Originally Published In:
Geo-Strata - Geo Institute of ASCE, Vol. 17, No.4, July/August 2013, pp. 46-48,50-52.
http://cedb.asce.org/cgi/WWWdisplay.cgi?310280

Figure 1. Soil mixing with potassium permanganate.

In Situ Remediation Using Soil Mixing

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Soil mixing, originally developed as a means for structural soil improvement, has evolved into a system for effectively treating soil in situ to meet environmental remediation cleanup objectives. Using soil mixing in remedial efforts has significant advantages over alternative methods, specifically in terms of assuring consistent, measureable delivery of reagents to contaminated media without significant lithology or permeability concerns. For specific target clean-up objectives, soil mixing often has a lower cost, requires less time, and is more sustainable than other traditional remedies.

The Evolution of Soil Mixing

Following a U.S. patent issued in 1954, there was little application of soil mixing in the U.S for the next several decades. The few early applications, in which cement grout was mixed with the soil using small augers 2-3 ft in diameter, were for structural support improvement. Japanese development of the technology saw the advent of multi-shaft rigs in the 1980s, where several columns of similar diameters could be simultaneously mixed. These rigs were used to form containment barriers and structural walls for excavation support.

Initial uses of soil mixing for remediation were primarily focused on in situ solidification/stabilization (S/S or ISS) of contaminated soils.

The first application of the multi-shaft systems and the first large-scale application of soil mixing in the U.S. was the Jackson Lake Dam foundation improvement project in 1986.

Initial uses of soil mixing for remediation were primarily focused on in situ solidification/stabilization (S/S or ISS) of contaminated soils. The first documented use of soil mixing for the remediation of contaminated soils was published in a U.S. Environmental Protection Agency Superfund Innovative Technology Evaluation (SITE) Program report in 1990. On this project in Hialeah, FL, PCB-impacted soils were locked up using cement and a chemical reagent. Concurrent with the application of soil mixing to remediation, larger augers, 6-10 ft in diameter, were developed to treat larger volumes of soil at lower cost. As understanding of the mechanical capabilities of soil mixing has grown among engineers and contractors, the range of reagents has expanded to include chemicals designed to alter the chemical characteristics of underground contaminants of concern, permitting the in situ treatment of contaminated soil and groundwater.

Description of Soil Mixing

Early applications of large-diameter soil mixing were implemented using crane-mounted turntables originally developed for caisson drilling. Over time, the industry shifted to more powerful and efficient excavator-mounted hydraulic-powered drills, also originally developed for caisson work. Now, large-diameter augers are commonly used to mix large volumes of soil and groundwater to significant depths, 20-50 ft below grade, with different combinations of liquid or solid reagents. They are even used for hot air stripping applications where hot air is pumped through a hollow kelly bar and mixed with the soils to promote contaminant volatilization. There are a range of different auger designs that apply to different soil types and depths of penetration. In order to provide comprehensive treatment of the contaminated media, mixed columns are overlapped to cover 100 percent of the target zone.

Accurate mixing of the reagent materials is important because of the high cost of the chemical additives. Typically, automated plants capable of accepting a variety of dry and liquid reagent combinations are used. Application rates can be varied horizontally, and to some extent vertically within a column, to deliver the appropriate volume of reagent to the varying levels of contaminant concentrations in impacted zones. Modern quality control equipment allows the drill rig operator to monitor the amount of reagent, in terms of weight per unit volume of grout, added to discrete vertical increments of a column. This ensures even vertical and horizontal distribution of the reagent within each column.

Advantages of Soil Mixing

Soil mixing often provides a number of advantages over other remedial technologies:

- Mixing of soil columns can be completed expeditiously compared to traditional in-situ chemical oxidation (ISCO) injection, pump and treat systems, and excavation/offsite disposal.
- Physically mixing the soil increases contact between the reagents and soil.
- Placement of mixed reagents is not limited to preferential flow paths, as with traditional ISCO injection remedies, and consistent dispersal can be ensured even in low permeability soils.
- Multiple steps of treatment with different reagents can easily be completed.
- Cost of treatment can be much lower than competing systems, particularly compared to excavation and disposal options.
- Mixing results in a much lower carbon footprint than excavation or other traditional treatment systems.
- Compared with offsite removal, soil mixing eliminates the need for excavation support/shoring systems, dewatering and treating groundwater, furnishing and placing clean backfill, and expensive offsite transportation and disposal.

Recently completed example projects highlight the broad range of reagents used with large-diameter soil mixing to complete in situ treatment projects.

Case Study 1 – In situ Chemical Oxidation and Solidification of TCE Contaminated Soils

During the spring and summer of 2010, soil mixing was used for the in situ chemical oxidation and soil solidification of trichloroethylene (TCE)-contaminated soils in New Jersey. Potassium permanganate (PP), a strong oxidizing agent commonly used to degrade organic contaminants, was chosen as the chemical oxidant for this project based on its effectiveness in bench scale tests. The soils were first

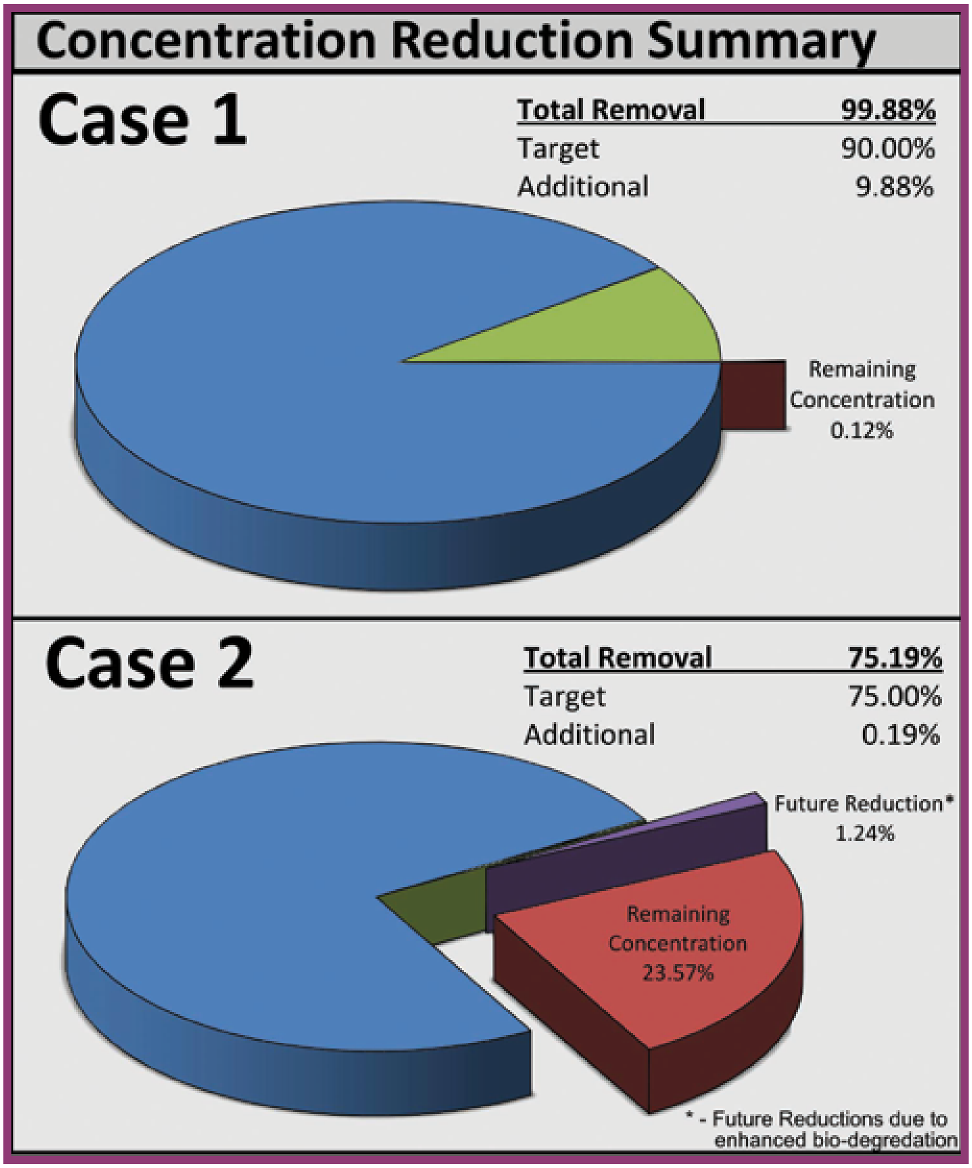

Figure 2. Summary of contaminant concentration reduction in the case study projects.

treated with PP (Figure 1), followed by soil solidification with Portland cement (PC). Approximately 7,500 CY were treated and solidified using a 9-ft-diameter soil mixing auger to depths up to 19 ft below the ground surface. The work was conducted prior to construction of a municipal building which covered part of the remediation area.

Preliminary bench scale studies and stoichiometric demand calculations indicated that a PP dosage greater than 6 x 10^{-3} lb PP/lb soil would result in a reduction of over 90 percent in TCE concentration. Using an assumed in situ dry soil density, this value was converted to a reagent weight per volume of soil, 17.5 lb PP/CY, for easier field application. Bench scale studies indicated that the reaction required 24 hours to complete before PC could be added. A low PC dose, 7-8 percent by dry soil weight, was injected to return the soil permeability to pre-mix conditions and to solidify the soil in the area of the municipal building.

Careful staging and execution of this project was important in order to allow continuous construction access to unfinished areas given the required 24-hour waiting period between PP and PC additions and the liquid nature of the PP-treated soils. The work was completed over a 15-week timeframe, including mobilization, demobilization, and miscellaneous site preparation activities. Post-construction samples met or exceeded the target permeability and compressive strength requirements, less than 1x10^{-6} cm/s and greater than 20 psi respectively, with average TCE concentrations less than 1 percent of their initial values (Figure 2).

Case Study 2 – Hot Air Stripping and Enhanced Biodegradation of Acetone-Impacted Soils

During the late winter and spring of 2012, soil mixing was used for the hot air stripping and in situ chemical oxidation of acetone-impacted soils in New York. The soils were first subjected to hot air stripping followed by treatment with calcium peroxide injected in conjunction with fertilizer nutrients and a phosphoric acid pH buffer (Figure 3). In total, approximately 17,000 CY were treated using a 9-ft-diameter soil mixing auger advanced to depths up to 27 ft below the ground surface.

Pre-construction treatability testing indicated that a 0.6 percent dosing of calcium peroxide would provide sufficient oxygen to promote aerobic biodegradation of acetone post-mixing/hot air injection to achieve up to a 75 percent mass reduction of acetone in the treatment area. Using an assumed soil density, the dosing values were converted to reagent weights per volume of soil:

- calcium peroxide – 21.6 lbs/CY,
- ammonium sulfate – 0.5 lbs/CY,
- potassium chloride – 0.25 lbs/CY, and
- phosphoric acid – 1.3 gallons/CY.

Figure 3. Chemical reagent injection (L) and hot air stripping (R).

The work was completed over a 10-week timeframe, including mobilization and demobilization. Post-construction samples indicated that a reduction in the average acetone concentrations of more than 75 percent had been achieved, with further reductions anticipated from enhanced biodegradation (Figure 2).

Comparison with More Traditional Techniques

For these two case studies, several traditional remedial alternatives were evaluated prior to the final selection of soil mixing. Geologic conditions, specifically the low permeability of the site soils, precluded the use of classic ISCO techniques on both projects because the distribution of the chemical oxidants would have been limited, reducing the treatment's effectiveness. When evaluating alternatives, total project cost and time to completion for soil mixing and alternative implementation methods were estimated based on the expected volume of contaminated soil, the target reductions in TCE/acetone concentrations, and experience with similar projects.

In addition, the Sustainable Remediation Tool developed by the Air Force Center for Engineering and the Environment was used to evaluate several sustainability-related metrics, including carbon footprint, for each remedial alternative. A comparison of the cost, time, and carbon footprint of excavation, the second most suitable remedial means for the case study projects, and soil mixing is shown in Figure 4. For each case study project, soil mixing resulted in a lower cost, a reduced time to completion, and had a lower carbon footprint than excavation.

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Importance of Design Mix Studies

Design mix studies, also referred to as bench scale studies, are ones conducted before construction to assess the feasibility of a selected remedial approach and to develop cost efficient mixtures of reagents for meeting site objectives. On environmental remediation projects, the site objectives often include soil permeability reduction and strength improvement as well as contaminant destruction. Bench scale studies are important for many different types of environmental remediation techniques, especially soil mixing, but are of even greater importance on in situ treatment projects due to the relatively high reagent cost.

For example, PP, a highly effective oxidant used for ISCO, is roughly $2/lb, which equates to a direct cost increase of $50-$70/CY for every 1 percent PP, by dry weight of soil, added. Although the application of in situ treatment for site remediation is growing, bench scale studies provide valuable information for convincing environmental authorities of the effectiveness of a planned in situ treatment strategy. The cost of bench scale studies are easily offset by the reagent cost savings achieved through design mix optimization and often reduce the time needed to obtain environmental authority approval for use of this in situ treatment approach.

Other Reagents

In addition to potassium permanganate and calcium peroxide, a number of other reagents have been injected via soil mixing for in situ treatment:

- zero valent iron (ZVI)
- sodium persulfate

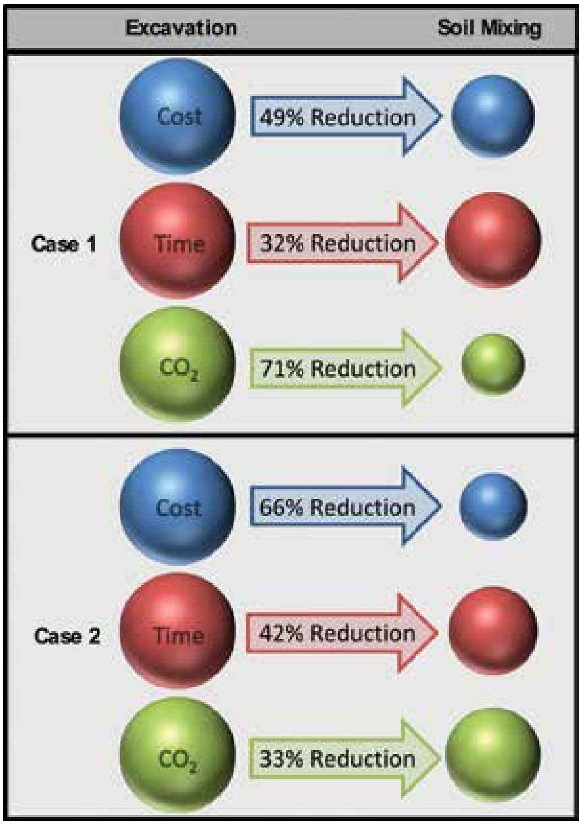

Figure 4. Comparison between excavation and soil mixing for the case study projects.

> Soil mixing batch plant and delivery systems can be designed to safely and effectively deliver almost any reagent or combination of reagents.

- ferrous sulfate
- calcium polysulfide
- hydrated lime (catalyst)
- vegetable oil (nutrient)
- activated carbon (sorbent)
- organophillic clay (sorbent)

Soil mixing batch plant and delivery systems can be designed to safely and effectively deliver almost any reagent or combination of reagents.

Next Steps in Green Remediation

Over the last two decades, soil mixing has developed from a primarily geotechnical construction technique into a cost-effective environmental remediation method through equipment advances and innovative engineering. In situ chemical oxidation, enhanced bioremediation, and air stripping are all proven technologies for soil and groundwater remediation which are recognized by federal and state environmental protection agencies, but are often less effective than necessary due to subsurface conditions. Soil mixing does not change the nature of these treatments, but increases their effectiveness by increasing direct contact with the contaminated media.

Innovative engineers will continue to develop cutting edge reagent combinations for the effective treatment and stabilization/solidification of impacted soils and groundwater, many of which will be most successfully implemented using soil mixing. Jet grouting, a process by which soils are mixed with high pressure jets of fluid and air, holds promise for further expanding the use of soil mixing in environmental remediation, particularly for sites with known subsurface obstructions or overhead work restrictions, such as in areas with a high prevalence of utilities or old foundations.

As the principles of "green remediation" become more commonplace, sustainability-related metrics will become an increasingly important factor in remedial method selection. Soil mixing provides an opportunity to not only reduce the overall environmental impact of a required remedial action, but also can result in substantial savings in time and cost.

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