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State of the Art of Soil Improvements with Case Histories

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State of the Art of Soil Improvement with Case Histories

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ABSTRACT

Soil improvement techniques for geotechnical construction can be broadly classified as densification, reinforcement, adhesion and excavation/ replacement. This paper presents an overview of selected soil improvement techniques, with significant case histories. The soil improvement techniques discussed include Vibro-Compaction, Vibro-Replacement (stone columns), Dynamic Deep Compaction, compaction grouting, chemical grouting, jet grouting and soil fracture grouting.

KEYWORDS

Soil improvement, case histories, Vibro-Compaction, stone columns, Dynamic Deep Compaction, compaction grouting, chemical grouting, jet grouting, soil fracture grouting.

INTRODUCTION

Soil improvement in the United States has seen remarkable growth since the mid-1970's and in situ Ground Modification techniques are now routinely considered for design and construction of new and retrofit projects. Vibro-Compaction was introduced into the United States from Europe in 1948 and has been used extensively to densify loose, granular soils for settlement control and liquefaction protection. Vibro-Replacement (stone columns) are a spin off from the Vibro-Compaction system, using the same type of equipment but backfilling with stone instead of sand. The stone columns thus formed will densify loose, granular soil and replace or displace cohesive soils, mainly to minimize settlement and to increase bearing capacity. Dynamic Deep Compaction was introduced into the United States in the 1970's, and has been used for the economical densification of loose ground. Much research on chemical grouting was accomplished in the 1970's by the Federal Highway Administration in anticipation of the proposed subway construction program in the United States. This research bore fruit, with chemical grouting being used extensively on the Washington, Baltimore, Pittsburgh and Los Angeles subway systems for soil stabilization. The use of compaction grouting has grown considerably since its development on the West Coast in the 1950's: rectification of sinkhole and settlement problems and the protection of structures from settling due to soft ground tunneling has been its main utilization. Jet grouting was introduced into the United States in the mid-1980's from Europe after being developed in Japan. Since then, it has been used on over 150 projects, mainly to solve underpinning, excavation support and groundwater control problems. Soil fracture grouting was also developed in Europe and introduced into North America in the 1990's.

VIBRO SYSTEMS

Vibro systems can be subdivided into three types: Vibro-Compaction, Vibro-Replacement (stone columns), and vibro concrete columns. All three use essentially the same equipment, a vibrating probe 12 to 24 inches (30.5 to 61 mm) in diameter. This probe is capable of generating horizontal vibrations that densify the adjacent granular soils. A combination of follower tubes can be added to the vibrating probe to reach treatment depths up to 100 ft (30.5 m). A flushing medium of water or air is used to aid in jetting the vibrator into the ground.

Vibro-Compaction is used to densify at depth soils which contain fines content less than 10% to 15% passing the number 200 sieve. It is effective in soils which contain less than 2% clay fraction.

Vibro-Replacement can be used to densify, drain, reinforce, and partially replace inadequate soils. In this technique, a 30 inch to 36 inch (0.76 to 0.9 m) stone column is formed as the probe is being withdrawn. The use of stone typically allows densification of granular soils with fines up to 20% passing the number 200 sieve. Permeability of the stone columns is typically two orders of magnitude or higher than the surrounding soils, which assists in controlling the pore water during and after a seismic event. The friction angle of the stone typically varies between 38 and 45 degrees, thus introducing reinforcing elements with shear strengths potentially greater than the surrounding soils. Depending on the installation method, wet or dry, the soils are either partially replaced or displaced, thereby enhancing the overall engineering parameters of the stone column - soil system.

Vibro concrete columns use ready mixed concrete rather than stone, introduced as the probe is being extracted. Vibro concrete columns are used to transmit loads past weak cohesive soils into an enlarged bulb at the base of the element, thus forming an end bearing load transfer device.

CASE HISTORY - VIBRO-COMPACTION

Wando Terminal

In South Carolina, a site improvement and liquefaction mitigation challenge involved the expansion of Wando Terminal, a state port facility in Mount Pleasant, near Charleston. Charleston was struck by a major earthquake in 1886. The South Carolina State Port Authority's expanded terminal was to serve as a docking facility and as a 56-acre (225,000 m^2) concrete-paved area for storing cargo containers. Beneath half the area, geotechnical engineers found marsh mud (very soft organic clay) to elevation -25 ft (-7.6 m) MLW (Fig. 1). The general contractor removed the mud by dredging and then backfilled the excavation with fine sand to elevation +10 ft (+3.0 m) MLW without dewatering. Vibro-Compaction was then performed to densify the 1,500,000 cy (1,150,000 m^3) of very loose sand backfill, stabilizing the foundation for the weight of the containers and reducing liquefaction potential (Hussin & Foshee, 1994).

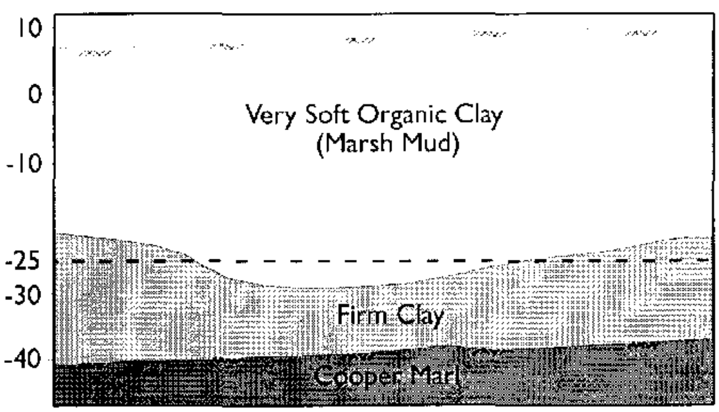

Fig. 1 Generalized Subsurface Profile

The basic component of the new container yard design was a massive and deep underwater embankment of clean, fine sand. Since such loose hydraulic fills are highly susceptible to liquefaction, protection of the embankment integrity during seismic shaking was a critical design issue. A peak "base" acceleration of 0.15 g was selected for the embankment liquefaction analysis. This acceleration corresponds to a seismic event with ≥ 90% probability of non-exceedance in 50 years.

The program involved filling the 27 acre (109,300 m^2) excavation with 1,500,000 cy (1,150,000 m^3) of underwater fill. The underwater fill was specified to be a fine sand with less than 1% clay and less than 5% fines (silt and clay) by weight. The specifications then called for the underwater fill to be densified in place using the Vibro-Compaction method (Fig. 2). Baseline borings and soundings performed prior to Vibro-Compaction confirmed the designer's expectations that the relative density of the hydraulically-placed fill would be extremely low. Standard penetration test N-values were typically no greater than 2 bpf, and piezocone tip resistances (Q_c) were generally less than 15 tsf (150 kPa). Initial test sections proved that the Vibro-Compaction process could easily densify the loose soils to the specified criteria.

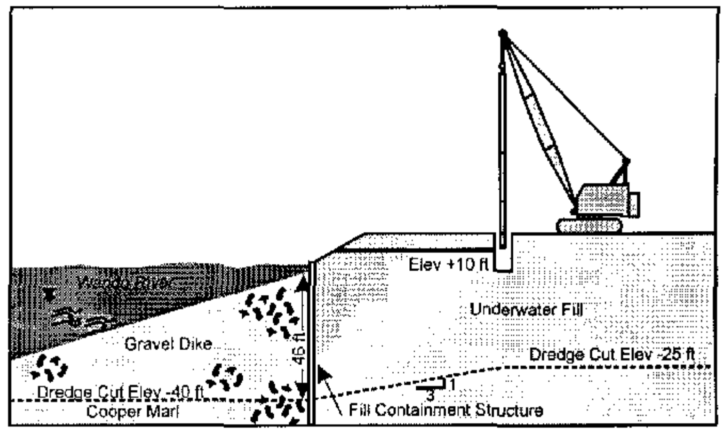

Fig. 2 Site Profile

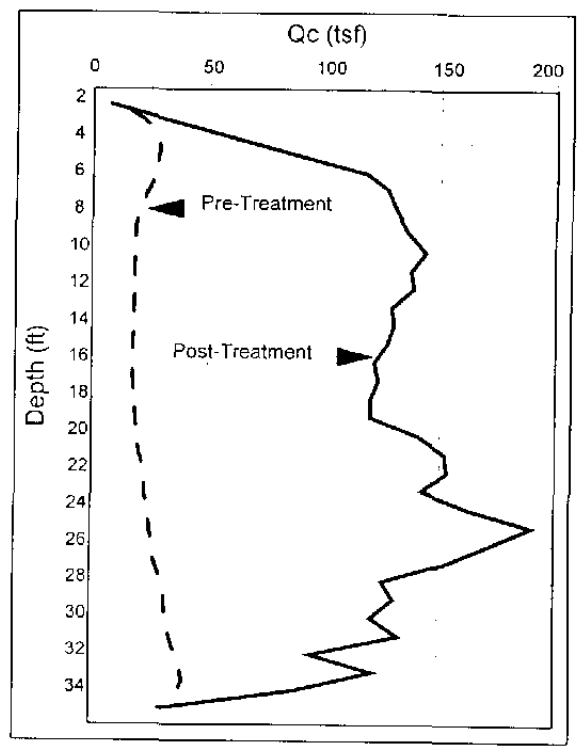

Fig. 3 Typical Piezocone Test Results

The Vibro-Compaction operation utilized 4 rigs working double shift, 6 days per week for 5 months. As the process continued, the site surface was lowered approximately 4 ft (1.2 m), changing 35 ft (10.7 m) of loose sand into 31 ft (9.5m) of dense sand.

Quality assurance (QA) testing of the Vibro-Compaction fill embankment consisted of numerous, random piezocone (ASTM D-3441) soundings and occasional soil borings with conventional Standard Penetration Testing (ASTM D-1556). The original goal of the QA program was to achieve one "passing" piezocone sounding for each 10,000 ft^2 (930 m^2) of embankment surface area.

In most areas, post-Vibro-Compaction Q_c values were well above 100 tsf (957 kPa), the minimum acceptance criteria being 88 tsf (842 kPa). A profile of the typical average Q_c before and after Vibro-Compaction is illustrated in Fig. 3.

CASE HISTORY - VIBRO-COMPACTION AND VIBRO-REPLACEMENT

Albany County Airport

The initial phase of the Albany County airport terminal facilities was constructed in 1959, and additions were made in 1967 and 1979. Ground improvement work by vibro systems had been implemented during the construction of these earlier phases. For the 1996-1997 additions, the Project Geotechnical Engineer recommended that a ground improvement program by Vibro-Compaction and Vibro-Replacement be implemented which would meet a set of specified seismic design and performance criteria. The actual design of the ground improvement work was specified to be the responsibility of the specialty subcontractor. Based on the results obtained from a test area where pre-improvement and post-improvement ground conditions were determined by in-situ testing, a stone column grid of 12 ft by 12 ft (3.6 m by 3.6 m) was determined to be the most cost-effective, and was adopted for the major portion of the project site. Nearly 1,600 stone columns were installed in the project (Soydemir, et al. 1997).

The proposed additions cover a footprint of approximately 280,000 sq ft (25,000 sq m) and have a steel-framed superstructure. The column design loads ranged between 80 kips (355 kN) and 550 kips (2,450 kN). Design live load for the floor slabs is 250 psf (12 kPa). The proposed construction, including the ground improvement work, was required to be implemented while the airport remained fully operational.

Relative to the ground improvement design and implementation, the following criteria were specified:

- *Design Earthquake*: Magnitude (M) = 6.0; Peak Ground Acceleration (PGA) = 0.15 g (where g is the gravitational acceleration).
- *F.S. (min.) against liquefaction = 1.25*
- *Allowable post-construction total settlement for the new additions = 1.0 in. (25 mm)*
- *Allowable post-construction differential settlement (i.e., across typical 30 ft (9 m) column to column spacing) for the new additions = 0.50 in. (12.5 mm).*
- *Allowable settlement of adjacent existing structures resulting from the implementation of the ground improvement work = 0.5 in. (12.5 mm)*

The average groundwater level was established to be at 5 to 6 ft (1.5 to 1.8 m) below the ground surface.

The stratigraphy underlying the project site was characterized as fine sand deposits, with an increase in silt content with increasing depth. Project specifications required the existing subsurface conditions be improved to a depth of 22 ft (6.6 m) to provide resistance to liquefaction and control seismically-induced settlements. The specifications called for the application of both Vibro-Compaction and Vibro-Replacement, with the design responsibility for these improvements to be developed by the specialty subcontractor.

Experience has shown that, in general, saturated sand deposits with fines content under about 25%, and clay content less than 2%, will respond positively to densification by vibratory ground improvement procedures. Also, it has been observed that uniform fine sands tend to simulate packing of spheres of the same size, and are difficult to pack into a denser configuration.

Based on the available grain size distribution data and early trial tests at the project site with Vibro-Compaction, it was anticipated that the required levels of densification would not be feasible by Vibro-Compaction alone. Therefore, in line with the project specifications, it was considered prudent that mitigation of potential liquefaction and control of seismically-induced settlements would be best addressed by stone columns. This would provide drainage against pore pressure buildup, as well as some densification. Also, at the heavily loaded column locations, installation of a group of stone columns at close spacing (i.e., as compared to the large spacing in the slab areas) would provide the necessary support capacity, eliminating the use of structural piles.

It was recommended that a design incorporating 3 ft (0.9 m) diameter stone columns at 10 ft (3 m) center to center, installed at a depth of 22 ft (6.6 m) be adopted for implementation, upon confirmation by means of two test sections in the field.

In order to optimize the rate of construction, it was initially decided to insert the vibrator into the ground by jetting, and feed the gravel/stone backfill at the grade level into the annular space created by the vibrator as it was withdrawn in 1 ft (0.3 m) increments. However, the Airport Authority concluded that the effluent generated by the wet vibratory procedure would not be acceptable since there was no practical way at the airport to handle the nearly 100,000 gal (380 m^3) of waste water expected to be produced daily. It was decided that the dry, bottom-feed procedure be adopted, in which the backfill is introduced into the ground near the bottom (tip) of the vibrator, in its penetrated position, through feeder pipes attached to the probe.

DYNAMIC DEEP COMPACTION

Dynamic compaction involves impacting the ground surface with weights ranging from 10 - 35 tons (9-31.8 tonnes). Typically, the weight is crane-hoisted. The required energy delivered to the ground is a function of the tonnage of the weight, the drop height, number of drops per point and grid spacing. Although more widely used to densify granular material, dynamic compaction is an effective treatment for construction debris fill, sanitary landfills and mine spoil.

CASE HISTORY - SAM'S CLUB

Dickson City lies within an area of Northeastern Pennsylvania that has been heavily strip-mined over the years. Vast tracts of untreated, loose, surface mine spoil are still evident. The geotechnical investigation prior to construction of a new retail warehouse on a previously mined site revealed that loose, strip mine turnover extended to a depth of 100 ft (30.5 m). The engineer recommended dynamic compaction to improve the mine spoil to a treatment depth of 30 ft (9.1 m) over the entire 130,000 sf (12,077 m^2) construction area, extending 10 ft (3.1 m) beyond the building footprint. The building footprint itself would then be excavated to a depth of 4 ft (1.2 m), geogrid and geosynthetic fabric placed, and controlled fill imported to re-establish site elevation. The geogrid would adequately distribute any stress to minimize material migration. This remediation approach would allow shallow spread footing construction of the 390 ft by 300 ft (119 m by 91 m), single story, steel frame warehouse-style building.

The specialty contractor performed the dynamic compaction program , using a 150-ton (136 tonne) crane to drop an 18-ton (16.3 tonne) weight from a height of 70 ft (21.3 m) to densify the spoil material. Primary drops were made on a 15 ft (4.5 m) square grid, with secondary drops then made at the centerpoint of the primary grid for a net drop location spacing of 10.6 ft (3.2 m). A total of six, randomly located post-densification Standard Penetration Tests were conducted that confirmed that the improvement requirement had been met to the full treatment depth. Following densification and excavation of the building footprint, the geogrid and then the geofabric and fill were placed.

COMPACTION GROUTING

Compaction grouting can be defined as the injection of less than 2 inch (50 mm) slump, slurry grout (normally a soil-cement with sufficient silt sizes to provide a plasticity, together with sufficient sand sizes to provide internal friction). The grout does not enter soil pores, but remains in a homogenous mass that gives controlled displacement to compact loose soils, gives controlled displacement to lift structures, or both.

The applications of compaction grouting are:

- arresting foundation settlement
- controlling soft-ground tunnel settlement
- providing preconstruction site improvement
- lifting and leveling slabs and foundations
- rectification of sinkhole problems
- densifying soils to mitigate liquefaction potential

Compaction grouting was developed in the Western United States in the 1950's and the technology is now being exported overseas.

In 1995, a U.S. National Science Foundation Research Program was awarded to North Carolina State University for the study of the fundamental aspects of the compaction grout process. In 1996, the University of Maryland began research into compaction grouting, using small scale physical models. After 40 years of compaction grouting use and many thousands of successful projects, the research program will help the technique to become more scientific.

CASE HISTORY - SINKHOLE REMEDIATION

The 1996 ASCE Merit Award for the Outstanding Civil Engineering Achievement was the remediation of a mammoth sinkhole in a phosphogysum stack in Polk County, Florida (Fuleihan, Cameron and Henry, 1997). The erosion sinkhole was discovered on June 27, 1994. The sinkhole measured 160 ft (48 m) across the top. A detailed investigation into the vertical extent of the sinkhole, including exploratory boreholes, gyroscopic and single-shot directional surveys and a crosshole seismic survey, determined that the sinkhole extended well over 400 ft (122 m) into the Floridan aquifer. The water within the gypsum stack is acidic with pH between 1.5 and 2.0. The plant utilizes wells pumping over 8 million gallons (30.3 million liters) of water per day from the aquifer for use in phosphate production. These wells were put into use to contain the acidic water on site until a permanent solution was found. After investigating many possible remediation techniques, it was elected to utilize compaction grouting to seal up the sinkhole. The depth of the sinkhole and the fact that equipment would have to drill from a safe distance around the sinkhole required over 450 ft (137 m) deep, angled holes to be drilled. This made this project the deepest compaction grouting project performed in North America. Another drilling complication was the acid groundwater which would eat into the steel pipes in a short period of time. Over 100 grout mixes were tested to develop an optimum mix that was pumpable, would not segregate or bleed, was compatible with the acidic water and would meet the desired strength and hydraulic conductivity over a wide range of slumps. The grout mix for the primary holes consisted of pea gravel, fly-ash, Type II cement, bentonite, water and a plasticizer. The more fluid secondary hole mix included fly-ash, Type II cement, bentonite and a plasticizer. The targeted range of strengths of the grout injected was 500 to 1,000 psi (3,500

CASE HISTORY - BOTTOM SEAL AT PHILADELPHIA INTERNATIONAL AIRPORT

A portion of a new commuter runway at Philadelphia International Airport was constructed over a former Superfund Site. The U.S. Environmental Protection Agency required thickening of a 2 to 3 ft (0.61 to 0.91 m) natural clay stratum to 5 ft (1.52 m) beneath 10,980 sq ft (1,020 m^2). It was determined to use jet grouting to thicken the natural clay stratum, with the following performance criteria:

1. The permeability of the cured grouted landfill mass must not exceed 1 x 10^{-9} m/sec (using landfill leachate as the permeant) so as to be sufficiently impermeable to act as a low permeability horizontal barrier.

2. The compressive strength of the cured grouted landfill mass must be sufficiently high - 1,300 psi (900 kPa) - so as to be capable of safely supporting the overlying landfill waste ash and earthen embankment loadings.

3. The elastic modulus of the cured grouted landfill mass must be sufficiently low - 18,000 psi (124,100 kPa specified) - to allow the material to respond in a flexible, pliable manner without cracking during consolidation of the underlying silty clay stratum induced by the earthen embankment loadings.

A series of laboratory tests were performed and the optimum mix design to meet the above criteria consisted of 11% by weight of Portland cement and NewCem and 89% by weight of a hydrated bentonite mixture. NewCem is a blast furnace slag consisting of calcium, aluminum, and magnesium silicates ground finer than ordinary Portland cement.

Adjacent to the area to be grouted, six pre-production tests were conducted on groups of three, interconnected Soilcrete columns in order to determine the maximum grout injection point spacing consistent with creating a continuous, low permeability, grouted waste mass. Varying parameters of center-to-center column spacing were employed as shown in Table 1. Lift and rotation speeds, and nozzle size were also varied, as shown in Fig. 5. Air and jet pressure remained constant for all six tests.

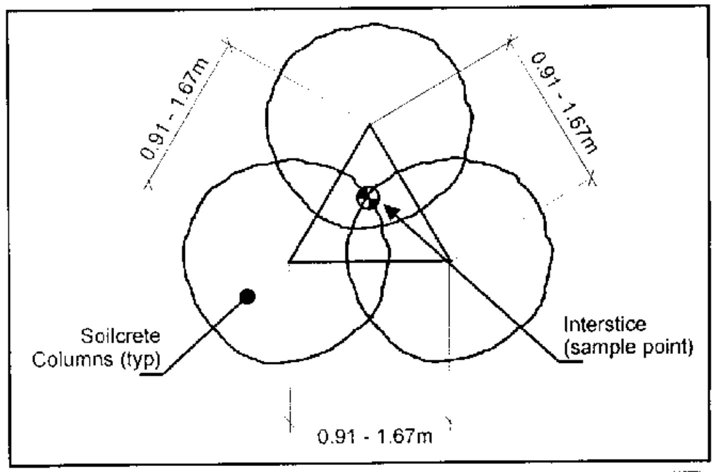

Fig. 5 Test Column Parameters

Based on the retrieval results of Soilcrete samples cored at the interstice of each test group, the final layout plan for production work was developed to allow the most acceptable results for providing a continuous, fully grouted zone. The test program illustrated that a 5.5 ft (1.67 m), center-to-center spacing of jet grouted columns could be used for the production work.

The site characteristics, which involved working in an open area with no sensitive structures nearby, made this project an ideal application of double-rod system jet grouting , and in order to excavate and replace the greatest amount of waste ash, a double-cut drilling and grouting program was developed. The grout was volumetrically batched on-site. Initially, the bentonite was hydrated overnight and then mixed with the pre-weighed and bagged NewCem/Portland cement materials using a colloidal shear mixer.

Table 1. Test Column Layouts

Test Group	C/C Spacing (meters)	Nozzles Size (mm)	Lift Rate (mm/min)	Rotation (rpm)	Grout Pressure (Bars)	Air Pressure (Bars)
1	0.91	4.0	450	18	400	8
2	1.06	5.5	400	16	400	8
3	1.22	5.5	400	16	400	8
4	1.22	5.5	300	12	400	8
5	1.37	5.5	300	12	400	8
6	1.67	5.5	215	8	400	8

to 7,000 kPa), but samples retrieved from the erosion cavity ranged from 1,500 to 8,000 psi (10,340 to 55,160 kPa). Over 3,800 cy (2,900 cu m) was injected in 50 grout holes between December 1994 and April 1995 to seal the sinkhole. The team, consisting of a committed owner, concerned regulators, creative engineers, and a responsive contractor, successfully completed the project in less than one year.

CHEMICAL GROUTING

Chemical grouting is the injection of fluid grouts into granular soils to increase the cohesion and impermeability of these soils, in effect making sand into sand-stone. In the 1970's, the Federal Highway Administration, anticipating significant subway construction throughout the United States, initiated a major research and development program on chemical grouting. This research has paid considerable dividends, assisting the soft-ground tunneling for construction of the Washington, Baltimore, Los Angeles and Pittsburgh subway systems.

In over twenty years of utilizing chemical grouting to assist construction of soft ground tunnels in the United States, the majority of the work has been performed from vertical pipes installed from the surface. However, in the late 1980's one of the largest utilizations of chemical grouting was for the Los Angeles Metro Rail System where both vertical and horizontal chemical grout pipes were installed (Gularte, et al., 1991) (Gularte, et al., 1992). The 6 inch (152 mm) horizontal pipe was placed straight for a maximum length of 318 ft (97 m).

CASE HISTORY - WASHINGTON AREA TRANSIT AUTHORITY (WMATA) GREEN LINE

In 1994 construction began on the WMATA Green Line in Washington, DC. Portions of the 2.9 mile (4.7 km) line pass beneath the historic Rock Creek Cemetery. Specifications precluded drilling from the surface and specified horizontal drilling and grouting in conjunction with short-segment mining by the New Austrian Tunneling Method (NATM) as an additional safeguard.

The grouting contractor proposed an alternative of horizontal directional drilling to install tube-a-manchette pipes over lengths up to 800 ft (244 m) and grouting through the nine-pipe array over the crown tunnel (Blakita and Cavey, 1995). The twin tunnels both had a radial curve and changed elevation by 15 ft (4.6 m) in their length. Borehole gyroscopes were used to conduct periodic alignment surveys. A grout mixture of 50% liquid sodium silicate, 6% organic reactant, 0.1% enhancer and 44% water was used.

JET GROUTING

Jet grouting is a ground modification system used to create in situ cemented geometries of soil known as Soilcrete. There are three traditional jet grouting systems (Fig. 4). Selection of the most appropriate system is generally a function of the in situ soil, the application, and the physical characteristics of Soilcrete required for that application. However, any system can be used for almost any application providing that the right design and operating procedures are used.

<u>Single-Rod Jet Grouting</u>. Grout is pumped through the rod and exits the horizontal nozzle(s) in the monitor with a high velocity [approximately 650 ft/sec (200m/sec)]. This energy causes the erosion of the ground and the placement and mixing of grout in the soil. Single-rod jet grouting is generally less effective in cohesive soils.

<u>Double-Rod Jet Grouting</u>. A two-phase internal rod system is employed for the separate supply of grout and air down to different, concentric nozzles. Grout is used for eroding and mixing with the soil. The air shrouds the grout jet and increases erosion efficiency. The double-rod system is more effective in cohesive soils than the single-rod system.

<u>Triple-Rod Jet Grouting</u>. Grout, air and water are pumped through different lines to the monitor. High velocity coaxial air and water form the erosion medium. Grout emerges at a lower velocity from separate nozzle(s) below the erosion jet. This separates the erosion process from the grouting process and yields a higher quality Soilcrete. Triple-rod jet grouting is the most effective system for cohesive soils.

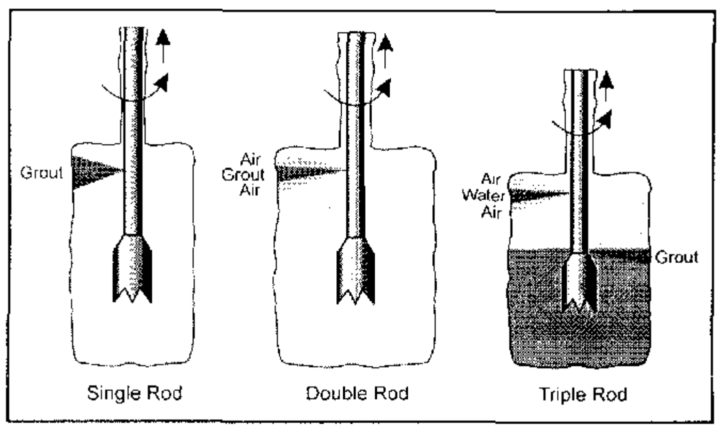

Fig. 4 Jet Grouting Systems

Since its introduction into the United States in 1987, approximately 150 projects have been successfully completed by the jet grouting system. The major applications have been for underpinning, excavation support and groundwater control. This latter application includes horizontal slab construction for bottom sealing and, as of 1997, this is the only proven method of forming a horizontal cut-off barrier.

Prior to production grouting, every injection location was pre-drilled to provide an accurate, top of clay elevation. Jet grouting was performed by rotary hydraulic drilling and grouting of alternate locations in a single-shift in order to allow the fresh Soilcrete to initially cure prior to grouting adjacent columns. Given that the site investigation had confirmed the thickness of the existing natural clay stratum in the target grout zone to be a minimum 2 ft (0.61 m), a 3 ft (0.91 m) thickness of jet grouting was required to meet the project requirement of a 5 ft (1.52 m) minimum thickness beneath the entire landfill (Fig. 6). At each column location, the double system drill rod was advanced to full depth and grouting initiated to cut and grout a 3 ft (0.91 m) lift. The drill rod was then advanced through the initial lift and a secondary cut made to ensure near complete replacement of the waste material. Spoil material created by the process was ejected from the drill annulus, and temporarily contained in preparation for subsequent permanent, on-site disposal.

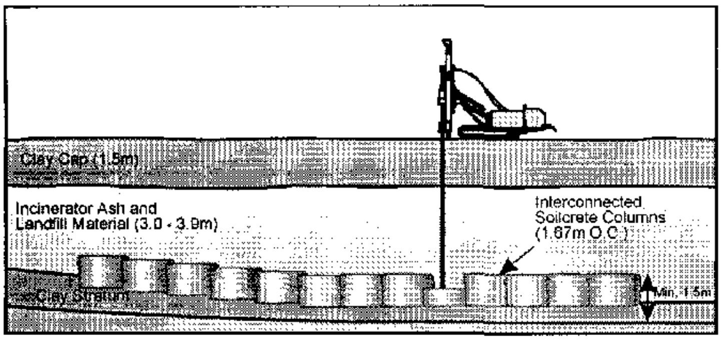

Fig. 6 Jet Grouting Construction Profile

In order to verify the consistency of the fully grouted zone, Cone Penetrometer Testing (CPT) was performed at interstitial points throughout the grouted area. Evaluation of CPT results confirmed that the grouting program had achieved a high percentage of replacement and that a minimum 3 ft (0.91 m), low permeability grout zone had been achieved at the bottom of the landfill, directly atop the thin, underlying natural clay stratum (Furth, et al., 1996).

SOIL FRACTURE GROUTING

Developed in Europe, Soilfrac Grouting is the injection and hydrofracturing with grout slurry of the soil between the foundation to be controlled and the process causing the settlement. Grout slurry is forced into fractures, thereby causing an expansion to take place, counteracting the settlement that occurs or producing a controlled heave of the foundation. Multiple injections and multiple levels of fractures create a complementary reinforcement zone.

CASE HISTORY - NEW ST. CLAIR RIVER RAIL TUNNEL

Completed in 1890, the existing rail tunnel between Sarnia, Ontario and Port Huron, Michigan was considered an engineering marvel of the time. However, its diameter is too small to accept modern, double-stack container cars. It was therefore elected to build a new tunnel with a 50% greater diameter. This 30 ft (9.2 m) diameter, concrete segment-lined tunnel has a length of 5,985 ft (1,824 m), 1,970 ft (600 m) of which lies beneath the St. Clair River bed. The tunnel was bored through the St. Clair till, a hard-to-soft silty clay (Kramer, et al. 1994; Drooff, et al., 1995). Mined from the Canadian side, the tunnel passed beneath a petro-chemical refinery, where some structures required protection from settlement, particularly a three-story research building. Settlement calculations estimated a maximum centerline surface settlement for the research building of 5.3 inches (135 mm). Six protective methods were considered for the research building.

1. Sub-surface barrier wall
2. Ground replacement
3. Underpinning
4. Jacking
5. Structural strengthening
6. Compensation (Soil Fracture Grouting) Grouting

After review of the alternatives, compensation, or soil fracture, grouting was selected. In order to protect the portion of the building within the zone of influence of the tunnel settlement, it was decided to place an array of horizontal grout pipes. These pipes were placed from two 32.8 ft (10 m) deep, 11.5 ft (3.5 m) diameter shafts. This allowed the sleeve port pipes for the grout injection to be placed midway between the bottom of the building foundation and the crown of the tunnel. One of the keys to a successful soil fracture grouting project is a precise surveying system so that any movement is instantaneously noted. For this project, an electro-leveling system was used. Developed by the aircraft industry, this system has an accuracy of 0.004 inches (0.10 mm). Beams, 6.6 ft (2 m) long, were attached to all the building's foundations to provide instantaneous movement monitoring. It was determined to precondition the soil and ascertain which grout port affected which foundation by pre-lifting the building by 0.2 inches (5 mm). The 30 ft (9.2 m) diameter earth pressure balance TBM took 108 hours to mine under the building, with a maximum of 0.15 to 0.24 inches (4 to 6 mm) of settlement recorded. After 12 months, the center of the building is down about 0.28 inches (7 mm) from its original elevation.

SUMMARY

Led by specialty contractors, new and refined soil improvement techniques continue to evolve to satisfy the many challenges of the design, construction, and environmental industries. It is hoped that this case history conference and, specifically, the papers' case histories will advance the State of the Practice of Soil Improvement.

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