The ability to economically treat large volumes of soil made large diameter (2.4 m to 3.0 m [7.8 ft to 9.8 ft]) single auger soil mixing equipment the equipment of choice for ISS applications in the U.S. High profile government-led efforts to clean-up projects further developed the technology. These included the Department of Energy-led project in Piketon, Ohio (1990s), where a combination of SSM and thermally enhanced vapor extraction was used to treat trichloroethylene (TCE) contaminated soils, and the Geiger Oil Superfund Site where ISS and IST were used to remediate chromium, lead, PCB and VOC contaminated soils near Charleston, S.C. in 1994. The technology had a great impact on the former manufactured gas plant (MGP) industry. From the late 1800s through the early 1900s manufactured gas (produced from the gasification of coal) was

**Soil Mixing in Contaminated Soils**

The term soil mixing commonly refers to any process by which reagents (wet or dry) are added to and mixed with unsuitable or contaminated soils. Other terms such as deep mixing method, shallow soil mixing, deep soil mixing, cutter soil mixing and trench cutting remixing deep wall are commonly used by engineers and contractors in the geotechnical industry to refer to soil mixing or a particular type of equipment. The purpose is similar: the efficient creation of a soil-reagent composite with improved properties relative to the in-situ soils. Improvements for contaminated soil mixing generally include factors such as strength increase, permeability reduction and contaminant mobility reduction. Contaminated soil mixing is commonly performed in-situ using single axis large diameter auger mixing with wet reagent addition. Large diameter auger mixing in this application is performed by pumping a liquid reagent mixture down through a hollow drill stem into a large auger (auger diameters in the 0.9 m to 3.7 m [3 ft to 12 ft] range) where the fluid is allowed to exit the system via ports on the back of the auger and is mixed with the soils. The result is a soil column evenly mixed or treated with the reagent. Subsequent columns are installed in an overlapping pattern to confirm 100% coverage of the target treatment area. In the geoenvironmental industry, the terms used to describe the application of soil mixing to the stabilization/solidification and treatment of contaminated soils are in-situ stabilization/solidification (ISS) and in-situ (chemical) treatment (IST).

**Contaminated Soil Mixing History**

The Nov/Dec 2013 Deep Foundations magazine included a brief overall history of deep mixing methods focused on soil mixing to solve geotechnical problems. Soil mixing of contaminated soils originated in the United States in 1988 when Geo-Con installed the first non-structural DSM containment wall to isolate PCB-contaminated soils and groundwater from a nearby river. The firm installed the wall using the first U.S. manufactured multi-auger soil mixing drill. In the same year, part of the U.S. EPA’s Superfund Innovative Technology Evaluation Program, Geo-Con also performed an ISS pilot project at a Florida Superfund site. This was the first U.S. EPA-led project using this technology.

In 1990, the first large scale ISS project used single auger soil mixing equipment at a contaminated site in Texas. By 1991, stabilization/solidification (S/S) was the recommended treatment technology for over a quarter of the U.S. EPA’s national priority sites, primarily using ex-situ techniques. After the initial applications succeeded, development and use of the in-situ S/S technology (ISS) was fueled by its advantages over alternative remediation options including eliminating the need for excavation support, dewatering (including the need for treatment of contaminated dewatering waters) and double handling of contaminated soils.

The ability to economically treat large volumes of soil made large diameter (2.4 m to 3.0 m [7.8 ft to 9.8 ft]) single auger soil mixing equipment the equipment of choice for ISS applications in the U.S. High profile government-led efforts to clean-up projects further developed the technology. These included the Department of Energy-led project in Piketon, Ohio (1990s), where a combination of SSM and thermally enhanced vapor extraction was used to treat trichloroethylene (TCE) contaminated soils, and the Geiger Oil Superfund Site where ISS and IST were used to remediate chromium, lead, PCB and VOC contaminated soils near Charleston, S.C. in 1994. The technology had a great impact on the former manufactured gas plant (MGP) industry. From the late 1800s through the early 1900s manufactured gas (produced from the gasification of coal) was
the source of light and heat for most major cities. The process of creating manufactured gas created a significant amount of wastes, the most prevalent of which were coal tars. Despite efforts to containerize the coal tar in subsurface holding tanks, pure product and by-products (benzene, toluene, ethylbenzene, xylene, among others) migrated into the soils and groundwater beneath and surrounding MGP sites. Some sources state that at one point in the U.S. over 50,000 MGP sites were operating. Tens of thousands of these sites still have heavily impacted subsurfaces. The ISS technology using soil mixing has proven to be one of the most cost-effective and technically sound means of addressing these sites. The Electric Power Research Institute (EPRI), Georgia Power and other utility owners have helped advance the technology through paid research and by specifying ISS for some of their MGP projects. The major projects that helped reinforce ISS for use on MGP sites include the use of soil mixing for the S/S of coal tar impacted soils on former MGP sites in Columbus, Ga., in 1992, and Cambridge, Mass., in 2001. Today, many major electric utilities have programs to remediate their MGP sites using the soil mixing technology.

**Containment Walls**

Soil mixed walls to contain contaminated soil and prevent lateral migration of contaminated groundwater are installed using the same equipment and techniques that are used in geotechnical applications. However, these walls are installed to be non-structural by design. Instead of strength improvement, the primary design parameter is horizontal permeability reduction. These walls are preferred over other more conventional, and often less expensive, cutoff wall types (e.g., slurry trench cutoff walls) where there is an elevated safety risk from exposure to harmful constituents. Examples of early applications of cutoff walls include two projects involving the containment of chemical warfare material with the included risk of encountering unexploded ordnances at a former U.S. Army facility in 1999. A more recent application involved installing a DSM wall at a DOE facility to contain tritium contamination in 2011.

In-situ solidification/stabilization (ISS) refers to processes that utilize a binding agent to manipulate the physical properties of contaminated soils in place. In most cases, ISS leaves the contaminants chemically unaltered, but their impact on the surrounding subsurface is greatly reduced. ISS is the most common form of soil mixing used for contaminated soil remediation and Portland cement is by far the most common binding reagent used. Other common reagents include lime, blast furnace slag, fly ash, activated carbon, bentonite clay and organophilic clay. Many of these reagents are used in combination with Portland cement to achieve property improvements that would not be possible if Portland cement were used alone. The most common improvement objectives for ISS projects are permeability reduction and strength increase, but contaminant mobility reduction objectives are becoming more common.

In terms of volume mixed, the most common application of ISS for contaminated soil remediation is for the remediation of DNAPL (dense non-aqueous phase liquids, those denser than water) impacted soils resulting from former manufactured gas plant (MGP) or wood treating operations. ISS has found widespread use in these applications because other remediation alternatives are limited by the properties of the coal tar and creosote byproducts found on these sites, both of which are viscous DNAPL materials at the temperature ranges found in the subsurface. Excavation and disposal can be
a competitive alternative to ISS for the remediation of these sites in terms of cost and treatment efficacy, but excavation and disposal cause greater impact to the surrounding community in nuisance odors, public health concerns and increased truck traffic than ISS. MGPs are commonly located in heavily traveled former industrial or commercial centers that have since been converted into mixed-use residential and commercial neighborhoods that are sensitive to the impacts caused by excavation and disposal operations. ISS has become an accepted alternative for MGP and wood treating site remediation, and in many cases, the preferred alternative.

In 2012, ISS was used to remediate MGP impacted soils in Sacramento, Calif. On this project, ISS with Portland cement and granular regenerated activated carbon was used to S/S 31,000 m$^3$ (41,000 cu yds) of coal tar impacted soils down to a maximum depth of 12 m (40 ft) below ground surface. This was the first documented use of ISS for an MGP site remediation in California. Another recent use of ISS was for the S/S of wood treating impacted soils in Portsmouth, Va. On this project, ISS with Portland cement and organophilic clay was used to S/S 36,000 m$^3$ (47,000 cu yds) of creosote impacted soils to depths ranging from 2.4 to 8.2 m (8 to 27 ft). This work was overseen by the Norfolk District of the U.S. Army Corps of Engineers.

In-situ Treatment

In-situ treatment (IST) refers to processes that use reagents to purposely alter harmful contaminants in place. In some cases, IST converts contaminants into inert compounds, and in other cases into less harmful compounds. IST is generally performed using one of two chemical processes, chemical oxidation or chemical reduction, referred to as in-situ chemical oxidation (ISCO) and in-situ chemical reduction (ISCR). Treatment objectives vary widely, ranging from contaminant mass reduction to complete contaminant mass destruction. Common reagents include zero valent iron (ZVI), potassium permanganate, sodium persulfate, ferrous sulfate, calcium polysulfide, biological nutrients and hot air. Commonly, other reagents are injected with the main reagent to catalyze the chemical reaction. These other catalyzing reagents include lime, soda ash, quick lime and phosphoric acid.

The widest application of IST to contaminated soil remediation has been in the use of ZVI and bentonite clay added to remediate chlorinated solvent impacted soil. The concept of using ZVI delivered in a bentonite slurry via soil mixing was developed and patented by DuPont in the early 90s. DuPont has since donated the patent and royalty rights to Colorado State University. In the authors’ experience, the
application of the ZVI/clay technology to solve environmental remediation problems has seen significant increase over the last half decade, after a relatively quiet period since the initial applications in the early to mid-90s.

The ZVI/clay soil mixing technology was used in 2011 to treat a TCE impacted source zone on the OMC Superfund Site in Waukegan, Ill. On the Waukegan project, the ZVI was delivered and mixed with the soils using a large diameter soil mixing rig in a mixture with bentonite and water. On that project, approximately 6,500 m³ (8,500 cu yds) of impacted soils were treated down to a maximum depth of 7.2 m (24 ft) BGS. Additionally, ISCR with the ZVI/clay technology was used in 2012 to treat PCE impacted soils at a former wastewater lagoon that contained wastes from a former industrial dry cleaning facility in Alberta, Canada. The Alberta project included soil mixing 7,500 m³ (9,800 cu yds) down to a maximum depth of 8 m (26 ft).

Less common uses of IST include oxidizing chlorinated solvents and other volatile contaminants through adding oxidants with or without catalysts. ISCO performed with soil mixing has grown rapidly over the last half decade as engineers and owners have adapted the technology to solve problematic sites. Soil mixing offers numerous benefits over other methods of performing IST, including the potential for a reduced construction schedule, a reduced cost, a reduced carbon footprint, and improved contact between the reagent and contaminated media in a low permeability or fractured subsurface.

IST was used in combination in 2010 with ISS for the ISCO and S/S of 5,700 m³ (7,500 cu yds) of TCE impacted soils down to a maximum depth of 5.8 m (19 ft) in East Rutherford, N.J. Potassium permanganate was used as the oxidant on that project. On another project, in Robbinsville, N.J., in 2011, a base-catalyzed sodium persulfate treatment was used on xylene and pesticide impacted soils. The soil mixing in Robbinsville included treating 2,100 m³ (2,800 cu yds) down to 4.6 m (15 ft) BGS. ISCO was also used in Norwich, N.Y. (2012) in combination with hot air stripping to treat acetone impacted soils. The treatment reagent used in Norwich, N.Y. was calcium peroxide mixed with the soils, down to a maximum depth of 8.2 m (27 ft), in conjunction with fertilizer nutrients and phosphoric acid. Prior to the treatment “polishing step,” designed to enhance long term biodegradation, a significant amount of the acetone was stripped from the soils using hot air soil mixing.

Potential Future Trends and Conclusions

- Increased scrutiny of sustainability related metrics in remedial method evaluation.
- A shift from S/S to treatment as regulators target gross concentration reduction rather than impact reduction.
- Increased application of ISS to the in-place remediation of saturated sediments. (See recent EPRI research, including information on the recent pilot study completed in Springfield, Mass., in 2013).
- Increased viability of ISS to more sites as more applicable leaching/diffusion tests are accepted. See the new EPA LEAF tests (methods 1313 – 1316) and the ITRC guidance document (2011).
- Increased application of jet grouting to environmental remediation projects.
- An increase in novel reagent combinations that will further expand the use of soil mixing to remediate historically difficult contaminants.
- Additional equipment modification and development, including improved batch plants, drill rigs and quality control that will make soil mixing more cost effective.

The current practices in the soil mixing of contaminated soils were developed over 30 plus years. The technology has been used to stabilize, treat and contain contaminated soils. The geoenvironmental industry has embraced this technology, particularly over the last 5 to 10 years, and should continue to support soil mixing for contaminated soil remediation. Better overall understanding of this technology by designers, acceptance of this technology by environmental regulators, the use of more realistic contaminant leaching methods, and the further refinement of equipment, technique, and quality control procedures will help further the growth of this technology.