Bioremediation and Sustainable Environmental Technologies—2017. Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies (Miami, FL; May 2017). ©2017 Battelle Memorial Institute, Columbus, OH, www.battelle.org/biosymp. A. Barton and S. Rosansky (Chairs)

Soil Blending

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BACKGROUND

The most difficult and persistent obstacle to successful subsurface remediation is access to residual contaminants. The distribution of residual contamination is heterogeneous by nature and accurate mapping is generally limited by the technological capability of tools and available funding for characterization. In addition, the contamination is often in a mixed zone of unsaturated, partially saturated and saturated sediments. As a result, technology wish lists include something that can address contamination at the cm^3 scale with sufficient speed to treat hundreds of m^3 per day cost-effectively. The soil blending process can homogenize the target area sufficiently to allow significantly improved contact of amendments with contaminants. Over the last decade, Redox Tech has completed numerous soil blending projects treating a variety of contaminants in a diverse suite of geologic environments. Many projects have dealt with recalcitrant contaminants in difficult settings. Soil blending has become a favorable alternative to dig-and-haul because it is viewed as more “green” and not a relocation of waste.

There are currently two main types of soil mixing equipment: large diameter augers and rotary drum blenders. Large diameter augers (up to 3 m diameter) are typically mounted and operated in a similar manner to conventional drilling rigs. Their strength lies in the ability to mix to great depths but they are not efficient at covering large areas. Rotary drum blenders are typically mounted at the end of excavators and can rapidly address large areas but are often limited in their depth. A key component of all soil blending equipment is the ability to effectively deliver power to the mixing head. Most commercially available rotary drum systems are not able to provide the power necessary to thoroughly mix cohesive materials like silts and clays.

Soil blending for environmental remediation has only recently joined the pantheon of soil mixing techniques that have traditionally been used for construction or stabilization. In construction and stabilization, there appear to be several distinctions or classifications of mixing including dry or wet mixing, and deep and shallow soil mixing. Soil mixing was first developed in 1956 by a private U.S. company (Bruce, 1996), which mixed injected grout with native soil in a bottom up approach. This technique was used in only a few tens of sites in the US to create cutoffs beneath dams and retaining walls where sediments were comprised primarily of sand and gravel. However, the technique became very popular in Japan where it was modified to incorporate other materials such as lime and named deep lime mixing (DLM). As opposed to creating cutoff walls in coarse sediments, the Japanese used the technique to stabilize soft clays. At the same time in a parallel effort, Sweden also developed techniques for lime mixing. The Japanese continued building on these techniques creating a dry jet mixing (DJM) method and other advances in the now linked field of soil mixing and grout injection generally known as cement deep mixing (CDM). These techniques have relied on large diameter (up to 3 m diameter) auger and paddle type vertical mixing methods where lateral coverage was accomplished by overlapping mixed cylinders. The Federal Highway Administration uses the acronym DMM (Deep Mixing Method) to broadly include all soil mixing methods “to improve soil strength, permeability, and/or compressibility characteristics” (FHWA, 2013).

Soil mixing for environmental remediation first relied on some of the large diameter auger methods developed for construction. In the early 1990s, auger mixers were used to blend sites to stabilize or encapsulate metal and hydrocarbon contaminants. In the mid 2000’s alternative methods of soil mixing were developed including cutting techniques (e.g., trenchers) and rotating toothed drums. Initially these techniques were used to install walls or permeable reactive barriers but eventually evolved into focused source zone treatment methods.

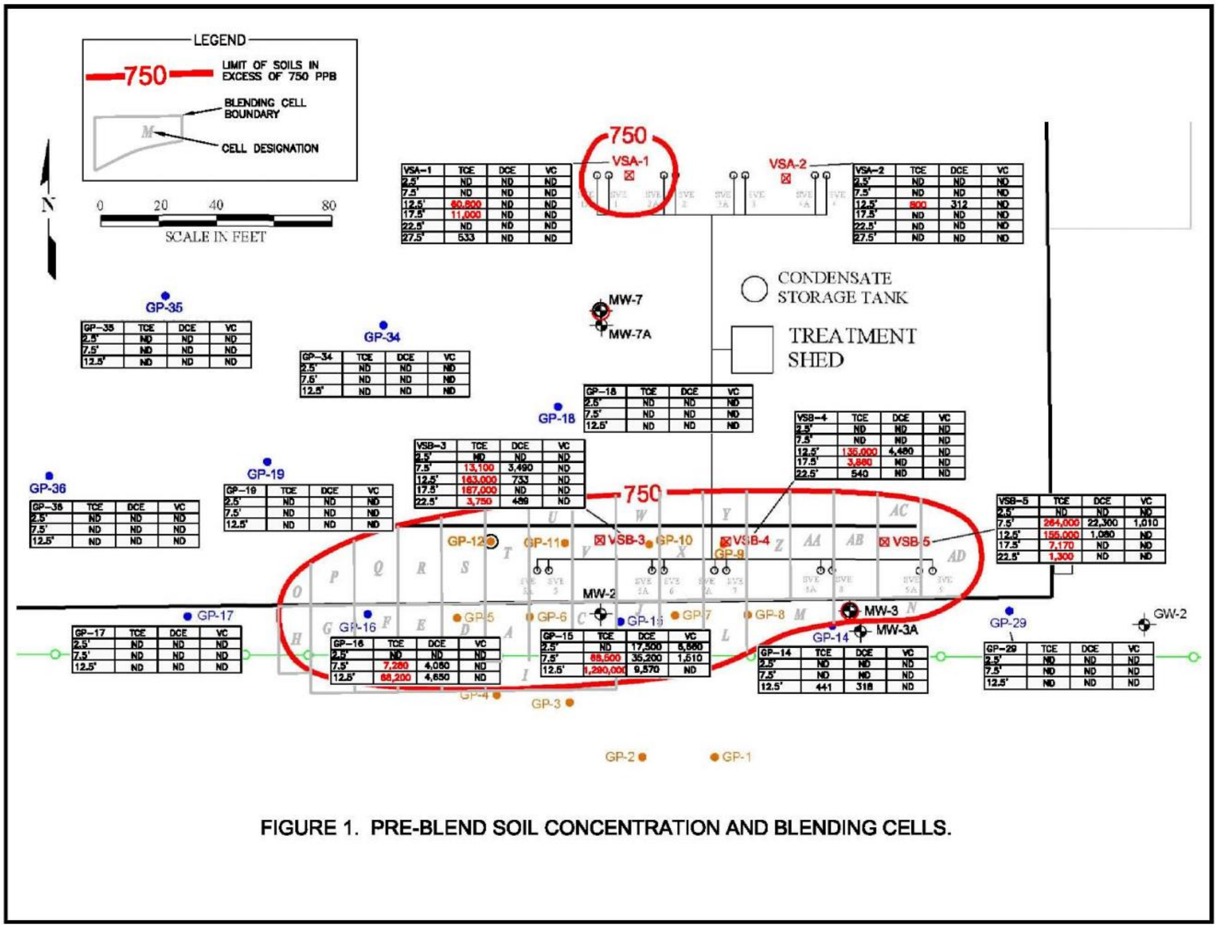
The development of high power, rotating drums have significantly improved the range and practical applicability of soil blending. The tools, originally developed for land clearing (e.g., stump grinding) were modified to increase power delivered to the drum rotating on a horizontal axle and attached to an excavator arm. These types of machines were first developed in Finland, Germany, and Italy for road preparation and later brought to the U.S. where the first environmental applications occurred in the mid 2000s. One of the earliest projects blended chemical oxidants (persulfate and base) to treat a high concentration and extensive chlorinated solvent plume in New Jersey. This site had a large amount of separate phase tetrachloroethene and despite a significant reduction of the contaminant mass, the site required additional phases of treatment. Since then other chlorinated sites have achieved complete remediation in single soil blending campaigns using both oxidants and reducing agents.

Blender Description. In situ soil blending involves using a powerful machine to effectively distribute chemical amendments throughout the soil medium to treat contaminants of concern. The chemical amendments can be oxidants, reductants, biostimulants, or soil stabilizers. Based on our experiences we have developed and modified the tools and process for soil blending. The in situ blender that we currently use is mounted on a large excavator with a modified diesel engine and hydraulic power system (Figure 1). The mixer is capable of mixing dry soil as well as sludge material to depths of 20 feet below ground surface without benching. With benching, we have blended to 32 ft (9.75 m) bgs. A 450 hp (336 kW) dedicated engine allows the blender to produce more than 20,000 ft-lbs (> 27,000 nm) torque at the mixing head. Unlike many commercially available mixing tools designed for shallow road preparation, this blender was specifically designed for deeper access needed for source zone remediation. The specially designed and coordinated hydraulic system and mixing motor/drum enables this blender to deliver more than twice the power of the most powerful commercial units. The soil blender uses hydraulic pressures of 5,000 psi (34,500 kPa), a 36-inch (91.4 cm) diameter mixing drum, variable drum rotation speeds up to approximately 140 rpm, and a range of teeth for optimal blending depending on soil types (including rock). The twin motors on the blending head can be individually controlled to facilitate performance in heterogeneous materials. These features allow the mixing drum to penetrate all soil types, even with the presence of backfill materials such as bricks, boulders, and rebar. In addition to optimizing for delivery of power, the blender was designed with proper housing and shielding components to protect hydraulic lines and other mechanical components when the head is mixing at depth and to allow for thorough decontamination and cleaning.

FIGURE 1. Redox Tech soil blender.

Applications. We have used the soil blending method to treat a variety of different contaminants employing several types of amendments and strategies. Soil blending provides comprehensive contact between the amendment and contaminant by disrupting the tortuous pathways in the soil matrix that make contact so difficult to achieve using other amendment application methods. The ability to address soils below the water table in place provides significant advantages over excavation and removal. We have performed several soil blends to treat chlorinated solvents using potassium permanganate. The primary advantages of using this oxidant are fast kinetics allowing rapid verification of concentration goals and the ability to stabilize soil directly after blending oxidant. Permanganate reactions typically occur in minutes to hours and do not require additional activation to oxidize chlorinated alkenes. We have also used other oxidants and oxidation enhancers like persulfate, and hydrogen peroxide, OBC (original mixture of persulfate and calcium peroxide), reducing agents and reduction enhancers like zero valent iron and ABC (carbon substrate, nutrients, pH buffer), and stabilization amendments for treating metals and similar recalcitrant contaminants.

In a recent application in central Iowa, we blended potassium permanganate in an area approximately 16,000 ft^2 (1487 m^2) to a maximum depth of 25 ft (7.6 m) that was comprised of low permeability, compacted glacial till with interbedded sand layers. The area was delineated based on a predetermined 0.75 mg/kg contour line and consisted of approximately 17,000 tons (15,422 MT) of soil. The target contaminants were chlorinated solvents with concentrations up to 1200 mg/kg (including NAPL) (Figure 2). Using an average oxidant dose of 5 g/kg (approximately 84 tons or 76 MT potassium permanganate) soil blending was successfully completed in 49 days for approximately $50 per ton. Post blending soil samples were non-detect over the entire blend area.



VSA-1	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	60,800	ND	ND
17.5'	11,000	ND	ND
22.5'	ND	ND	ND
27.5'	533	ND	ND

VSA-2	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	800	312	ND
17.5'	ND	ND	ND
22.5'	ND	ND	ND
27.5'	ND	ND	ND

GP-35	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	ND	ND	ND

GP-34	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	ND	ND	ND

GP-18	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	ND	ND	ND

VSB-4	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	135,000	4,480	ND
17.5'	3,880	ND	ND
22.5'	540	ND	ND

VSB-3	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	13,100	3,490	ND
12.5'	163,000	733	ND
17.5'	187,000	ND	ND
22.5'	3,750	489	ND

GP-36	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	ND	ND	ND

GP-19	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	ND	ND	ND

VSB-5	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	264,000	22,300	1,010
12.5'	155,000	1,080	ND
17.5'	7,170	ND	ND
22.5'	1,300	ND	ND

GP-17	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	ND	ND	ND

GP-16	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	7,280	4,080	ND
12.5'	68,200	4,650	ND

GP-15	TCE	DCE	VC
2.5'	ND	17,500	6,660
7.5'	68,500	35,200	1,510
12.5'	1,290,000	9,570	ND

GP-14	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	441	318	ND

GP-29	TCE	DCE	VC
2.5'	ND	ND	ND
7.5'	ND	ND	ND
12.5'	ND	ND	ND

FIGURE 1. PRE-BLEND SOIL CONCENTRATION AND BLENDING CELLS.

FIGURE 2. Iowa blend layout.

In 2007, we remediated a 40 ft x 60 ft x 22 ft deep (52,800 ft^3 or 1495 m^3) site in South Carolina contaminated with laboratory wastes including chlorinated and aromatic solvents by blending 43 tons (39 MT) of zvi and 82.5 tons (75 MT) of clay (Ovbey et al., 2010). At this site, tests were performed to assess the distribution of zvi during blending using the rotary drum, which found uniform distribution of iron at the specified mass fraction over the entire blending depth and lateral extent. The action achieved the cleanup objective for the site.

At a site in Rhode Island we blended 5 tons (4.5 MT) of potassium permanganate to treat a source target volume of 56,700 ft^3 (1606 m^3). The upper 10 ft (3.3 m) of soil was temporarily removed to allow access to the 10 to 18 ft (3.3 to 6 m) bgs interval (top of bedrock). After blending, the upper soil was replaced and graded. In addition to directly treating the blended area, permanganate was observed in downgradient and sidegradient monitoring wells screened in the bedrock indicating a pervasive treatment blanket well beyond the boundaries of the blend.

In 2008, persulfate and quicklime were blended at a site in Louisiana to treat petroleum hydrocarbons and chlorinated solvents. Approximately 24.25 tons (22 MT) of persulfate were activated by the heat generated from 112.5 tons (102 MT) of calcium oxide blended into the 20 ft (6.7 m) deep target area (72,900 ft^3 or 2064 m^3). An additional 5.25 tons (4.8 MT) of hydrated lime were then blended to stabilize the soil. Contaminant reduction soil strength targets for construction were met. The soil blending area was below an active trucking facility, so the blended soil had to support large loads after mixing was completed.

In April 2009, potassium permanganate was blended at a small (500 ft^2 or 46.5 m^2, TD = 8 ft or 2.4 m) TCE contaminated site in Yorkville, Illinois where there was a prior attempt (October 2008) to mix oxidant and soils using a conventional backhoe and excavator. The remedial goals were relatively modest – to reduce TCE mass fractions below the soil saturation threshold determined to be 1,300 mg/kg. Initial mass fractions were as high as 10,000 mg/kg in some locations. The initial attempt using the backhoe and excavator was able to reduce concentrations but was unsuccessful at reaching the remedial goals. The soil blender was deployed to the site and was able to achieve regulatory objectives by blending 1.3 tons (1.2 MT) of permanganate in one day for a cost of approximately $50 per ton inclusive (Figure 3). Soil blending with a backhoe or excavator bucket approach often doesn't achieve the necessary uniformity. Also, the production rates with bucket mixing are much lower than with a rotary blending approach.

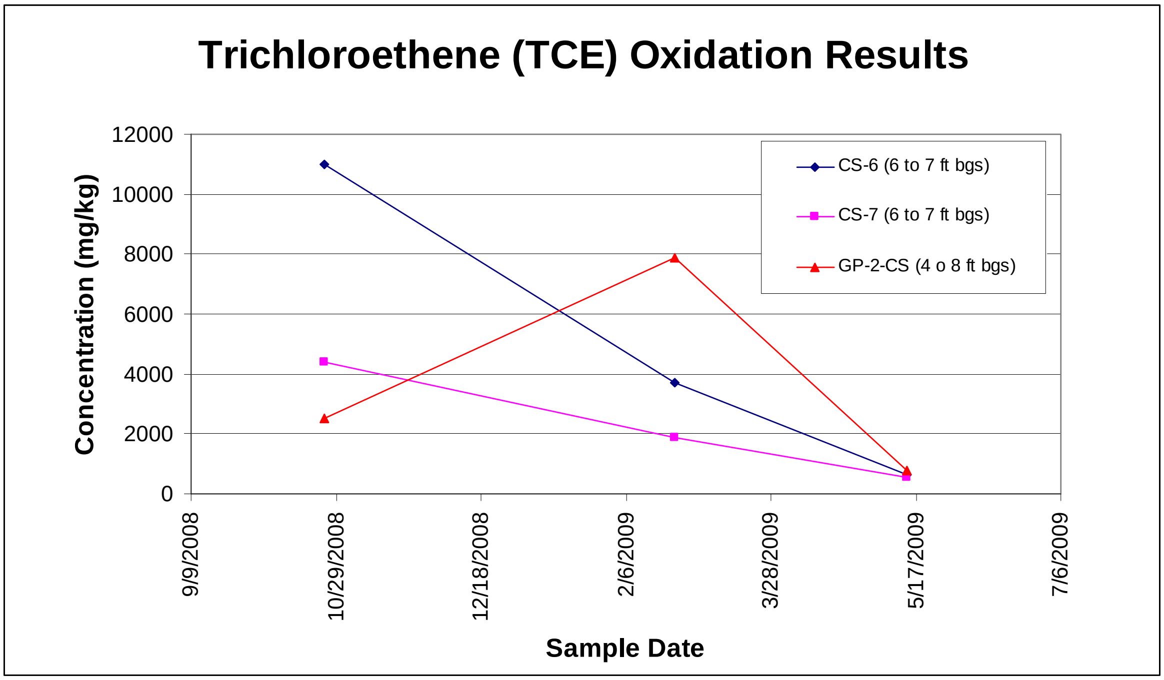


FIGURE 3. Performance comparison of backhoe soil mix (October 2008) and soil blender (April 2009).

Persulfate and hydrated lime were used in a soil blending event to treat pentachlorophenol at a former wood treating site in Wilmington, NC in 2006. Prior efforts using injections were only partially successful due to heterogeneous distributions of contaminants as well as heterogeneous distributions of amendment despite being in an area (Figure 4) that would typically be described as homogenous coastal sand. Electrical conductivity prior to and post injections clearly showed tortuous injection pathways (Figure 5). Similar electrical conductivity measurements before and after soil blending showed a much greater, more homogenous distribution of amendment (Figure 6). Pentachlorophenol concentrations were reduced by more than three orders of magnitude after blending and satisfied regulatory requirements.

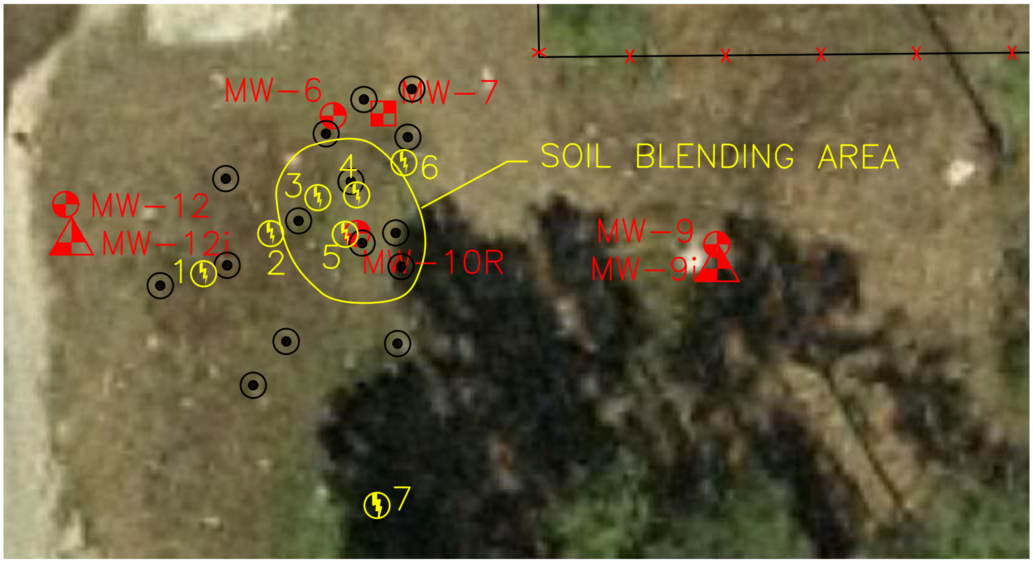


FIGURE 4. Plan view Wilmington site – black bullseyes are injection points; yellow lightning are electrical conductivity measurements.

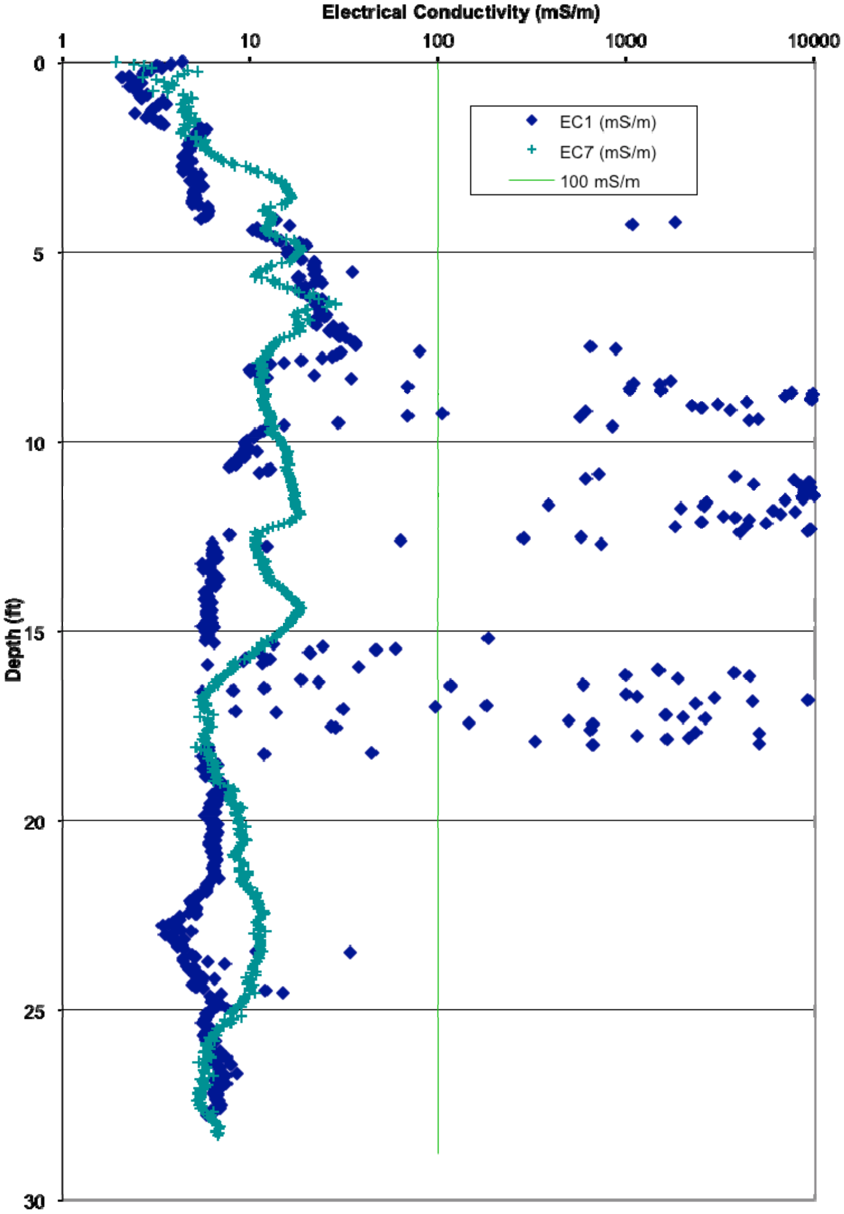


FIGURE 5. Background electrical conductivity and near injection point.

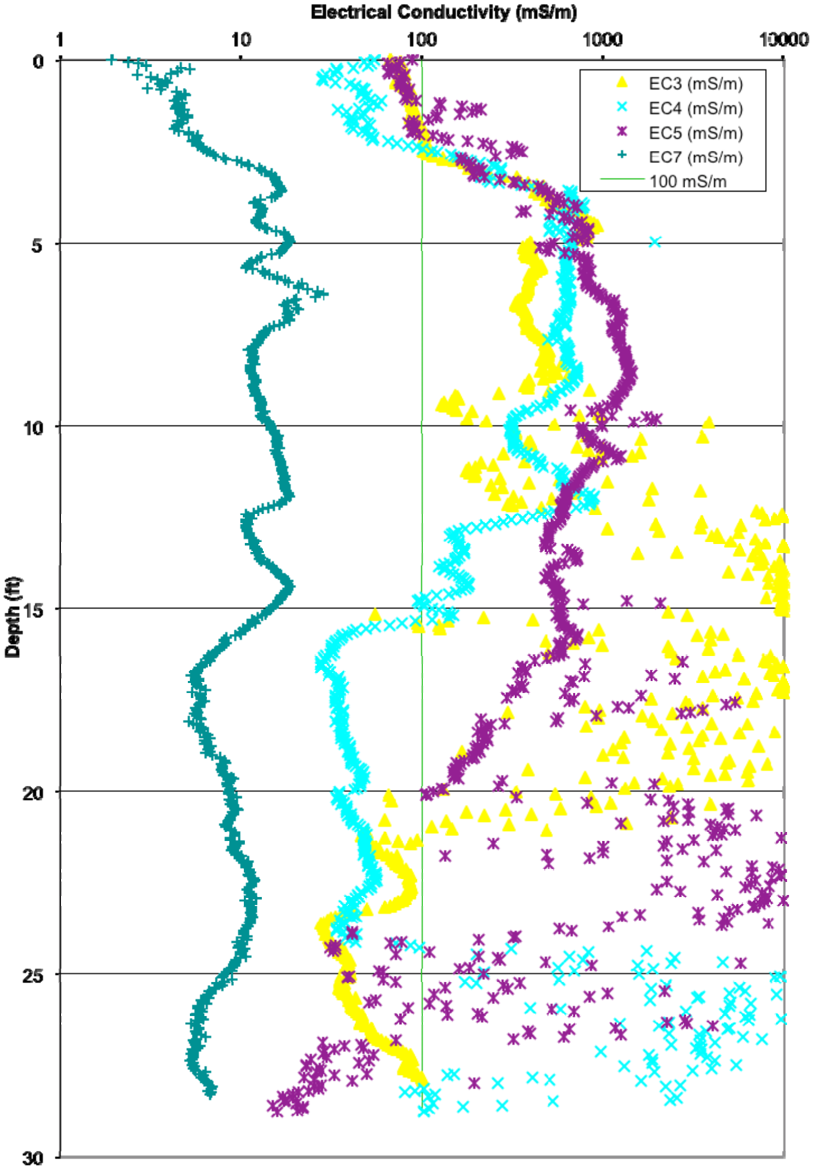


FIGURE 6. Electrical conductivity in the blending area.

Costs. The ability to effectively remediate heterogeneously distributed contaminants without being constrained to preferential pathways can be a significant performance, and therefore, cost advantage over other methods. For source zones, as dig and haul costs have increased, the cost for soil blending has become a competitive alternative for many contaminants. The cost for environmental soil mixing is typically between $14 and $20 per ton, while the cost for amendments can range from $5 per ton (bulk soil mixed) to more than $60 per ton for an average total range of between $40 and $60 per ton. This is consistent with data from the FHWA, which shows that DMM averages $65 per ton (not including mobilization). The costs associated with dig and haul include excavation/loading which typically ranges from $4 to $12 per ton, transportation at approximately $0.10 per ton per mile, and landfill tipping fees ranging from $10 per ton to more than $100 per ton. Hazardous waste landfill tipping fees are in the upper part of this range and because of the difficulties in permitting new landfills (both hazardous and non-hazardous) these costs keep increasing. Potential liabilities associated with landfills that have become contaminant sources have also dampened clients' enthusiasm for a dig and haul approach.

CONCLUSIONS

We have designed, built, and implemented new machinery that enables rotary drum blending above and below the water table with head and arm fully submerged in silts and clays, as well as sand and into partially weathered rock. We have used this strategy to treat contamination by chemical/biological oxidation, chemical/biological reduction, and chemical/physical stabilization techniques to depths up to 32 ft (9.75 m) bgs and with footprints ranging from 500 ft^2 (46 m^2) to acres. The cost is competitive with other subsurface remediation technologies, and is more effective than any other strategy for enabling contact between amendment and contaminant above and below the water table. The blending approach results in real treatment rather than mere transfer to a long-term storage facility (landfill). Tens of thousands of truckloads of soil that would have been transported to a regulated landfill have been treated in place.

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