AUTHOR'S COPY
GEOENVIRONMENT 2000
New Orleans, LA 1995

CONTAINMENT, STABILIZATION AND TREATMENT OF CONTAMINATED SOILS USING IN-SITU SOIL MIXING

Steven R. Day[1] and Christopher R. Ryan[2]

Abstract

Soil Mixing is a technique that has increasingly been relied upon for the insitu remediation of contaminated soils. Depending on the application, large or small diameter (4 to 0.3 meter) mixing augers can be used to inject cement, bentonite or other reagents to modify soil properties and thereby remediate contaminated soils and sludges. A major advantage of the method is the capability to treat soils at depth (up to 35 meters deep) without excavation, shoring or dewatering. Recent advances in soil mixing technology include lower permeability additives for groundwater barriers, additives for the fixation of waste-contaminated soils and combination of soil mixing with hot air injection and vapor extraction technology to remove volatile organic chemicals.

Advantages of soil mixing over alternative technologies include lower cost, less exposure of wastes to the surface environment and eliminating off-site disposal. These advantages have made soil mixing the technique of choice on many projects.

The information presented in this paper is intended to provide engineers and owners with the level of understanding necessary to apply soil mixing technology to a specific site. The most important steps in implementing the technology are site investigation, feasibility estimate, selection of performance criteria, selection of appropriate materials bench scale testing, and construction.

Introduction

The remediation of sites with contaminated soils increasingly utilizes insitu soil mixing to contain, stabilize or otherwise treat soils to permit the safe closure and/or development of these sites. Recent advances in the equipment and growing experience with the method have led to a wider range of applications. As an environmental remediation technique, soil mixing is usually quite competitive with most conventional treatment, disposal and /or containment methods and has special advantages in health and safety, speed of construction and reduced liability.

Insitu soil mixing generally involves mechanically mixing soils with a drilling fluid, which carries a stabilizing reagent. The mixing is carried out by a crane-mounted, high-torque turntable that turns one or more special mixing augers into the soil without excavation. Currently at least two variations of the method are available. Shallow soil mixing (SSM) uses a large (1 to 4 meters diameter) single auger to mix soils up to about 10 meters deep. Deep soil mixing (DSM) uses multiple (2 to 8) smaller (0.8 to 1 meter) diameter augers to mix soils up to 35 meters deep.

The technique has proven to be suitable for the injection of a wide variety of reagents. When mixing soils, nearly any reagent, which can be mixed with water into a grout, is usable. In some cases, compressed air can be substituted for grout to accommodate special processes. When mixing sludge, dry powdered reagents can also be mixed without water, thereby minimizing swell and simplifying material handling. The mix zone can be covered with a removable hood to minimize reagent dusting and/or capture fugitive emissions.

---

[1]District Manger and [2]President of Geo-Con, Pittsburgh, PA

Soil mixing has also proven compatible with or an enhancement or even replacement for other remediation techniques. DSM is sometimes used to provide an impermeable barrier in lieu of a slurry cutoff wall or sheet pile wall. DSM is advantageous because of its reduced disposal volume, greater stability during construction and structural capability. SSM can be combined with soil vapor extraction or biological treatment to loosen soils and deliver reagents or nutrients uniformly and at depth. New applications and combinations of soils mixing with other remediation techniques are still possible.

Shallow Soil Mixing

SSM uses a single large mixing auger or tool to process and mix soils. A single column of mixed soil is created by each SSM stroke. A picture of one such tool is shown in Figure 1. Fluid reagents (e.g. grout, slurry, or air) are pumped through the hollow stem Kelly-bar supporting the auger and exit at the tip for mixing with the soils. Dry reagents, (e.g. powdered cement, pellets, or similar materials) are placed over the top of the mix zone where the action of the tool pulls them into the column. Mixing is accomplished by turning the auger while repeatedly cycling up and down through the zone to be treated.

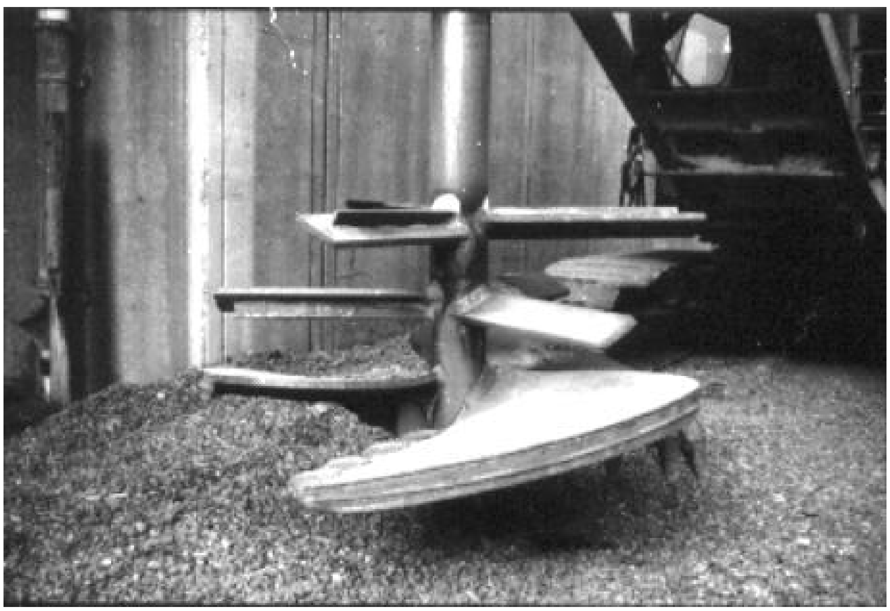

Figure 1. Mixing Auger – 2.4 m diameter

Areal treatments and SSM walls are created by overlapping primary and secondary SSM columns (Figure 2). Overlaps may be as little as 10% of the column diameter for areal treatments or up to 20% for structural wall applications. It is always

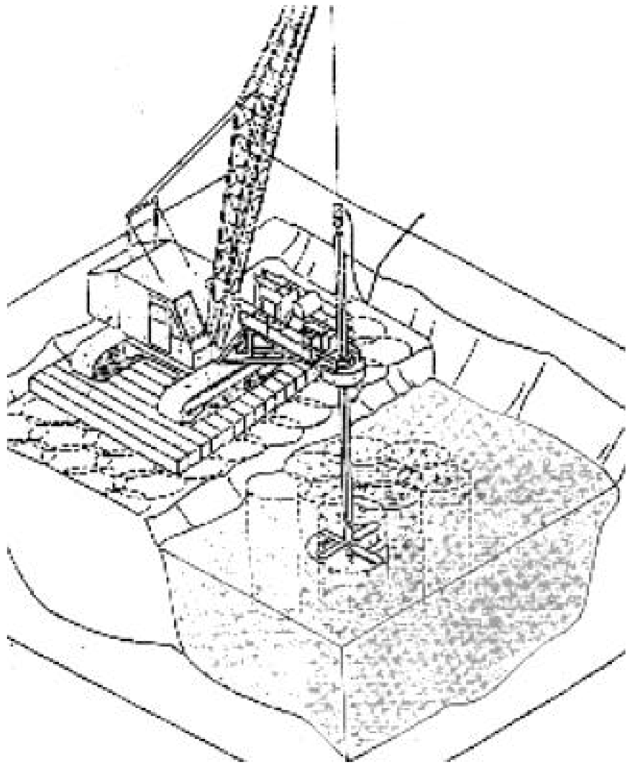

Figure 2. SSM Mixing Pattern

advisable to map the treatment pattern on a plan view of the area to ensure adequate coverage and optimum overlaps.

SSM column size and mixing depth are a function of equipment capabilities, and mixing conditions. For example, a deeper application in harder soils may require a smaller auger or more torque than a shallower application in fluid sludge. Auger design is critical in effectively transferring torque and maximizing penetration. An auger designed for mixing sludge with dry cement may be unsuitable in mixing oils with heated air.

Another advantage of SSM is the capability of the technique to work under a removable hood. A hood is an open-bottom cylinder, which covers the surface of the column while mixing is performed directly beneath. The hood is lowered onto the soil or sludge and the mixing blades are started while reagents are introduced. A negative pressure may be kept on the headspace of the hood to pull any vapors or dust to a vapor treatment system on completion of a column; the blades are retracted inside the hood. The hood and mixing unit are then moved to an adjacent location overlapping the previous column and the process repeated until the desire area is treated.

Deep Soil Mixing

DSM uses multiple augers to process and mix soils. A panel of mixed soil is created by each DSM stroke. A picture of the DSM equipment is shown in Figure 3.

Fluid reagents (e.g. slurry or grout) are pumped through the hollow stem augers and exit at the tip for mixing with the soils. At present, the multiple auger configuration and greater depth capability of DSM precludes the mixing of dry reagents. Mixing is accomplished by counter-rotating the augers while moving the tooling up and down through the soil. DSM is better suited to deeper applications. Generally, the bottom 3 meters of each DSM stroke is double mixed to ensure homogeneity of the entire stroke.

An important characteristic of DSM is that the multiple augers physically overlap. The design of the DSM auger overlaps guarantees continuity without the need for extensive survey of separate strokes. The most common DSM equipment uses four, 0.8 meter augers. DSM is used for both areal and wall applications but is more commonly used as a wall. Continuity is afforded by advancing 3 augers with each stroke and redrilling the fourth. See Figure 4.

Reagent Delivery Systems

While the SSM or DSM equipment may be similar for different applications, the reagent delivery systems may be completely different. For example, mixing dry cement with sludge requires a pneumatic system capable of weighing and transferring dry powder; mixing a grout with soil requires a high-volume grout plant. A large hot air compressor is required for soil vapor injection/extraction applications.

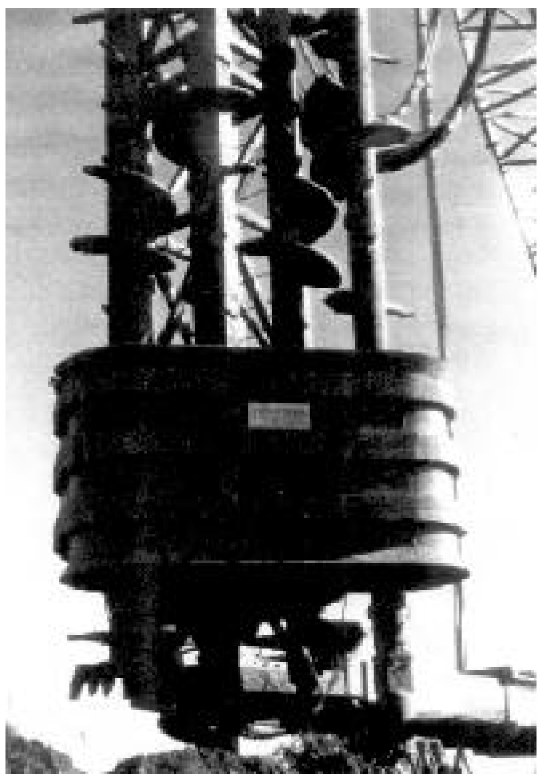

Figure 3. DSM Equipment

The simplest and most flexible system is the grout plant. Reagents are stored in silos or pre-weighed bags and added to water in a colloidal mixing tank with appropriate pumps. A wide variety of reagents can be mixed in a grout plant including cement,

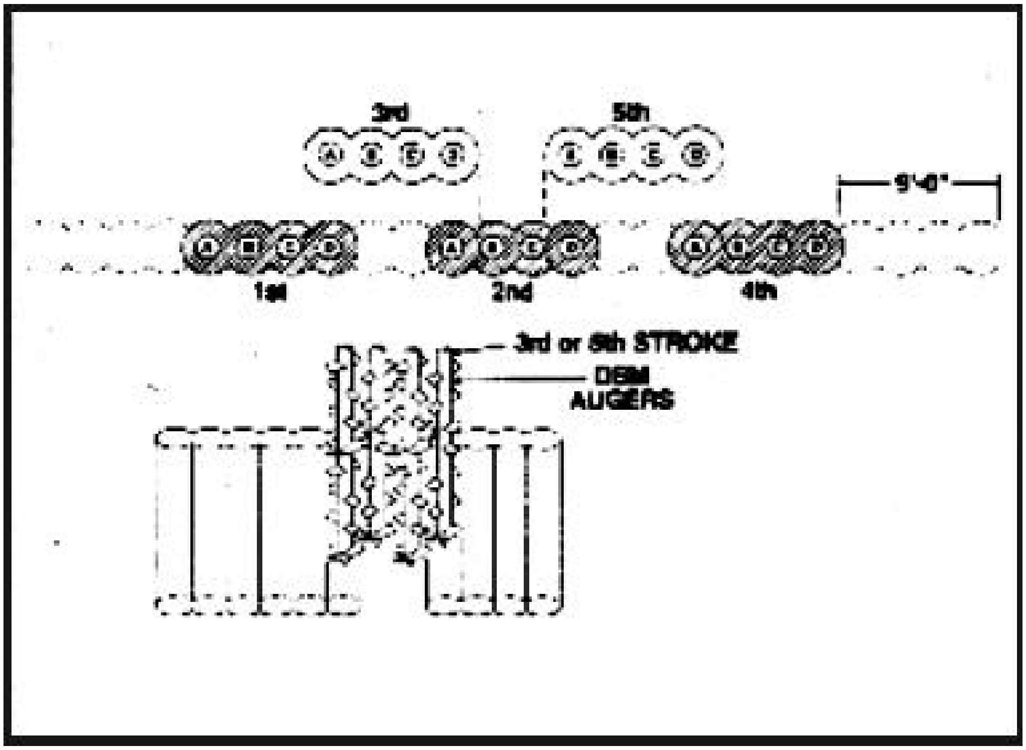

Figure 4. Typical DSM Drilling Pattern

bentonite, fly ash, silicates, activated carbon, and nearly any other fine-grained, processed product. Quality control relies on weight and volume measures which can be easily crosschecked by viscosity and/or density checks on the grout.

Fluid reagents are mixed with the soil in proportions based on the performance objectives or the project and drilling conditions, When drilling soil, the ratio of grout to soil is usually in the range of 20 to 50% by weight.

Fluid injection and mixing creates an increase in soil volume known as swell. The amount of swell is a function of soil type, injection volume, reagent type and operating conditions. Typical swell is about 15% of the treated volume. Often, a small starter trench is excavated prior to mixing to contain the swell. When the starter trench is in uncontaminated soil, and can be large enough to contain all the excess, a 0% net swell can be realized.

Reagent proportions and ingredients in the grout should be selected based on pre-construction bench scale studies. Bench scale studies can model insitu conditions and develop the appropriate minimum grout and soil-grout recipes based on laboratory testing. The results of the bench scale study may also provide useful data on off-gassing potential, swell, mixing requirements, and setting times. Performance objectives typically used include strength, permeability and leaching potential.

Case Study – Chemical Stabilization Using SSM

A former Manufactured Gas Plant (MGP) site adjacent to the Chattahoochee River in Columbus, Georgia was to be converted into a city park. A site assessment determined that extent of MGP materials, primarily coal tar, present in the oils and groundwater on the site. Petroleum hydrocarbons and other man-made materials were present at depths ranging up to 10 meters.

The site soils consisted of fill materials and stream alluvium underlain throughout the site by a relatively impermeable saprolite. Total Poly-Aromatic Hydrocarbons (PAH) concentrations in soil ranged from 1,500 ppm to 26,000 ppm. The MGP site location and characteristics dictated that the insitu stabilization technology should provide a uniform mix of the affected soils and have provisions to control organic vapors and dust.

The remedial design called for the following treatment criteria for the stabilized soil: a minimum Unconfined Compressive Strength (UCS) of 0.4 MPa after 28 days; a maximum permeability of less than 1 x 10^{-5} cm/sec; and leachate from the treated soil, obtained from TCLP extraction, with total PAH's less than 10 mg/l. Bench scale treatability test results indicated that the treatment criteria would be met with 10% (by dry weight of soil) addition of Portland Cement.

The 75,000 cubic meter of insitu stabilization was accomplished within the 20 week fast-track schedule by working around the clock, seven days a week. The effectiveness of the SSM stabilization system in providing the correct dosage, thorough mixing, and adequate coverage of the subsurface zone to be treated was confirmed by the fact that only one column out of over 1800 was remixed due to a questionable UCS test result. The analytical results of the stabilization QA/QC sampling program showed permeabilities in the 10^{-7} range and the total PAH's in the TCLP test were well below the 10 ppm limit set in the treatment criteria as shown in Figure 5. The figures shown for "treated soils are the total concentrations of PAH's while the figures for "treated soil" represent the leachability as measured in a TCLP test.

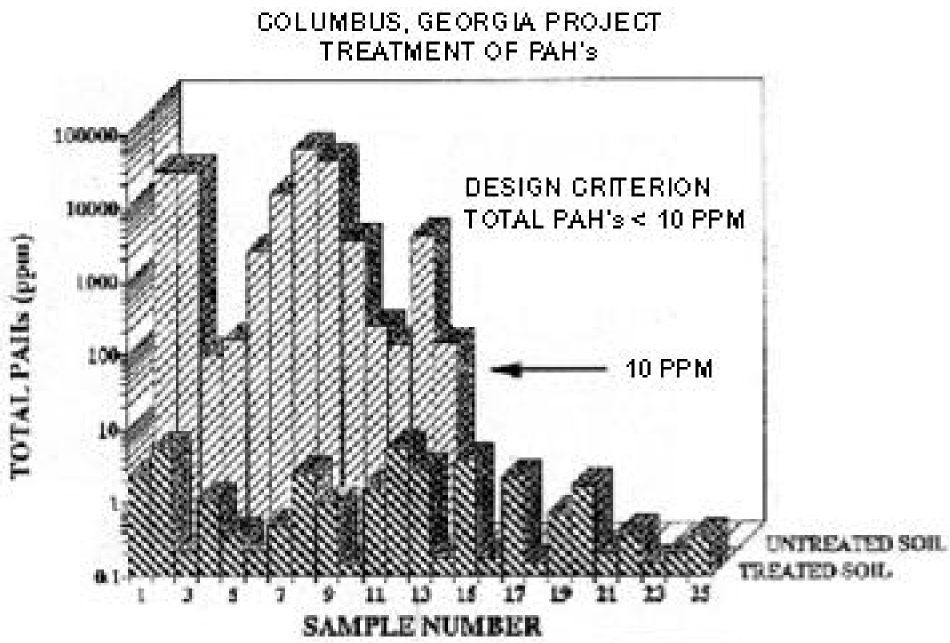

Figure 5. Columbus Mixing Results

The first phase of the remediation included the construction of a cement stabilized soil-crete containment wall parallel with the riverbank. See Figure 6. Due to greater strength and permeability requirements, this section used a 25% cement addition. The 125 meter long by 2.5 meter wide barrier wall was keyed one meter into the saprolite and had a permeability of 10^{-8} cm/sec and a 28 day USC of over 2 MPa. This barrier wall served two purposes: it acted as a retaining wall allowing for the removal of the contaminated soils on the riverside of the wall and it prevented any potential migration of contaminates from the site to the river.

The remaining area (approximately 6000 sq. m.) was treated by SSM using a primary and secondary 2.5 meter diameter pattern with a 20% overlap. The SSM columns ranged from 8 to 10 meters in depth.

Figure 6. Columbus Site Under Construction

The end result was the redevelopment of the site into a public park (Figure 7) that was the centerpiece of the Columbus' quintecentenial Columbus Day Celebration in 1992.

Figure 7. Columbus Site Completed and Returned to Public Use

VOC Extraction Using SSM and Heated Air

A nuclear fuels processing plant in southern Ohio had a one-third hectare plot that was formerly used for the land farming of waste oils and degreasing solvents. The silts and clays on the site were contaminated to a depth of 6.7 meters with VOCs to levels over 100 ppm and were leaching into the shallow (4 meters deep) groundwater table. After extensive testing and a full-scale pilot project, scientists of the Oak Ridge National Laboratories selected SSM with hot air injection and vapor extraction as the remedy.

The pre-construction studies provided considerable useful information but could not fully define the optimum mixing time, nor the potential risk of retreatment. Because the soils were loosened (not solidified) by mixing with air, retracking the crane over the treated soils was considered impractical and unsafe. Adding soil vapor extraction (SVE) to the process solved these problems. The SSM/SVE process diagram is shown in Figure 8.

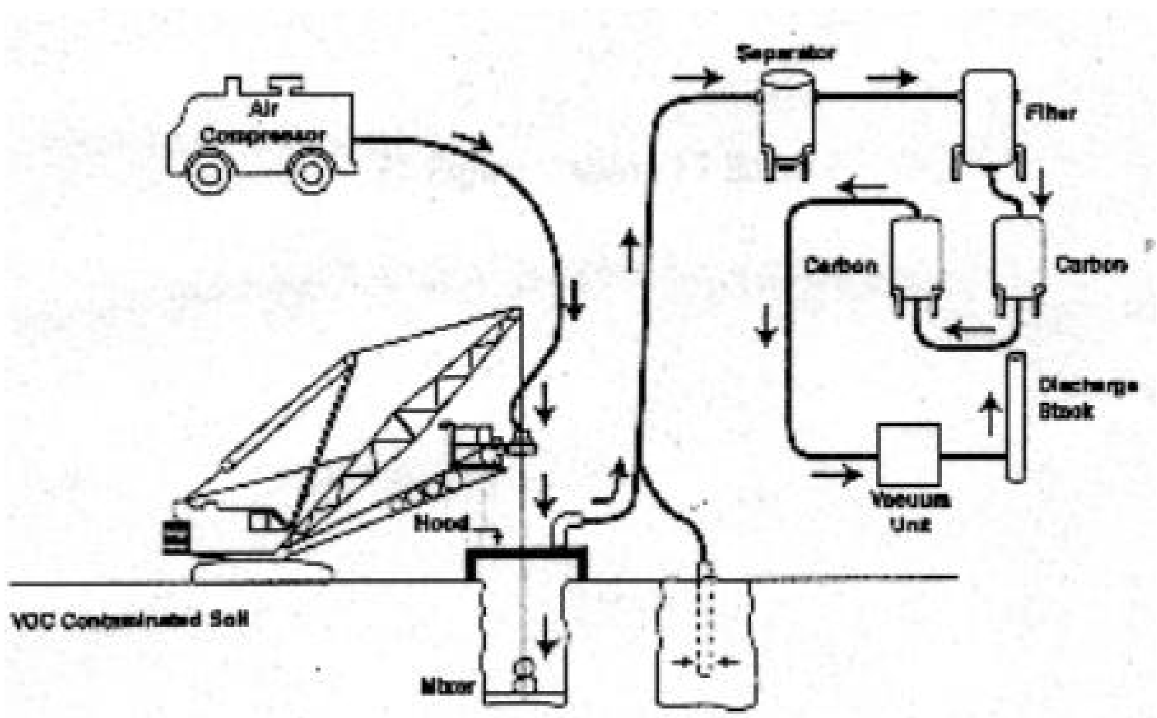

Figure 8. Soil Mixing and Vapor Extraction Process Diagram

The project work was performed by first sampling discrete intervals of the soils from one of every three SSM columns. After initial sampling, SSM was performed using compressed air heated to about 250 F as the drilling fluid. See Figure 9. The VOC off gas from the mixing was monitored by a FID (Flame Ionization Detector). As the mixing progressed, VOC readings were observed by the FID and the mixing effort could be concentrated in the areas of highest contamination. The amount of VOCs removed was calculated from the air flow rate and FID readings and confirmed by post-remediation soil sampling.

The soil remediation generally required about 1 to 4 hours of mixing and air injection per stroke. The SSM columns were 2.4 meters in diameter with a 10% overlaps. Temporary SVE wells were installed in about one of every three SSM columns and operated for a few days to a few weeks. The treatment of 680 columns was completed in 10 weeks operating around the clock.

Figure 9. View of SSM/TEVE in Progress

The project was subjected to extensive quality control and testing including an on-site laboratory equipped with a gas chromatograph. The on-site laboratory was used to test soil samples, carbon loading, and the discharge stack. Typical results from soil sampling are shown in Figure 10.

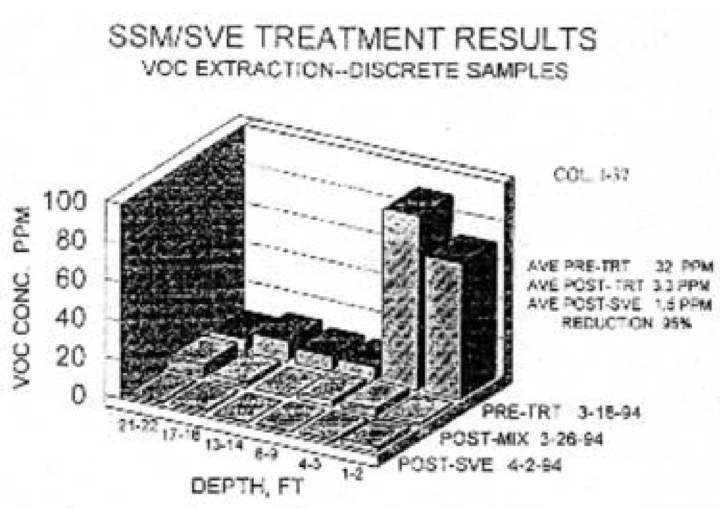

Figure 10. SSM/SVE Typical Result

Post-construction sampling results were compared to pre-construction sampling to derive a percent VOC removed. The overall removal percentage was 90% or about 500 kg of VOCs.

Vertical Barrier Construction Using DSM

A chemical plant located in Houston, Texas had a problem with leachate from several sediment ponds migrating underground toward an adjacent bayou. The leachate contained relatively high proportions of volatile organic compounds (VOCs) which could represent a problem for conventional barrier construction methods like slurry walls, since excavating any amount of the contaminated soil and bringing it to the surface should cause the release of obnoxious and potentially dangerous amounts of VOCs into the atmosphere. In addition, the local regulatory authority required any soil excavated from the ground be incinerated. The DSM process was selected to form the vertical barrier wall because no excavation of the contaminated material would be necessary. A second advantage of the DSM process was the elimination of the risk of trench collapse in this area of soft soils and high water table.

The soil profile consisted of shallow (3 m deep) fills of sand and pond sediments overlying interbedded sand and silty clay layers. A reliable aquiclude was found at depths of approximately 15 meters in the form of the stiff clays of the Beaumont Formation. The groundwater table was generally within a meter or two of the ground surface.

The barrier was designed as a down-gradient wall and constructed between the sediment ponds and the adjacent bayou. Figure 11 shows the work in progress. The total length was 700 m and the average depth 16 m. A one-meter key into the stiff Beaumont clays was required.

Pre-construction laboratory studies were carried out to determine the optimum mix ration to meet the design requirement of 1×10^{-7} cm/sec. Since strength was not a criterion, only bentonite was considered as an additive: various ratios of bentonite to water and slurry to soil were tested. Bentonite content of the slurry was varied from 5 - 9% by weight and the slurry addition rate was varied from 30 – 40% by volume. These mix variations produced relatively little effect on permeability, with all results in the 10^{-8} cm/sec range. This finding was primarily a result of the soil stratigraphy on the site, which was mostly clay with interbedded sands. When blended vertically as with DSM, these soils produced an ideal base mix. The blended soils had approximately 50% passing the 200 sieve with a Plasticity Index of about 25. The final mix selected was 6% bentonite slurry with a 35% addition rate to soil by volume.

In the field, samples were taken from the mixed wall using a specially designed sampler that was pushed down in to the fluid soil-grout mix. About half the samples were taken at a 6 m depth; these were reconsolidated in the laboratory at a pressure of 0.85 kg/cm^2 and the permeability was measured in the triaxial cell. Deeper samples were taken at depth that varied slightly but were generally about 12 m. For these samples,

All tests met the design criterion of 1×10^{-7} cm/sec. There was some improvement as the consolidation pressure was increased to 1.7 kg/cm^2. The results are shown in Figure 12. job progressed from the start of the alignment to the end, which was attributed to an increasing percentage of fines in the mixed soil column.

Figure 11. DSM Work in Progress

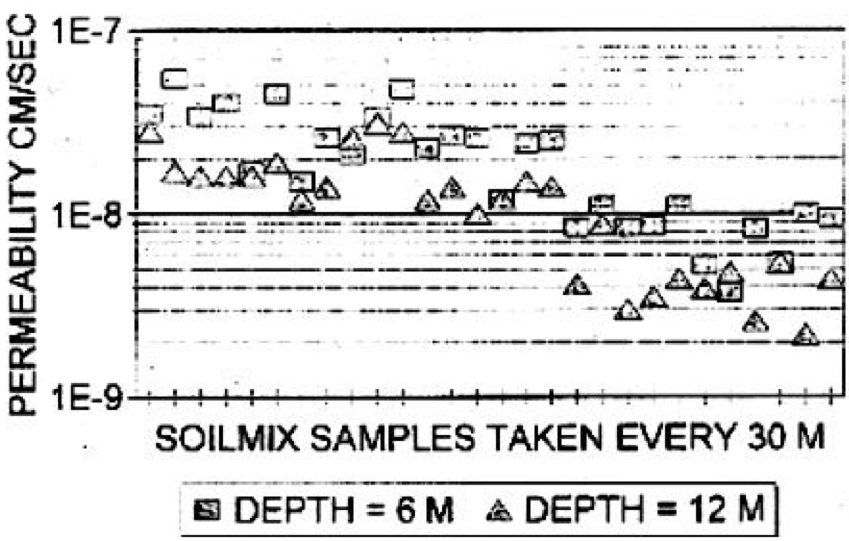

Figure 12. DSM Permeability

Design Considerations

The design of a soil mixing project with an environmental application must recognize the contributions of all the disciplines involved including construction, equipment, geotechnical and chemical expertise. In general, the steps required to design a soil mixing project generally proceeds in the following order.

1. Identify alignment or area to be treated.
   Contaminated area and depth
   Depth to aquiclude

2. Characterize waste and soils
   Soil boring investigation
   Chemical analysis of samples

3. Develop reagent requirements
   Bench scale study
   Estimate of material usage
   Determine regulatory feasibility

4. Design approach
   Performance objectives
   Dimensions of treatment area
   Appurtenances and support facilities

5. Constructability review
   Cost estimate
   Construction feasibility

The steps listed above may require several iterations if unusual conditions are discovered in the design process. Key areas of concern are the comprehensive soils investigation, reliability of the bench scale study, and reasonable performance criteria. The soils investigation must not only define the limits of the contamination but also the type and resistance of the soils. A typical soils investigation will include SPT (Standard Penetration Tests), grainsize, soils classification, and chemical analysis of samples. The bench scale study should use representative samples and produce results that allow for natural soil variability. Various additives and mix rations should be tested. The materials and ratios selected must be compatible with the soil mixing equipment. Performance criteria often are a compromise between regulatory dictates and engineering possibilities. TCLP levels as low as 1 ppm are possible with some contaminates (VOCs, PAH, PCB, etc.) but unrealistically low standards must be avoided. Unconfined compressive strengths are generally in the range of 0.25 to 3.5 MPa (35 to 500 psi). The permeability of soil mixed materials is generally in the range of 10^{-5} to 10^{-8} cm/sec. New developments in reagent technology and test methods may improve performance.

Construction Quality Control

The testing and monitoring of a soil mixing project is a relatively simple matter given adequate planning and a thorough understanding of the technology. The following items generally require documentation and verification:

1. Reagent materials and manufacturer's certificates

2. Grout mix proportioning including viscosity, density, homogeneity, etc.

3. Reagent application and mixing ratio with soil.

4. Overlap and depth verification.

5. Sampling of mixed soil for performance testing.

Sampling and testing can be difficult with soil-cement mixtures. Stabilized materials may be harder than soil, yet much softer than rock. Shelby tube sampling and rock coring may both fail to provide representative samples. It is recommended that samples of soil-cement be obtained from depth before the mixture can set for the casting of cylinders.

Summary

Insitu soil mixing provides a proven means for the remediation of contaminated sols and sludges. Methods and equipment are available for areal and wall treatments. Soil mixing has significant advantages in safety, risk, and cost in remediating contaminated sites.

BIBLIOGRAPHY

1) Ryan, Christopher R. and Walker, Andrew D., "Soil Mixing for Soil Improvement -Two Case Studies," Insitu Soil Modification, Ohio River Valley Soils Seminar, ASCE, Louisville, KY, October 16, 1992.

2) Adaska, Wayne, S., Ten Bruin, Wayne, and Day, Steven R., "Remediation of Oil Refinery Sludge Basin," Cement Industries Solution to Waste Management, Calgary, Canada, October 7-9, 1992.

3) Aldridge, C. Wayne and Naguib, Aiman, "Insitu Mixing of Dry and Slurried Reagents in Soils and Sludge Using Shallow Soil Mixing,' 85th Annual Meeting & Exhibition, Air and Waste Management Association, Kansas City, Missouri, June 21-26, 1992.

4) Ryan, Christopher and Jasperse, Brian H., "Deep Soil Mixing at the Jackson Lake Dam," ASCE Geotechnical and Construction Divisions Special Conference, June 25-29, 1989.

5) US EPA, "International Waste Technologies/Geo-Con Insitu Stabilization/Solidification," Superfund Innovative Technology Evaluation, Application Analysis Report, August 1990.