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Latest Groundwater Remediation Technologies for Chlorinated Volatile Organic Chemicals

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ABSTRACT: Remediation of contaminated groundwater at hazardous waste sites is undergoing a tremendous shift from the conventional "pump and treat" containment remedies to more effective and aggressive source area technologies in combination with Monitored Natural Attenuation (MNA). This paper presents information on the latest trends in groundwater remediation for Chlorinated Volatile Organic Chemicals (cVOCs) and compares some of the "hottest" technologies. An example conceptual site model is presented, with focus on cVOCs in a sandy shallow aquifer. Contaminant "states" shown include mobile/pooled Nonaqueous Phase Liquid (NAPL) (free product), residual NAPL, sorbed contaminants, and dissolved contaminants. General strategies for groundwater remediation are applied to source zones, plumes, and a combination of the two. Source zone strategies include containment, aggressive source zone treatment, and partial mass removal from source zones. Strategies for the plume include containment, complete plume treatment, plume "hot spot" treatment with MNA for rest of the plume, and MNA for the entire plume. Applied source zone and plume technologies are discussed; some of them are common and others are relatively new technologies. After a qualitative comparison of these technologies, example applications are presented on two in situ strategies: electrical resistive heating coupled with enhanced reductive dechlorination (bioremediation) and Zero Valent Iron/clay-soil mixing.

INTRODUCTION

Groundwater has been contaminated with chlorinated voiatile organic chemicals (cVOCs) at thousands of sites in the United States. A majority of the more than 1,600 sites on the US Environmental Protection Agency's (US EPA) National Priorities List (NPL) include trichloroethene (TCE), tetrachloroethene (PCE), Vinyl Chloride (VC), 1, 1, 1-trichloroethane (1, 1, 1-TCA), 1, 1-dichloroethane (DCE), 1, 2-DCE, or other cVOCs on their list of chemicals of concern. Conventional pump and treat (P&T) systems have been the most frequent remedy used on these sites where contaminated groundwater is extracted from an aquifer and treated aboveground. However, after evaluating long term operating results from the conventional P&T systems, the remediation community has questioned the use of this technique as technically appropriate and cost effective to restore groundwater quality at many sites (Bryda and Simon, 1994/95).

Since the turn of the century, remediation of contaminated groundwater at hazardous waste sites has undergone a tremendous shift from the conventional P&T containment remedies to more effective and aggressive source area remediation technologies. US EPA changed the status of 80 of its 729 P&T projects on the NPL (US EPA, 2004). These remedies were changed to in situ groundwater treatment or non-treatment remedies such as institutional controls or Monitored Natural Attenuation (MNA).This paper provides information on the latest trends in groundwater remediation for cVOCs and compares some of the more widely used technologies. In order to understand the contamination problem, background is presented on "typical sites". This is followed by an overview of general strategies and a number of technologies for remediation, including a comparison of the technologies. Finally, example applications of two in situ strategies are presented.

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CONCEPTUAL SITE MODEL

Conventional P&T systems attempt to "flush-out" the contaminants by physical displacement and their effectiveness has depended on the contaminant "states". In general these "states" can be classified in four categories: (1) mobile/pooled NAPL such as a free product, (2) residual NAPL, (3) sorbed contaminants, and (4) dissolved phase. The mobile/pooled NAPL consists of interconnected globules that can move and flow into a monitoring well. Globules are not connected in the residual NAPL and thus cannot move or flow into a well. The sorbed contaminants are primarily in a non-mobile state with or on the soil particles. In the dissolved phase, contaminants are mixed with bulk/flowing groundwater. They also exist in lower permeability layers, (e.g., when they form a halo around NAPL) in a state of "matrix diffusion."

Figure 1 presents an example conceptual site model, assuming a sandy shallow aquifer contaminated by cVOCs. The source zone shows the contaminants in the four states mentioned above. The plume zone is downgradient of the site (source zone) and consists of flowing groundwater with very highly dissolved, lower concentration cVOCs. Sorbed contaminants will also exist on the soil in the plume area. In the source zone, among the four contaminant states, it is easiest to capture the contaminants in the dissolved phase using P&T systems, but these systems are not effective with those in residual NAPL and sorbed contaminant states. When the mobile/pooled NAPL is extracted, it leaves discontinuous "blobs" of NAPL entrapped in the porous medium (more residual NAPL).

REMEDIATION STRATEGIES

The general strategies for remediation of groundwater contaminated with cVOCs that apply to source zones and plumes are as follows:

Source Zone

The first component of a strategy for source zones is often containment. Containment of the source zone is critical in many situations to stop or limit the plume from spreading. Aggressive source zone treatment can be considered to remove all, or as much as possible, of the contaminant mass out of the subsurface. If this aggressive source zone treatment is successful, containment may not be necessary. It may also allow the source zone to eventually return to background conditions, but this is very rare and is typically very expensive.

Partial mass removal attempts to remove as much of the contaminant mass as is economically and practically feasible. This strategy is often used in an attempt to reduce the mass flux from the source zone. If the mass flux can be limited, natural attenuation processes may be sufficient to keep the plume from spreading without containment, and may even allow the plume to shrink. Long time periods may be required for the natural attenuation process to allow the plume to completely shrink and also allow the source area to return to background conditions.

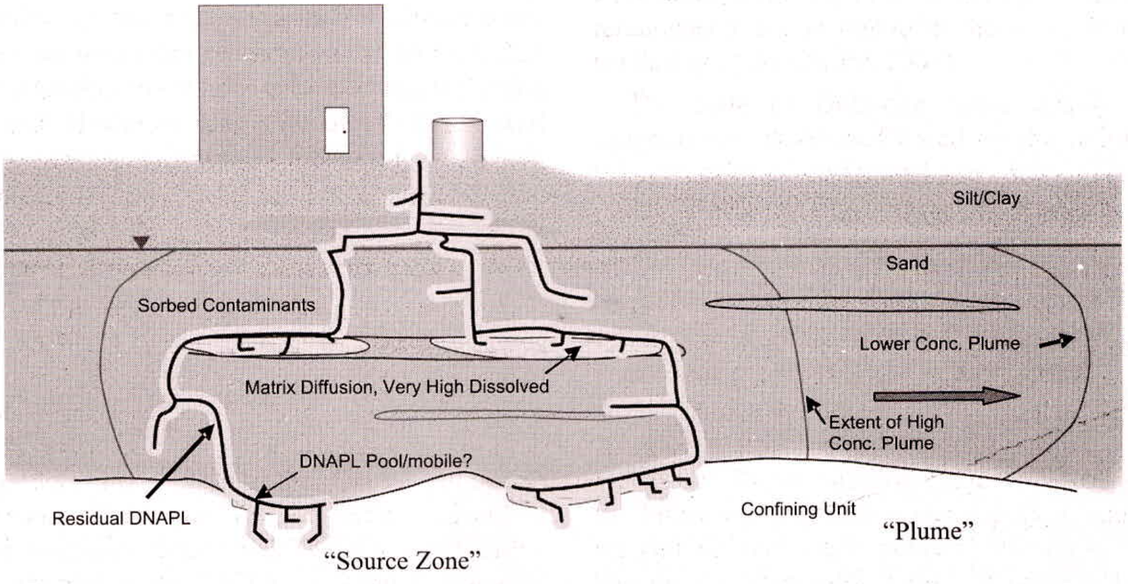

Fig. 1: Example Conceptual Site Model

Plume

The strategies for remediation of the plume include: (1) containment, (2) complete plume treatment, (3) plume "hot spot" treatment with MNA for the remaining plume, and (4) MNA for the plume.

A containment approach may be used to stop the toe of a plume from spreading. This approach is used when the plume has the potential to migrate to sensitive receptors. Complete plume treatment can be attempted for small plumes, but is often impractical and uneconomical for large plumes. Hot spot treatment is often used in combination with MNA. Treatment of the highest concentration areas of a plume may reduce the time for the natural attenuation process to shrink the rest of the plume. MNA is often used for low risk plumes and when no other approach is economical or practical.

In many cases, the general strategy used for a site is a combination of the above for both source zone and plume.

SOURCE ZONE TECHNOLOGIES

Source zone treatment has been implemented or is currently planned at about two-thirds of all NPL sites (US EPA, 2004). Commonly applied technologies for source zone treatment are presented below and evaluated in a later section.

Excavation

This traditional technology is still applicable on smaller sites where excavation and disposal of soils is cost effective and is able to remove most or all of the source of groundwater contamination at the site. In many cases excavation is applied to "hot" zones of the source area. In most situations excavations must proceed below the water table to capture all of the source. This maybe difficult at many sites, especially those with mobile DNAPL that may have migrated deep into the formation. The cost of disposal may also limit the applicability of excavation, especially when the soil is a listed hazardous waste according to US EPA Resource Conservation and Recovery Act (RCRA) regulations.

Containment

The most widely used containment technologies are permeable reactive barriers, physical barriers, and hydraulic barriers. Permeable Reactive Barriers (PRBs) are installed across the groundwater flow path, allowing the passage of water while prohibiting the movement of contaminants by employing treatment agents within the wall such as zero-valent metals, chelators, sorbents, and biological substrates such as mulch (biowalls). The contaminants are either degraded or retained in a concentrated form by the barrier material, which may need to be replaced periodically. PRBs with zero-valent iron have been widely applied in the United States and other countries. Biowalls have been gaining more interest in recent years because of the potential for lower costs. Physical and hydraulic barriers are more traditional. Physical barriers contain groundwater through the use of a vertical, engineered subsurface, impermeable barrier. Hydraulic barriers are created by pumping of groundwater.

In Situ Chemical Oxidation (ISCO)

ISCO is one of the in situ technologies where groundwater is treated in place without extracting it from the aquifer. In situ technologies make up 42 percent of all source control treatments at NPL sites (US EPA, 2004), and ISCO is one of the more widely used in situ technologies. It involves injection or delivery of strong oxidizing chemicals that typically convert hazardous contaminants to nonhazardous or less toxic compounds. The oxidants most commonly used include permanganate, hydrogen peroxide, persulfate, and ozone.

Enhanced Reductive Dechlorination (ERD)

ERD is also known as bioremediation. It involves the delivery of organic substrates into the subsurface so that microorganisms can degrade the organic contaminants. In most applications, the microorganisms use the organic substrate that is delivered as the food source and use the cVOCs as their electron acceptor in place of oxygen. The organic substrates that are most commonly used include lactate, emulsified vegetable oil, molasses, and a number of proprietary products.

Multiphase Extraction

This technology uses a vacuum system to remove various combinations of contaminated groundwater, separate-phase product, and vapors from the subsurface. The system typically lowers the water table around the well, exposing more of the formation. Contaminants in the newly exposed vadose zone are then accessible to vapor extraction. Once above ground, the extracted vapors or liquid-phase organics and groundwater are separated and treated.

Air Sparging/Soil Vapor Extraction

These technologies are often applied in combination. During air sparging, air or oxygen is injected into a contaminated aquifer. Traveling vertically and horizontally through the soil columns, injected air strips and volatilizes the VOCs and flushes them into the unsaturated zone. During Soil Vapor Extraction (SVE) a vacuum is applied to the soil in the unsaturated zone to induce the controlled flow of air and remove VOCs from the soil.

The less commonly applied source zone technologies are as follows:

Steam Flushing

Steam flushing, also called Steam Enhanced Extraction (SEE) is an in situ thermal technology that involves the injection of steam into an aquifer to mobilize and volatilize cVOCs. Vapors rise to the near-surface soil where they are removed by vacuum extraction (SVE) and then treated.

Electrical Resistive Heating (ERH)

This is an in situ thermal technology that applies electrical current to the ground through electrodes. As the electrical current travels through the subsurface, the resistance to flow of electrons generates heat. The electrodes are installed vertically, typically at a spacing of 10 to 25 ft (3 to 8 meters [m]). ERH enhances the recovery of cVOCs in soil and groundwater by heating the contaminants, raising their vapor pressure, thus increasing their volatilization, and making them available for removal by SVE.

Conductive Heating (also called In Situ Thermal Destruction [ISTD])

This in situ thermal technology applies heat and a vacuum simultaneously to the soil through heater wells. Heat flows into the soil primarily by conduction from the heaters which are operated at 500 to 800°C. As soil is heated, cVOCs are vaporized and destroyed by several mechanisms including evaporation, boiling, oxidation, and pyrolysis. Typically about 95 to 99 percent of the contaminants are destroyed in situ before reaching the surface (Baker and Kuhlman, 2002).

Surfactant/Cosolvent Flushing

Large volumes of water, supplemented with surfactants, cosolvents, or treatment compounds, are injected into the subsurface and flushed through the aquifer. The surfactants and cosolvents enhance the solubility of the contaminants, and/or mobilize NAPLs. The solution of surfactant, cosolvent and contaminants is recovered with recovered wells and treated above ground.

In-situ Chemical Reduction

This more recent in situ technology involves injection of various chemical reductants, most commonly Zero Valent Iron (ZVI), into the subsurface to degrade the contaminants. ZVI may be mixed with water as a slurry and injected. Alternately, pneumatic fracturing, using nitrogen gas for fracturing, may be used to distribute the ZVI throughout the treatment zone. In situ chemical reduction degrades the cVOCs into non-hazardous chemicals. Injection of nano-scale ZVI is an emerging technology that is still being developed.

ZVI-Clay Soil Mixing

This is another new technology that involves ZVI. Rather than injecting granular ZVI, it is mixed with the source zone soil using large soil mixing equipment (such as augers). Bentonite clay is also added with the ZVI to reduce the permeability of the formation, to further reduce the mass of flux of contaminants from the source zone.

PLUME TECHNOLOGIES

Similar to source zone treatment, remedies implemented or currently planned at about two-thirds of all NPL sites included plume treatment (US EPA, 2004). Commonly applied plume technologies are as follows.

Pump and Treat (P&T)

This is the most widely used groundwater plume remediation technology. Although its effectiveness has been questioned, it remains a necessary component of many groundwater remediation efforts and can be appropriate for both restoration and plume containment.

Monitored Natural Attenuation (MNA)

MNA relies on natural attenuation processes within the context of a carefully controlled and monitored approach. These are physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of cVOCs. MNA is typically relied upon to stop plumes from migrating and to possibly shrink plumes so as to restore the plume area to background conditions.

Containment

These technologies are similar to those described under source zone technologies (PRBs; physical and hydraulic barriers).

In Situ Chemical Oxidation (ISCO)

This too is similar to that described under source zone technologies.

Enhanced Reductive Dechlorination (ERD)

This too is similar to that described under source zone technologies.

Air Sparging/SVE

It is used for plume remediation similar to that described earlier for source zone remediation.

The less commonly applied plume technologies are as follows.

Phytoremediation

This process uses plants to partially or substantially remediate cVOCs in groundwater and soil. It uses a variety of plant biological processes and the physical characteristics of plants to aid in plume treatment. Phytoremediation encompasses the following methods in this treatment: (1) degradation (for destruction or alteration of organic contaminants), (2) accumulation (for containment or removal of contaminants), (3) dissipation (for removal of contaminants into the atmosphere), and (4) immobilization (for containment of contaminants). For containment of shallow plumes, deep rooting trees maybe used to remove groundwater through evapotranspiration.

COMPARISON OF TECHNOLOGIES

Based on the experience of the authors, Table 1 presents a qualitative comparison of some of the in situ technologies described above that are used in the treatment of cVOCs in groundwater. It identifies their niche area (source zone and/or plume), and rates them on three criteria (effectiveness, implementability, and cost) on a scale of 1 to 4, with 4 being the best. The following text provides rationale for these comparisons.

ISCO and ERD

ISCO is applicable in areas with low to moderate levels of cVOCs (plumes to moderate concentration/mass source areas). ISCO may be used for NAPL treatment (very high concentrations), however, the chemical dose will increase significantly, and at best is likely to result only in partial mass removal. Consequently, if significant NAPL is present, the plume may re-establish itself within a few years after ISCO treatment of the source zone. The effectiveness of ISCO depends on the oxidant distribution and the oxidant demand. The distribution will be a function of the subsurface conditions and the delivery method used. The oxidant demand will be a function of the mass of contaminant, but very often more important is the natural oxidant demand of the soil and groundwater. ISCO is relatively easy to implement, depending on the approach used. For example, direct push technologies can be used to deliver oxidant solutions to relatively shallow formations. ISCO is a comparatively rapid remediation process, typically taking a few months. However, re-injection may be required. It is moderately costly to apply. The cost may be a function of the number of re-injections required.

ERD is best suited for low to moderate levels of cVOCs in the plume area. Its use in source zones has met with some success, but its application to very high concentration areas with mobile or residual DNAPL is

Table 1: Comparison of In Situ Remediation Technologies

	Niche	*Rating on a Scale of 1 to 4, with 4 the Best.*		
		Effectiveness	*Implementability*	*Cost*
ISCO	Source and plume	2 (source) 3 (plume)	3	3
ERD-Bioremediation	Plume, source	2 (source) 3 (plume)	3	4
Steam Flushing	Source	4	1	1
ERH	Source	3	1	1
Conductive Heating	Source	4	1	1
Surfactant Flushing	Source	2	1	1
ZVI ClaySoil Mixing	Source	3	3	2

questionable and should be considered closely since it may require many years of continuous implementation in the source zone to see significant results. ERD can be effective in plume remediation, but is sensitive to microbiological and geochemical conditions. Addition of especially cultured microorganism (e.g., dehalococcoides) may be required in some situations. Delivery methods for the organic substrate used for ERD may be very similar to those used for ISCO (e.g. direct push methods). ERD is relatively easy to implement, but the process is slow (usually a year or more to complete) and re-injection or semi-continuous injection will be required. The cost is low to moderate, but may be a function of the number of re-injections required.

The effectiveness, implementability, and cost of both ISCO and ERD will depend on chemical delivery methods. In fact, most of the challenges and poor performance of both ISCO and ERD are a result of poor delivery of the chemicals. The delivery method that can be used will vary depending on the type of chemical being injected (e.g., a recirculation system is not effective for highly viscous or very reactive chemicals). A few of the delivery methods that may be considered include direct push technologies in a grid, injection wells in a grid, injection wells in rows with drift of the chemical (inject and drift), well to well recirculation with continuous recirculation, in well circulation wells, and soil mixing.

Since ISCO and ERD may use the same delivery methods, selecting one of these two technologies often comes down to the geochemistry of the site and how it impacts the overall cost. ISCO typically takes less time to implement, resulting in a lesser operational cost. But the chemical costs are often higher for ISCO than ERD. This is especially true if the geochemistry is reducing and the natural oxidant demand of the soil is high. Sites with very oxidative conditions may be more conducive to ISCO.

Thermal Technologies

Steam Flushing, ERH, and conductive heating have their niche in the heavily contaminated source area where the objective is to remove the vast majority of the contamination. The cost for each is high, with conductive heating possibly the most expensive. They all require fairly significant expenditures for equipment rental and the energy input.

Steam flushing is most applicable in relatively high permeable formations that will allow the steam to easily flow. Steam flushing is usually highly effective; however, it may leave a few pockets of contamination. Its implementability is low, as it depends on a complex process using steam generation, vapor and water treatment, and control of in situ heating. It works best when steam is readily available. The time to remediate is usually rapid (months).

ERH may be better suited to implementation in lower permeable formations than steam flushing. Its effectiveness is variable and uncertain, as it depends on electrical current movement resulting in non-uniform heating. With a moderately complex process requiring a power source, electrodes, and vapor recovery wells and treatment, its implementability is low, as it requires a significant amount of operations oversight. Also, off-gas treatment can be challenging.

Conductive heating (or ISTD) is probably the most effective of all technologies discussed in this paper. Very high temperatures can be achieved by the electrical heating elements and the conduction of the heat into the formation is relatively uniform. Like the other thermal technologies, conductive heating is challenging to implement, as it too has a moderately complex process requiring a power source, thermal wells, and vapor recovery wells and treatment. Close spacing of thermal wells may be required to be effective in the entire contaminated area. Moreover, it requires significant operational oversight.

Surfactant/Cosolvent Flushing

Surfactant/Cosolvent Flushing is applicable to highly contaminated source zones with relatively high permeable and homogeneous formations. It has a variable effectiveness (fair to uncertain) and may leave pockets of contamination. This technology has a low implementability due to its complex process involving selection of surfactant, mixing of surfactant, and treatment of produced fluids. It also requires significant operational oversight. The cost of surfactant/cosolvent flushing is high, as treatment of produced fluids may be very expensive.

ZVI-Clay Soil Mixing

ZVI-Clay Soil Mixing's niche is in a source zone with moderate to high levels of contamination. It is applicable to low or high permeability soils. It has a good to moderate effectiveness, although the technology has not been implemented sufficiently in the field to say conclusively. The primary advantage of this approach is its superior delivery of the treatment chemical (in this case ZVI). The clay also reduces the flux of any contaminants that may remain in the source zone. The implementability of ZVI-clay soil mixing is moderate. Relatively large mixing augers may be used at some sites. In addition, a second step of stabilization with cement may be necessary since the mixed soil may have low structural strength. The cost of ZVI-clay soil mixing is moderately high, and is a function of the cost of the iron and the mixing.

APPLICABILITY OF TECHNOLOGY TO SOIL TYPE

In situ treatment technologies are significantly impacted by the subsurface soil types. Figure 2 compares the technologies cited in Table 1 for their applicability to different types of soil (clay, silt, sand, and gravel). Since ISCO, ERD, and surfactant flushing rely on delivery of chemicals to the subsurface, they are most applicable to coarser grained soils where injected fluids may be more easily transported through them. To deliver the chemicals into finer grained clays and silts, some type of enhanced delivery system will be required, such as fracturing (pneumatic or hydraulic) or soil mixing. These types of delivery systems are also significantly impacted by subsurface heterogeneities. Layers or stringers of finer grained soils that are layered with coarser grained soils will have less exposure to the injected chemicals and will therefore undergo less treatment.

Steam flushing is impacted in a similar manner as ISCO and ERD to the soil type since steam must be flushed through the subsurface. ERH and conductive heating are not impacted by low permeability soils since their method of heating does not require movement of fluids through the soil. ERH and conductive heating may be more expensive in coarse-grained soils since cool groundwater may more easily enter the treatment zone in these types of settings, requiring even greater energy input to heat the soil.

ZVI-clay soil mixing is not impacted by soil type, except those soils that are difficult to mix. This could include gravels with very large cobbles or boulders, or very sticky clays that form clay balls.

SUMMARY

Remediation of groundwater contaminated with cVOCs has undergone a shift in strategy and technology during the last 10 years. In general, site owners are avoiding pump and treatment systems that have long and expensive operations periods. More aggressive remediation technologies for source zones and plumes are being attempted in order to reduce the long term operational and monitoring costs. MNA is also becoming a standard component of most remediation strategies.

In situ treatment technologies have matured since the turn of the century. Increased applications of ISCO and ERD are evident at hazardous waste sites, but many challenges remain with these and other technologies. Effective and efficient delivery of treatment chemicals is one of the biggest challenges. Also, various in situ thermal technologies can remove the most mass of contaminants; however, they are also the most expensive applied technologies. A good, life cycle analysis of the cost and benefits (net environmental benefit) of the potentially applicable technologies should be performed for each site.

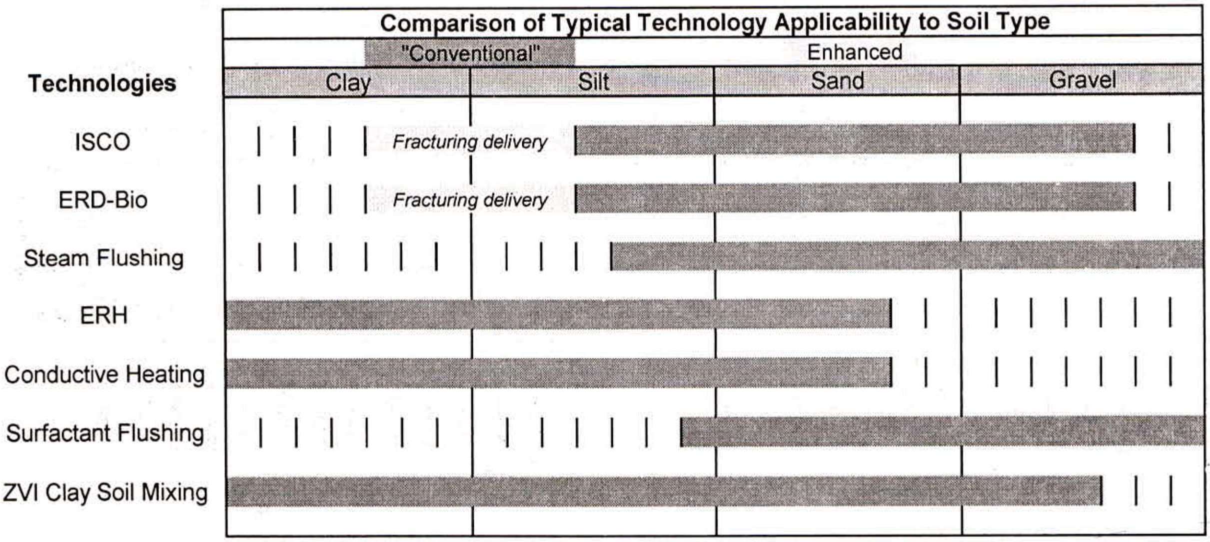

Fig. 2: In-Situ Technology vs. Soil Type

EXAMPLE APPLICATIONS

More details are presented below on two applications of in situ strategies: ERH coupled with ERD, and ZVI-clay soil mixing.

ERH Coupled with ERD

Full-scale application of ERH, followed by ERD was conducted at a former dry cleaning facility (Hudson *et al.*, 2006). Soil and groundwater at the site were impacted by tetrachloroethene (PCE). PCE concentrations in groundwater as high as 42,000 micrograms per liter (µg/L) were detected. During a 9 month period, an area defined by monitoring wells with PCE concentrations greater than 2,000 µg/L was treated using ERH. Initial monitoring conducted during the cooling period indicated that a dissolved plume remained in some portions of the treatment zone at concentrations greater than several thousand µg/L. The ratio of biodegradation daughter products (e.g., cis 1, 2 DCE) to PCE in groundwater was significantly greater than prior to implementation of ERH. To evaluate whether the reductive dechlorination process could be enhanced, an enhanced ERD pilot study was implemented. A soluble substrate (lactate) was periodically injected into two injection wells in the portion of the original treatment area at which VOC concentrations in groundwater were greatest (Figure 3). Downgradient groundwater was monitored to assess the impact on Reductive Dechlorination (RD). The pilot study indicated a significant enhancement of the RD process. The monitoring well installed downgradient of one of the injection wells went from total Cvoc and PCE concentrations of 26,021 and 8,090 µg/L, respectively, to total cVOCs and PCE concentrations of 7,356 µg/L and 142 µg/L, respectively, after about 1 year. This represents a 72 percent reduction in total cVOCs and a 98 percent reduction in PCE concentration. Full-scale application of ERD at this site is currently continuing. To date, PCE concentrations have declined over 99 percent on average in groundwater samples from the site.

ZVI-Clay Soil Mixing

Full-scale ZVI-clay soil mixing was conducted at a dry cleaning facility that had high concentrations of perchloroethene (PCE) (Bozzini *et al.*, 2006). A 10,000 square foot (930 m^2) source area was delineated using membrane interface probe (MIP) technology, and soil and groundwater sampling. The contamination extended from the water table (roughly 7 feet [2 m] below ground surface [bgs]) down to 20 ft bgs. At 20 ft (6 m) bgs, there was a clayey-silt layer that prevented further downward migration of DNAPL. The estimated volume of contaminated soils was 7,000 cubic yards (5350 m^3). Mobile DNAPL was observed in several wells at the site. Soil mixing with ZVI clay addition was implemented at the site in February 2005. A laboratory treatability study indicated a PCE half-life on the order of 30 days would be achieved with ZVI concentration of 2 percent and bentonite of 1 percent. The project included site preparation, removing and re-routing utilities, abandoning monitoring wells, removing soil and concrete debris, soil mixing, site stabilization, utility installation, construction of a parking lot, and monitoring. Since the site was located in a highly developed portion of a military base, monitoring well and utility removal had to be complete prior to mixing. The soil mixing was completed during a 17-day period in February 2005. A crane was used to turn a 10 ft (3 m) auger while injecting the slurry of ZVI and clay (Figure 4). A total

Fig. 3: Lactate Injection Equipment used at the Site

Fig. 4: ZVI-Clay Soil Mixing at the Site

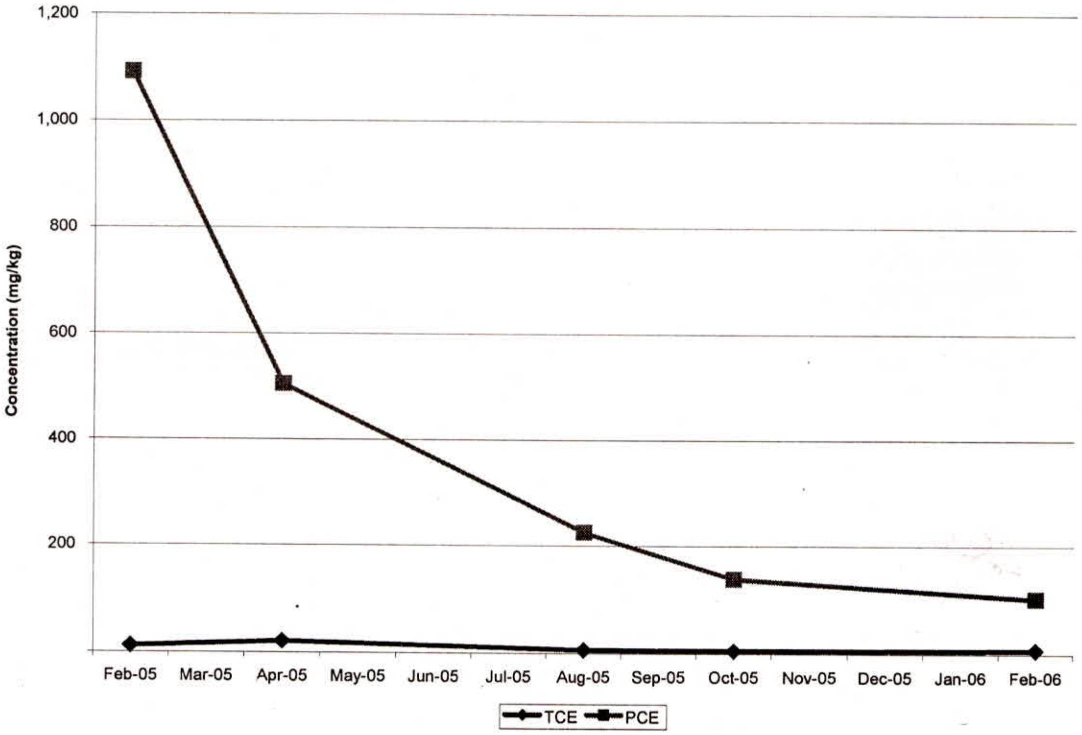

Fig. 5: Average PCE and TCE Soil Concentrations (mg/kg) Over Time

of 200 tons of ZVI and 100 tons of bentonite were mixed to create 146 overlapping columns. Off-gas was treated with activated carbon. After allowing approximately 6 weeks for settlement, 196 tons of cement were added to the top 5 feet (1.5 m) of soil over the treatment area to stabilize the site for a parking lot. The results of the treatment are encouraging. One year after the treatment, PCE soil concentrations over the entire treatment area were reduced by 82 percent, with a median concentration reduction of 99 percent (see Figure 5).

Reductions were lower in about 20 percent of the area where mobile DNAPL had been present prior to treatment. Soil concentrations were reduced 61 percent in this area and 99 percent in the remainder of the treated area. Overall reduction based on a weighted average of these results is 91 percent. ZVI was still present in the treatment area, so continued treatment is likely to continue. Groundwater concentrations of PCE were reduced by more than 96 percent in the treatment area, but DCE concentrations did increase significantly in one groundwater well. Downgradient water quality improved after the treatment, with PCE reduction of 67 and 90 percent. Hydraulic conductivity within the treatment area was reduced 50 to 400 times (one to two orders of magnitude), so there should be a significant reduction in mass flux from the treated area.

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