed relative to baseline concentrations after approximately two years. Degradation products (cis-1,2-DCE, vinyl chloride, ethene) were consistently detected in source area monitoring wells (due to several processes, including degradation via ZVI) and Continuous Multichannel Tubing (CMT) wells throughout the monitoring period, and acetylene (via degradation from ZVI) was detected in one monitoring well (IS17MW04) in four of eight post-installation groundwater sampling events and in two CMT intervals (CMT-1-Middle, CMT-1-Lower) during three sampling events. Soil vapor results identified gaseous "higher coupling products" (>C3, e.g., propane, propene, butane, pentane, and hexanes) associated with the β-elimination pathway induced by the ZVI addition in the vadose zone directly above reaction columns.

Ability to Place Reaction Columns and Ease of Amendment Delivery: Site clearing activities were required (e.g., removal of trees and ground debris) to accommodate large installation rig/equipment. Additionally, the heavy rig required timber mats be laid in the demonstration area to retain mobility in muddy conditions. The Bomber rig has limited ability to install columns on steep slopes, to advance columns in areas with large tree roots and has limited mobility in tight spaces (e.g., between wells, trees, etc.). The Grout Bomber rig itself has a footprint of 12-ft x 10.5-ft and requires support from an Elkin mixer (truck-powered mixer with an 8-ft x 10-ft footprint) and the hopper/amendment pump (4-ft x 3-ft trailer-mounted equipment). Additional footprint requirements include a bermed overspill/mixing area (~8-ft x 8-ft), storage area for amendment raw materials, and room for a reaching forklift to move sacks from the storage to the Elkin mixer. Loss of amendment was limited to clogging events when operators would detach hosing and clean out pump hopper and hoses. Some material loss occurred at ground surface due to "over pumping" by pump operator. During normal operation, very minimal amendment loss was observed, and collection/reuse of the over-pumped amendment can be managed using shovels.

5.0 COST ASSESSMENT

Costs associated with the field program have been used to develop costs for a typical full-scale implementation of the Grout Bomber technology at a chlorinated solvent source zone. Standard costs for implementation of the field demonstration include: i) baseline characterization activities (groundwater sample collection; analytical costs, labor); ii) remedial amendments (ZVI, oil) and other materials (sand, bentonite); iii) day rates for the Bomber equipment (excavator, Elkin mixer, fork-lift, and labor (four personnel); iv) labor for site supervision; v) standard supplies, shipping, and equipment rental; and vi) sample analysis of groundwater after reaction column installation. Actual costs for the field demonstration at Site 17 were higher than typical site conditions due to site clearance and preparation, weather delays and weather-related expenses, geophysical surveys, installation of CMTs and soil vapor probes for performance monitoring, and analytical costs for

CMTs and soil vapor probes. These costs may not be incurred at all sites. Including only standard costs, the total cost for the field demonstration was $399K, which translates to ~$77/yd^3 of treatment volume. The cost for installation of the reaction columns (excluding baseline and performance monitoring) was $294K, or ~$56/yd^3 of treatment volume.

6.0 IMPLEMENTATION ISSUES

This ESTCP project utilized the Grout Bomber compaction grouting technology to quickly install ~800 vertical reaction columns in a low-k site source zone. Re-purposing of the Grout Bomber technology for installation of ZVI reaction columns in low-k media presented a few implementation issues associated with: i) preliminary pilot testing to determine appropriate remediation material mixture that satisfied both pumpability and treatability criteria, ii) site access and a large area for equipment staging, and iii) general mobility of large equipment in a tight work environment.

7.0 REFERENCES

SERDP/ESTCP, 2013. SERDP and ESTCP Workshop on Long Term Management of Contaminated Groundwater Sites, Strategic Environmental Research and Development Program, November 2013.

SERDP/ESTCP, 2018. SERDP and ESTCP Workshop on Research and Development Needs for Chlorinated Solvents in Groundwater, Strategic Environmental Research and Development Program, October 2018.