IN-SITU
SOIL MODIFICATION

Louisville, Kentucky
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INTRODUCTION

Although the process of soil mixing originated in the United States in the 1950’s, its major development has occurred over the last twenty years in Japan. To date, while there have been thousands of projects performed in Japan using some form of soil mixing, it is only recently that it has found a wide application on sites in the United States. Significantly, it was in the United States that its potential use for remediation of hazardous waste sites was first recognized and implemented. In North America to date, it has been used for foundation block stabilization, retaining walls, cutoff walls systems and the fixation/solidification of contaminated soils, with over forty contracts completed.

Soil mixing is divided into two categories, Shallow Soil Mixing (SSM) and Deep Soil Mixing (DSM) with, as the names imply, different depth capabilities.

SHALLOW SOIL MIXING

The process uses a crane-mounted drill attachment which turns a single-shaft, large diameter auger head (normally 6 ft to 12 ft) which consists of two or more cutting edges and mixing blades. As the auger head is advanced into the soil, grout is pumped through the hollow Kelly bar and injected into the soil at the pilot bit. The cutting edges and mixing blades blend the soil and grout with a shearing action. When the design depth is reached, the auger head is normally raised to expose the mixing blades at the surface and then allowed to readvance to the bottom to ensure complete mixing.

The mixing head can also be enclosed in a bottom-open cylinder to allow for closed system mixing of waste and powdered reagents. The dry treatment chemicals are then transferred pneumatically, with the system designed to control dust and potential airborne contaminants.

A total of 110,000 cy of hydrocarbon contaminated sludge has recently been stabilized using closed system mixing at the Amoco Refinery in Whiting, Indiana, using dry cement as the reagent (Ryan and Jasperse, 1989).

Even though the auger is driven by a drill platform producing more than 300,000 ft lbs of torque the large diameter of the augers limits the effective depth of treatment for SSM to around 40 ft.

DEEP SOIL MIXING

For depths greater than this up to around 100 ft or for harder soils, the sister technique, Deep Soil Mixing (DSM), is used. The DSM rig is similar to the SSM machine except that up to four hydraulically driven 3 ft diameter auger/mixing shafts are used to limit the torque requirement. The rig is illustrated in Figure 1.

Grout flow to each of the augers is controlled by electronic flow meters which, depending on drill rates, send a predetermined amount of grout per foot of drilling depth to be mixed in the column.
For support of deep excavations, H-beams are dropped and vibrated into the DSM soilcrete columns immediately after mixing, to provide a structural system. This type of DSM wall has major advantages over other shoring systems, especially when a high groundwater table is present. This approach was used successfully recently, to shore the 40 ft deep excavation required for a new 60 mgd wastewater pumping station in San Mateo, California (Reams, Glover and Reardon, 1992).

DSM has many applications; but for large volume shallow applications DSM is often not economical, as was the situation for the two case studies to be described in this paper. SSM was the preferred option on both sites, one application involved site remediation while the other was for conventional geotechnical construction. Both projects demonstrate very effectively the adaptability of the process to a wide range of site conditions.
CASE HISTORY ONE
Crofton, British Columbia

Project Background

In 1990-91 a coastal pulp and paper mill, located at Crofton on the southeast coast of Vancouver Island, British Columbia, installed secondary effluent treatment facilities including two large spill tanks.

The two concrete tanks had diameters of 270 ft and 180 ft and a height of 35 ft and were to be located on an area of land previously reclaimed from the sea by uncontrolled dumping of sand and silt spoil in the 1950’s.

Ground Conditions

The site generally consisted of pit-run sand and gravel surface deposits, over desiccated, very stiff, becoming loose and soft sand and silt fill. The average thickness of the fill crust was 6 ft overlying typically 12 ft of loose deposits. The fill was underlain by about 4 ft of medium dense beach sand overlying very dense, overconsolidated silt, which is an inter-till deposit. The groundwater was typically 10 ft below the site surface. A typical section through the site is shown on Figure 2.

The fill materials are characterized by the following gradation limits:

<table>
<thead>
<tr>
<th>% Passing U.S. Standard Sieve Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>#40</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Average</td>
</tr>
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The variation of the fill strength is represented by the penetration profile envelope shown on Figure 3.

Design Considerations

The mill is located in an area of potentially high seismic activity (Puget Sound Seismic Zone) which has a maximum magnitude of 7.5 (Richter scale). The design seismic horizontal peak firm ground acceleration (PGA) is 0.26 g at the National Building Code of Canada (NBCC) minimum risk level of 10% probability of exceedance in 50 years (475 yr return period). The new facilities are designed to survive the NBCC event but not the lower risk, high magnitude events considered possible in the region.

The liquefaction potential was evaluated by comparing the cyclic shear stress ratio values, based on the design PGA with the values required to cause liquefaction, for a Magnitude 7.5 earthquake, as proposed by Seed. The analyses indicated a zone of loose fill between 5 ft and 10 ft thick could liquefy under the design event.

A fundamental element of the design approach was the involvement of the owner and his civil consultant in reviewing the foundation alternatives with respect to their hazard reduction potential, relative to their cost. The interaction between the project group produced the concept of partial foundation treatment. The partial treatment approach required positive support to the tank walls but allowed the tank floor to settle.
Figure 2. Typical Section Through Site

Figure 3. Penetration Resistance Profile
Foundation Alternatives

Several foundation alternatives were initially reviewed for their static condition benefits and included the following groups:

- preload
- excavate and replace
- ground improvement
- piles.

After consideration of the seismic loads and cost factors, the ground improvement alternate was adopted. The final selection of the specific ground improvement technique involved consideration of the following methods:

- dynamic compaction columns
- jet grouting
- soil mixing
- vibro-mortar columns.

Bids were accepted from specialist geotechnical contractors based on a performance specification and was not method specific.

The large diameter soil mixing technique (soilcrete columns) offered by Geo-Con was reviewed and adopted for the tank wall support. This was the first time that this method of support had been used in North America.

Soilcrete Column Design

The 12 ft diameter soilcrete columns were designed as a continuous tangential ring beneath the tank walls. The large and small tanks were supported on 71 and 45 columns, respectively. Eighteen additional columns were used to support some ancillary tanks and also to provide an arched "dam" connecting the two rings of tank columns, thereby providing ground restraint to facilities located between the two tanks.

The column 28-day compressive strength of 125 psi was specified to provide adequate strength for the tank wall foundation maximum bearing pressure of 9 ksf. The column strength was based on an empirical ratio between compressive and shear strengths of 0.3. As noted below, a substantial increase in strength occurs following the 28-day period.

The column and foundation geometry was determined from stability analyses under static (full tank) and dynamic (almost empty tank) loadings. Normal bearing capacity, force and moment equilibrium analyses were carried out for the static case. In the seismic case, similar analyses were carried out but assuming the contained soil acted as a heavy fluid with an acceleration component (0.13 g), which was also applied to the soilcrete column. Substantial loss of support was assumed for the external grade, together with the same acceleration component. Based on the results of the analyses, the soilcrete column was embedded 0.9 m into the dense till, the column was located to create a stabilizing eccentric vertical load and surplus tensile capacity in the ring beam foundation was required. A schematic arrangement of the foundations and soilcrete columns is shown in Figure 4.

Soilcrete Column Construction

Construction commenced with preliminary insitu mix trials to obtain the appropriate combinations of water-cement ratio, grouting rate and mixing rate. The water-cement-soil ratio initially was based on laboratory trials using site soils and was adjusted on site as the early test results became available. The basic mix design was 300 lbs per cubic yard of soilcrete of cement with a water-cement ratio of 1.8 to 1. The procedure was also varied by the superintendent to reflect variations in material and groundwater conditions. Some initial
problems with obstructions such as boulders and logs were experienced. Where the auger paddle could not displace the obstruction, it was displaced or removed by a backhoe, obtained from nearby construction activities.

Samples were obtained from the soilcrete at various depths below the ground surface by a discrete sampler. Three cylinders were made from each sample and stored for testing. The results of the cylinder tests are summarized on Figure 5, with all samples meeting or exceeding the specified strength.
Figure 6 shows the SSM rig in operation and Figure 7 the completed columns.

CASE HISTORY TWO
Pittsburgh, Pennsylvania

Project Background
At 2,400 beds, the $112.5 million Allegheny County Jail in Pittsburgh, PA, will be one of the largest county jails in the U.S.A.

The disused downtown site chosen by the Urban Redevelopment Authority of Pittsburgh sits alongside the Monongahela River, adjacent to Liberty Bridge, on what was previously the old CSX Railroad facility. The southern edge of the site is bound by the retaining wall of the Parkway East (Interstate I-376); one of the main transport arteries of the Greater Pittsburgh Area.

Previous investigatory activities at the site had indicated the presence of hydrocarbon contamination from a former underground storage tank. Limited soil remediation was therefore necessary in advance of the construction of the ten-story building.

This second case study presents the use of Shallow Soil Mixing as a value engineered alternate to microfine cement permeation grouting, which was originally specified for the insitu fixation and consolidation of the contaminated soils adjacent to the Parkway structures.

Ground Conditions
Petroleum hydrocarbons had affected site soils at three separate locations over the estimated area of 32,000 sq ft. The depth of varied from 3 ft in two areas to over 20 ft contamination in the area next to the retaining wall. Total Petroleum Hydrocarbon (TPH) concentrations ranged from less than 50 ppm up to 11,000 ppm with levels varying from the surface to the groundwater table which was located at 25 ft. below existing grade.

A typical soil description for the excavation area was sandy silt to silty clay with cinders, rocks and brick pieces. Standard penetration tests ranged from 2 to 13 blows per foot.

The higher loaded sections of the retaining wall were founded on piles which apparently transferred load to the underlying bedrock. The present condition of these timber piles was unknown. In other sections, loads decreased as the Interstate ramped down, with the wall on spread footings only.

Remediation Method Considerations
The remedial approach preferred, from a cost and construction standpoint, involved the decommissioning and disposal of the existing pumping station and product lines and the removal of the affected soils down to groundwater for offsite disposal. The excavated areas would then be backfilled with clean fill and soil.

This immediately raised the question of the stability of the retaining wall and hence the Parkway if the proposed excavations were made.

The ultimate adoption of Shallow Soil Mixing and Jet Grouting to solve this combined environmental and structural problem made this site unique and of specific interest, as to the author's knowledge this was their first application in tandem.
Figure 6. SSM Rig in Operation

Figure 7. Completed SSM Columns
Initial stability assessment focused on two arrangements, namely a cut slope from the footing level of the walls or the construction of a retaining wall along the Parkway. The latter method was discounted after discussions with PennDOT, the wall owners, since the required bracing or tiebacks may have interfered with the piles holding the structure in place. In addition, the lengthy design review process required by the owner and possibly the U.S. Department of Transportation, since an Interstate highway was involved, could have delayed the project by up to 12 months.

Discussions with the PA Department of Environmental Resources (PADER) indicated a willingness to consider a cut slope arrangement. However, they stipulated that any contaminants left in place must be fixated to reduce their potential mobility.

Accordingly, the Geotechnical Consultant investigated the potential for limited fixation of the hydrocarbon contamination in situ to the extent necessary to support the Parkway East structure.

It was recommended that permeation grouting with a microfine cement grout would adequately fixate the hydrocarbons and that the zone should extend 25 ft at the base of the retaining wall from the foundation level to the groundwater table. Figure 8 illustrates the area requiring stabilization. This would allow for a near-vertical excavation to be performed against the grout zone to remove the remaining contaminants, with a minimum factor of safety against failure of 1.5.

![Figure 8. Cross-section of Stabilized Area](image)

Emphasis was placed on the use of a microfine cement grout for improved permeation, injected using the end of casing method, in order to optimize filling of soil pores to fixate the hydrocarbons and densify the materials. Although Ordinary Portland Cement would have been adequate in the coarser general fill and debris, a microfine cement was selected for use since portions of the subsurface contained fine granular soils which required fixation to prevent water infiltration. The strength requirement was secondary and was specified as an unconfined compressive strength of 500 psi in order that the zone would be capable of supporting its own structure on near-vertical slopes.

PADER and PennDOT both concurred with this approach and the project was placed out for bid in the Spring of 1991.

Remediation Method Selection

Geo-Con, Inc., was the low bidder on the Remediation Contract and offered a value engineering alternate to the microfine cement grouting specified, namely the use of Shallow Soil Mixing (SSM) in conjunction with single-phase Jet Grouting. This
alternate was attractive both technically and commercially and after review and acceptance the contract was awarded on this basis. The remainder of the cleanup work was implemented as planned.

The advantages of soil mixing on the site were numerous and were key in the client’s decision to sanction its use.

- The technique is independent of soil type. This is a very significant advantage over permeation grouting which will prove ineffective in silts and clays. With soil mixing everything in the area is mixed and treated.

- The system has a vertical blending action which will tend to “average out” the soil stratigraphy and produce a well-mixed, homogeneous soilcrete block.

- Treatment is carried out in one pass with no additional work in problem areas as required by the split-space grouting approach.

- Cement grout is metered at a fixed rate into the ground, and the precise volume of ground treated in an identical manner is precisely known. The fixed mixing vanes assure the full column diameter and column contact. This is very important technically. With permeation grouting, the quantity of grout accepted per unit volume of ground is totally dependent on soil type, is therefore variable and is difficult to quantify due to the random nature of grout travel and actual injection elevation.

- Contaminants within the ground are locked in place within the soilcrete after thorough dispersal. Permeation grouting does not provide this dispersal effect with contaminant concentrations remaining at their original levels within a cement impregnated soil matrix.

- The result is a stabilized mass free of any significant pockets of untreated materials. The greater quantity of stabilized material generated by these processes effectively creates a more stable end product with typically higher and more consistent unconfined compressive strengths and lower constituent leaching.

- The SSM technique can produce a greater volume of treated ground per day than traditional grouting, thus easing pressure on the schedule and relieving the risk of time overruns.

- The soil mixing system does not involve the pressurizing of the ground that is required during grouting, with no possibility of uplift.

Soilcrete Block Design

In order to create the block of stabilized soil, a total of 2,200 cy of contaminated soil required treatment, extending 175 ft. along the Parkway and under Liberty Bridge.

As shown in Figure 9, three rows of 8 ft diameter columns on a 6 ft x 6.7 ft grid were installed.

They were formed on a primary and secondary sequence within each row, with the installation of the secondary columns timed to occur before the adjacent primary columns reached full strength. In this manner, block of ground over the full width were completed as the soil mixing progressed along the wall.

However, in order to stabilize/fixate areas that could not be accessed safely with the 150-ton crane jet grouting was necessary. These zones were limited to those adjacent to the timber piles and under Liberty Bridge. In these areas 3 ft diameter jet grout columns were formed, either contiguous or on a 2.5 ft triangular grid.
For both techniques, the stabilizing reagent was a Portland Cement slurry.

In the case of SSM, based on previous experience, a cement replacement by dry weight of soil of between 15% and 20% was adopted with sufficient water added to the grout mix to provide enough lubrication for a satisfactory auger penetration rate.

For the jet grouting, the parameters were set at:

- Grout Pressure - 5,000 psi
- Lift Rate - 1 ft/min
- Grout Flow - 40 to 45 gals/min
- Rotation - 1 rpm

A neat cement grout of water-cement ratio by weight of one was felt adequate to produce in excess of the specified 500 psi compressive strength at 28 days.

It was the intention to produce similar strengths for the SSM columns at an earlier date in order for excavation to proceed quickly after column construction, thus ensuring compliance with the very tight overall project schedule of 60 days.

Grout control was performed by frequent checks on the grout mix unit weight by use of a mud balance.

Construction

The SSM rig consisted of a high torque turntable mounted on a 150-ton crane which powered the 8 ft diameter auger. Figure 10 illustrates the rig in operation. Grout was supplied by a high-speed, continuous-mix, colloidal grout plant. This consisted of a storage silo, 1,000-gallon colloidal mixer and a progressive cavity pump. This same setup was used for the jet grouting with the exception of the use of a 350 HP high pressure, triplex piston jet pump. This pump was rated at pressures up to 20,000 psi and flow rates up to 170 gpm. While plant was being assembled, initial shallow excavation of contaminated material away from the retaining wall took place, along with concrete removal operations and soil sampling to establish waste characterization profiles. Test pits were also dug along the line of the wall to confirm the location of the piles.

The jet grout drill stem was mounted on a diesel hydraulic DK70 drill rig fitted with a Wirth Rotary Head as shown in Figure 11. The 2-1/2 in. grout pipe was advanced to the groundwater table and a check ball seated at the end of the grout pipe to initiate lateral flow through jet nozzles located on the sides of the
Figure 10. SSM Rig in Operation

Figure 11. Jet Grouting in Progress

Figure 12. Trial SSM Column with Completed Block to Left
grout pipe. As the grout was pumped, the pipe was rotated and extracted at the
set levels thus creating the jet grout columns. Exhaust material in small
quantities, of very similar properties to the insitu soilcrete, was channeled
into the open excavation to be incorporated as suitably fixated backfill
material.

All grouting work was completed within twenty days with initial excavation of a
vertical face against the stabilized block taking place only four days after
column construction, thanks to the excellent early soilcrete strengths obtained.
(See Figures 13 & 14.) Figure 12 gives a good indication of the columns
produced.

Excavation and backfilling operations involving 10,000 cy of soil went smoothly
with no unforeseen difficulties.

Throughout all operations the requirements of 29 CFR 1910.120, the Occupational
Safety and Health Administration’s (OSHA) Hazardous Waste Operations and
Emergency Response Standard were strictly complied with.

Strength Results

Wet samples were retrieved from columns for testing from each day’s work. These
samples were taken by a special sampling tool below the surface of the column
immediately following installation. The tool, mounted on a beam and deployed by
the crane, consisted of a cylinder with a bottom flap that could be activated
from the surface.

Compressive strength tests were performed in accordance with ASTM C29, the
results of which are shown in Figures 13 and 14.

These results indicate some interesting general trends:

1. Higher soilcrete strengths are produced by SSM than by jet grouting for both
short and longer term curing periods.

2. A much quicker early strength gain for the SSM compared with jet grouting
and better strength gain with age.

Even though more cement is used per unit volume of treated soil in jetting, these
results demonstrate, for the particular soils present, that SSM is a more
effective tool, producing higher strengths with lower material and construction
costs. This is partly the result of the cement wastage inherent in jet grouting.

CONCLUSIONS

These two case histories demonstrate the technical and commercial advantages that
can often be achieved by the use of Soil Mixing techniques, to treat insitu both
hazardous and nonhazardous materials.

REFERENCES

Stabilization and Fixation Using Soil Mixing. ASCE Geotechnical Special

REAMS, D., CLOVER, J.B., AND REARDON, D.J. (1992)
Deep Soil Mixing Shoring System to Construct a 60 mgd, 40 ft Deep Wastewater
Pumping Station. Internal Report, HDR Engineering, El Dorado Hills, CA.
Figure 13. Soilcrete Strengths, Short Term

Figure 14. Soilcrete Strengths, Long Term