Economical Alternatives for Containment Barriers

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ECONOMIC ALTERNATIVES FOR CONTAINMENT BARRIERS

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Abstract

Fixation, barriers, and containment of existing landfills and other disposal areas are often performed by in-situ auger type soil mixing and jet grouting. Cement or other chemical reagents are mixed with soil to form both vertical and horizontal barriers. Immobilization of contaminants can be economically achieved by mixing soil and the contaminants with reagents that solidify or stabilize the contaminated area. Developed in Japan, and relatively new to the United States, the first large scale application was for a vertical barrier at the Jackson Lake Dam project in 1986. This technology has grown in both the civil and environmental field since. The paper describes current United States practice for Deep Soil Mixing (over 12 meters in depth), and Shallow Soil Mixing for vertical barriers and stabilization/solidification, and Jet Grouting for horizontal and vertical barriers. Creating very low permeability barriers at depth with minimal surface return often makes these techniques economical when compared to slurry trenches. The paper will discuss equipment, materials, soil and strength parameters, and quality control.

Introduction and Origin of In-situ Soil Mixing

Soil mixing, both deep and shallow, and jet grouting are now accepted technologies in both the civil construction and environmental remediation markets in the United States. However, this recently accepted technology had an unorthodox path to acceptance.

In 1962 Norman Liver, working for Intrusion-Prepakt Co. in Cleveland, patented an auger-based soil mixing technique that has become the basis for the world's current technology. Originally there was little acceptance in the United States and development was stagnant; but in the early 1970s and into the 1980s, the Japanese took the technology and made rapid advances. By the late 1980s, approximately 2,000,000 cubic meters of soil mixing and jet grouting were being performed annually in Japan, much of it in their coastal cities, ports and harbors (1995 DSM). Current Japanese practice utilizes soil mixing to transform soft clays into hardened, cemented barriers, water and contaminant cutoff walls and mass foundations for piers, wharves and building. Over 200 rigs work continuously in this $ 1.0 billion-plus per year industry in Japan. In comparison, the United States, with twice the population, has six rigs.

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Acceptance in the United States

In-situ soil mixing re-emerged in the United States in 1986 when a Japanese specialist company, Seiko-Kogyo, performed a demonstration in California. Seiko was assisted by Geo-Con, a domestic specialty foundation contractor. The next year, Geo-Con and SMW Seiko redesigned and won a $ 16 million contract for Morrison-Knudsen Co. to use the process on a Bureau of Reclamation project, Jackson Lake Dam in Wyoming. The soil mixing was used to provide a vertical cutoff and also improve the capability of the dam's foundation to resist liquefaction. After the commencement of this work, a project in Michigan for a contaminant containment barrier was performed in 1987 to 1988; and since then, many other various soil mixed wall and cutoff barriers have been constructed.

Presently over 50 projects have been completed in the United States. In the soft clays of Boston, deep and shallow soil mixing have been used for over 56,000 square meters (600,000 square feet) of structural and cutoff walls. Presently, the largest project to date in the United States is underway in Boston as part of the enormous Central Artery/Tunnel construction program. In this project deep soil mixing, shallow soil mixing and jet grouting will be used to solidify 600,000 cubic meters (780,000 cubic yards) of organic silts and soft clay. The design for this Fort Point Channel section is to provide mass solidification of unstable soils improving the compressive strength from 36kPa (0.75 kips per square foot) to an average of 2400kPa (50 kips per square foot), equivalent to the strength of a soft rock. This ground treatment and solidification will allow deep excavation, 18 meters (60 feet) plus below the water table, for cut and cover tunnel sections to provide a link between I-93 and the Massachusetts Turnpike.

The In-situ Soil Mixing Process

Deep Soil Mixing

In-situ soil mixing in the United States is divided into two general categories: Deep Soil Mixing (DSM) which is generally considered treatment depths greater than 12 meters (40 feet) and Shallow Soil Mixing (SSM) which is generally considered treatment depths less than 12 meters (40 feet) deep.

For DSM the typical equipment used consists of a set of two to four tools, top driven by either hydraulically or electrically powered motors. These motors and the shafts they power ride up and down a set of specially designed leads, which in turn are supported by a crane or may be structurally integrated into the crane body itself. The mixing tools consist of thick-walled rods, usually 250 to 300 mm (10-12 inch) diameter, with 50 to 75 mm (2-3 inch) diameter center holes, for slurry conveyance. Attached along each rod are mixing paddles which are designed to overlap with the paddles on the adjacent, counter rotating rod to create a pugmill-like mixing environment for the soils and injected slurry. At the bottom of each rod is a cutting head, also with a hollow center, that is designed to lift the soil to the mixing paddle area where it is blended with the previously injected slurry (Figure 1). As the rods and paddles penetrate the soil, they continuously rotate and mix the slurry and soil together. When the bottom of the stroke is reached, further slurry is injected while the shafts maintain that depth and mix for a short period to ensure blending of the bottom of the column. The rods are then slowly pulled from the ground with continued rotation and slurry injection at a reduced rate.

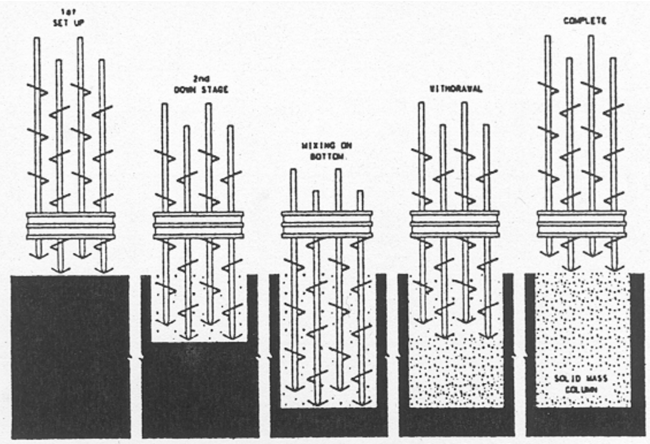

Figure 1: Multiple Shaft Auger Mixing System

The multiple–shaft design provides several benefits. For installing barrier or cutoff walls, a pattern of overlapping of adjacent panels is adopted. Primary strokes are spaced at appropriate intervals, and secondary strokes later re-penetrate the outer shafts of the primary strokes to ensure continuity of the wall. Other drilling and mixing patterns can be created that will allow block treatment and perimeter enclosures (Figure 2). In this way contaminants can be enclosed or treated and solidified into a cemented (or other reagent) mass.

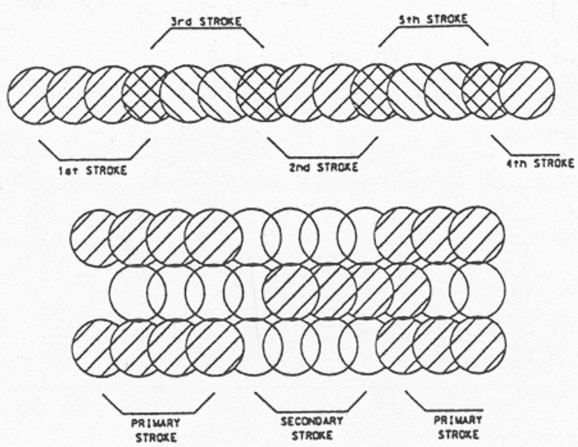

Figure 2: Multiple Shaft Auger Mixing Patterns

Shallow Soil Mixing (SSM)

Many applications of in-situ soil mixing, particularly in the environmental remediation areas, are located near the ground surface (less than 12 meters [40 feet] deep). In these cases it is often possible to use a single, large-diameter tool to perform the mixing process. This method, SSM, is usually faster and far less expensive, largely because the equipment is simpler and the larger diameters employed mean much more soil can be treated in each meter of penetration. For example a typical DSM system will treat 1.5 to 2.25 m3 per meter of stroke (0.6-0.9 cy/foot), whereas an SSM system will treat 5 to 9 m3 per meter of stroke (2-3.5 cy/foot)

SSM equipment consists of a single-auger mixing tool generally 2-4 meters (6-12) feet in diameter. This process was developed in the United States and utilizes standard domestic cranes to support a caisson turntable and a Kelly bar driven mixing tool. The Kelly bar is hollow-stemmed to allow for slurry injection. The mixing tool has carbide cutting teeth, combined with a short auger flight that contains jet ports to inject the slurry into the soil.

SSM can be used to treat a number of contaminants through stabilization, solidification, fixation, neutralization and permeability reduction. It is very effective on heavy metals and can treat low levels of organics. With the use of lime as a reagent, acidic soils and sludges can be neutralized. The following show reagents and the contaminants on which they are generally effective.

Contaminant	Solution	Reagent
Heavy Metals	Stabilization	Cement, flyash, kiln dust
PCBs	Stabilization, fixation	Cement, flyash, bentonite proprietary reagents
Organics	Stabilization, solidification	Cement, flyash, bentonite proprietary reagents
Creosotes	Stabilization	Cement, flyash
Acidic Soils and Sludges Dust	Stabilization, neutralization	Lime, cement flyash, kiln dust
Asbestos	Stabilization	Cement, flyash, lime

Technical and Economic Considerations

In-situ mixing offers many technical and economic advantages over conventional slurry wall trench installation for barriers.

Less spoil disposal – Since the soils and slurry are mixed in-situ, the amount of spoil removed is limited to approximately the volume of slurry added, usually from 10-30% of the treated volume. In trench excavation, all of the soils must be removed. In cases where the soils are contaminated, it is obvious that the savings in disposal costs can be significant.

Capable of greater treatment depths – Standard depths of 25 meters (82 feet) are available in one stroke. by adding sections of mixing tool, depth is limited only by time and soil type. Depths of treatment of up to 40 meters (131 feet) have been completed in the United States and 60 meter (200 feet) depths have been achieved in Japan.

No open trench – When the mixing tools are withdrawn, that section of the wall is complete. This eliminates open trenches that pose potential safety and quality control problems due to possible trench collapse. Exposure to volatilization of VOCs is minimized.

Less working area is required – Since the mixing is performed in-situ, space for above-ground mixing is not required. The batching of the cement is containerized and the slurry may be pumped great distances if required. Distances of 600-1200 meters (2000-4000 feet) are not uncommon.

Superior mixing of slurry with soil – The pugmill mixing environment that is created by overlapping mixing paddles produces a very homogeneous product. Conventional methods mix the soil backfill above the ground with tracked excavating equipment resulting in uneven blending. By mixing in-situ, the amount of slurry or reagent required also is minimized.

Better quality control is achieved – During this mixing process, there are a number of quality control measures that are used to control mix quality and ensure thorough blending. Specific gravity of the slurry is controlled at the mixing plant to ensure the proper proportions of agents are blended. In-line flow meters are used with digital readouts to instantaneously monitor flow rates and record total flows. When integrated with penetration rate controls, the flow rate per foot can be optimized and controlled. Electronic monitoring of penetration of the shaft will record instantaneous penetration rates as well as record total distance traveled (depth). Testing of the final mixed-in-place soil and slurry is accomplished by grab samples at various depths after withdrawal of the tools from the hole. subsequent core or test drilling will confirm that the proper amount of slurry injection and mixing have been performed.

Barrier and Stabilization Materials

Generally, the purpose of the soil mixing treatment is to increase the strength and/or lower the permeabilities of in-situ soils in order to construct a barrier or stabilize contaminants. Cement is by far the best reagent for strength increase, but it can be cost prohibitive if massive amounts are needed to achieve the required strengths. Other reagents, some of which are process by-products and economically purchased, can be mixed with cement to reduce cement usage or can be used alone. Types of strength increasing reagents follow:

Cement
Lime Kiln Dust (alone or with cement)
Flyash (with cement)
Lime (alone)
Gypsum (with cement)

Use of these reagents also lowers the permeability of the final soil mixed product.

Sands and coarse grained soils are the easiest to mix, but even very stiff clays can be treated, albeit with slower penetration rates and increased slurry usage. The following table shows a range of typical values for strength and permeability of treated soils. This data is based on over twenty-five projects performed in the United States using DSM, SSM, and jet grouting.

Soil Type	Cement Usage	UCS	Permeability
Sludge	240 ro 400 kg/m^3 (400 to 700 lbs/cy)	70-350 kPa (10-50 psi)	$1x10^{-6}$cm/sec
Organic silts and clays	150 to 260 kg/m^3 (260 to 450 lbs/cy)	350-1400 kPa (50-200 psi)	$5x10^{-7}$cm/sec
Cohesive silts and clays	120 to 240 kg/m^3 (200 to 400 lbs/cy)	700-2100 kPa (100-300 psi)	$5x10^{-7}$cm/sec
Silty sands and sands	120 to 240 kg/m^3 (200 to 400 lbs/cy)	1400-3500 kPa (200-500 psi)	$5x10^{-6}$cm/sec
Sands and gravels	120 to 240 kg/m^3 (200 to 400 lbs/cy)	3000-7000 kPa (400-1000 psi)	$1x10^{-5}$cm/sec

Note: Strengths can generally be increased with additional cement. Permeability can be lowered with the use of bentonite or proprietary reagents.

Although adding cement does decrease the permeability of soils, it generally is not to the order of magnitude required for effective in-situ barriers. Bentonite is by far the superior material to mix into the soil for this purpose. Generally, cement is also added to create a soil-cement bentonite product, which is impermeable, flexible and has some strength. The following table shows results compiled from several projects.

Soil-Cement-Bentonite Soil Mixing Project Results

Soil Types	Job Type	Water/ Cement Ratio	Bentonite/ Water Ratio	Additional Reagent Ratios*	Grout/ Soil Ratio	UCS 28 day (kPa)	Hydraulic Conductivity (cm/sec)
Fine sandy silt, silty sand, trace gravel	Jet Grouting	2	0.05	None	0.36	120 – 140 (14 day)	$3.3x10^{-7}$
Medium dense sand to sandy gravel, loose silty sand to soft sandy silt	Deep Soil Mixing (DSM)	1	0.04	None	0.32	420	$9x10^{-8}$
Sand, sand with clay	DSM	1.2	0.064	FA/W=.21	0.3	1,400 to 8,400	$6x10^{-7}$ to $2x10^{-8}$
CL-ML	DSM/Jet Grout	1.5	0.02	FA/W=.4 Gyp/W=.2	0.38	1729	$1x10^{-7}$

*Additional reagents include fly ash and gypsum

Costs

As previously stated, the largest DSM project in the U.S. is currently underway in Boston involving 600,000 m3 (800,000 cy) of treatment. Addition sections of both shallow and deep mixing, as well as jet grouting, have since been bid. some of the work will be carried out to depths of 40 meters (130 feet) below existing ground and 37 meters (120 feet) below the mean sea level on land reclaimed from the harbor. Costs for the work in a busy industrial area even to these depths are surprisingly economical. Prices for shallow soil cement mixing at approximately $65 per m3 ($50 per cy) have been bid. For deeper work, both DSM and jet grouting, the prices have varied from as low as $120 per m3 ($90 per cy) for DSM to a range of $190-$220 per m3 ($150-$170 per cy) for jet grouting (1994-1996 Various Bid Documents).

A typical DSM cutoff or barrier wall can be installed in place, with cement or a combination cement-bentonite, for as little as $150/m2 ($15/sf). Production rates are on the order of 100-150 m2/shift (1000-1500 sf/shift).

Applications of DSM

Jackson Lake Dam

The Bureau of Reclamation's Jackson Lake Dam project was the first major application of DSM in America-1986. This dam, located near Jackson Hole, Wyoming, was built in the early 1900s and required major safety upgrades. DSM was used on the project to construct a deep cutoff wall to minimize seepage through the foundation. In addition, because of seismic considerations, liquefaction of the underlying sands was a major concern. A honeycomb pattern of DSM was used here to contain the soils in the event of liquefaction.

Cutoff construction—Reduction of seepage under the dam foundation was to be obtained by a cutoff wall on the upstream face. Conventional methods of constructing the wall were rejected as too costly and problematic because of the nearness of the lake itself and also the depth required, 34 meters (112 feet).

To construct the cutoff wall, a three-auger shaft machine, of Japanese design with leads integral to the crane, was employed. The cutting heads and mixing paddles were 86 cm (34 inches) in diameter and the shafts were 46 cm (18 inches) on center. This configuration created a wall with a minimum width of 60 cm (24 inches). The permeability required in the silty sand foundation material was $1x10^{-5}$cm/sec and the strength required to resist seismic forces was 4500 kPa (660 psi).

DSM for Liquefaction Control – In order to improve the soils underlying the dam to resist liquefaction, a different pattern of DSM was adopted. here, honeycomb-shaped cells were installed using a Seiko-designed two-auger mixing tool. With a UCS of 4500 kPA (660psi) and a corresponding shear strength of 1400 kPa (200 psi) for the soil-mixed columns making up the cells, the sandy soils would be contained during an earthquake.

The Jackson Lake project was completed in 1988 with all permeability and strength criteria being achieved. A total of 100,000 cubic meters (130,000 cubic yards) of soil were treated for containment and barrier purposes to the satisfaction of the Bureau of Reclamation.

Bay City, Michigan

Shortly after the Jackson Lake project commenced, the first DSM project using American-made equipment began. This application was a vertical cutoff wall to control the migration of PCBs from an industrial site in Bay City, Michigan. Approximately 2 km (1.5 miles) of wall was required to be constructed around two different contaminated sites and was extended into the underlying glacial till to provide an aquaclude. Because impermeability was a key requirement, a bentonite-cement slurry was employed as the injection and mixing medium to achieve a permeability of less than $1x10^{-6}$cm/sec.

The American designed and made equipment employed a four-auger mixing shaft arrangement with 0.9 m (3 feet) diameter cutting heads. The leads were free-standing and supported by a standard Manitowoc crawler crane. Rather than electric motors, as used on the Japanese equipment to drive the auger and mixing paddle shafts, this design employed hydraulic motors powered by a Caterpillar diesel engine.

On this project certain obstacles and structures prevented the use of DSM to install the wall in some areas. Where this occurred, jet grouting was employed to complete the wall and containment. Jet grouting employs a single rod with a small diameter bit, typically 100mm (4"),"it to advance it into the ground. In this process, high pressure pumps are used to deliver slurry at 40 MPa (6000 psi) through 2 to 3 mm diameter nozzles. In some cases compressed air is used to increase the efficiency of the jets in mixing the soil. This use of both DSM and jet grouting represented the first U.S. combined application of these techniques on a single project.

Single these early projects in 1986-1989, over 50 DSM projects have been completed in the United States. Because of the flexibility of the patterns that can be employed, the depths that can be achieved, the technical and quality superiority, and economics, it is likely that this technology will be employed on more and more projects in the future.

New Technology

During the last several years, at least two new soil-cement mixing methodologies have been developed. Two of these, Jacsman and Geo-Jet, promise further refinement in the speed and quality with which soil and cement can be mixed.

Each of these methods employs mechanical mixing as in conventional soil-cement mixing, but combine it with the hydraulic action of high pressure jets, as used in jet grouting, to achieve rapid advancement of the tools and add energy to mixing.

In the Jacsman system, two mixing shafts are mounted on a rotary head. The shafts counter-rotate at speeds of 20-40 rpm while jet nozzles, mounted along the mixing heads, spray a mixture of cement and water into the ground. The jets intersect and mix the area between the mixing paddles. Since there is 360 degree rotation of both shafts, the jets also engage soil throughout the treated soil area. This process is similar to that of a milkshake machine with the added benefit of jets of milk to break the ice cream down. As of 1996, the Jacsman has been successfully employed on approximately 20 projects in Japan to depths up to 20 meters (65 feet).

Geo-jet is a process invented by a Californian, Lonnie Schellhorne, and a few years ago. In this process a single-axis rotary head drives a single flight, auger shaped tool. At or near the advancing blade of the tool, high pressure jets are assembled to break the soil immediately after it has been shaved by the advancing auger. As with Jacsman, the speed of advance is helped by the combination of the auger cutting action with the mixing action of the high pressure hydraulic jets of cement milk.

Both new technologies, Jacsman and Geo-jet, may provide a superior product to the current “mechanical only” mixing methods being used in both shallow and deep mixing. Sampling that has been done on soils mixed with the Geo-jet technique have shown good mixing.

Summary and Conclusions

Soil mixing has come full circle, from its invention in the United States in the 1960s, through its development in Japan during the 1970s and 1980s, to its acceptance as a significant technique for ground treatment and soil remediation in both the civil and environmental fields.

Soil mixing is an ideal solution for barriers and containment in most soils;

*Its high strength and homogeneity ensure a permanent barrier;
*Low permeabilities make it ideal for water and contaminant barriers;
*Spoil production is reduced compared to trenching methods;
*A high degree of confidence in quality can be assured;

*Jet Grouting and SSM can be used to supplement or solidify; and
*New techniques combining jet and mechanical mixing will bring costs down.

The use of the techniques described provide the engineer and the owner with a sophisticated, sure method of controlling the migration of wastes.

References

(1995) DSM Association Brochure.
(994-1996) Various Bid Documents for Central Artery/Tunnel, C09, A8, C3A1.